Searches for Higgs Decays into New Light Bosons

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University of Massachusetts Amherst

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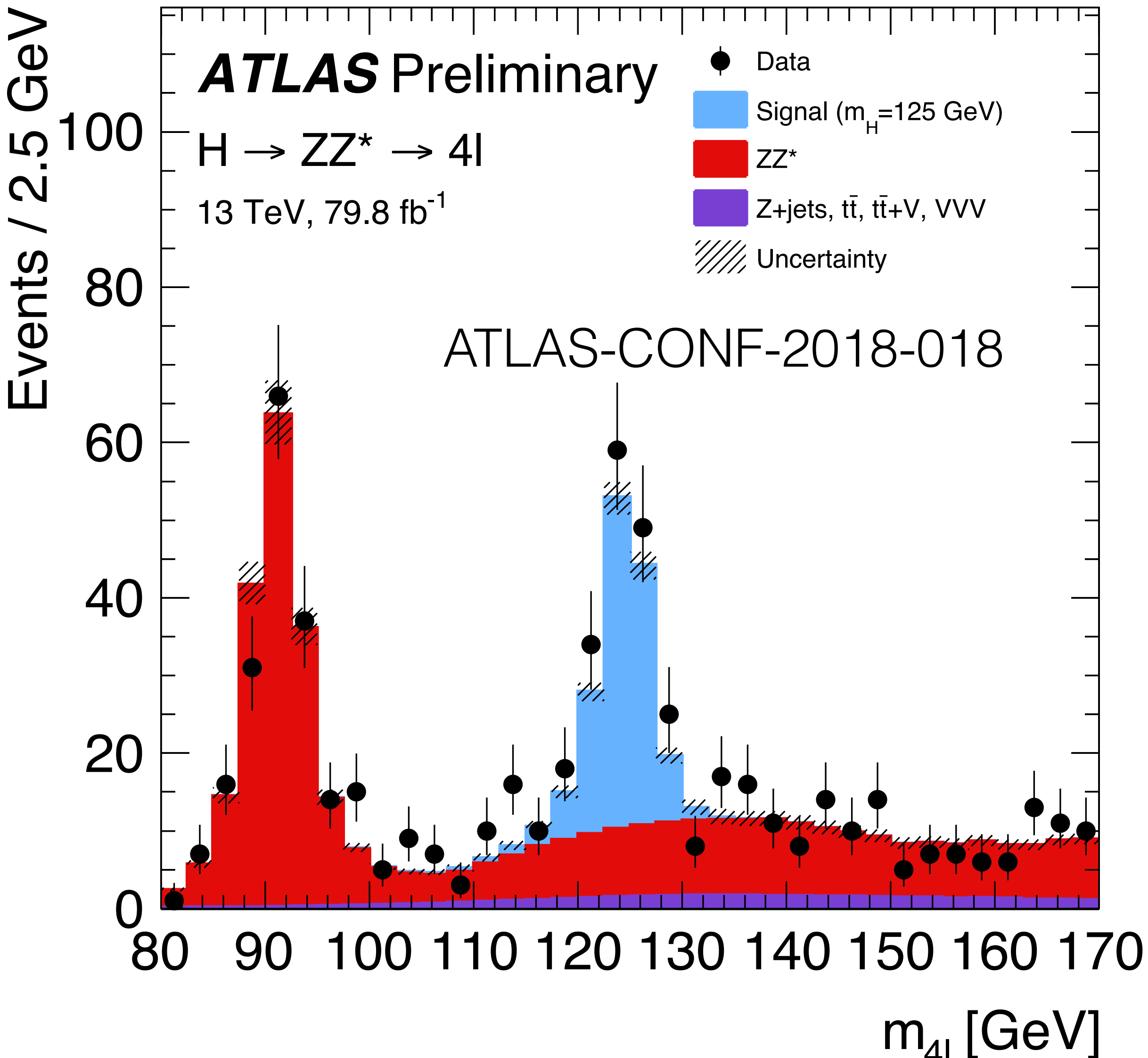
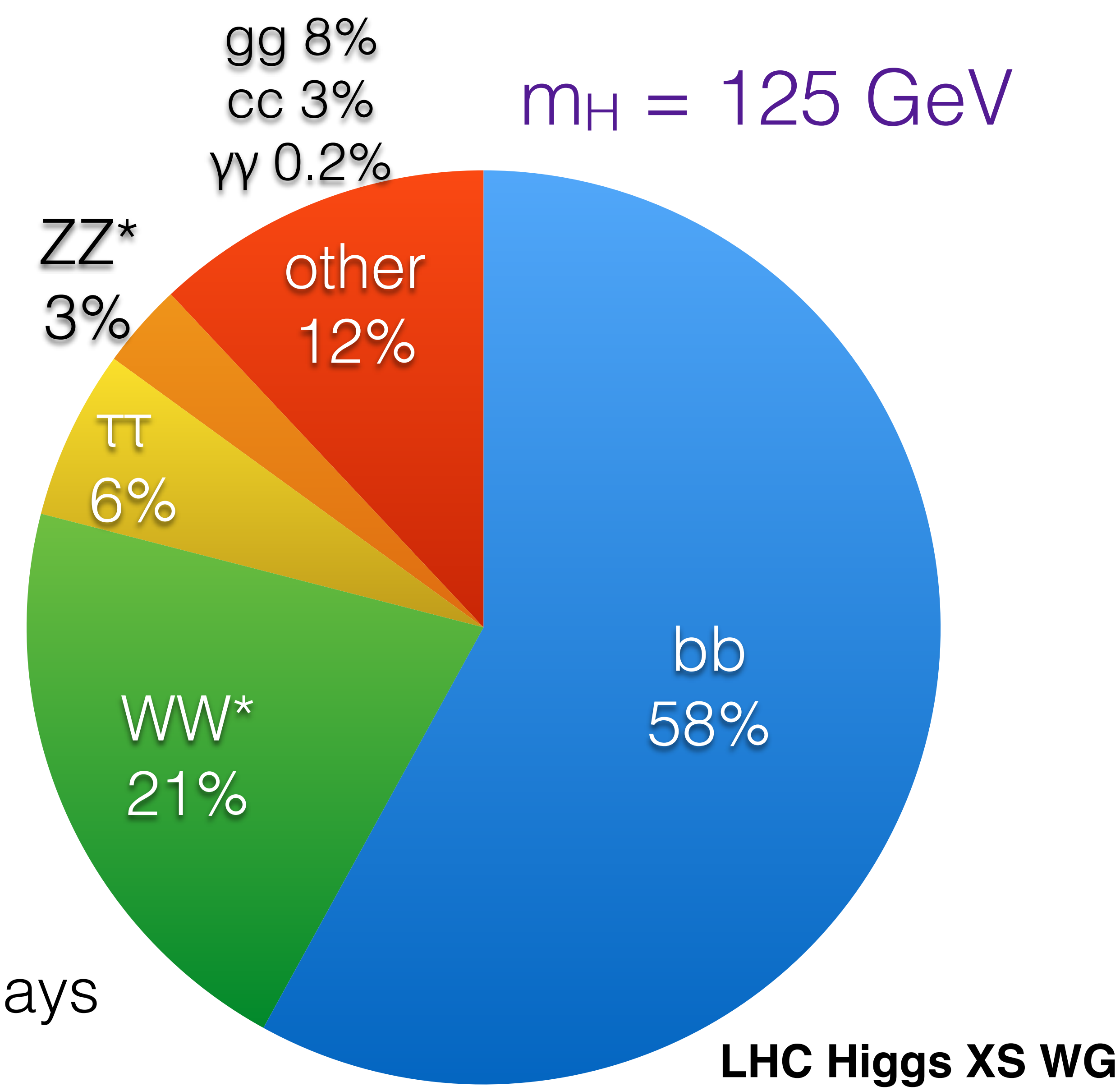
January 16th, 2019

Higgs Boson Decays



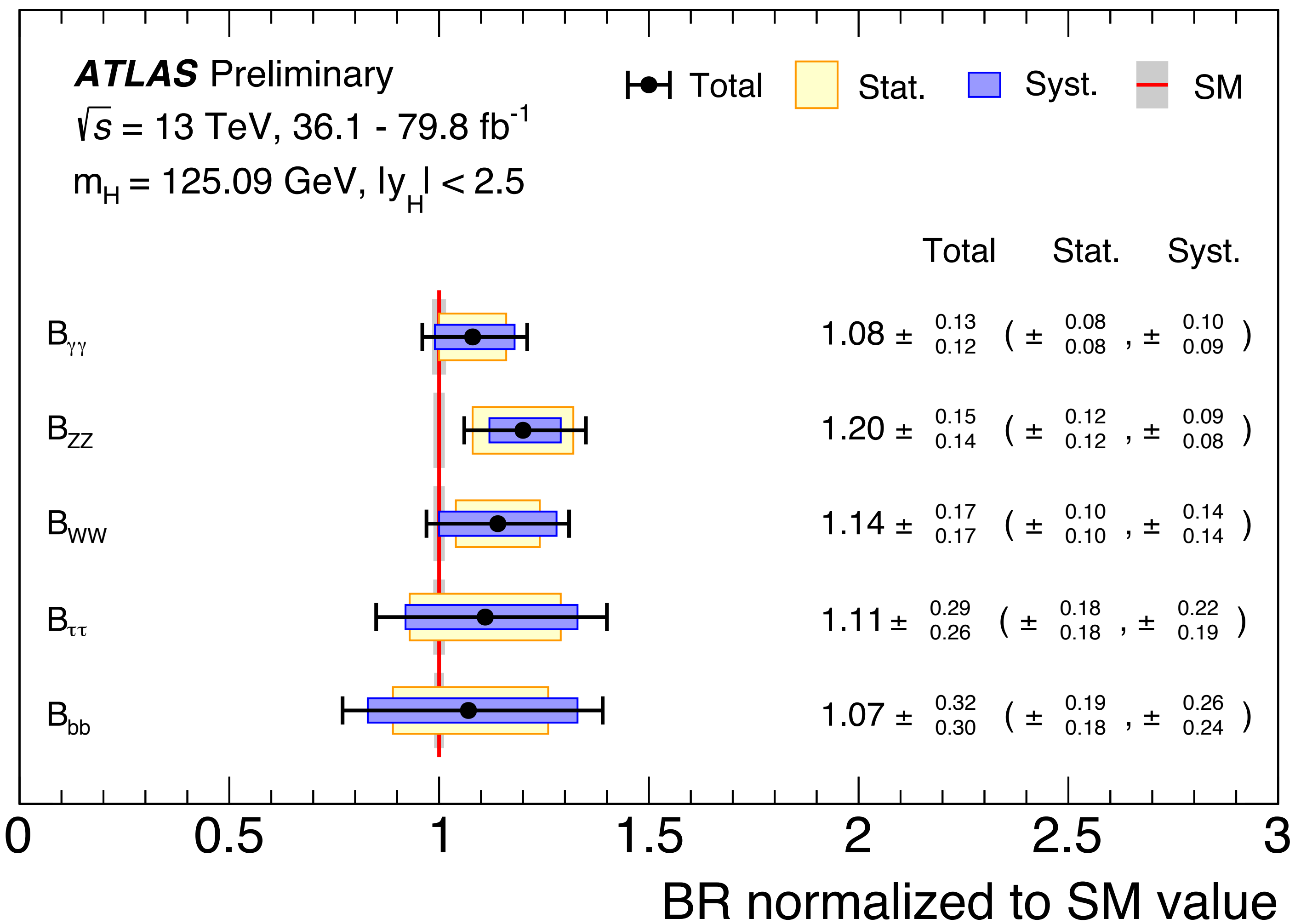
Higgs boson branching ratios in the SM



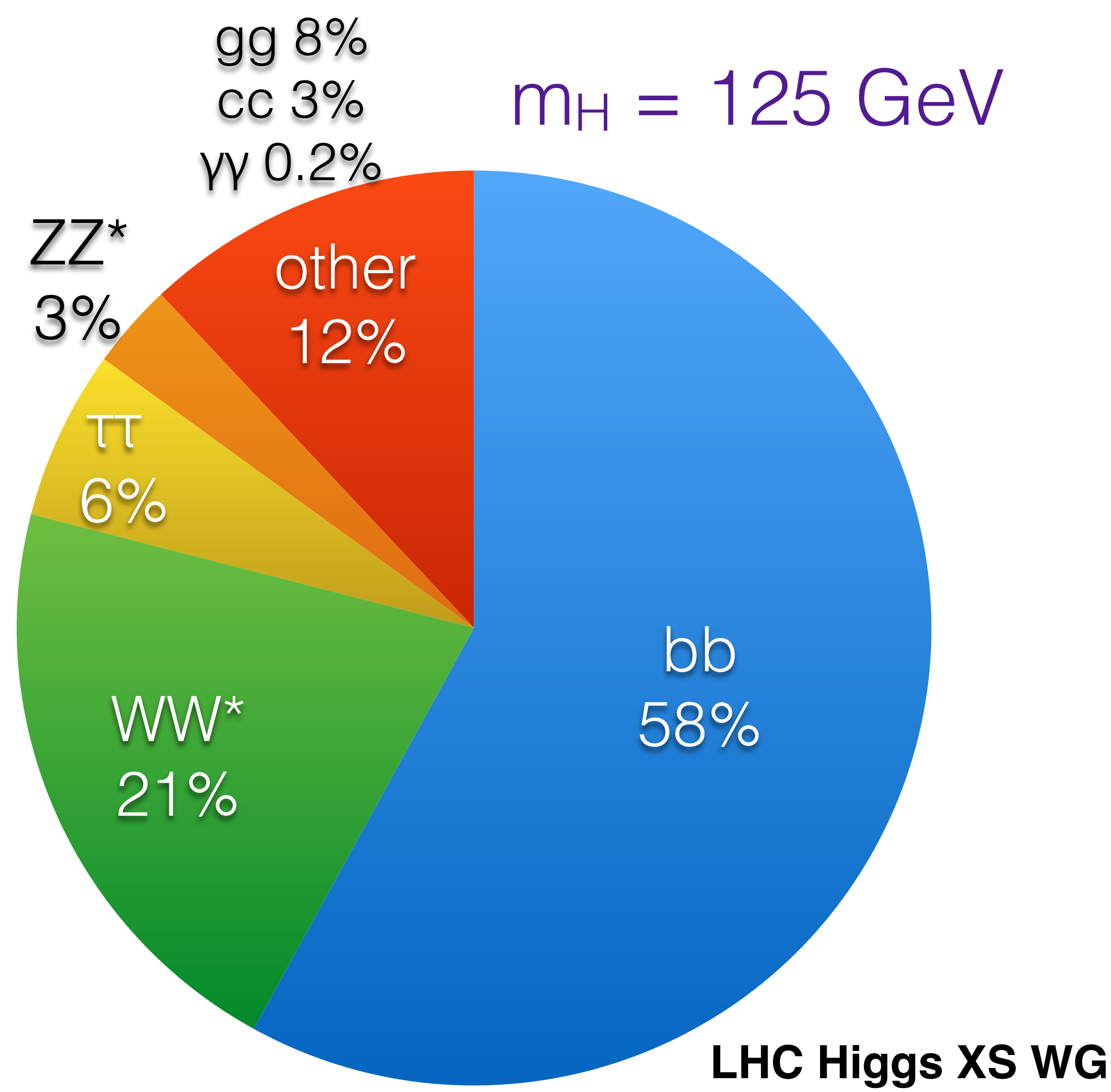
- Higgs boson observed as a resonance in several decay channels
- Many BSM theories predict additional decays
  - Higgs Portal models of dark matter
  - Theories of Neutral Naturalness
  - Models with an extended Higgs sector e.g. 2HDM+S, NMSSM

SM Higgs Boson Decays

ATLAS-CONF-2018-031



Higgs boson branching ratios in the SM

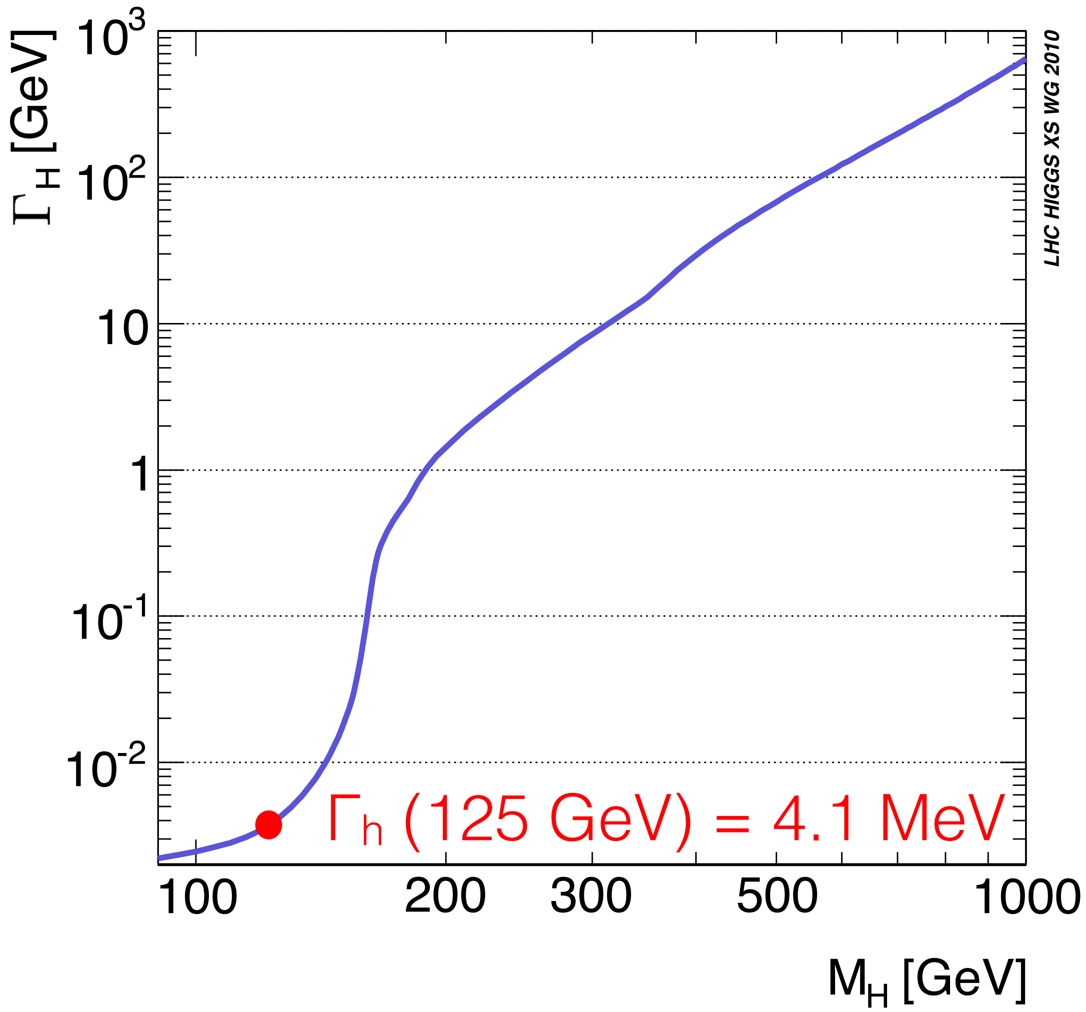


Available measurements are only able constrain BSM decays to ~ < 25%

Exotic Higgs Decays

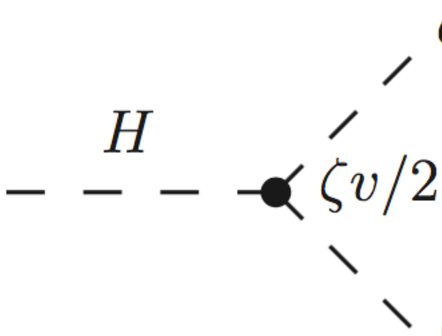
Higgs decays in the SM are suppressed by small Yukawa couplings, loops, or multi-body phase space

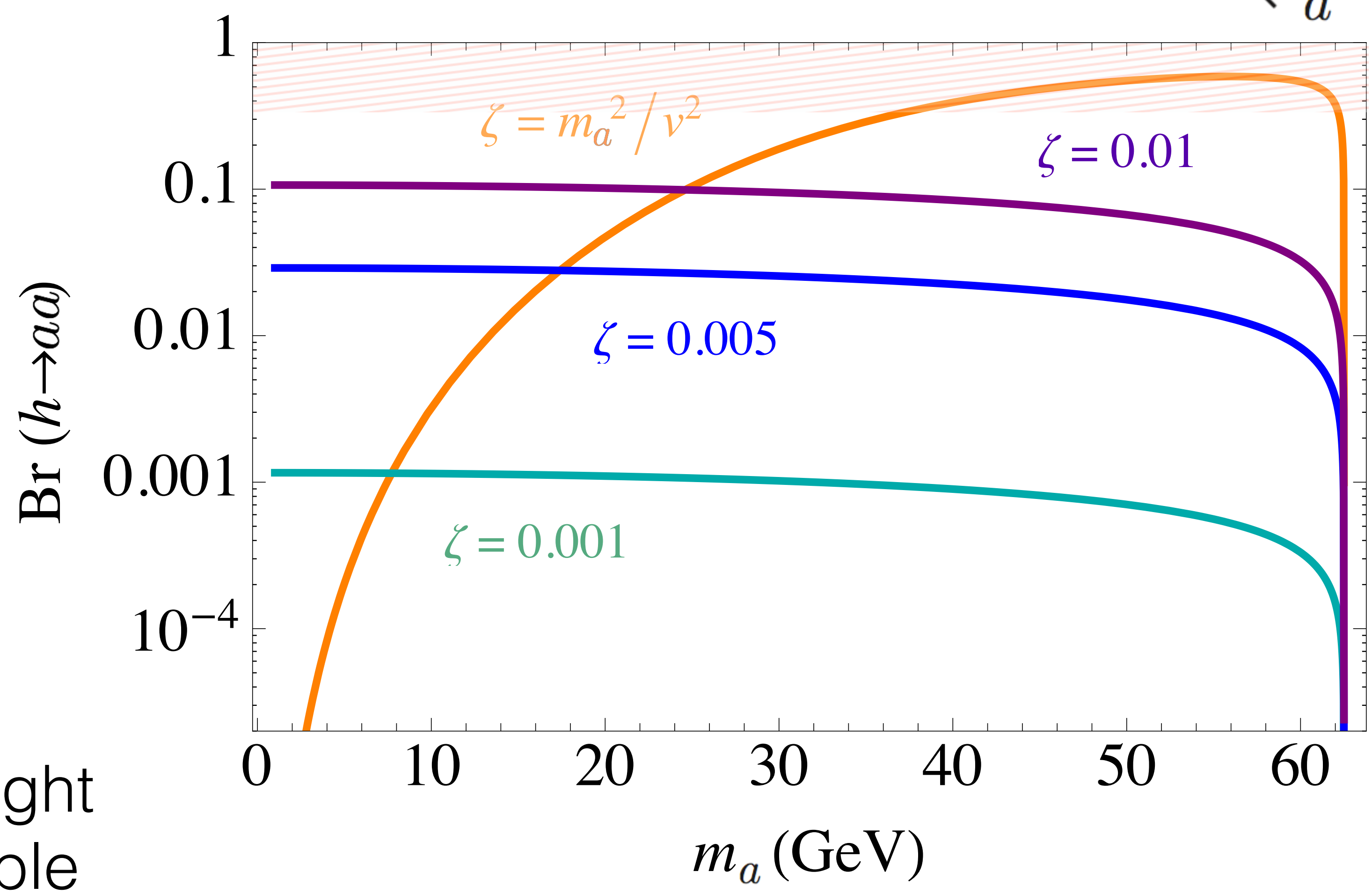
Dominant decay to b-quarks suppressed by tiny coupling y_b ~0.017



even a small coupling to another light state can open up additional sizable decay modes

Simple example: one new scalar



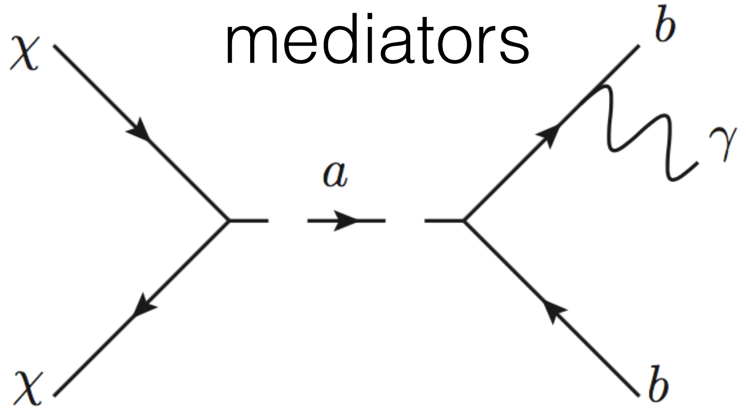


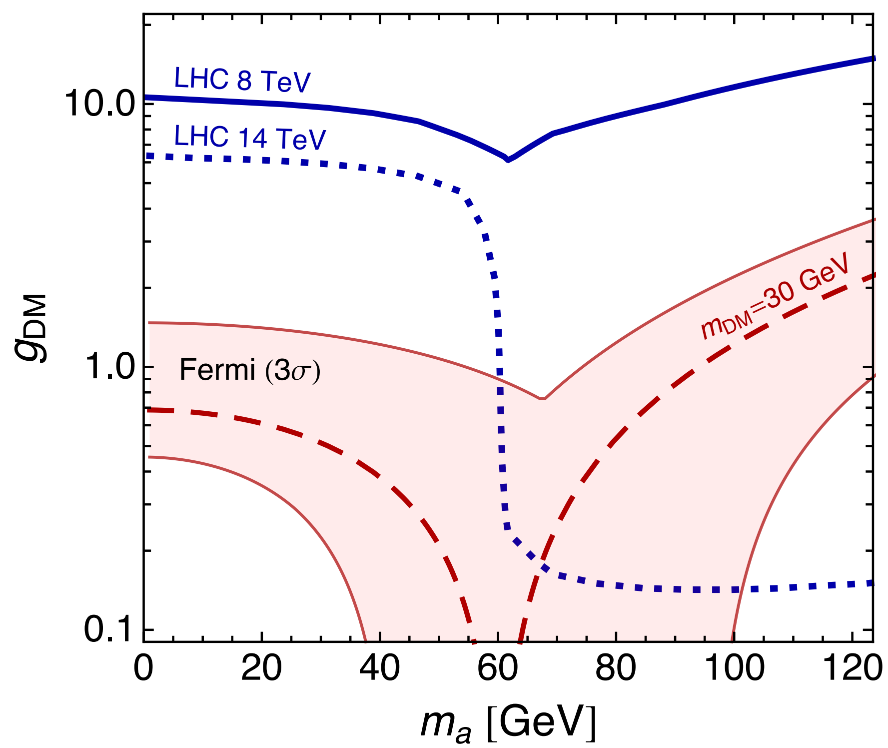
Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

Motivations for New Light States

Dark Matter

Light (pseudo-)scalars as mediators

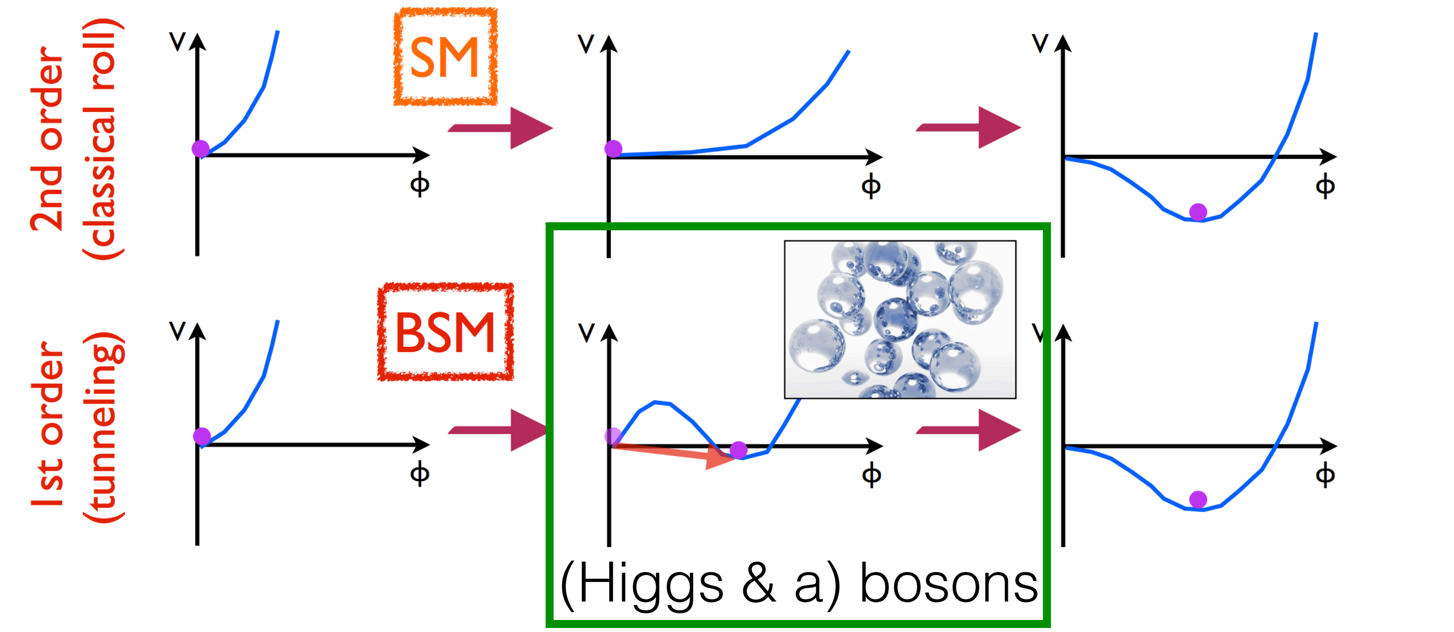




Fermi-LAT, arXiv:1511.02938
C. Boehm et al. arXiv:1401.6458

EW Baryogenesis

EW symmetry breaking as a 1[st] order phase transition



Profumo, Ramsey-Musolf, Shaughnessy, JHEP 0708, 010 (2007) arXiv: 0705.2425, and many others

Naturalness

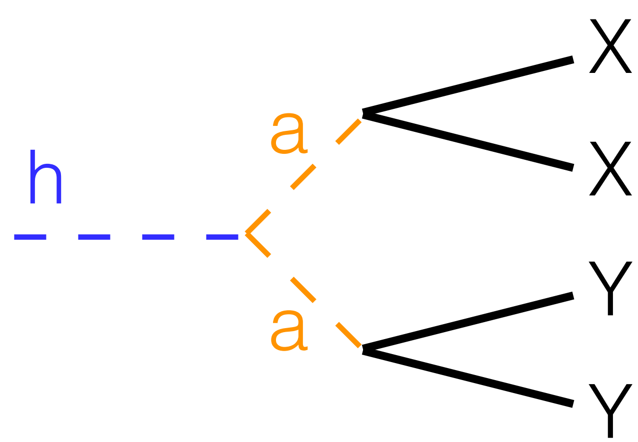
Chacko, Goh, Harnik 2005
Craig, Katz, Strassler, Sundrum 2015

Strong CP problem

More on axions later…

BSM Decays and Couplings

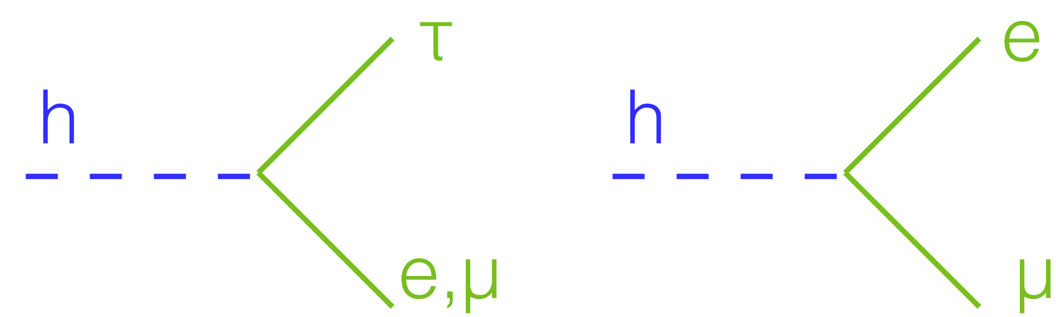
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

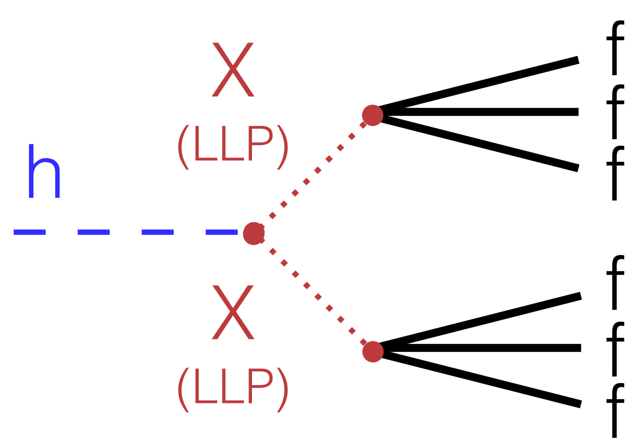
lepton decays



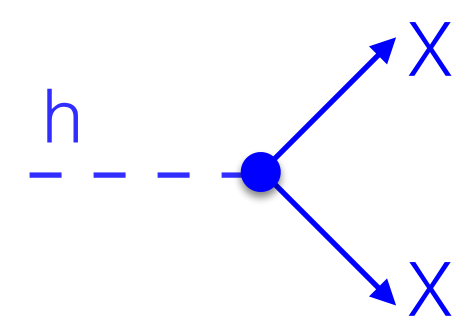
FV in quark sector also considered

Long lived particles (LLP)

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



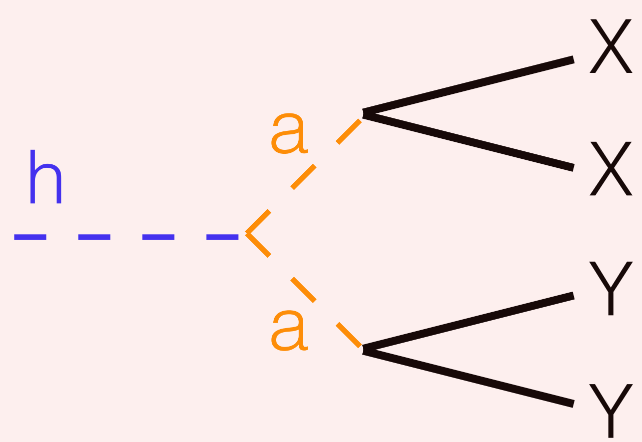
Invisible Decays



X gives E_T^{miss} signature

BSM Decays and Couplings

Higgs Decays to new particles



X and Y are SM particles

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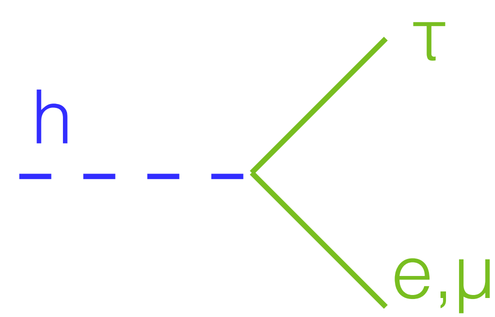

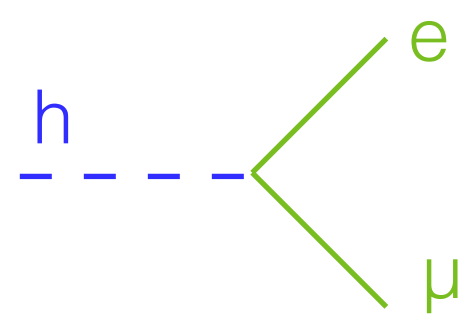

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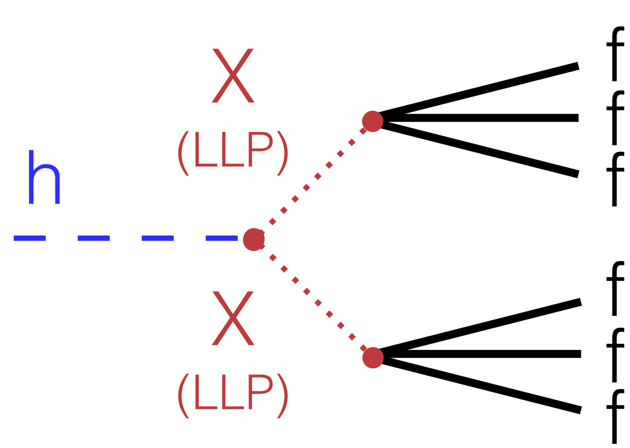
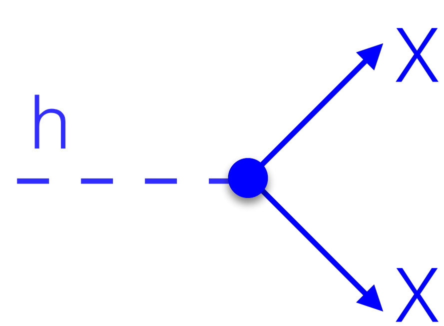
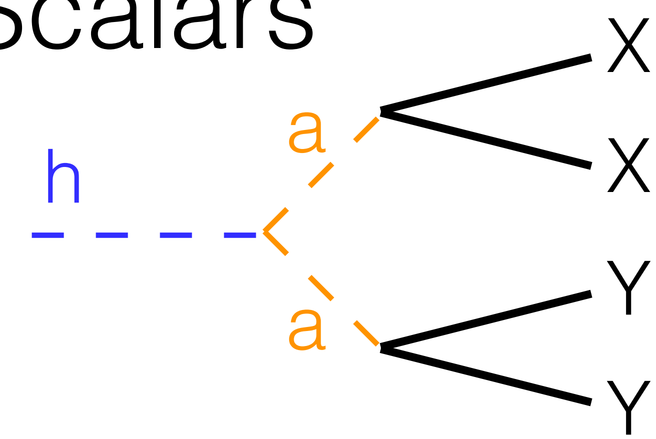


Invisible Decays

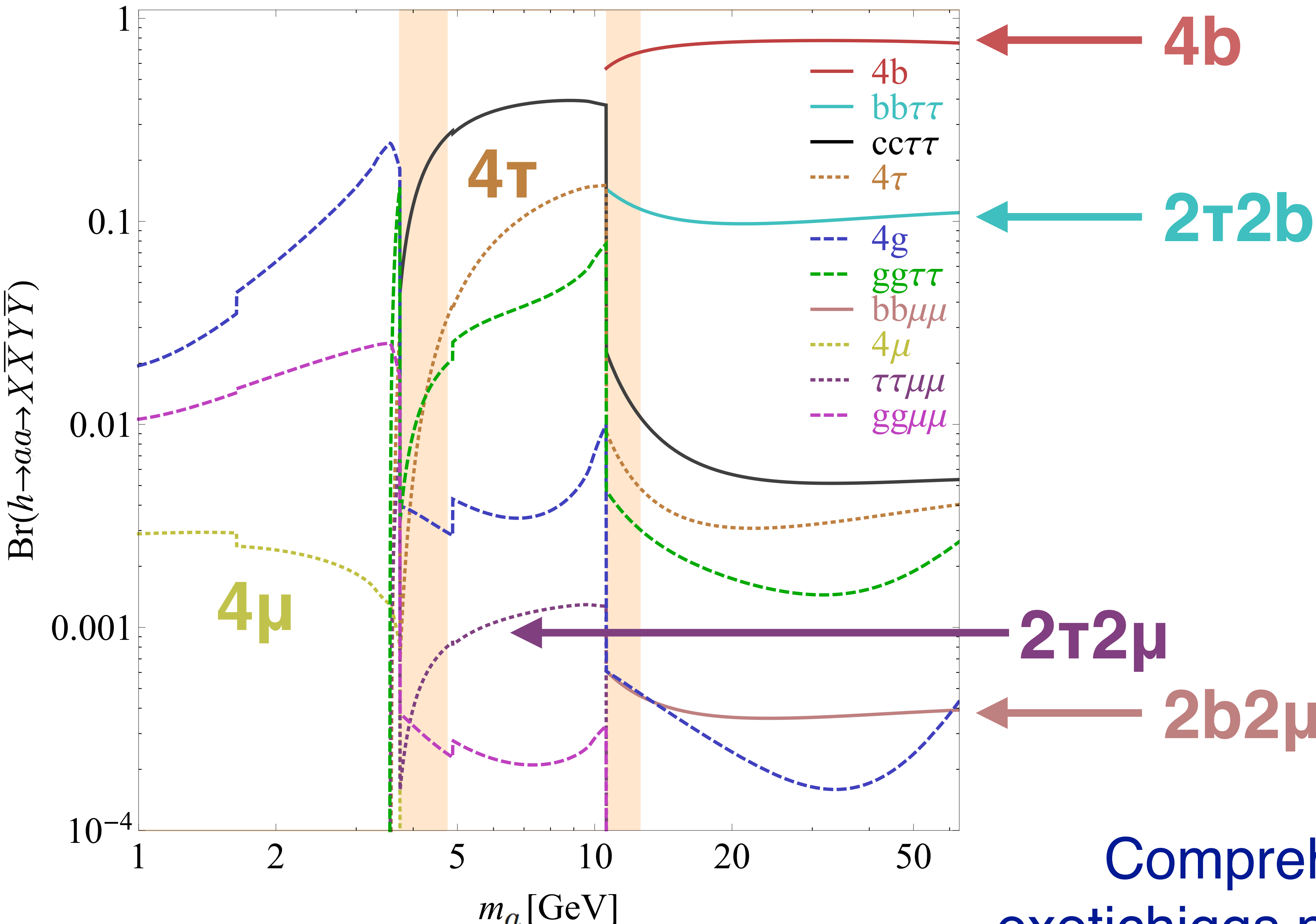


X gives E_T^{miss} signature

Higgs Decays to Light (Pseudo-)Scalars



challenging signatures because decay products are low p_T and may be overlapping



b-jets and taus
largest BR
low S/B

adding muons
small BR
high S/B

pair Br:SM Yukawas

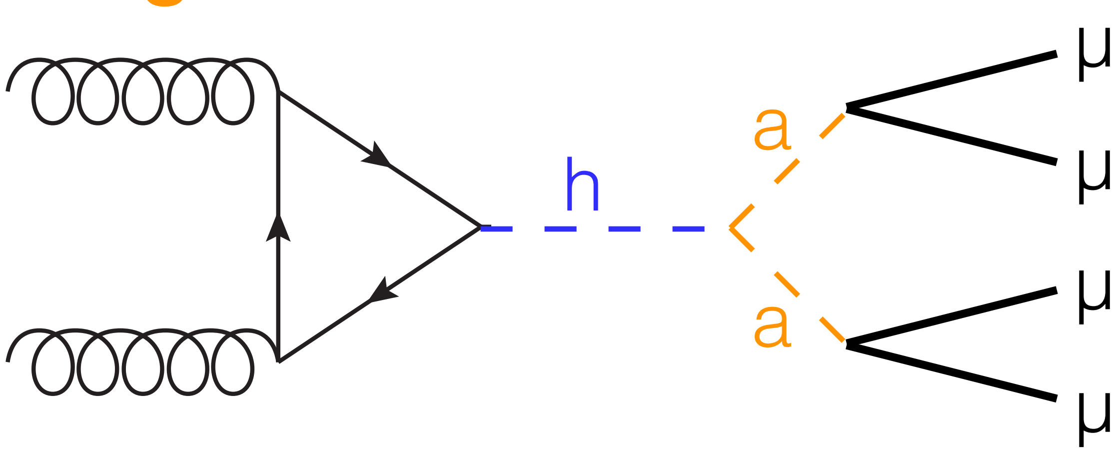
Example benchmark SM+S model

Comprehensive review
exotichiggs.physics.sunysb.edu

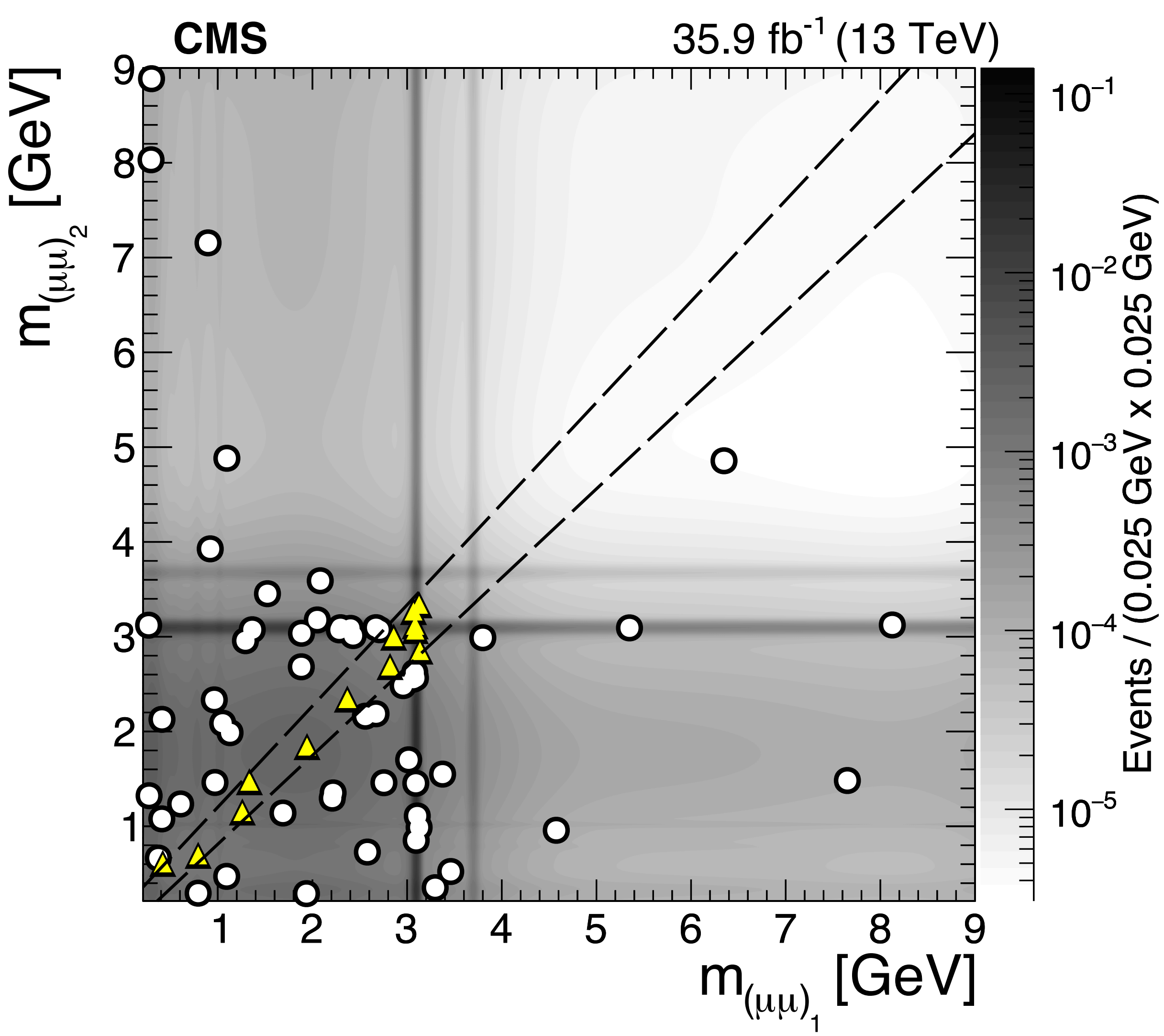
Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

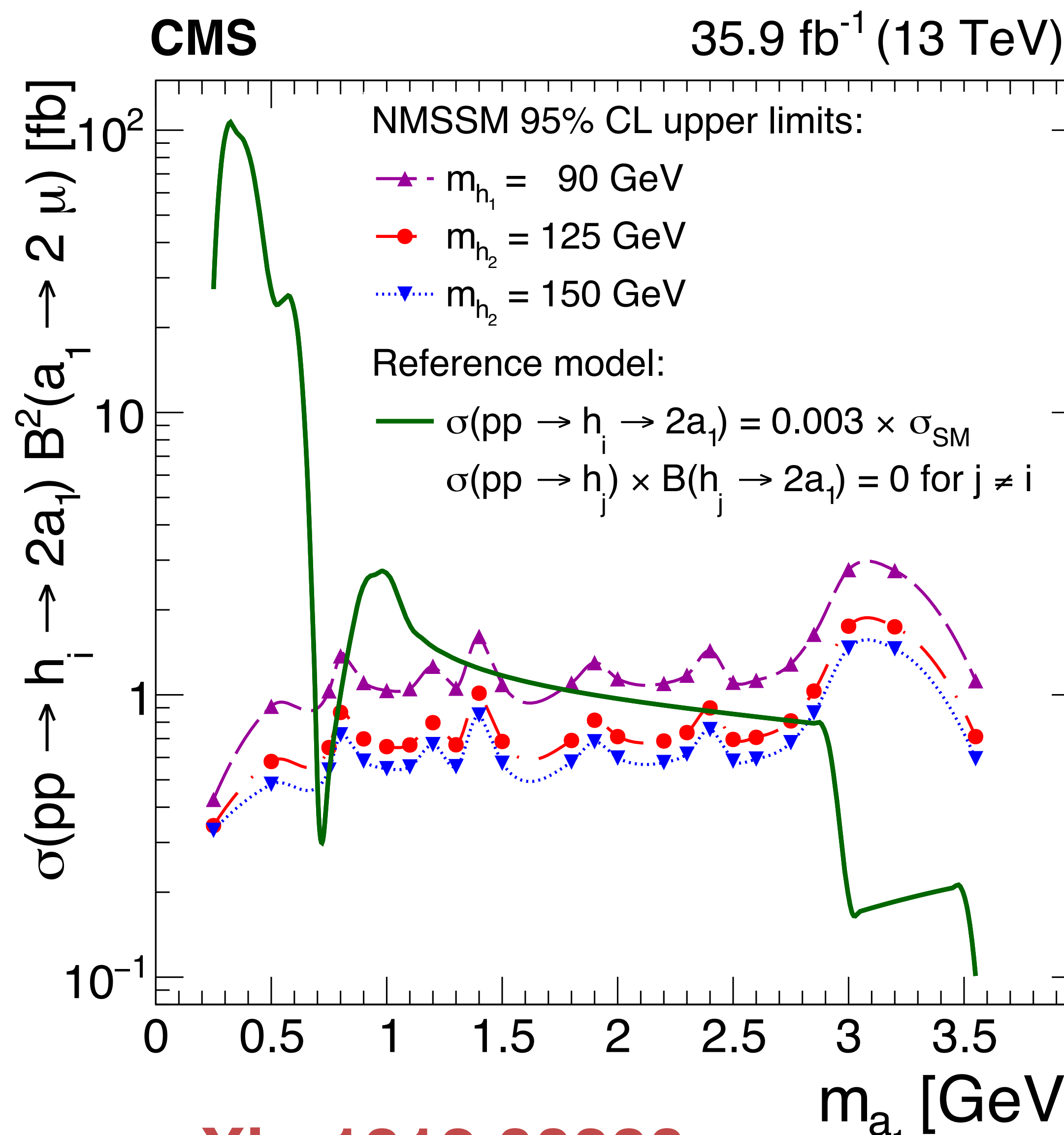
Higgs to Light Scalars: $h \to 2a \to 4\mu$

Signal target $2m_\mu \lesssim m_a \lesssim m_\tau$



- Strategy
  - Events with 4 muons
  - Search for excess in pairs of similar mass $m_{1\,\mu\mu} \sim m_{2\,\mu\mu}$
- Main backgrounds bb and J/Ψ events

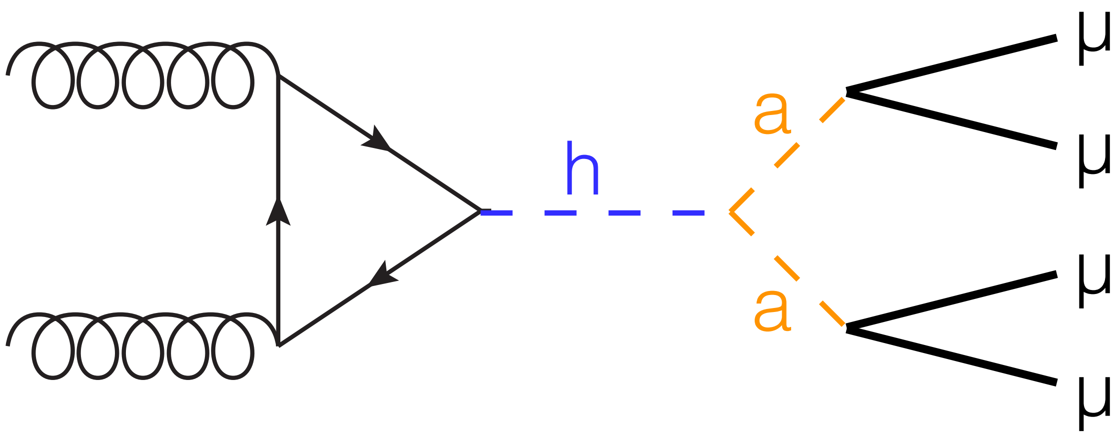




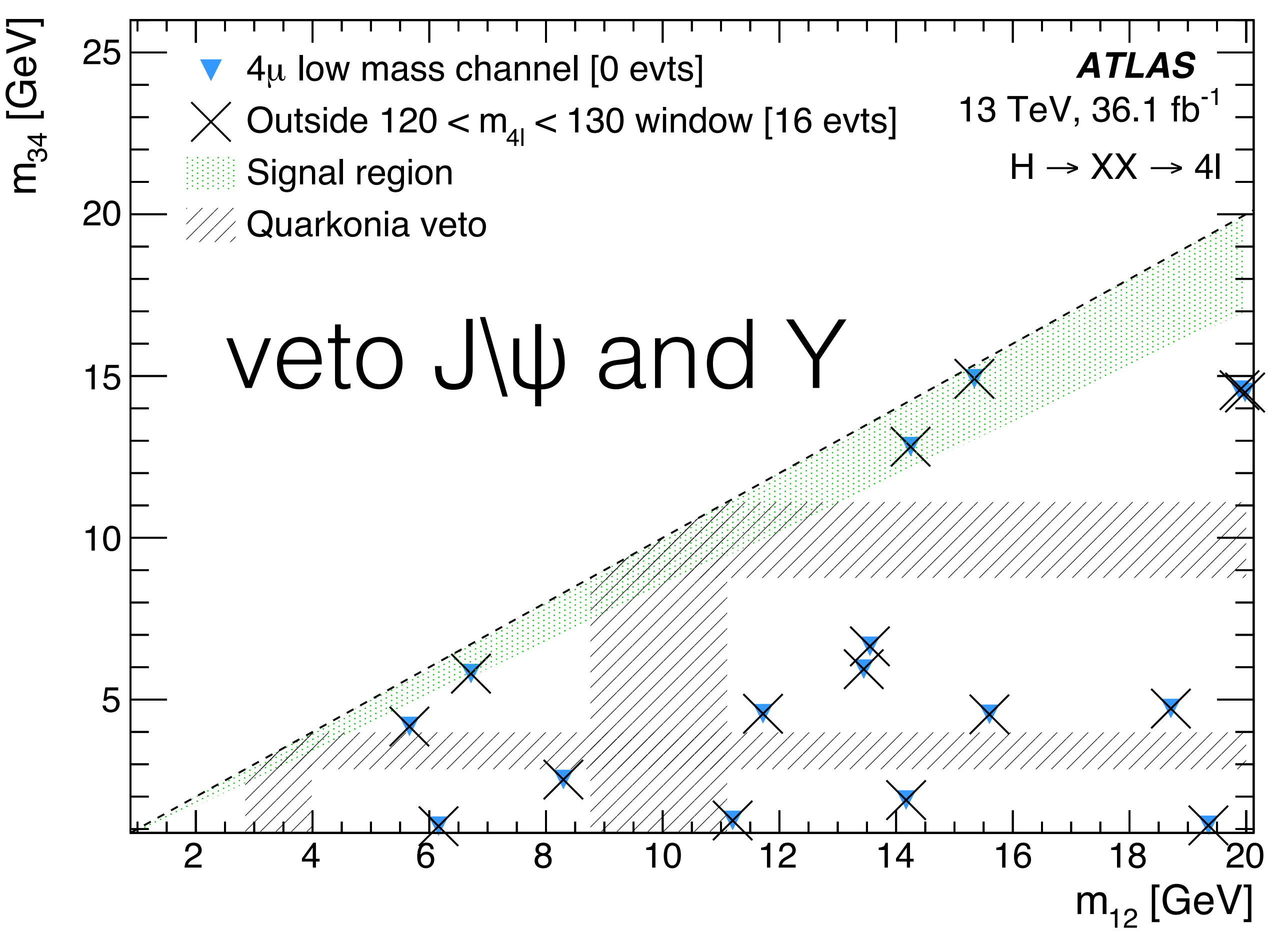
arXiv:1812.00380

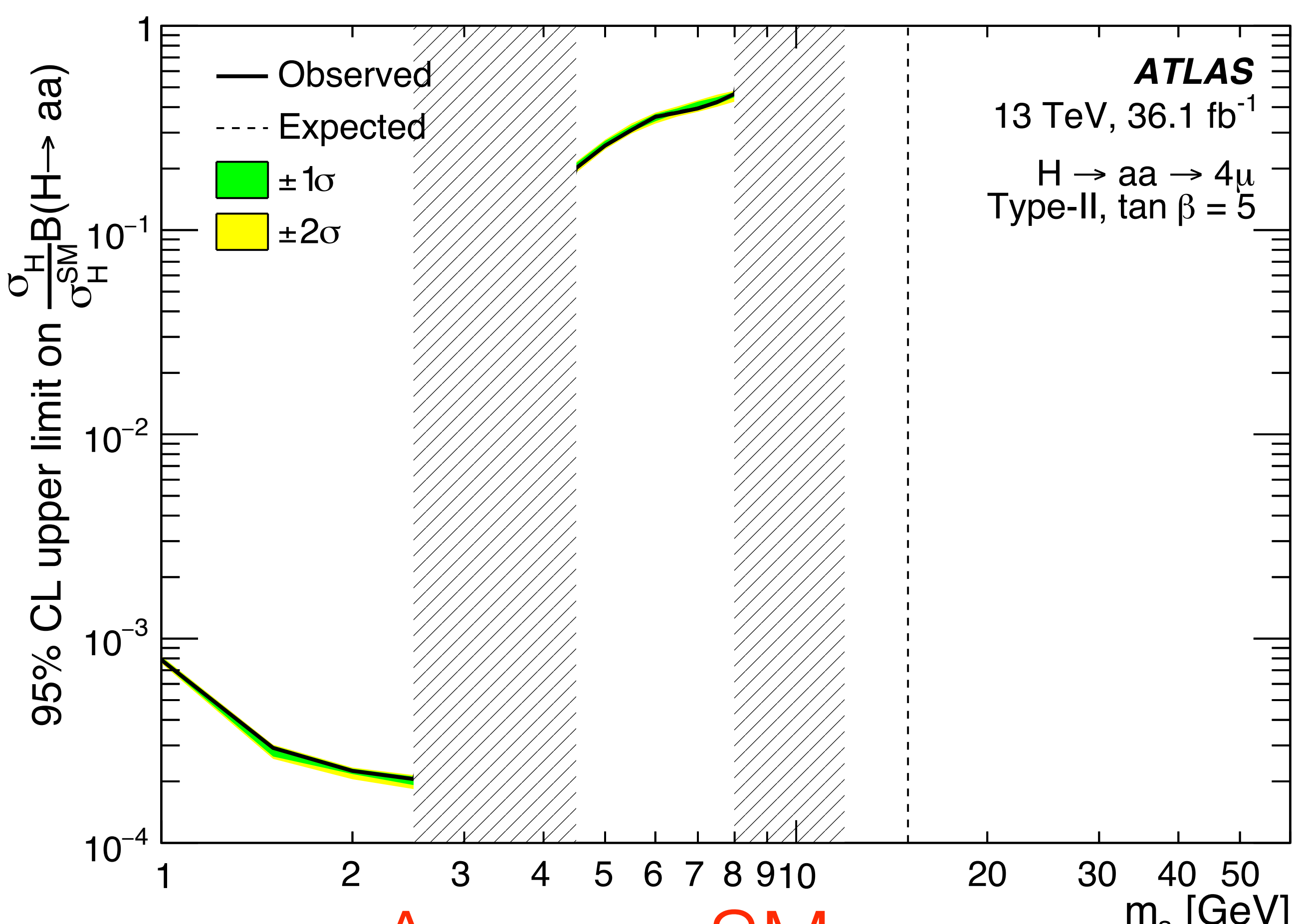
Higgs to Light Scalars: h→2a→4μ

Signal target $2m_\mu \lesssim m_a \lesssim m_h/2$



- Strategy
  - Events with 4 muons
  - Search for excess in dimuon pairs of similar mass $m_{12} \sim m_{34}$ **with $m_{4\mu} \sim m_h$**
- Main backgrounds bb and J/Ψ events & electroweak processes (ZZ, h→ZZ*, etc)



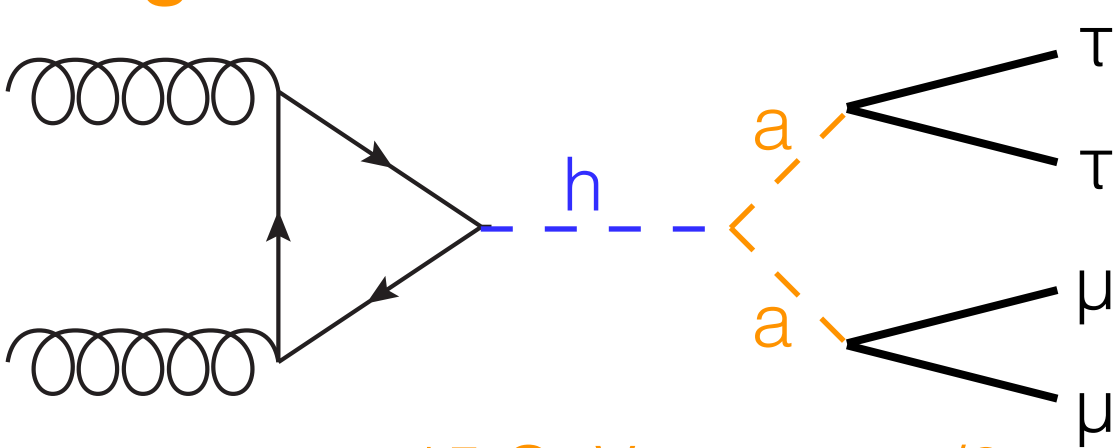


Assume SM σ_h

JHEP 06 (2018) 166 arXiv:1802.03388

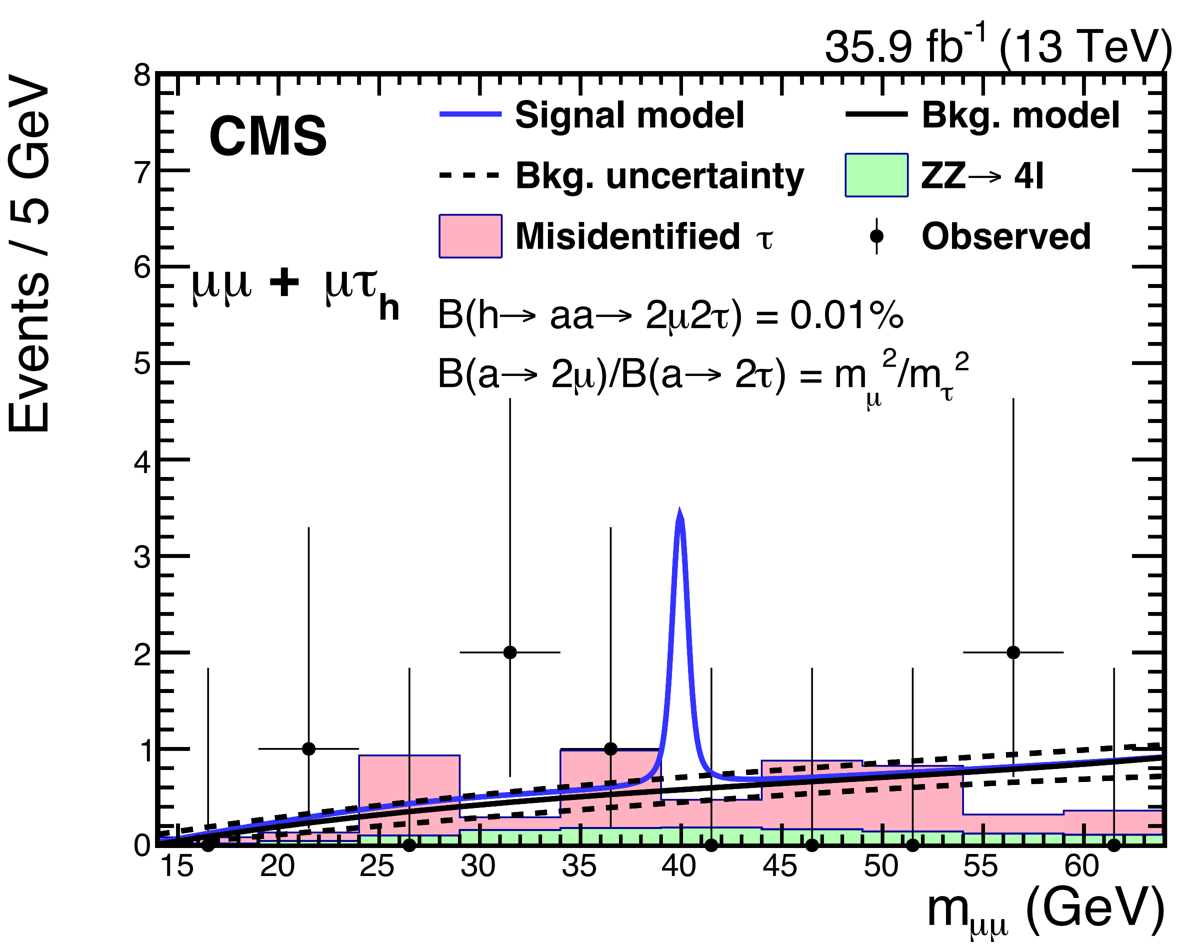
Higgs to Light Scalars: h→2a→2μ2τ

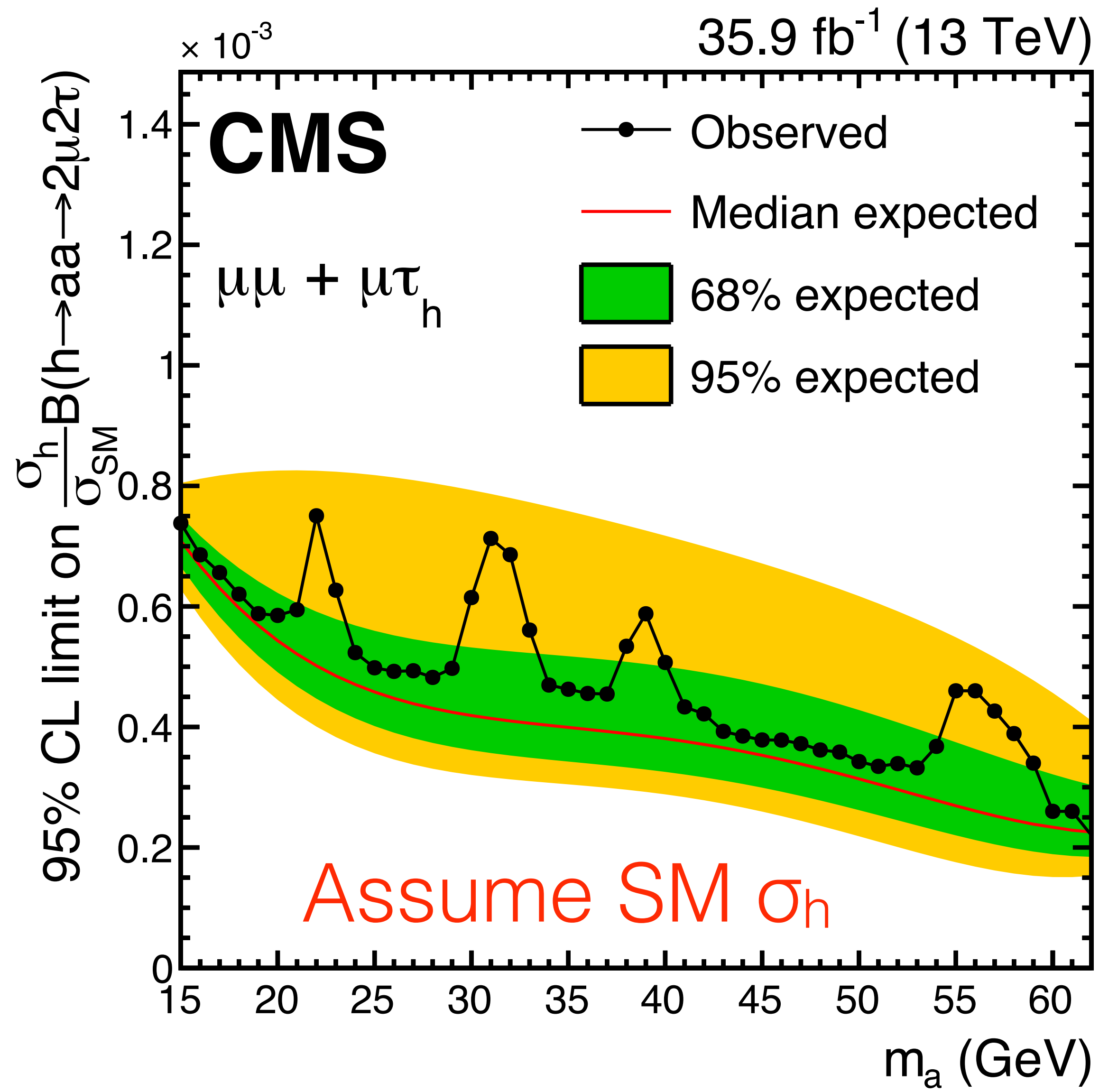
Signal



target 15 GeV ≲ m_a ≲ $m_h/2$

- Strategy
  - Events with 2 muons and 2 taus (e,μ,τ_h)
  - Search for excess in dimuon spectrum
- Main backgrounds misidentified τ & ZZ

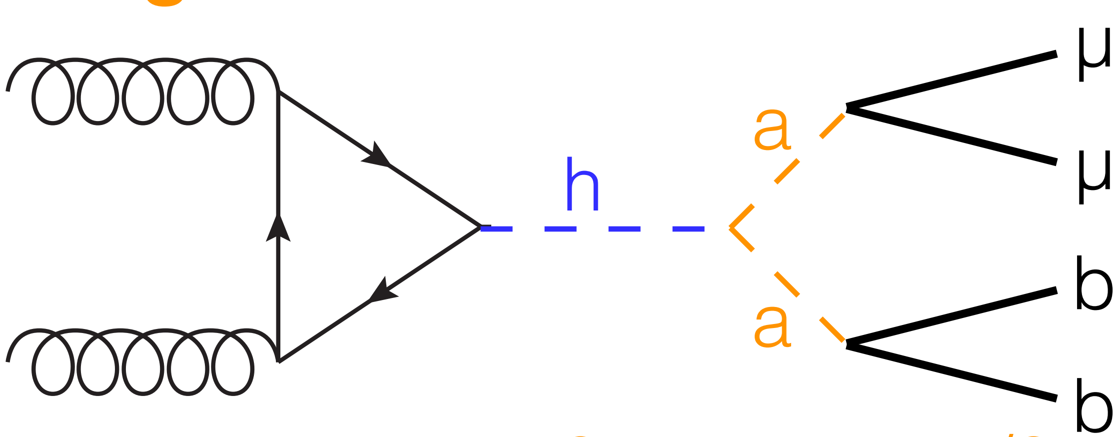




JHEP 11 (2018) 018 arXiv:1805.04865

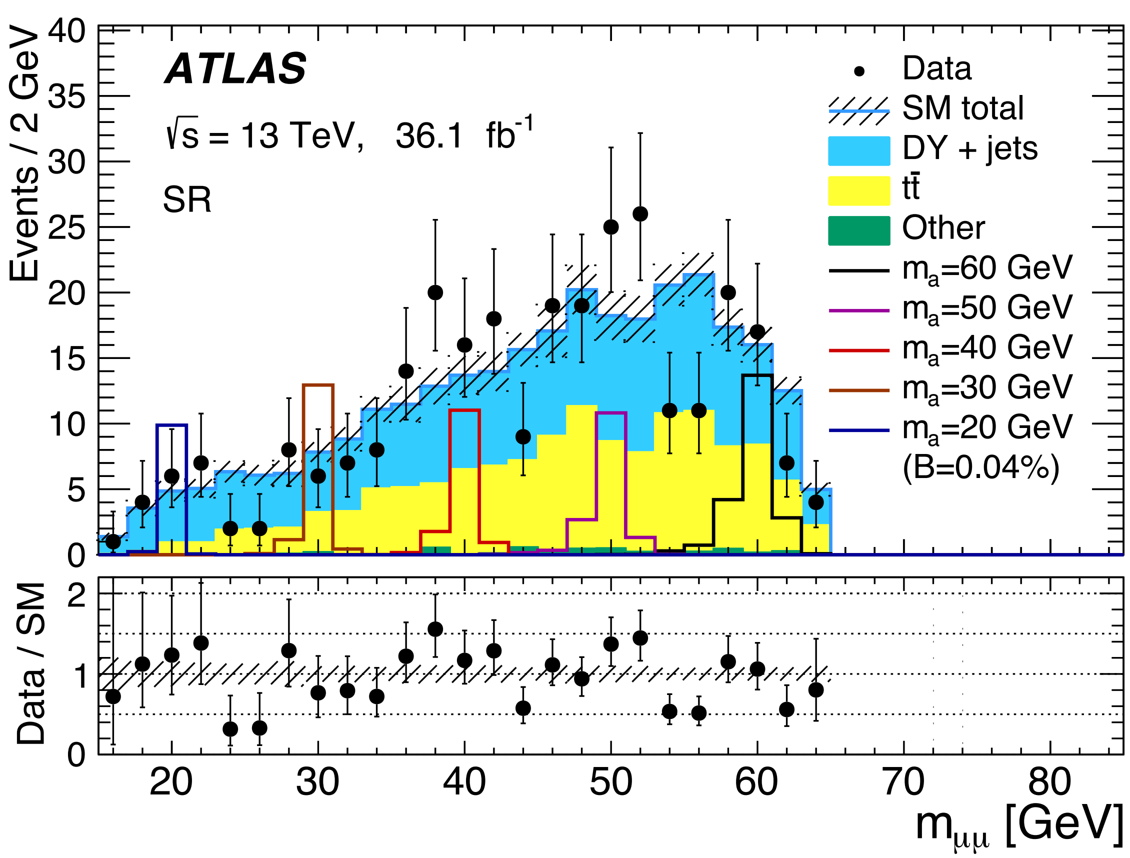
Higgs to Light Scalars: h→2a→2μ2b

Signal

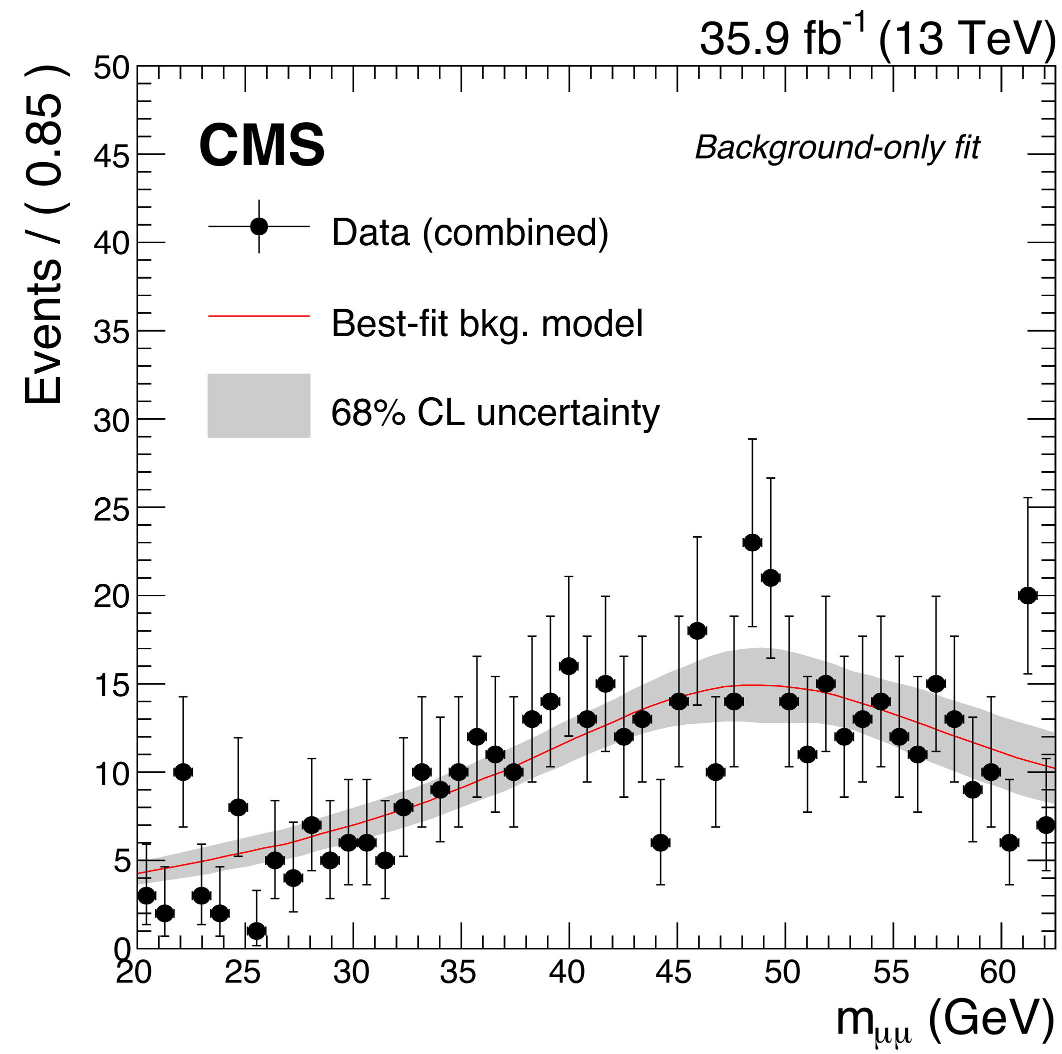


target $2m_b \lesssim m_a \lesssim m_h/2$

arXiv:1807.00539



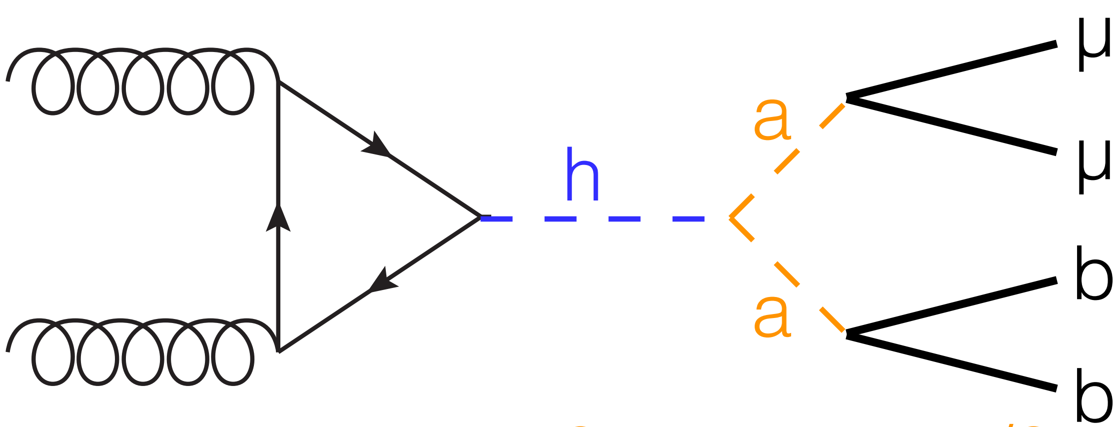
- Strategy
  - Events with 2 muons and 2 b-jets
  - Search for excess in dimuon spectrum
- Main backgrounds Z+jets and tt



arXiv:1812.06359

Higgs to Light Scalars: h→2a→2μ2b

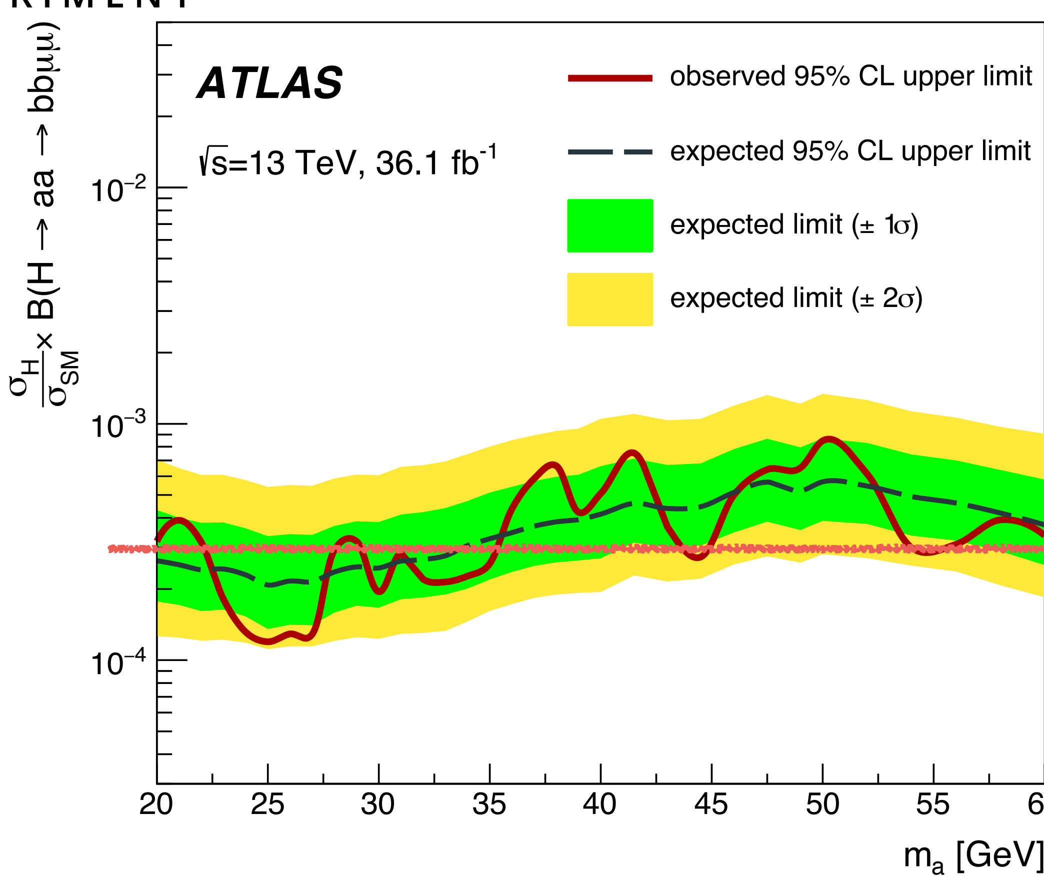
Signal



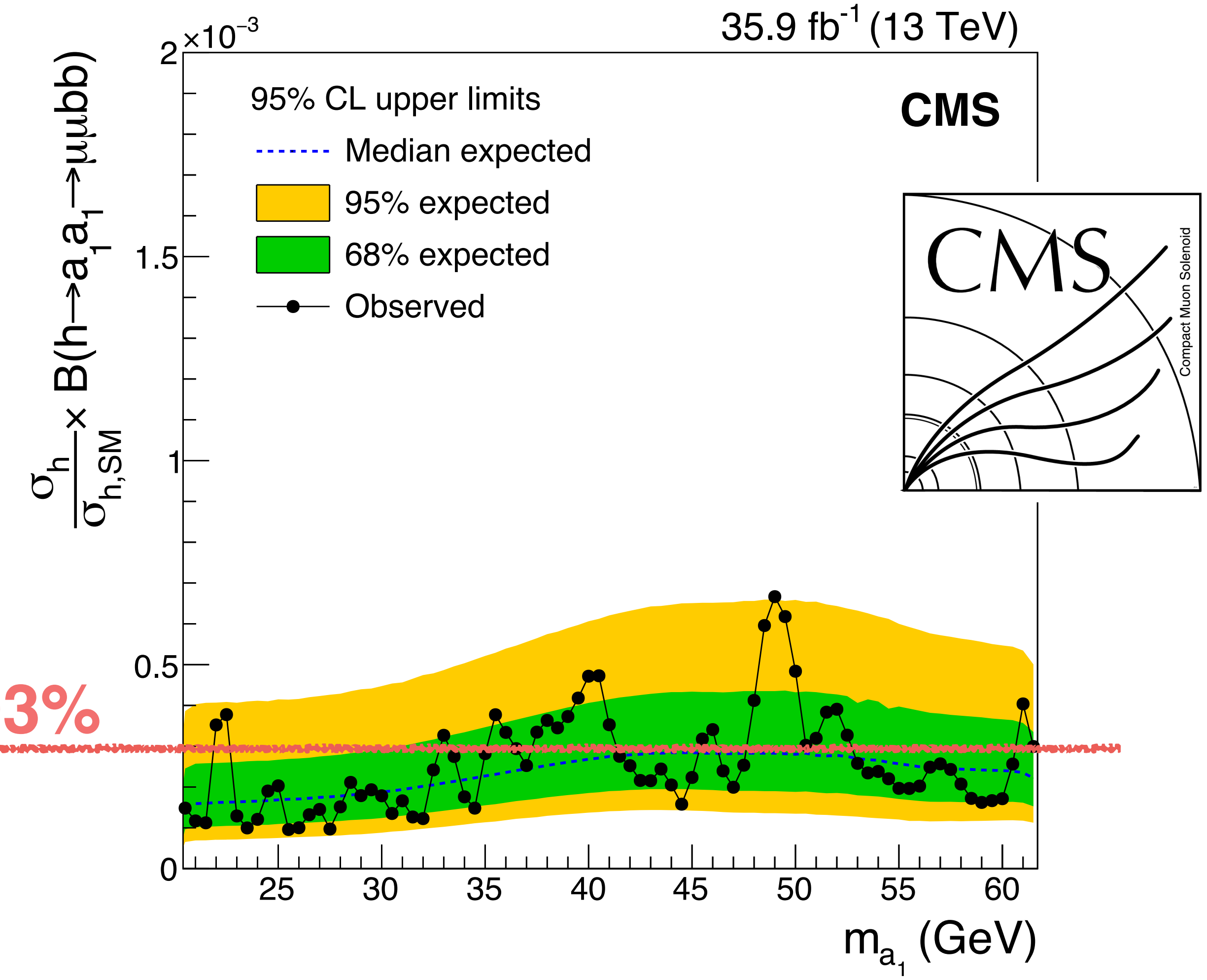
target $2m_b \lesssim m_a \lesssim m_h/2$

- Strategy
  - Events with 2 muons and 2 b-jets
  - Search for excess in dimuon spectrum
- Main backgrounds Z+jets and tt

arXiv:1807.00539



0.03%



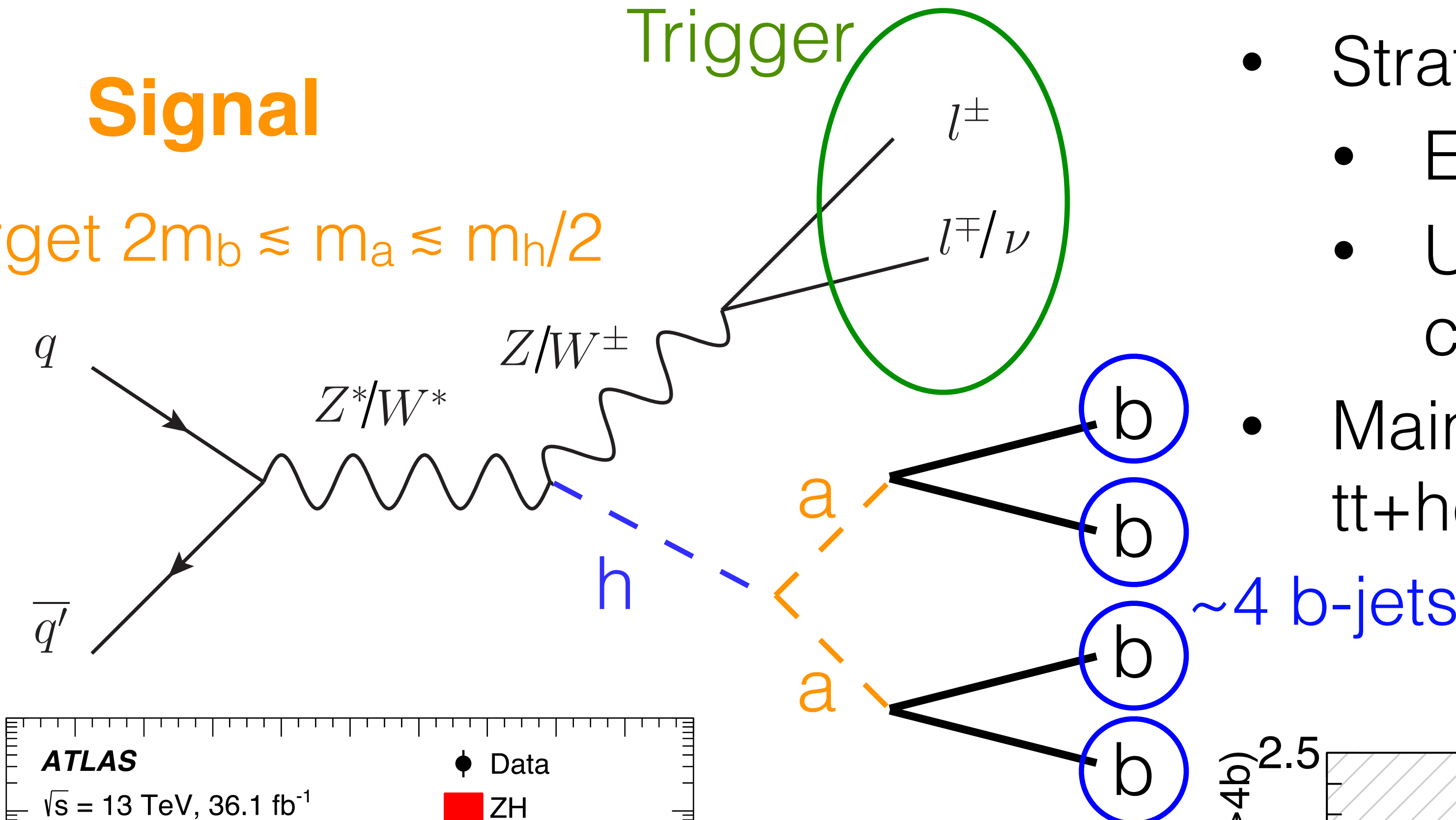
arXiv:1812.06359

Assume SM σ_h

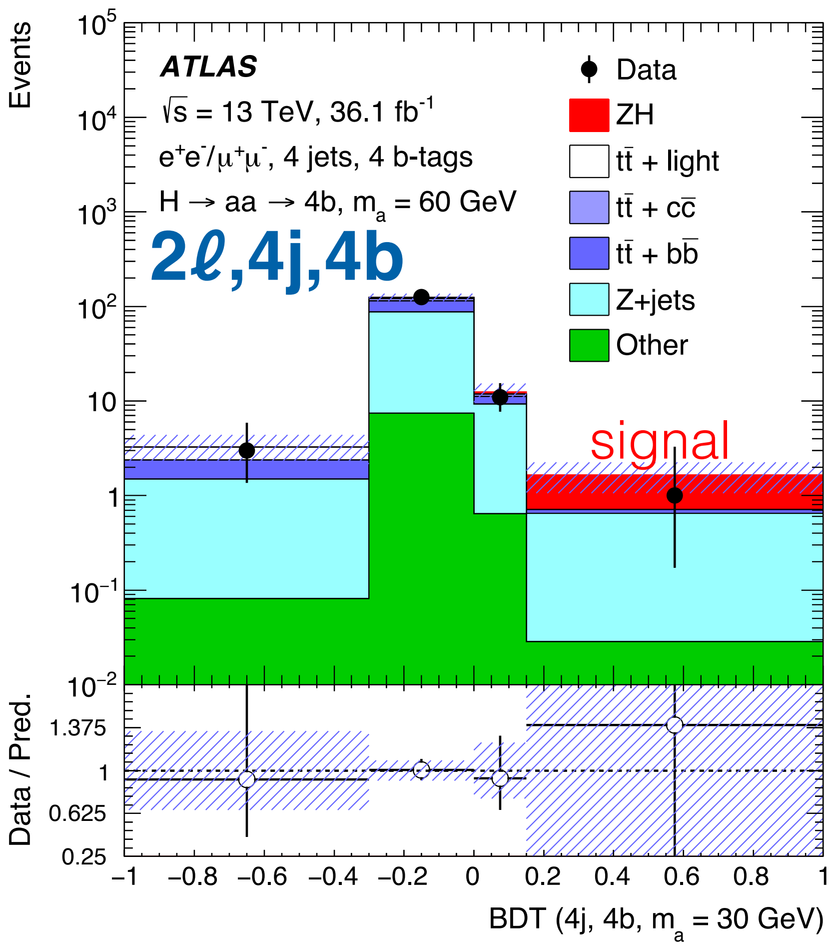
Higgs to Light Scalars: h→2a→4b

Signal

target $2m_b \lesssim m_a \lesssim m_h/2$



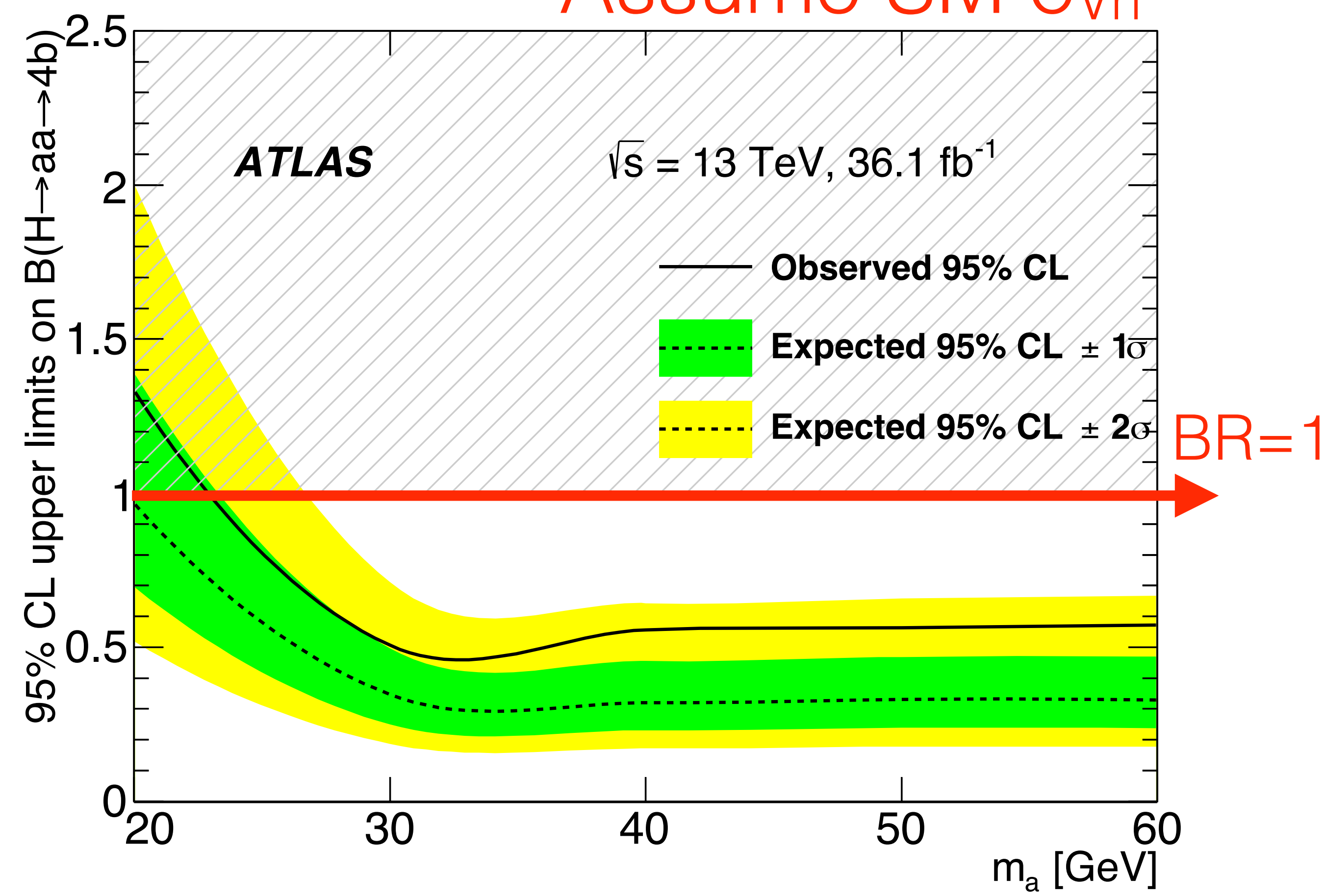
- Strategy
  - Events with 1/2 leptons & 3/4 b-jets
  - Use multivariate technique and complex background modeling
- Main backgrounds Z+heavy flavor & tt+heavy flavor



Sensitivity driven by 2ℓ

loss in sensitivity at low m_a due to merged jets

Assume SM σ_{Vh}



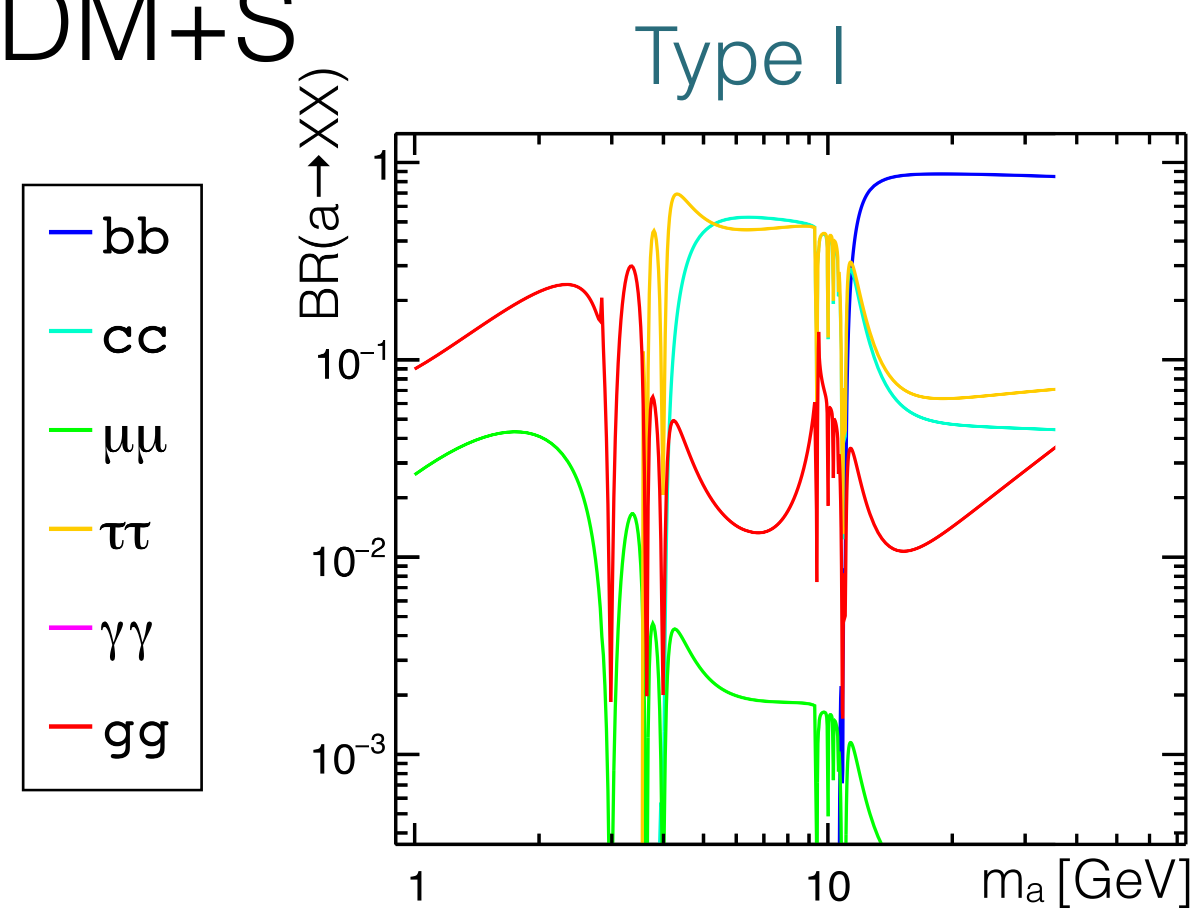
JHEP 10 (2018) 031 arXiv:1806.07355

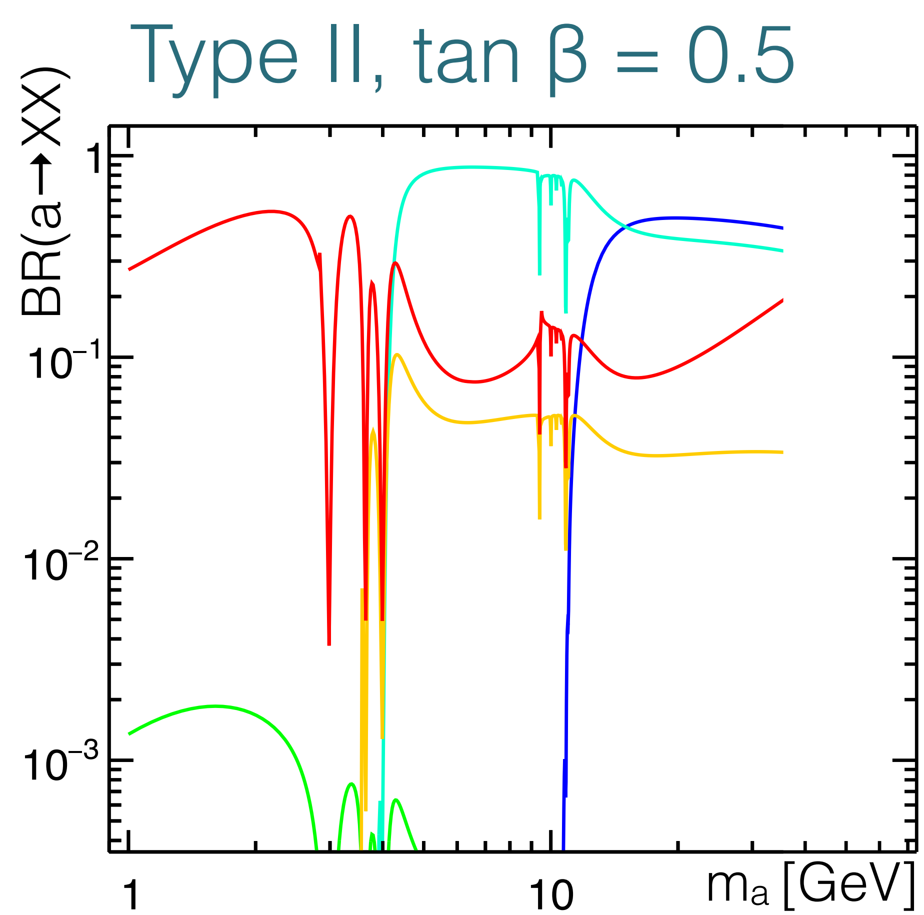
Benchmark Models: 2HDM+S

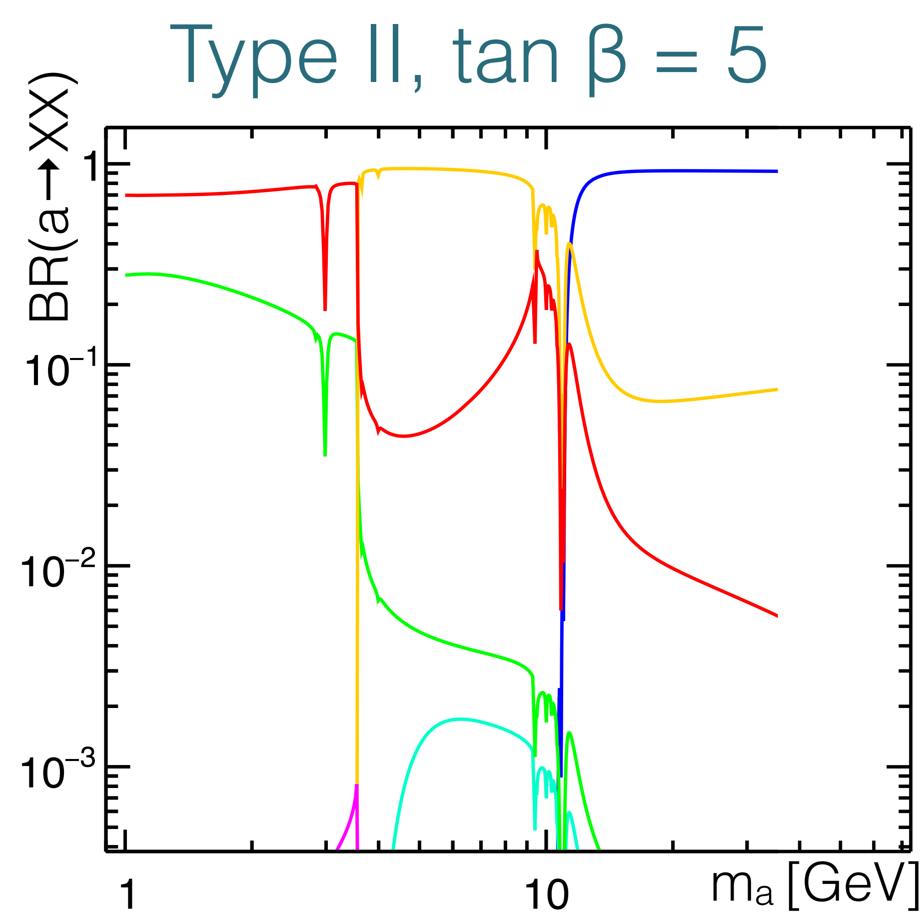
- **Type I:** all fermions couple to H_2
- **Type II:** MSSM-like, d_R and e_R couple to H_1, u_R to H_2
- Type III: lepton-specific, leptons/quarks couple to H_1/H_2 respectively
- Type IV: flipped, with u_R, e_R coupling to H_2 and d_R to H_1

New calculations including quarkonia regions JHEP3(2018)178

From LHC Higgs XS WG on Exotic Decays







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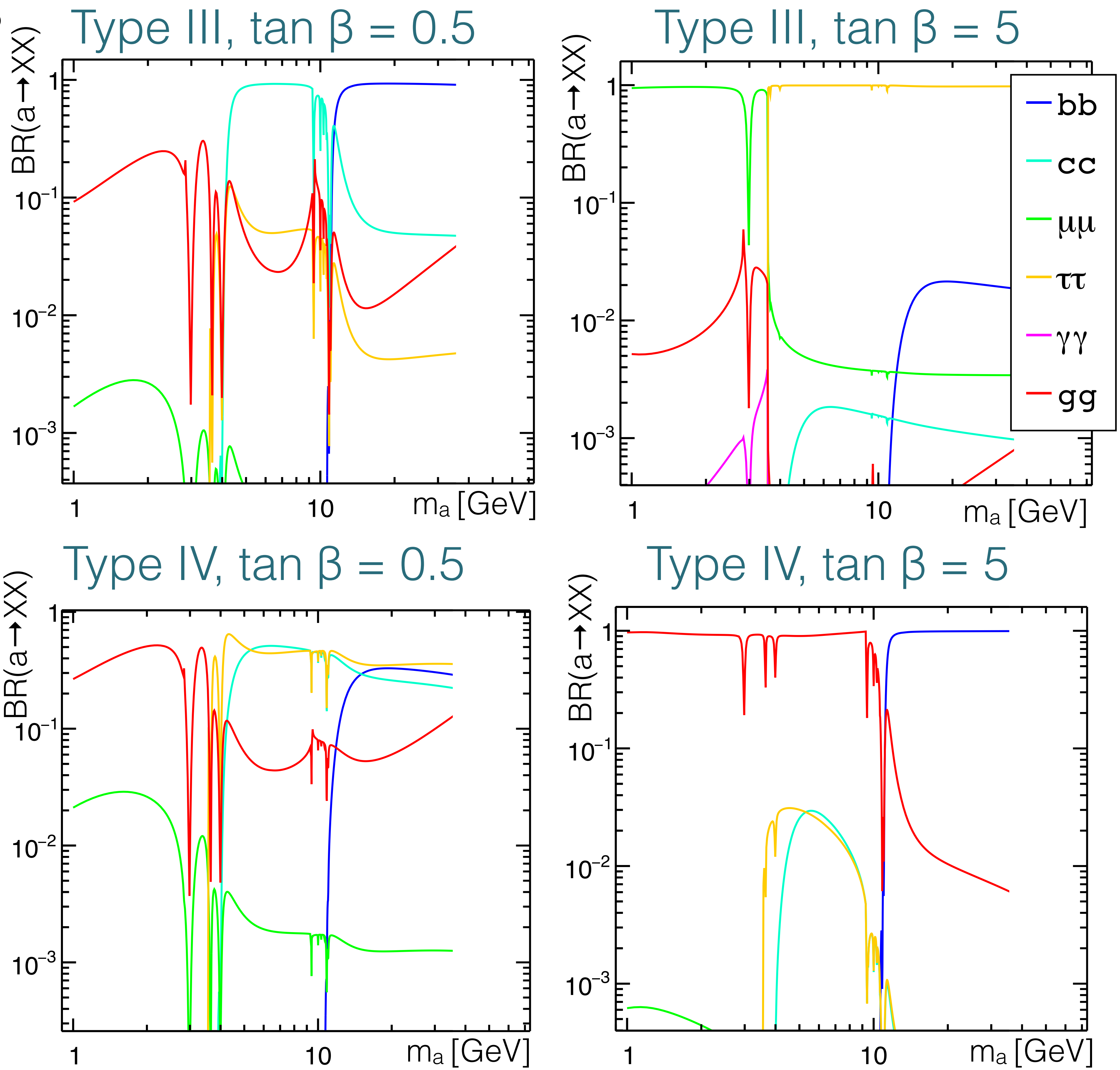
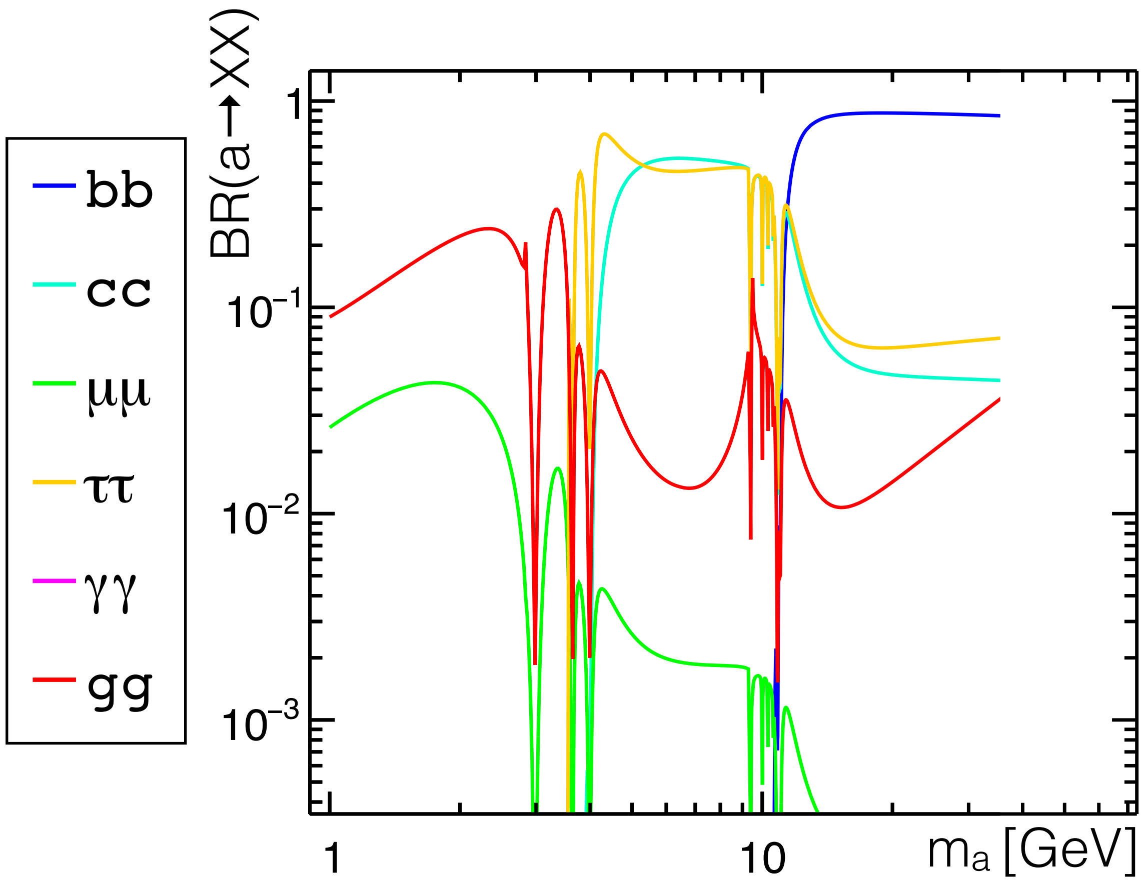
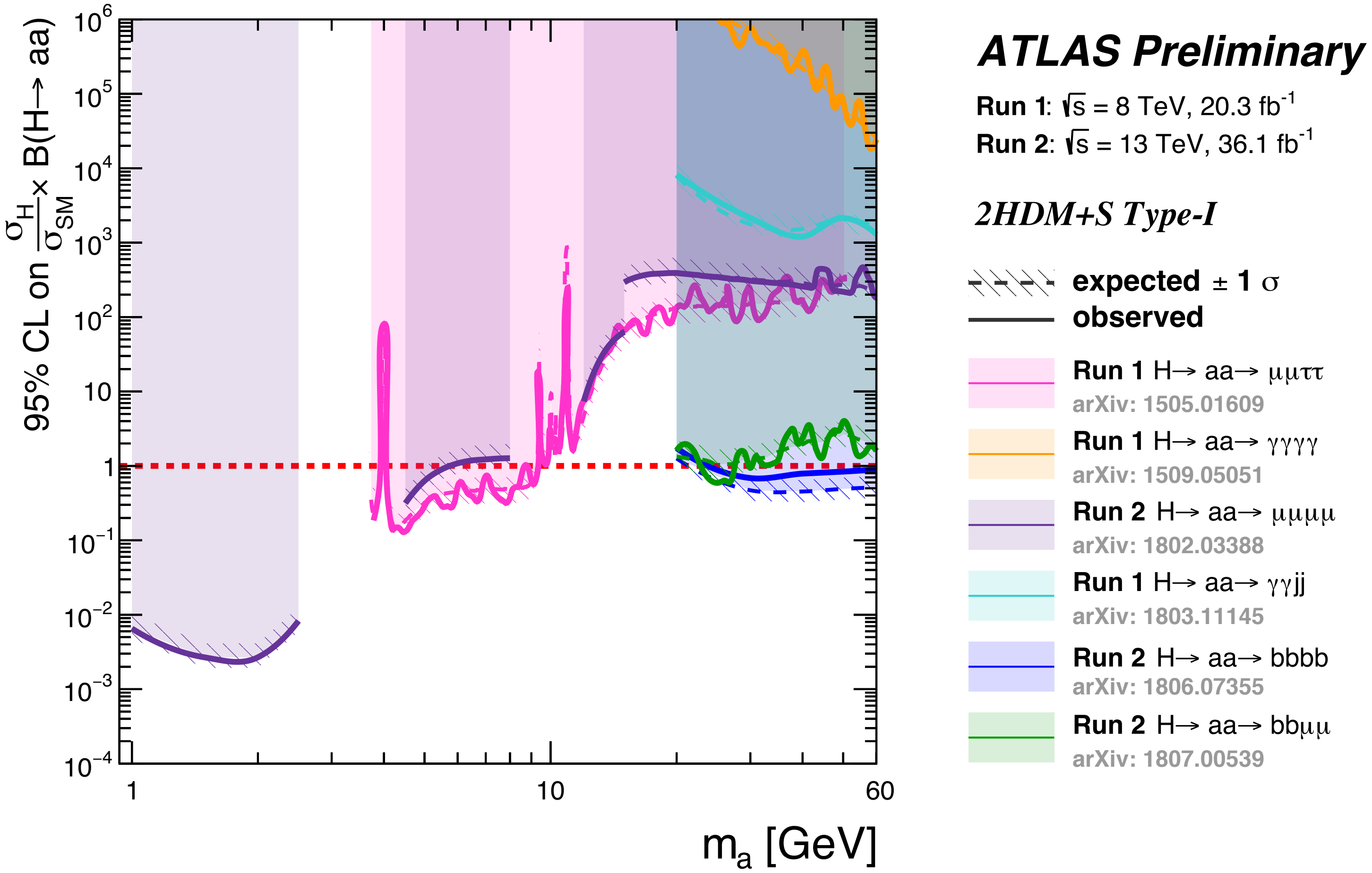


Higgs to Light Scalars: Summary

Results are model dependent → assume BR(a→XX)

Example benchmark model 2HDM+S Type I





JHEP3(2018)178

ATL-PHYS-PUB-2018-045

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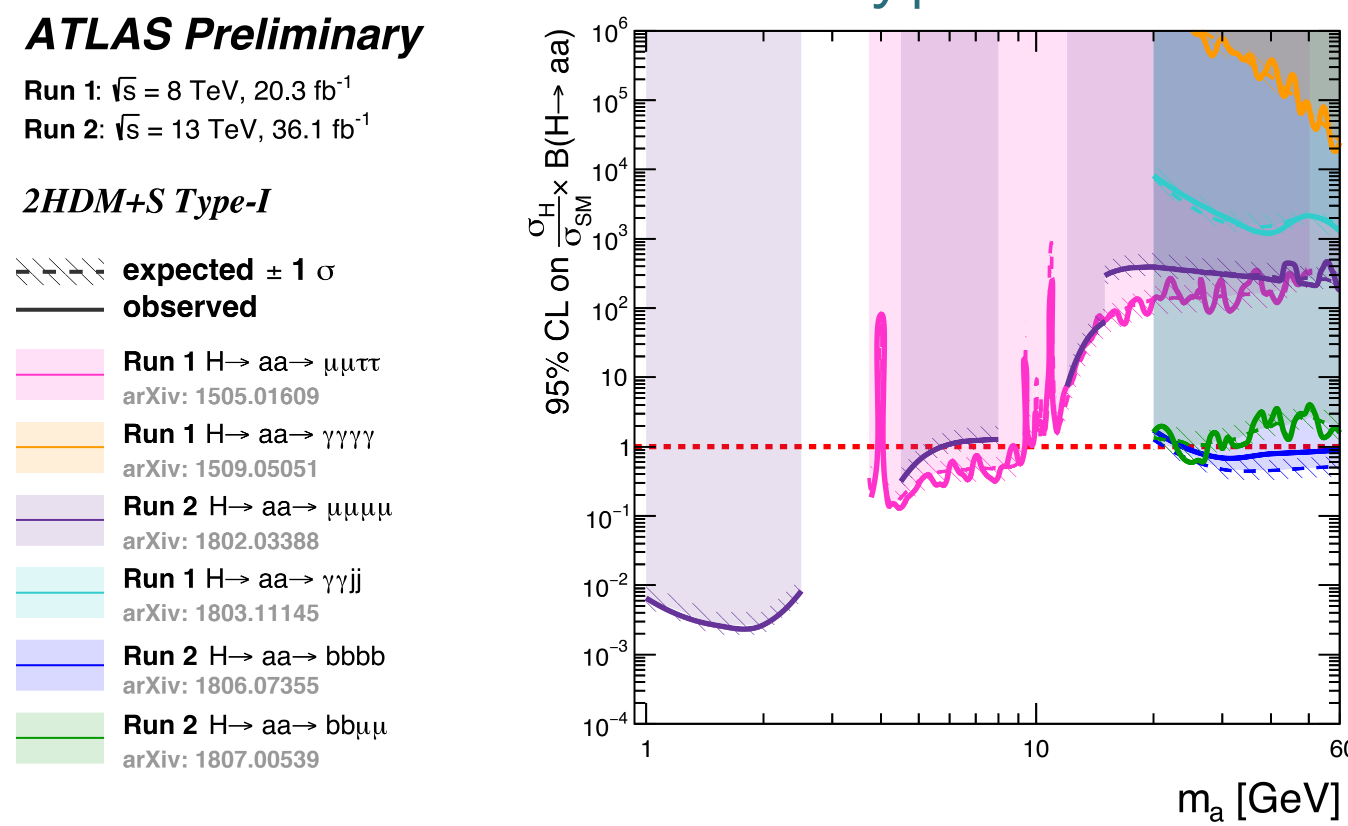
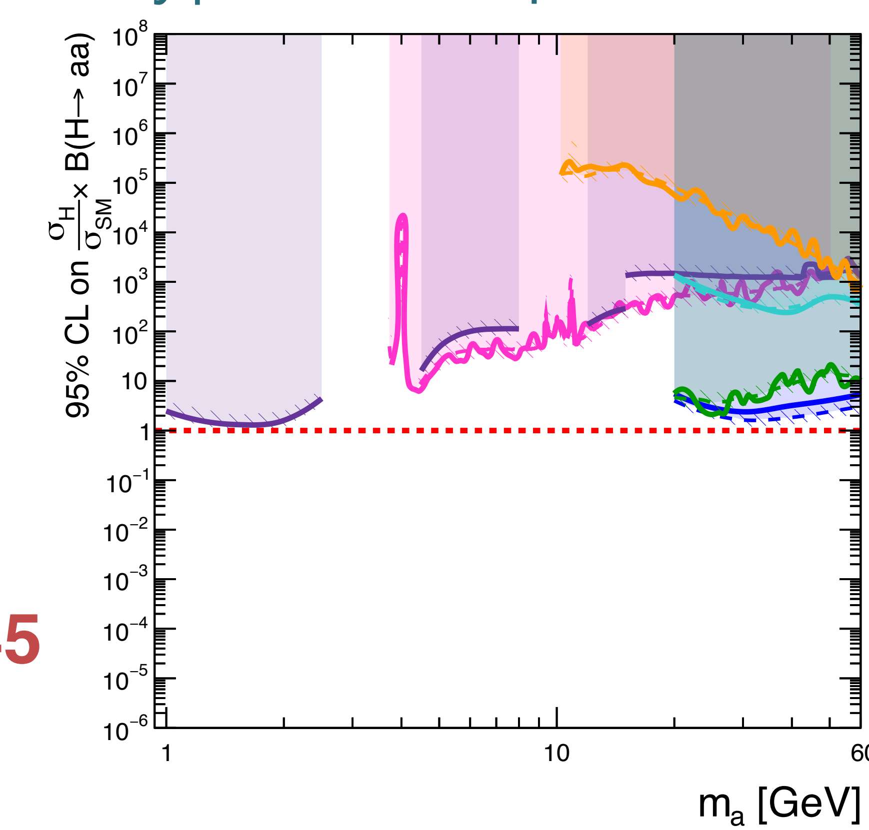
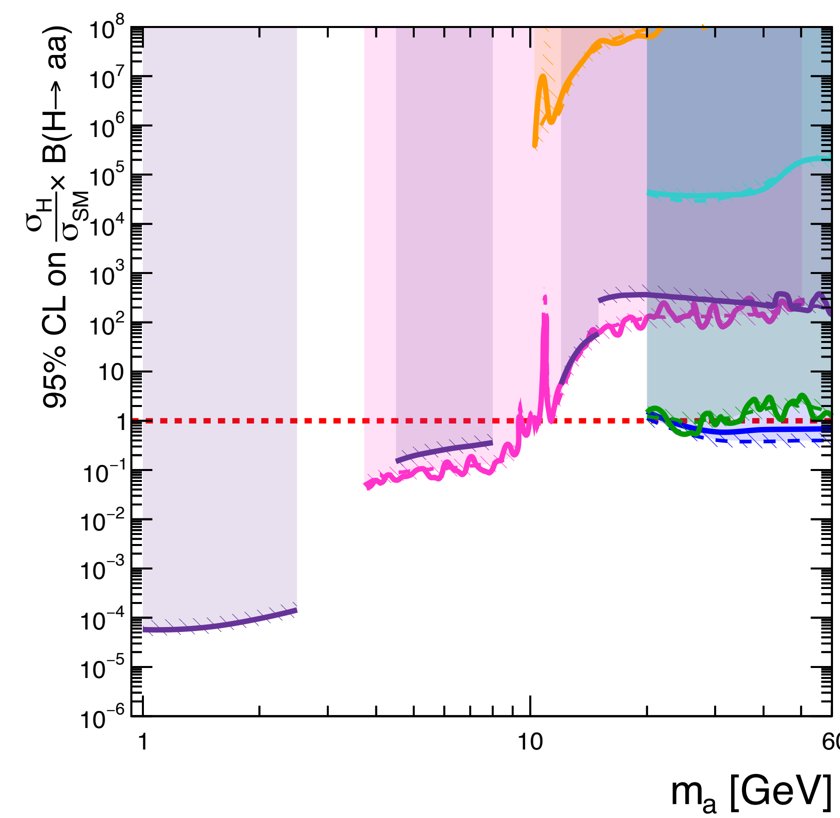
Type I



Type II, tan β = 0.5



Type II, tan β = 5



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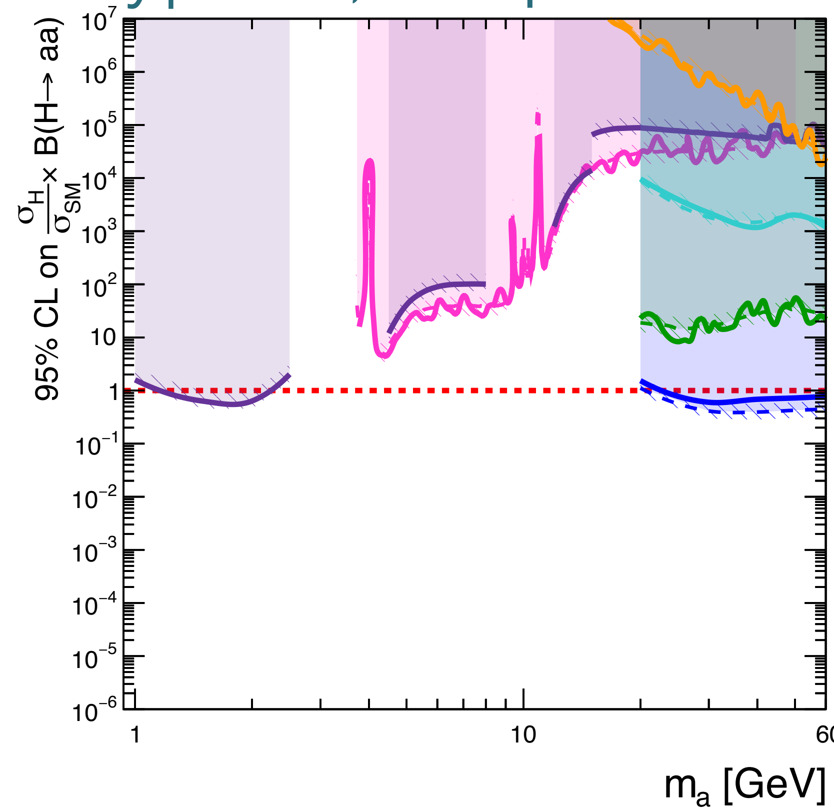
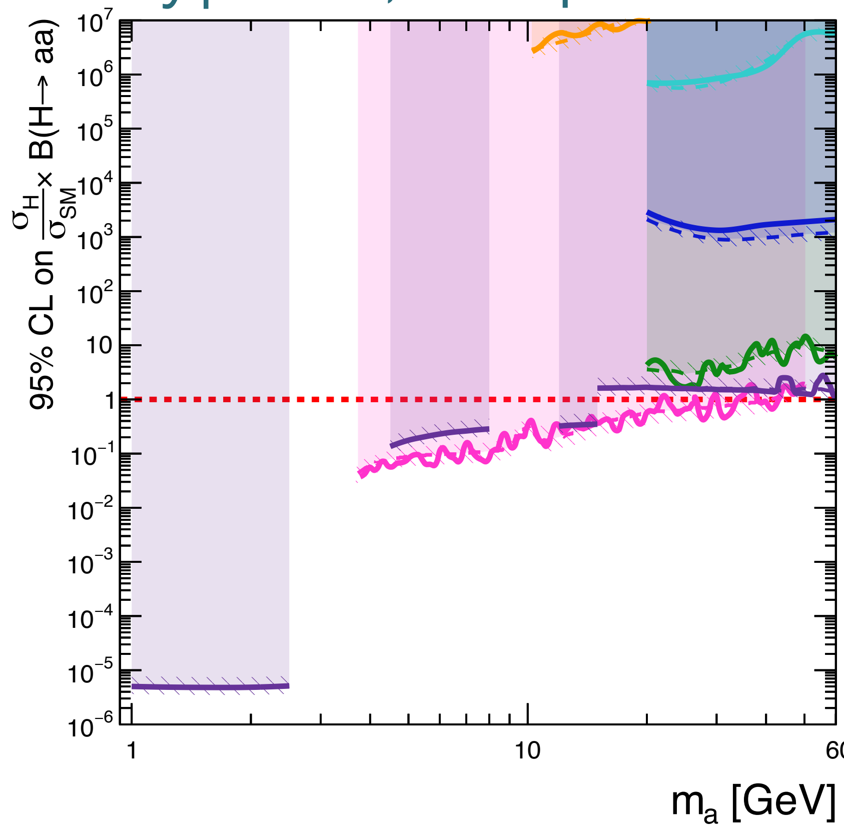
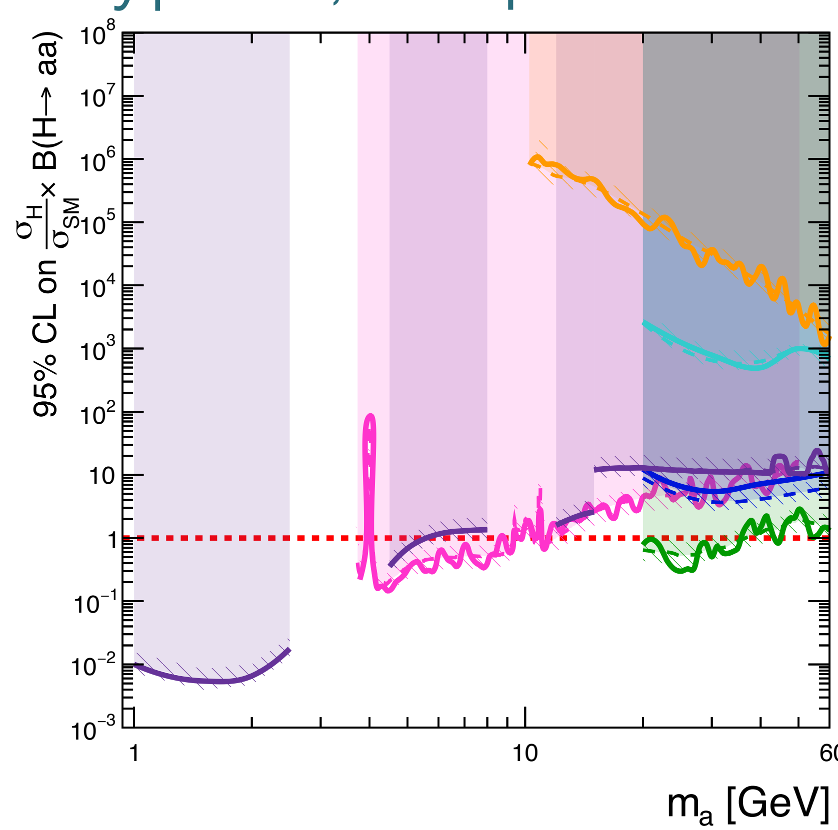


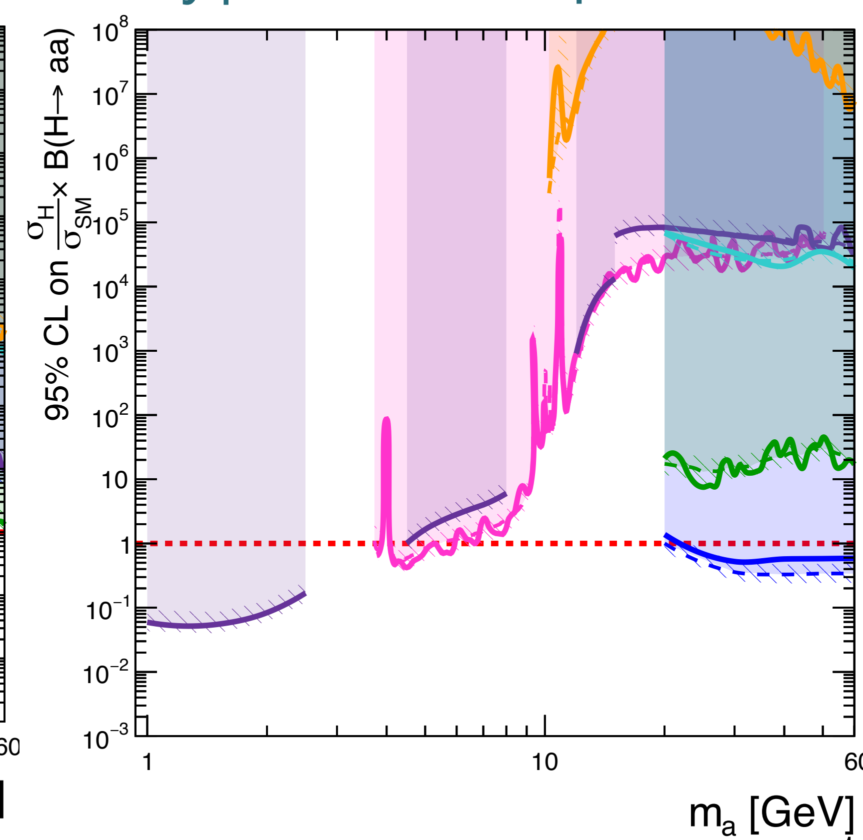
Type III, tan β = 5



Type IV, tan β = 0.5



Type IV, tan β = 5



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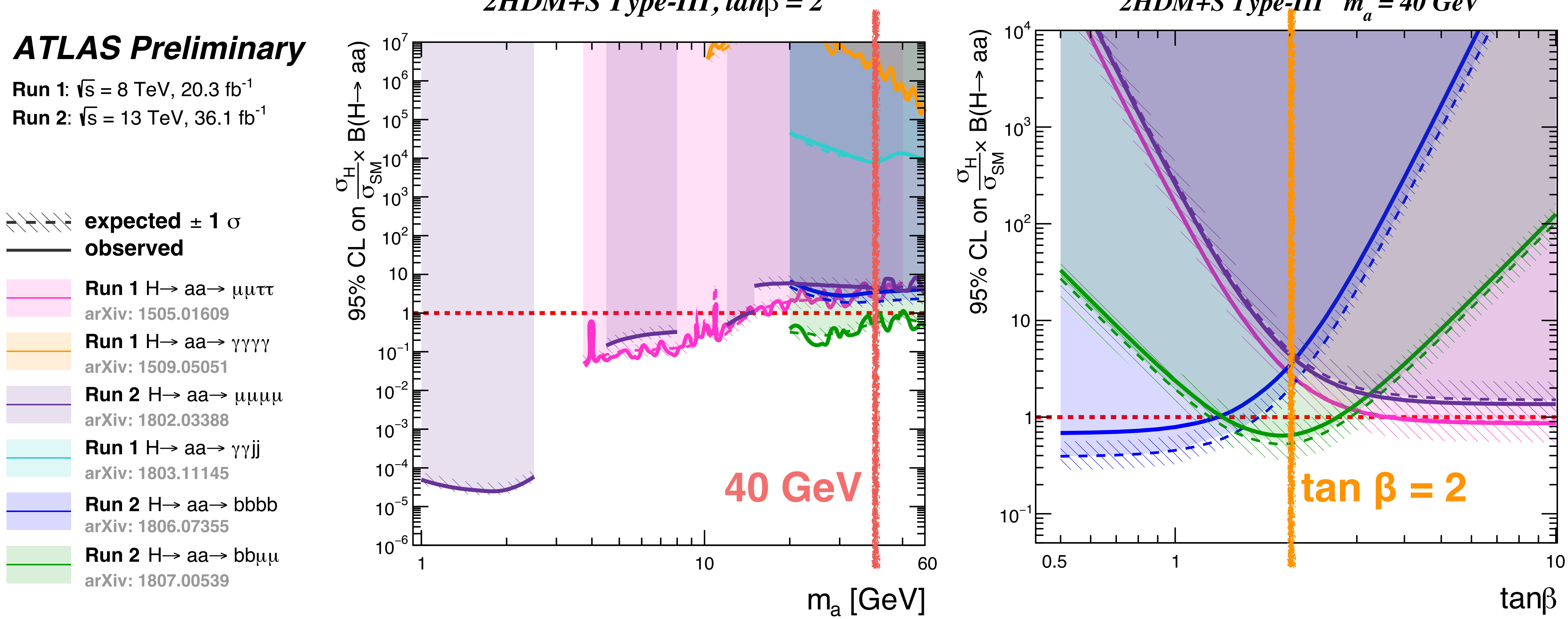
Higgs to Light Scalars: Summary



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Analyses starting to probe interesting region

→ stay tuned for updates with full 13 TeV dataset

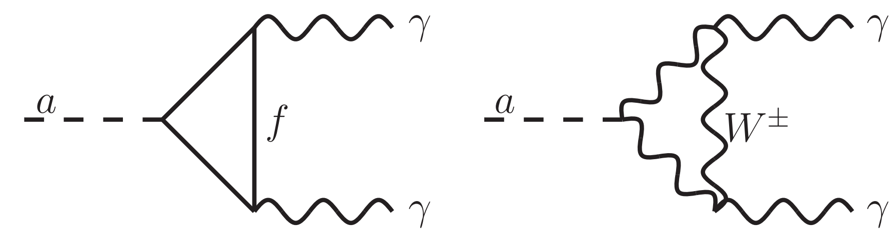
Axion-Like Particles (ALPs)

From M. Neubert

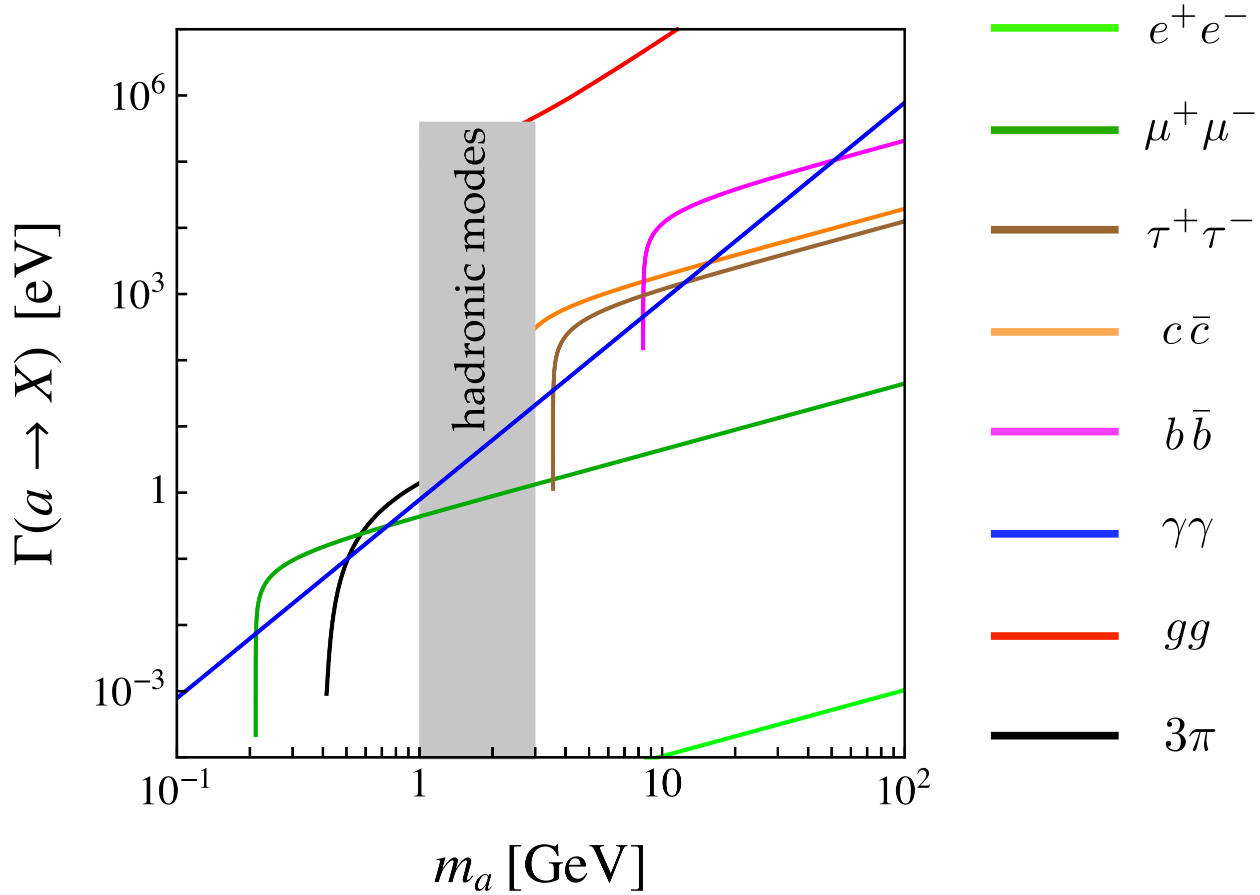
Couplings of an axion-like particle a to the SM are described by

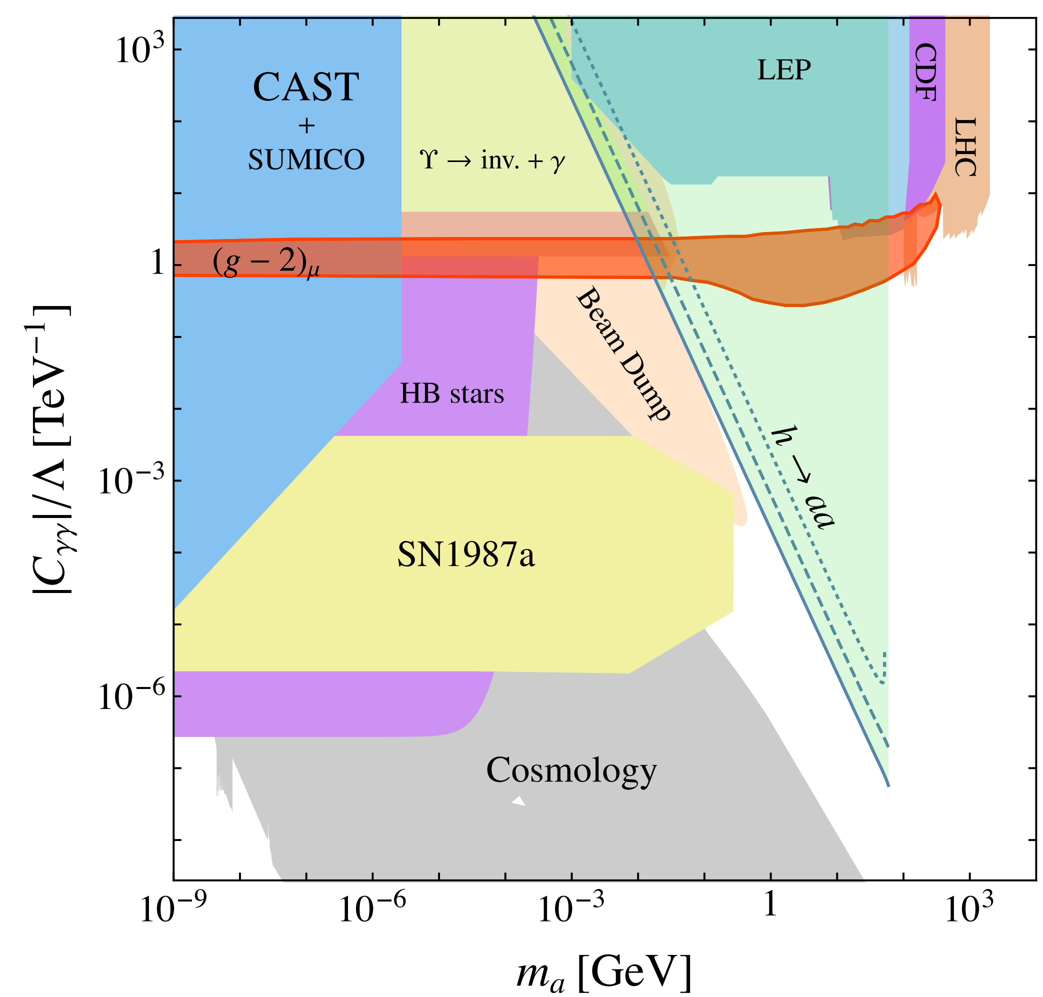
$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f$$
$$+ g_s^2\, C_{GG}\,\frac{a}{\Lambda}\,G^A_{\mu\nu}\,\tilde{G}^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + g'^2\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

[Georgi, Kaplan, Randall 1986]



Several interesting channels at the LHC e.g. h→aa→4g, 4γ, 2γ2g



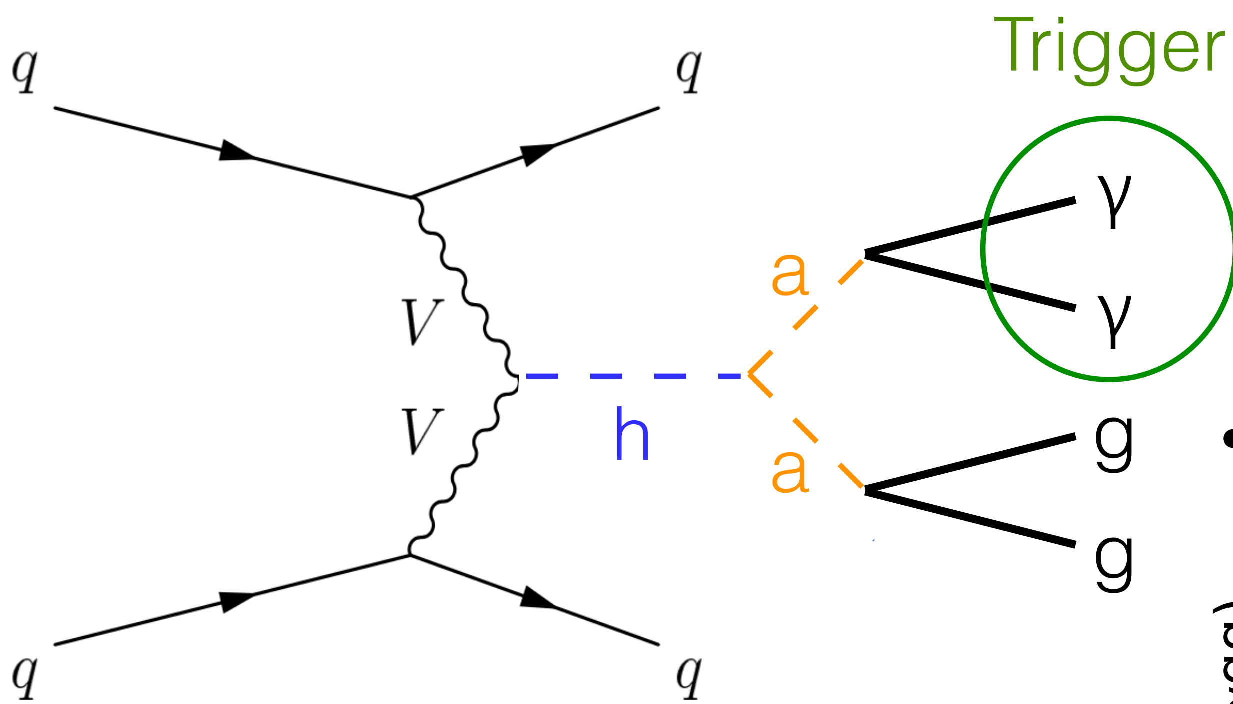


See presentation by M. Neubert at workshop last Friday

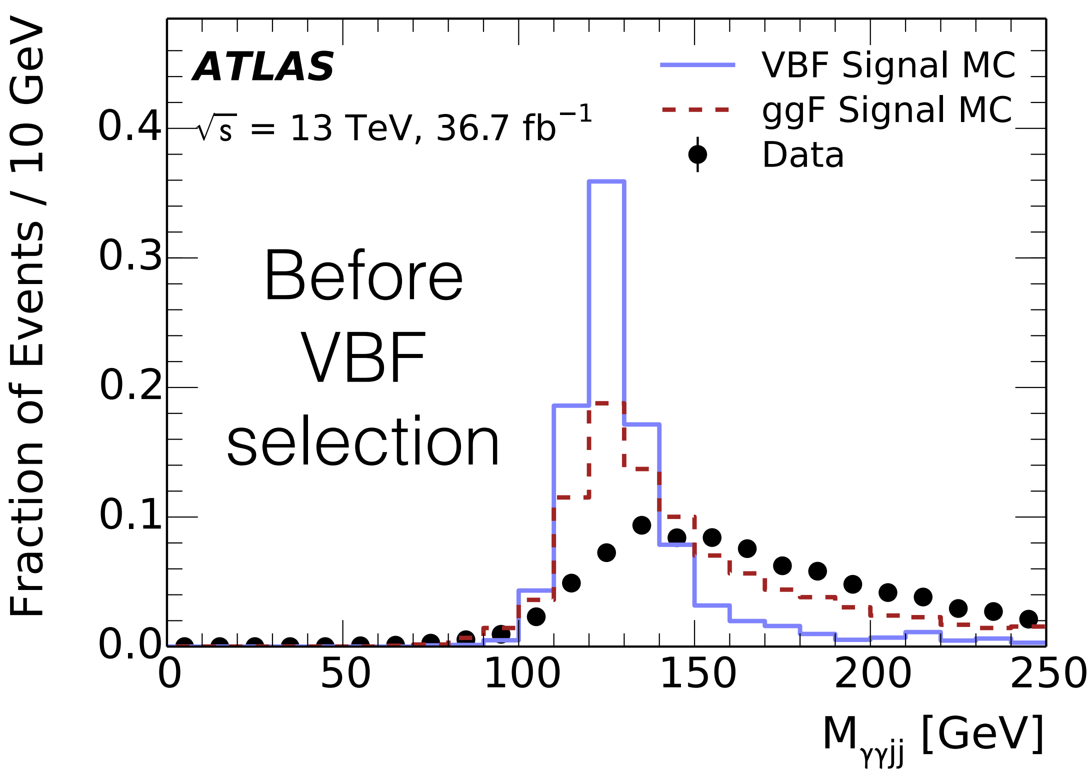
[Bauer, Neubert, Thamm: 1704.08207, 1708.00443, 1808.10323 (+Heiles)]

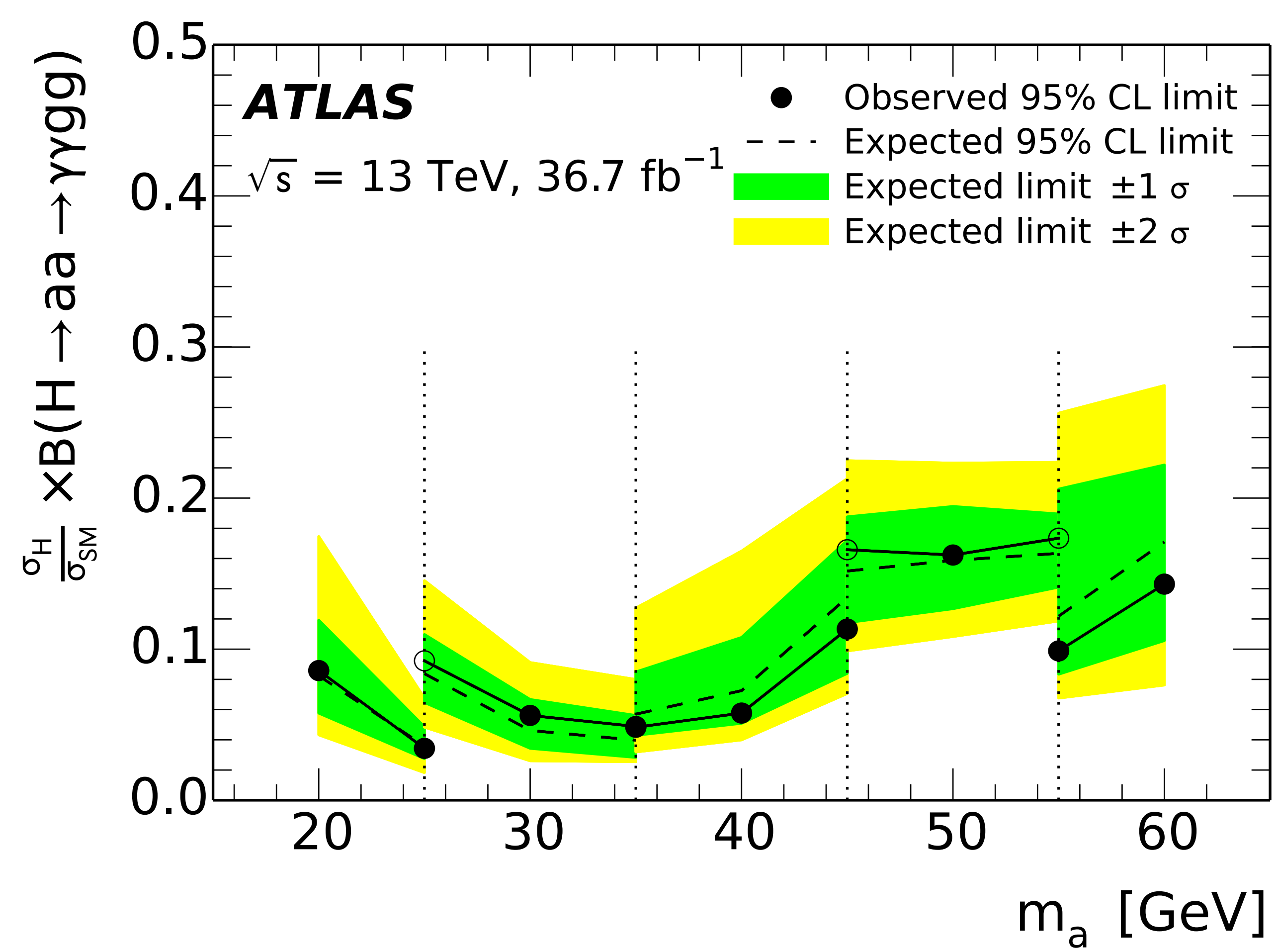
ALP-like Signatures: $h \to 2a \to 2\gamma 2j$

Signal target $2m_b \lesssim m_a \lesssim m_h/2$



- Strategy
  - VBF selection: 2 jets with large rapidity gap $\Delta\eta(j_1,j_2)$ & large mass m_{jj}
  - Select 2 photons and 2 more jets with $m_{\gamma\gamma} \sim m_{jj}$
- Main backgrounds γγ+multiple jets

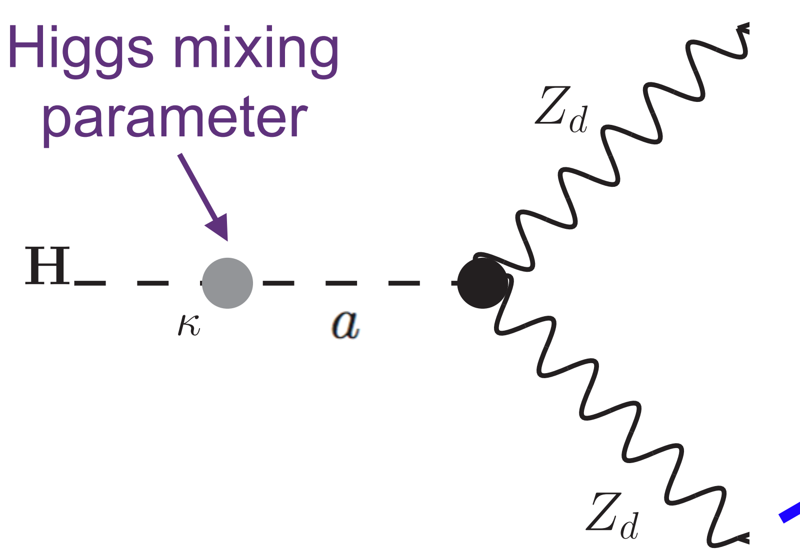




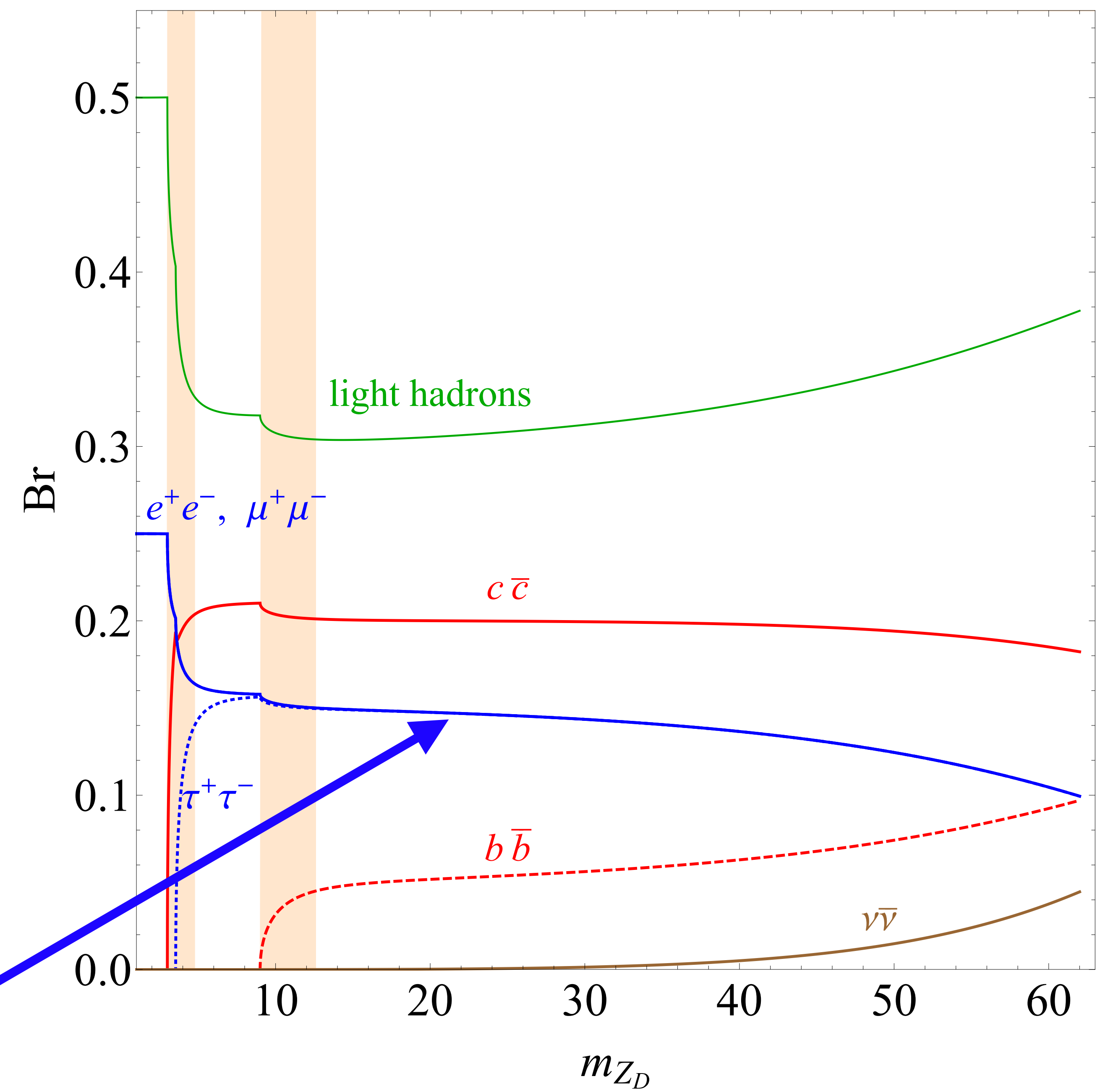
PLB 782 (2018) 750 arXiv:1803.11145

Models with Exotic Decays to Vector Fields ($Z_d Z_d$)

- Models with additional $U(1)_D$ gauge symmetry predict a new vector field (Z-dark, Z_d)
- Phenomenologically, it has been used to explain the muon anomalous magnetic moment and anomalous cosmic ray spectra in experiments like PAMELA and AMS



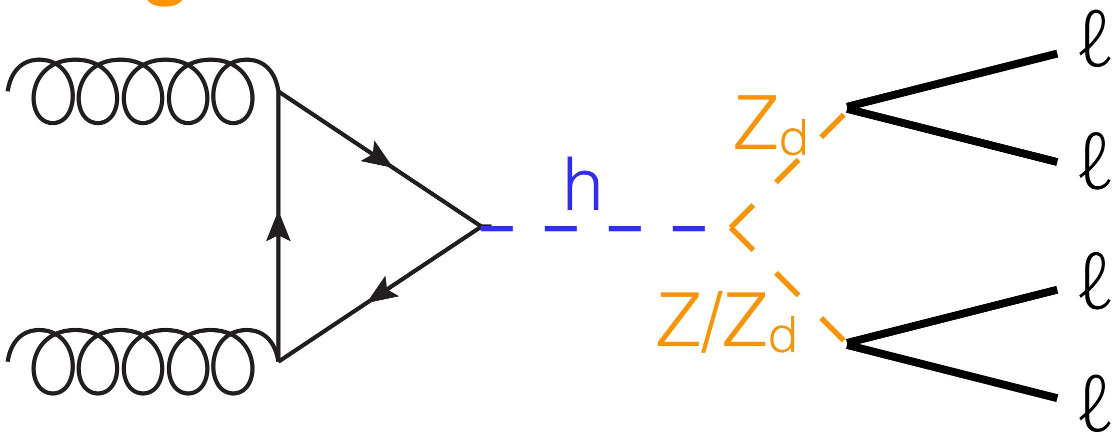
exotichiggs.physics.sunysb.edu



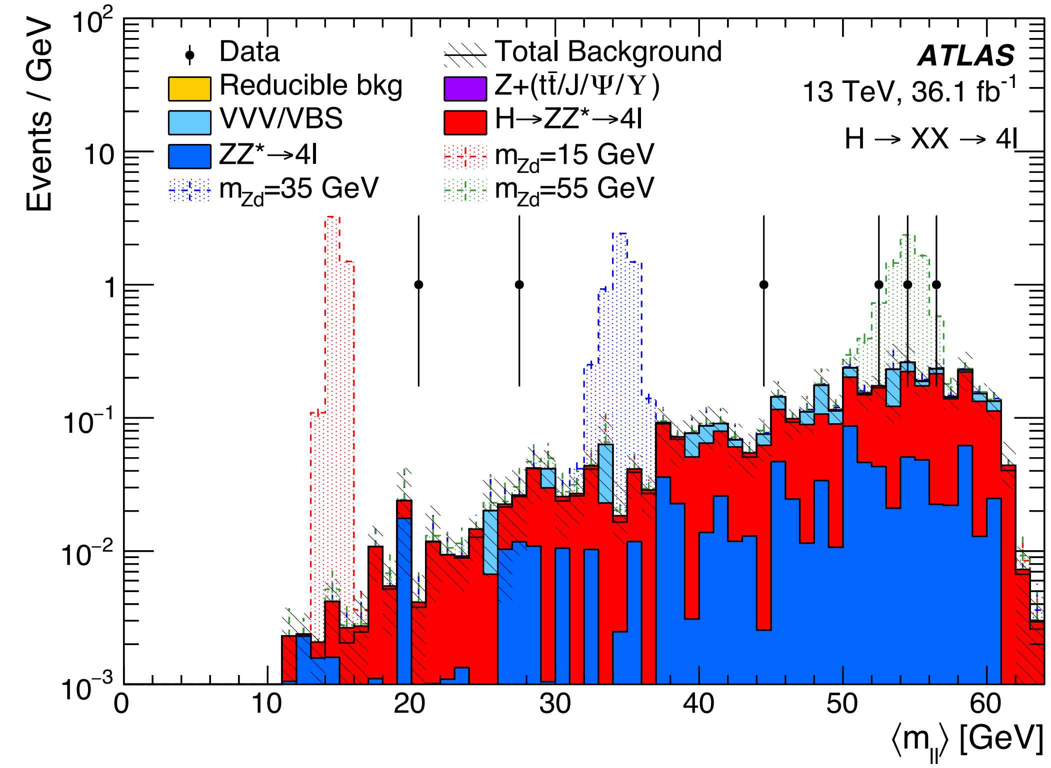
Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

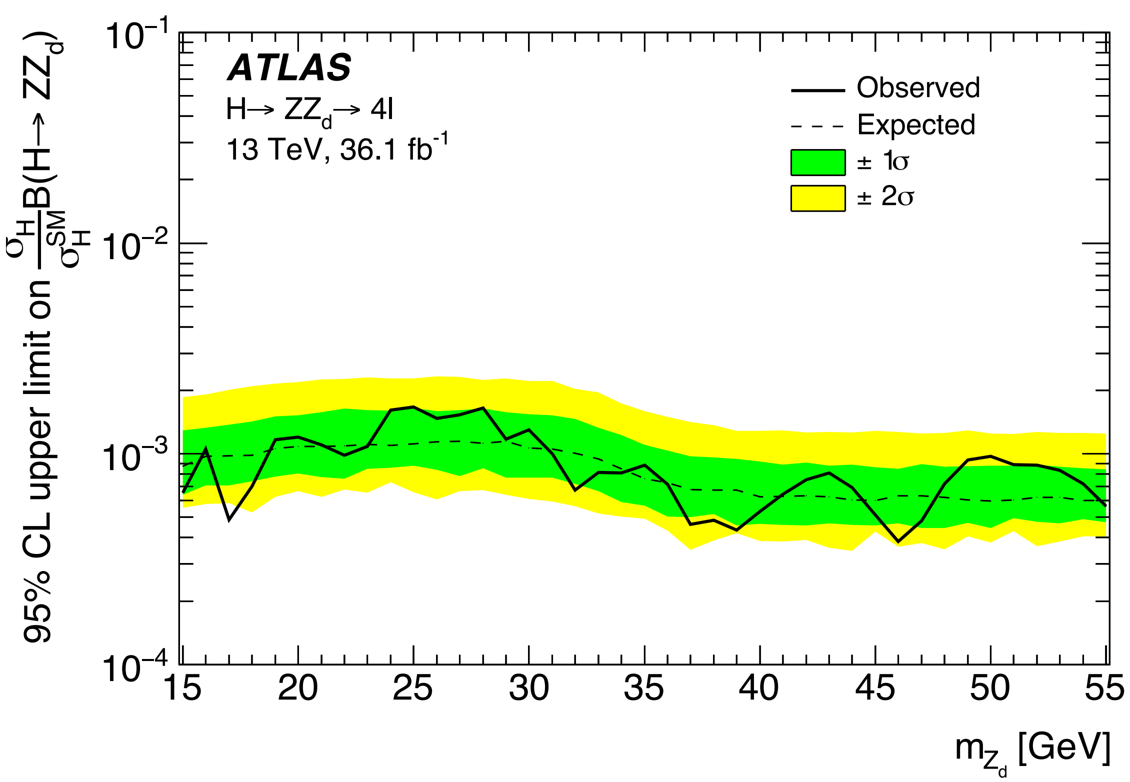
Z-Dark Signatures: h→Z_d Z_d→4ℓ

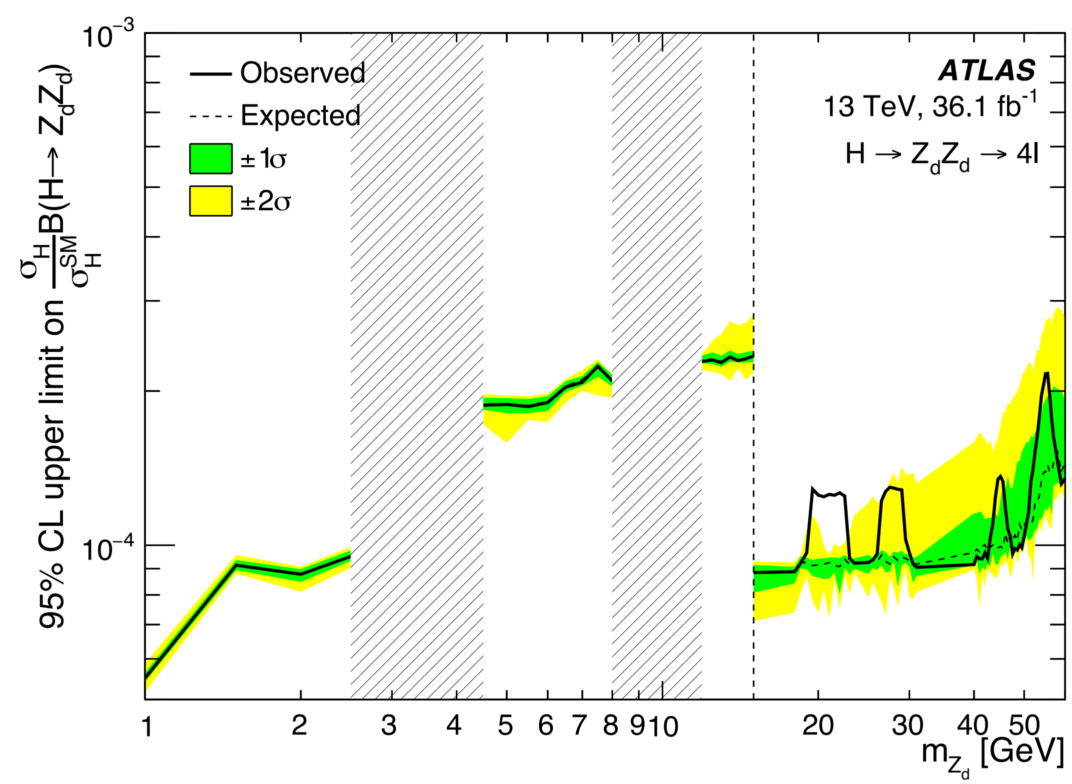
Signal



- Similar strategy as 4μ, but including 4e and 2e2μ categories
- Main backgrounds electroweak processes (ZZ, h→ZZ*, etc)



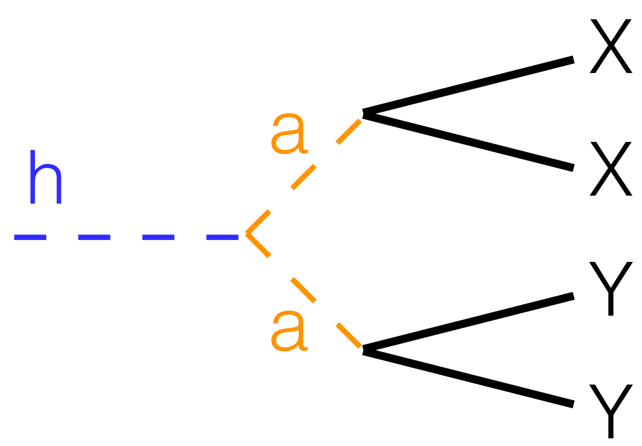




JHEP 06 (2018) 166 arXiv:1802.03388

BSM Decays and Couplings

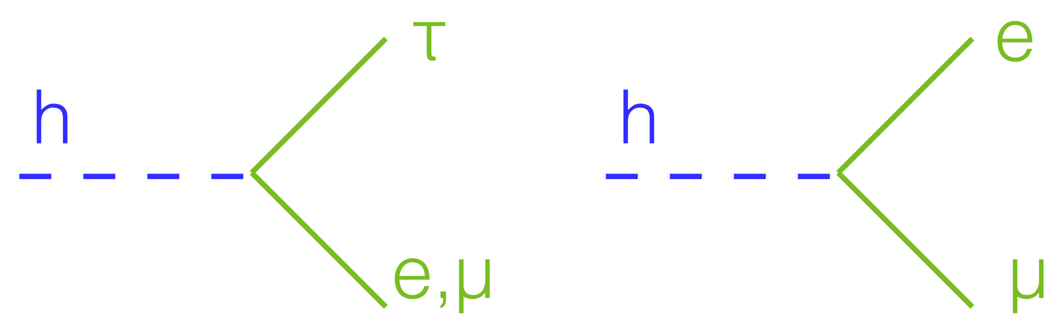
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

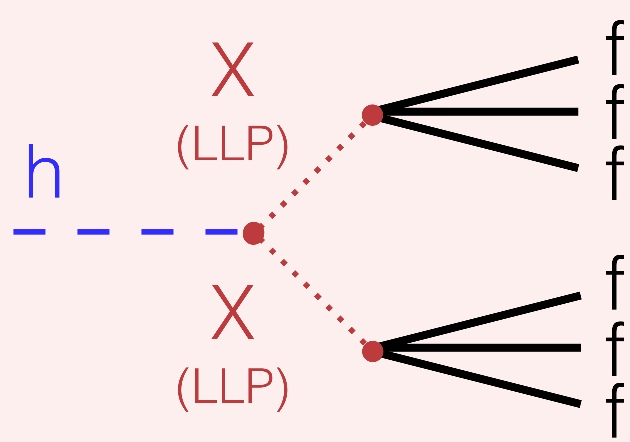
lepton decays



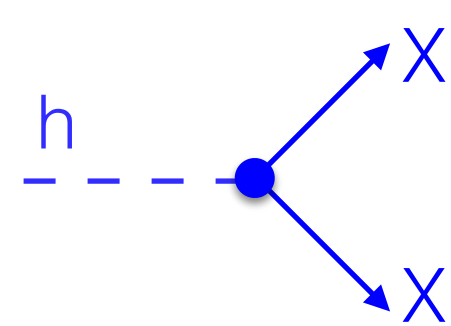
FV in quark sector also considered

Long lived particles (LLP)

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



Invisible Decays



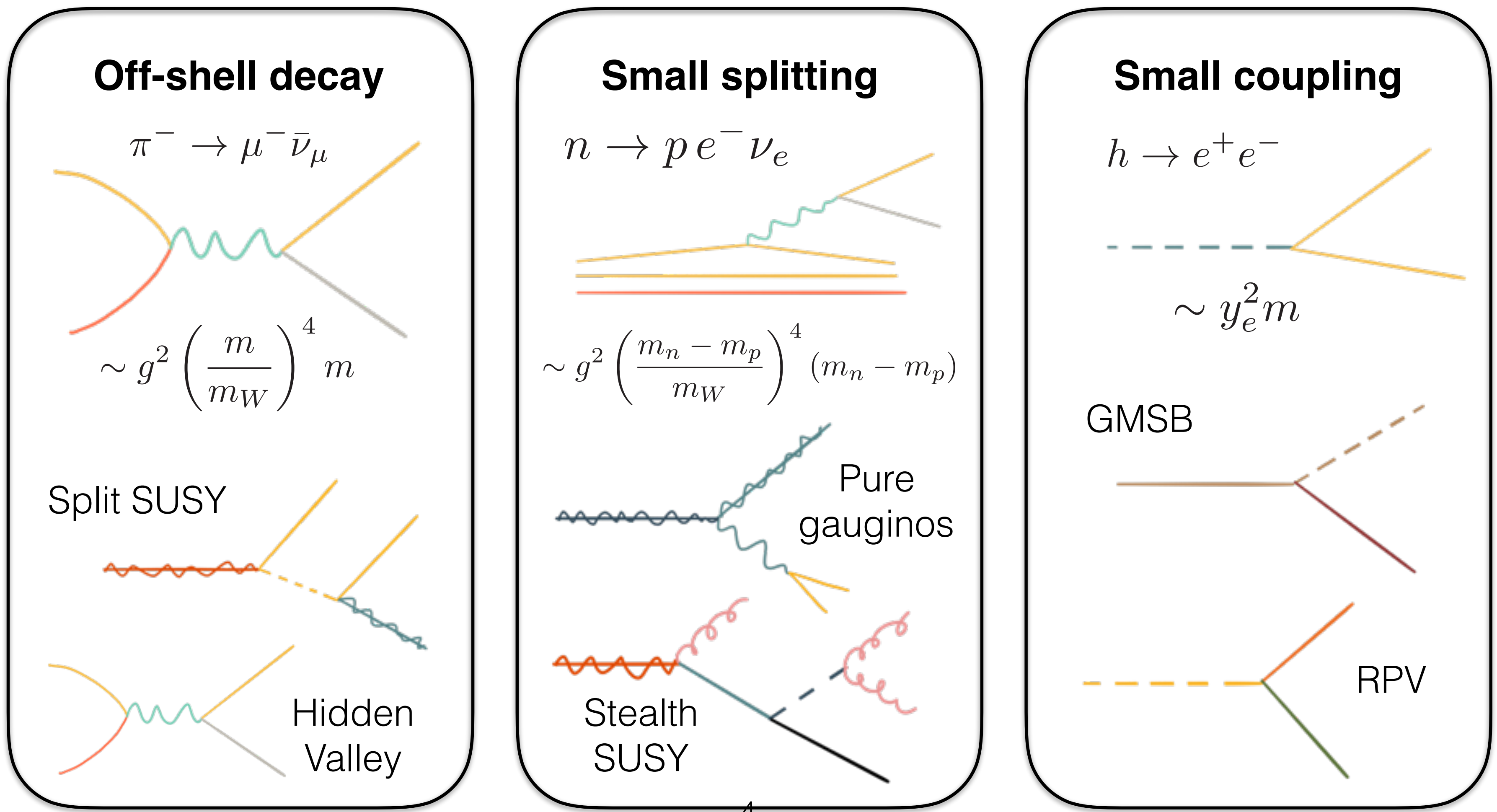
X gives E_T^{miss} signature

Motivating LLPs

LLPs are generic in SM & BSM

$$\Gamma \sim g^2 \left(\frac{m}{M}\right)^n m$$

E.g. small couplings, hierarchy of scales

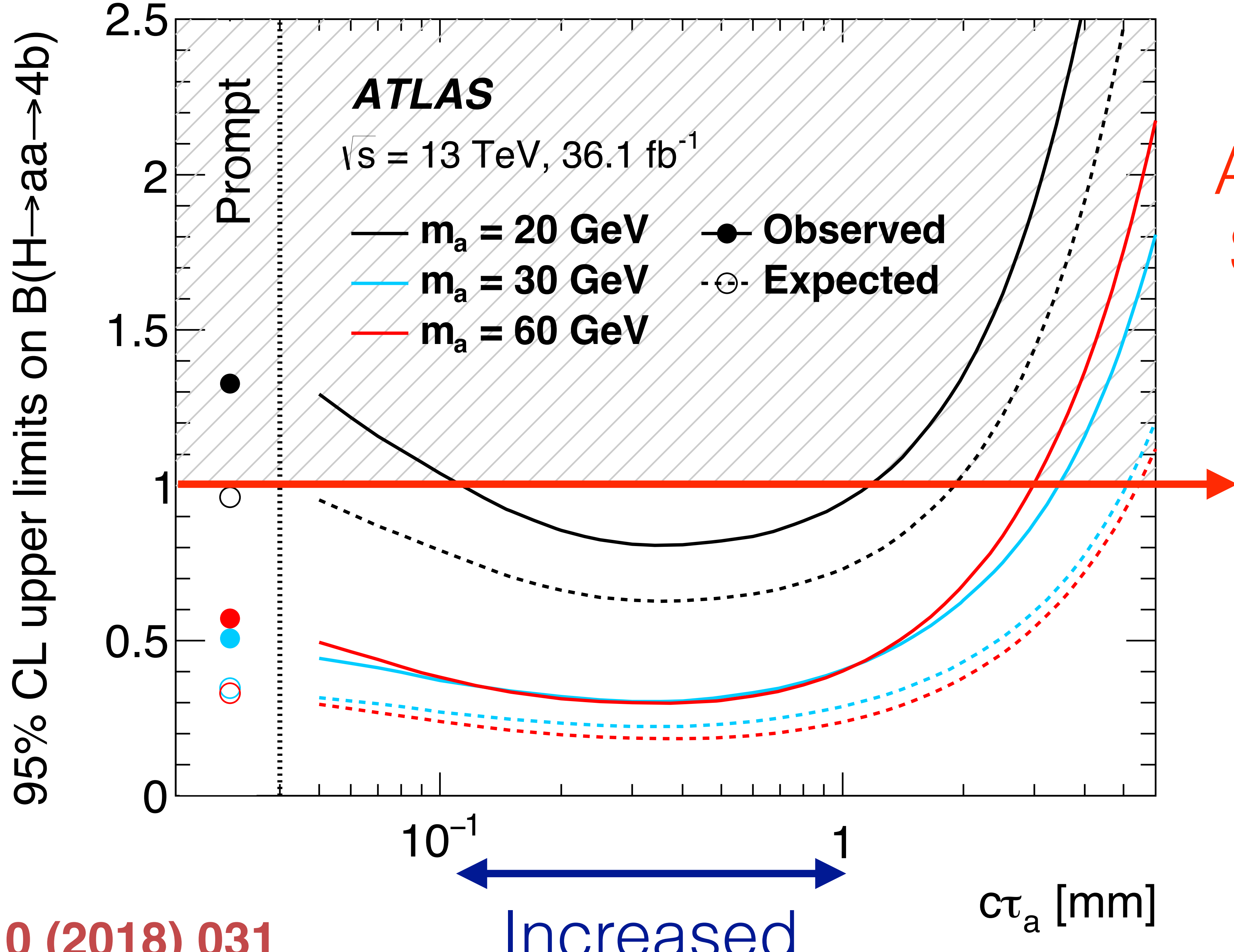


From N. Craig

- Many models motivating Higgs decays to LLPs, for example
  - NMSSM [Chang, Fox, Weiner 2005]
  - Hidden Valleys [Strassler, Zurek 2006; Han, Si, Strassler, Zurek 2007]
  - Twin Higgs [Chacko, Goh, Harnik 2005]
  - Fraternal twins [Craig, Katz, Strassler, Sundrum 2015]

See presentation by N. Craig at workshop last Thursday

Higgs to Light Scalars: h→2a→4b
Long-Lived Interpretation



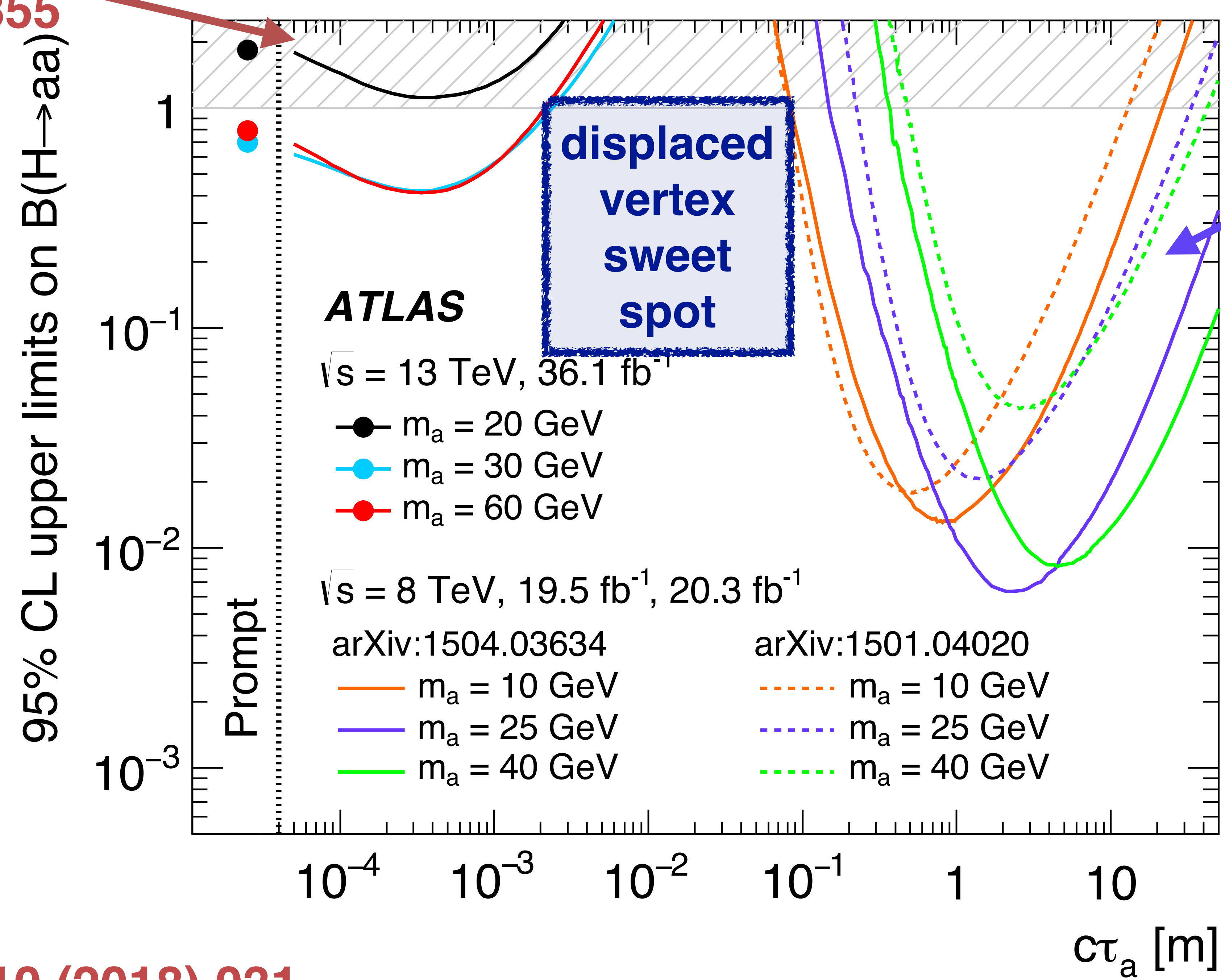
Assume SM σ_{VH}

JHEP 10 (2018) 031
arXiv:1806.07355

Higgs to Light Scalars: h→2a→4b Long-Lived Interpretation

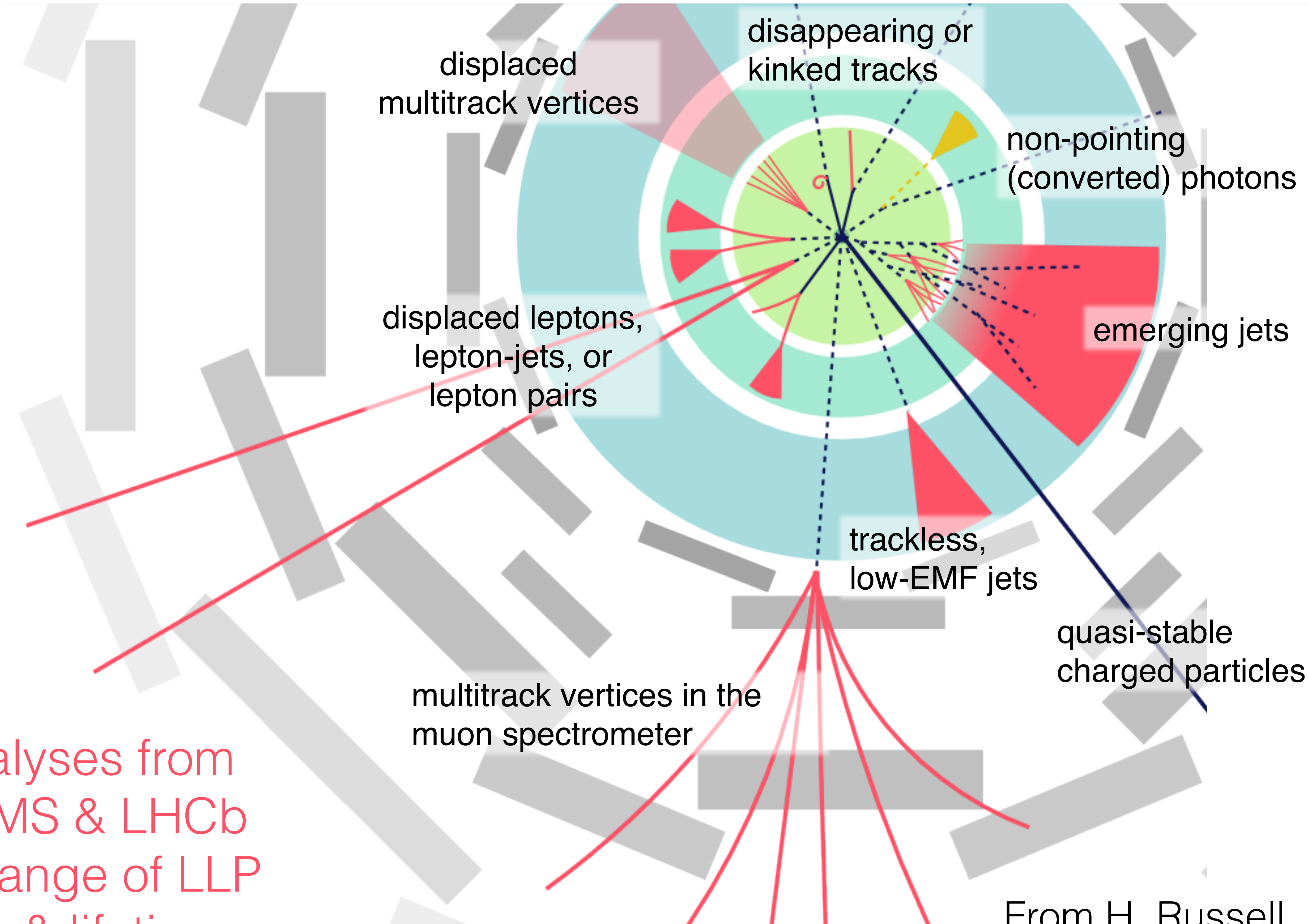
This result
arXiv:1806.07355

Dedicated long-lived searches



JHEP 10 (2018) 031
arXiv:1806.07355

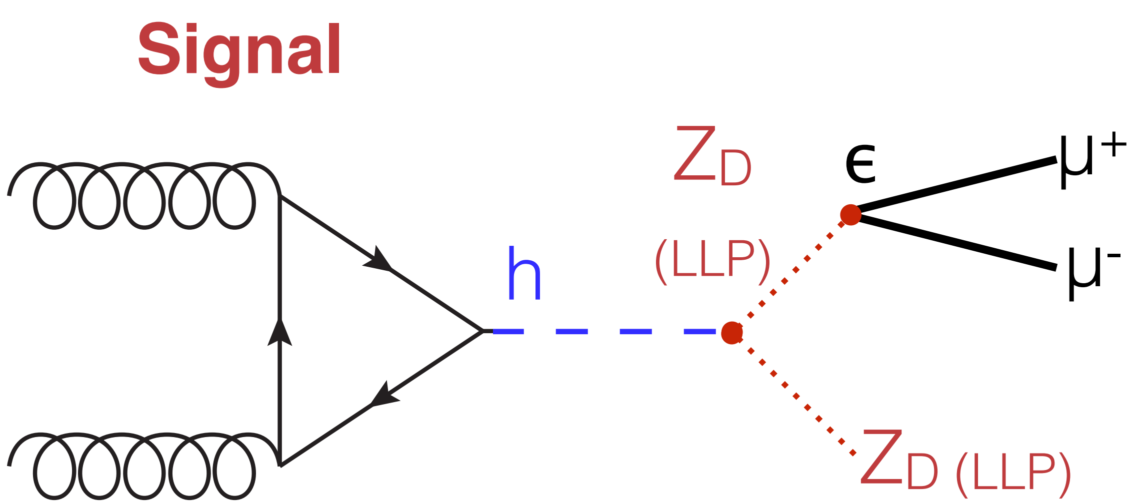
LLP Experimental Signatures



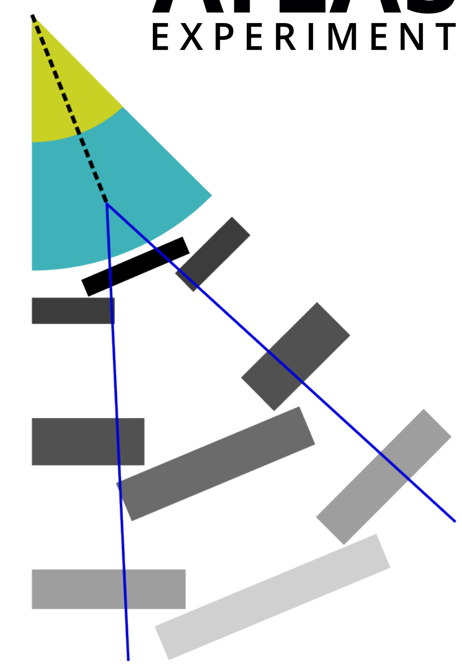
Many analyses from ATLAS, CMS & LHCb targeting range of LLP signatures & lifetimes

From H. Russell

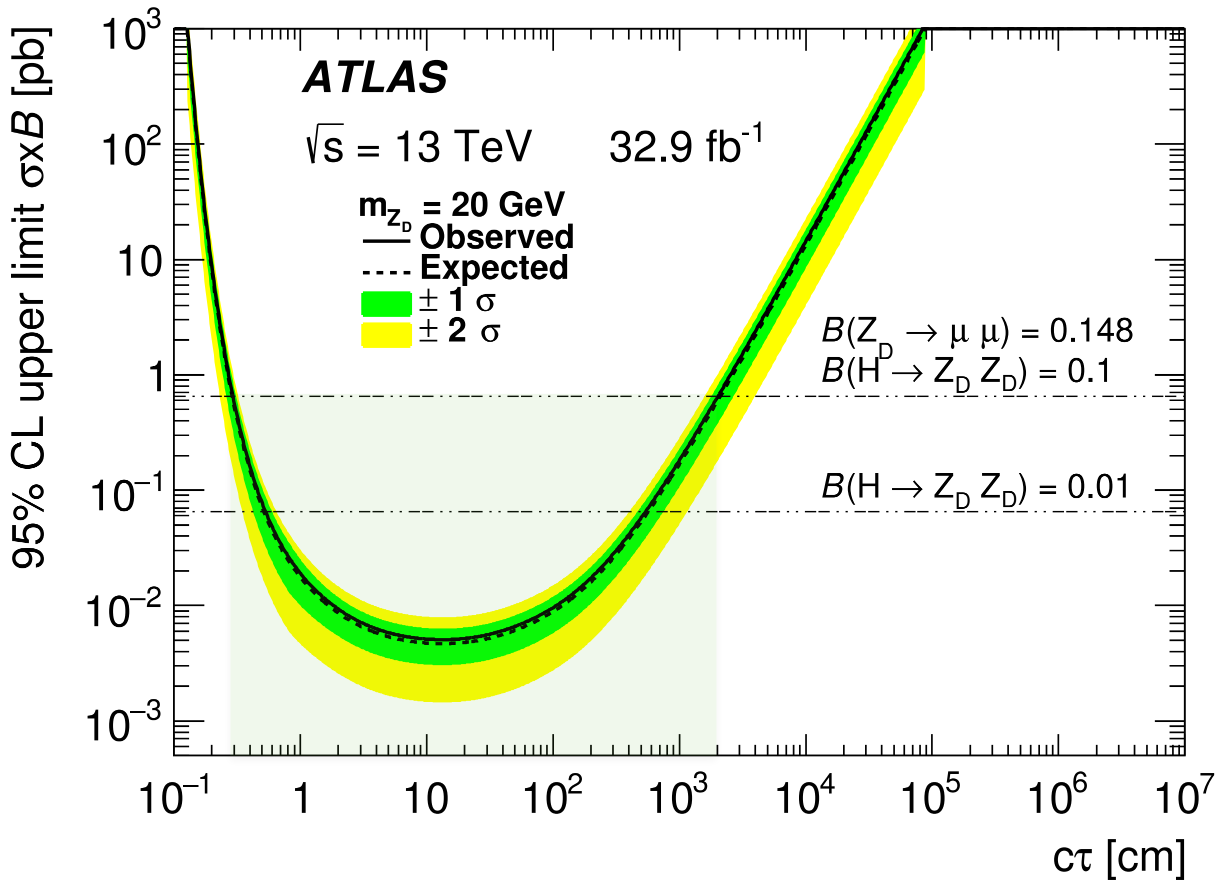
Long Lived Decays: h → displaced muons

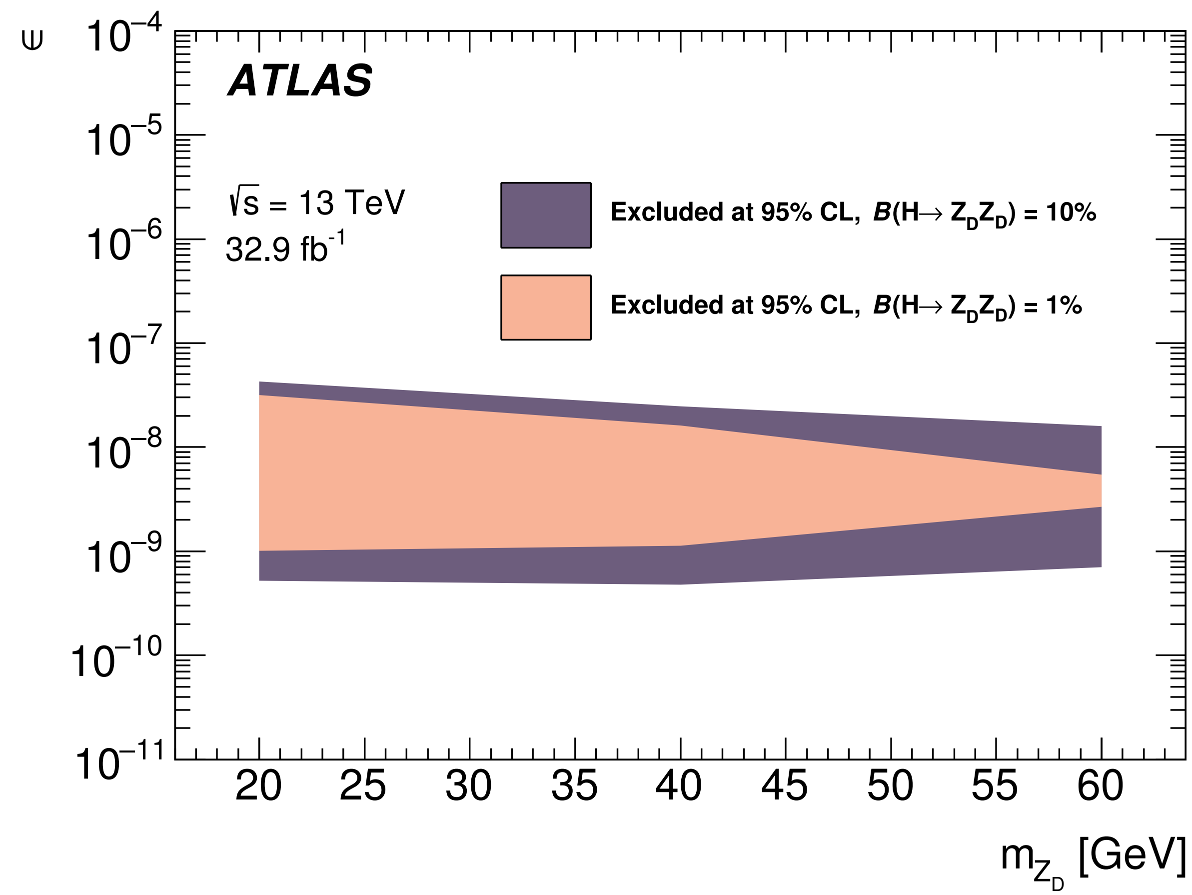


- Strategy
  - Search for displaced vertices (DV) in the muon system
  - No tracks in inner detector
- Low backgrounds



In ATLAS can detect dimuon DVs in large decay volume

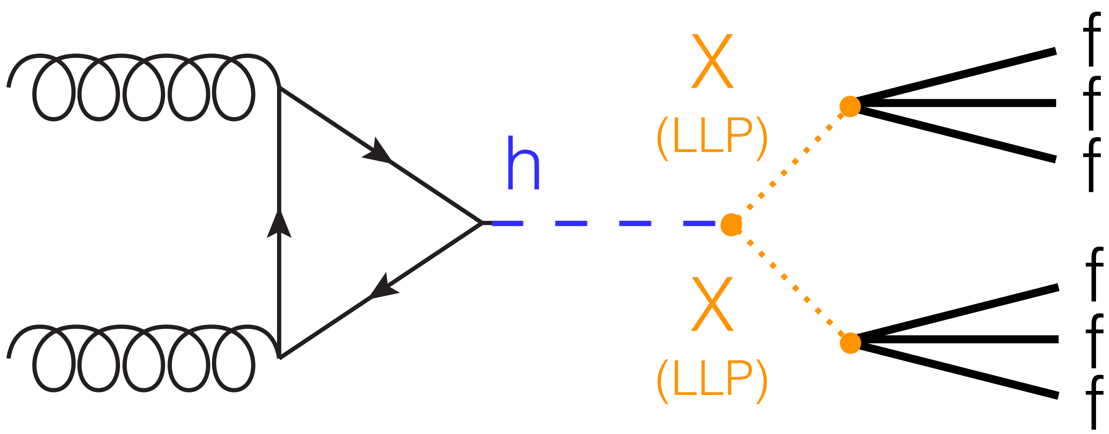




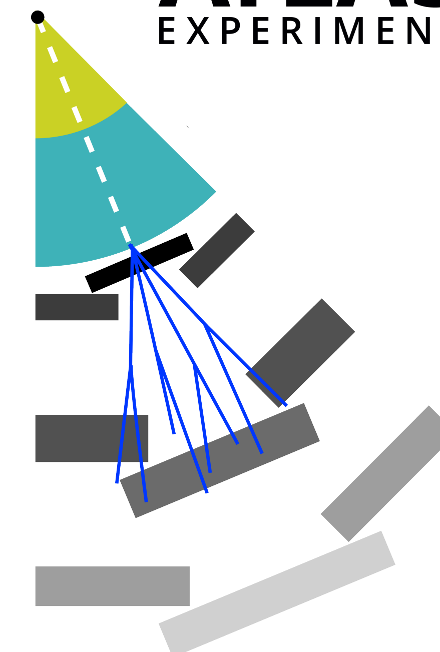
 Phys. Rev. D 99, 012001 (2019) arXiv:1808.03057

LL Decays: h → displaced jets in muon system

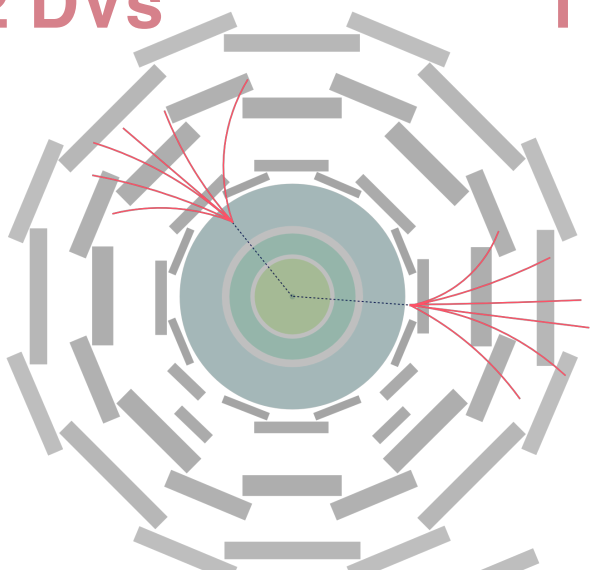
Signal



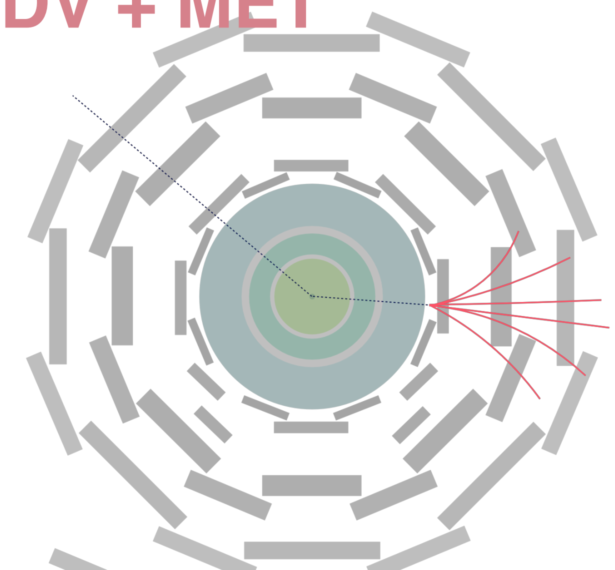
- Strategy
  - Search for multitrack displaced vertices in muon system
  - No tracks in inner detector nor calorimeter signals



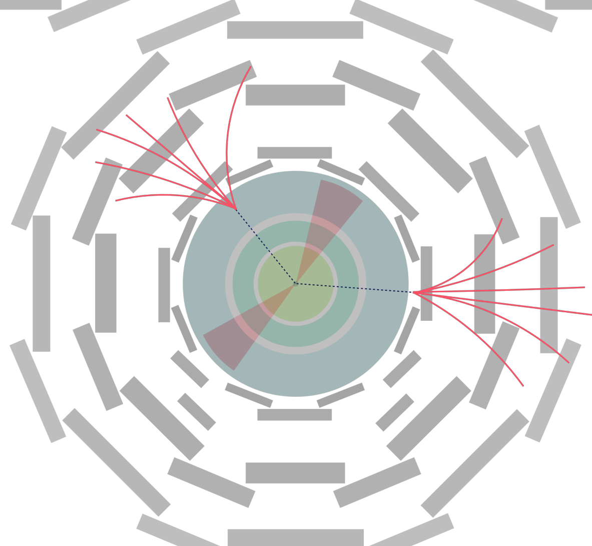
2 DVs

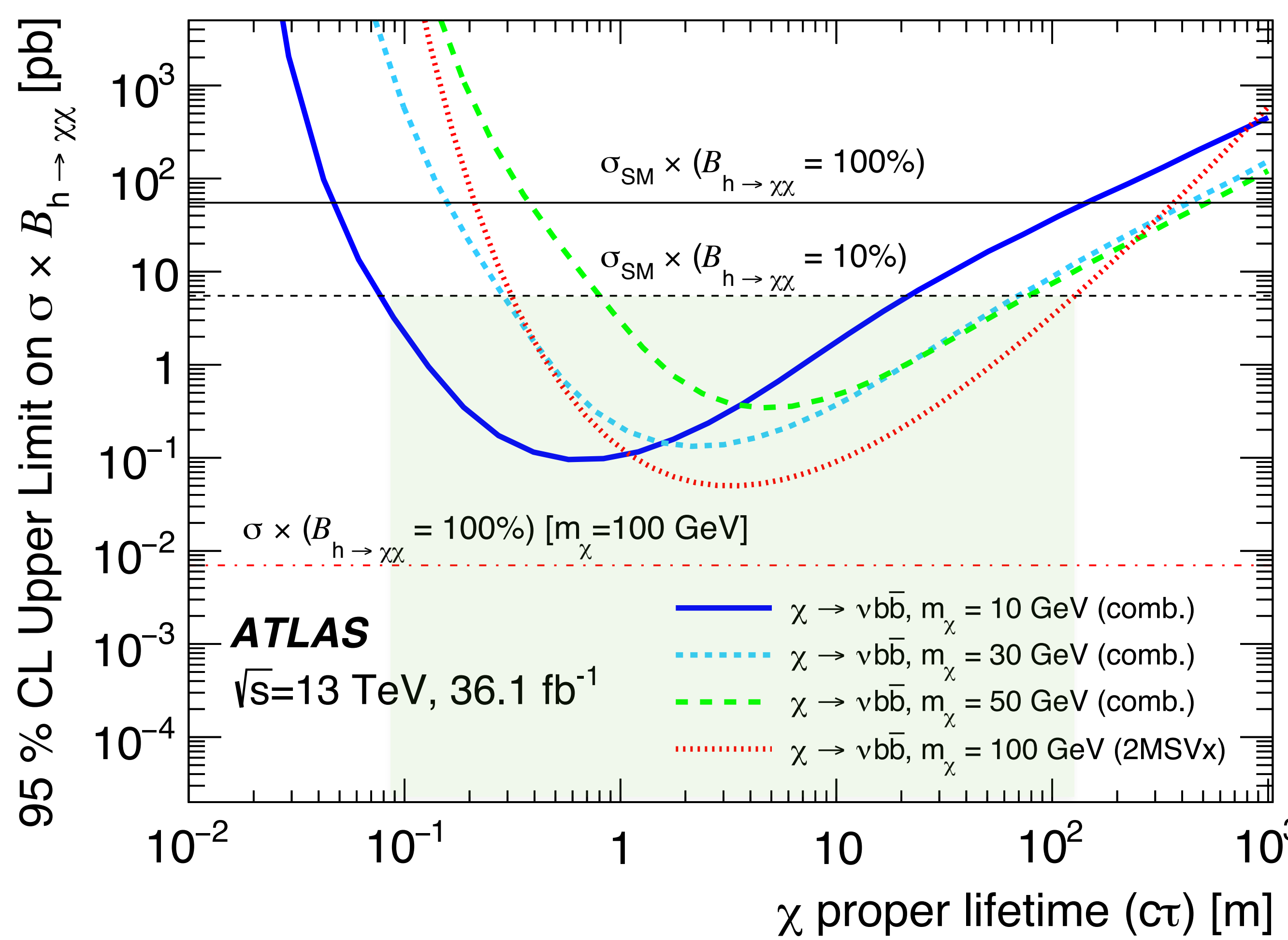


1 DV + MET



2 DVs + 2 prompt jets

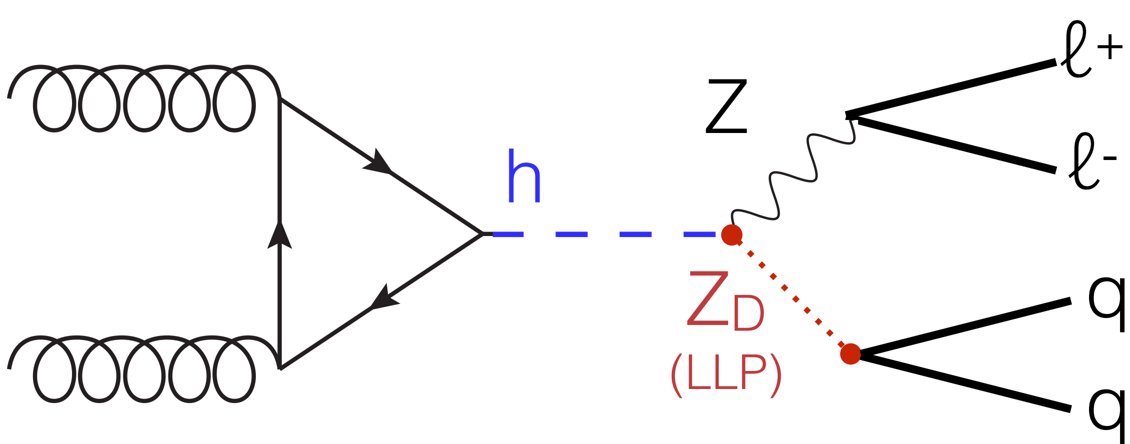




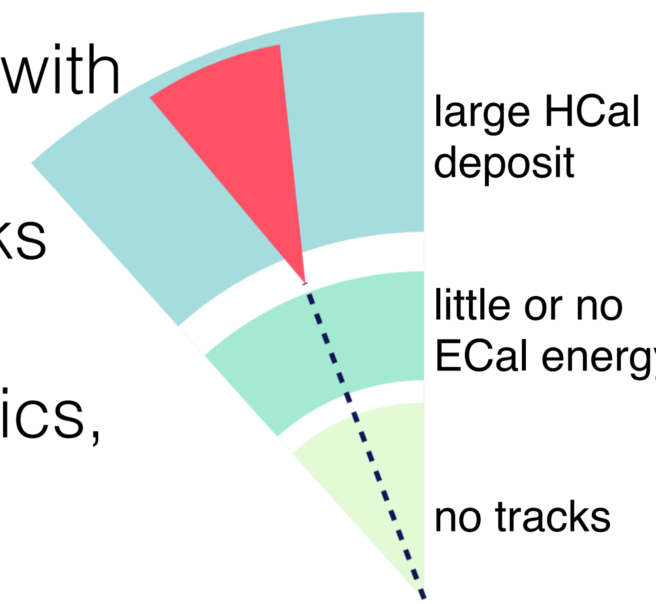
arXiv:1811.07370

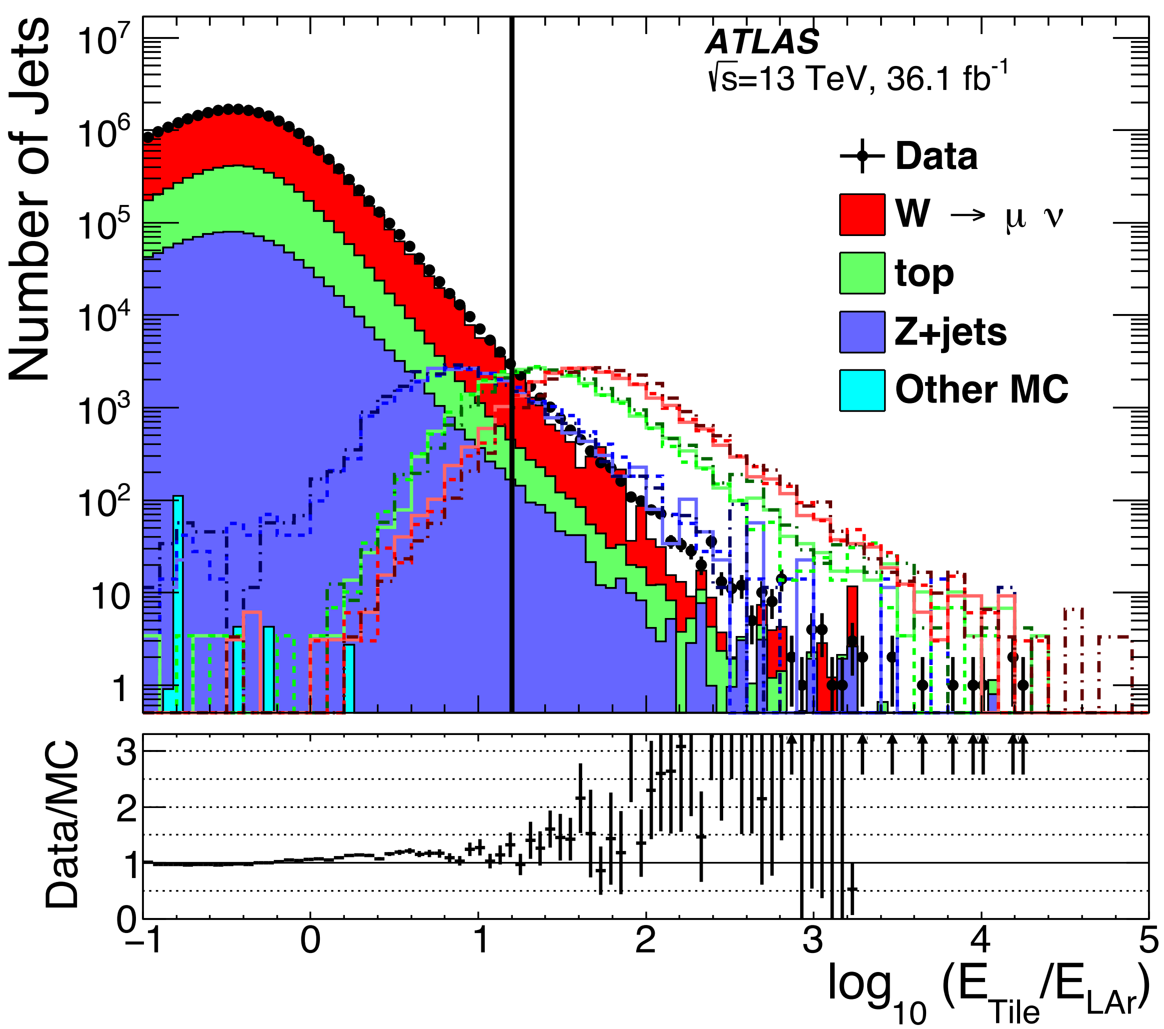
LL Decays: h → displaced jets in calorimeter

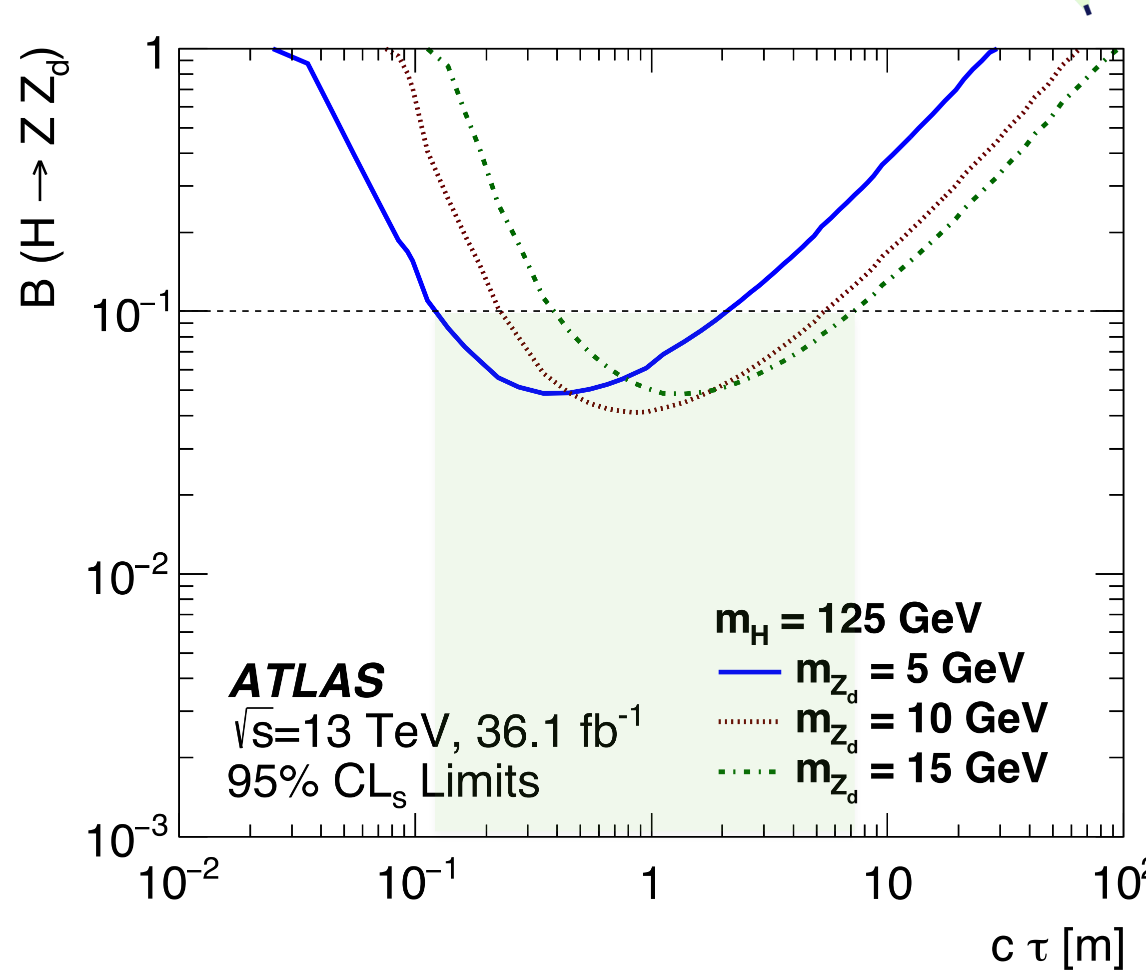
Signal



- Strategy
  - Search narrow jets with low ECal energy & no associated tracks
- Low backgrounds → non-collision: cosmics, beam halo, …



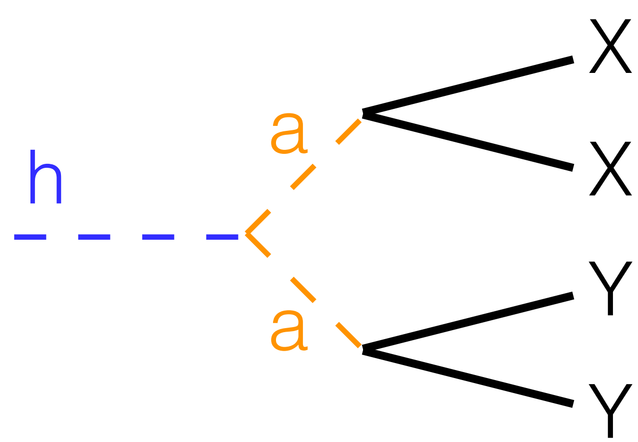




arXiv:1811.02542

BSM Decays and Couplings

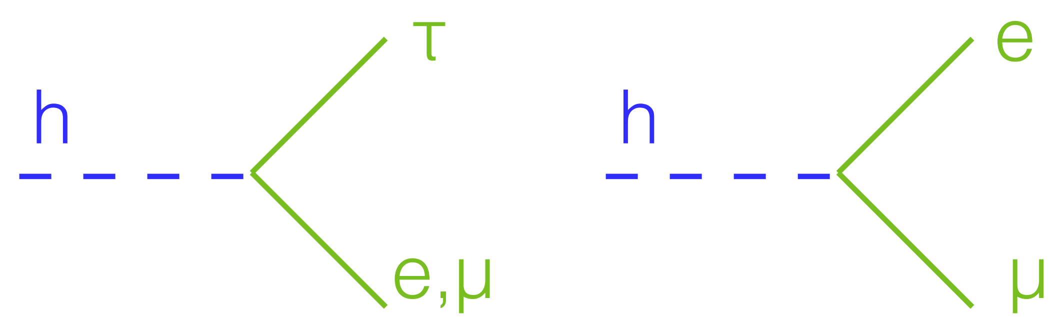
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

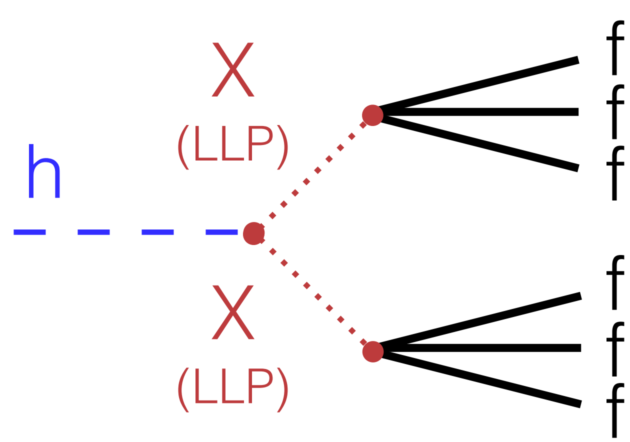
lepton decays



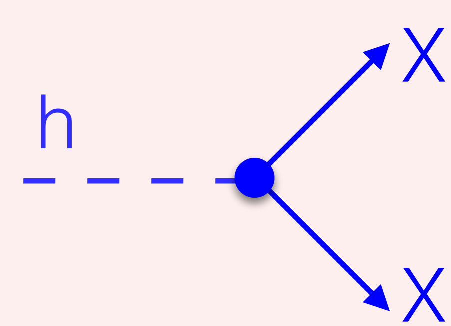
FV in quark sector also considered

Long lived particles (LLP)

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



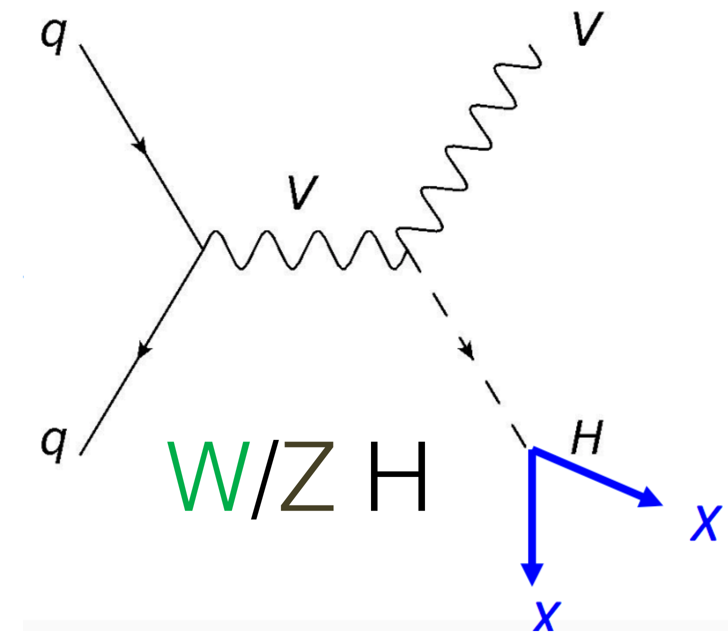
Invisible Decays



X gives E_T^{miss} signature

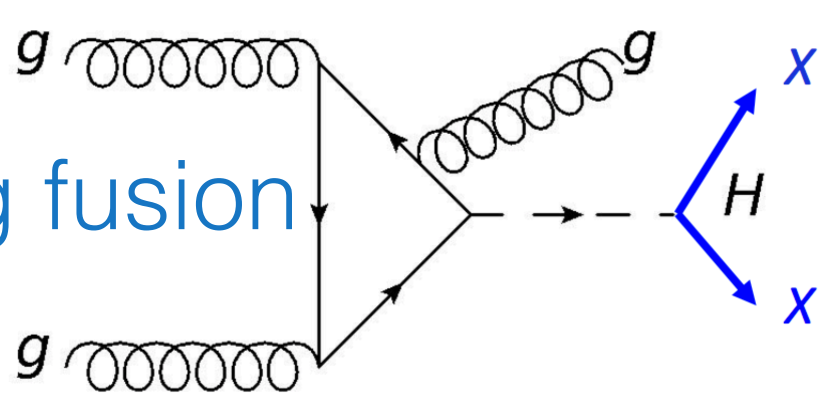
Invisible Decays

Many analyses targeting different Higgs production modes

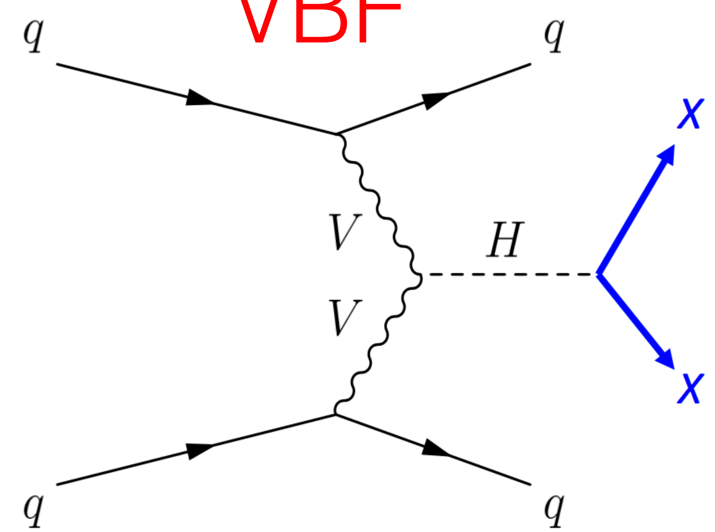


W/Z H

gg fusion



VBF



Z→ℓℓ: smallest σ
high S/B

2 OS/SF leptons (e^+e^-/$\mu^+\mu^-$)
Invariant mass close to m_Z

largest σ
low S/B

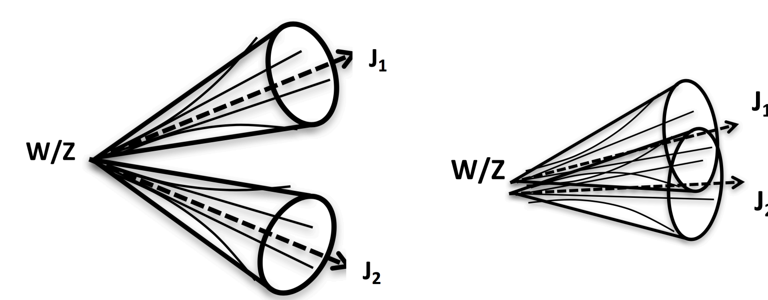
High p_T jet recoiling against large E_T^{miss}

medium σ
high S/B

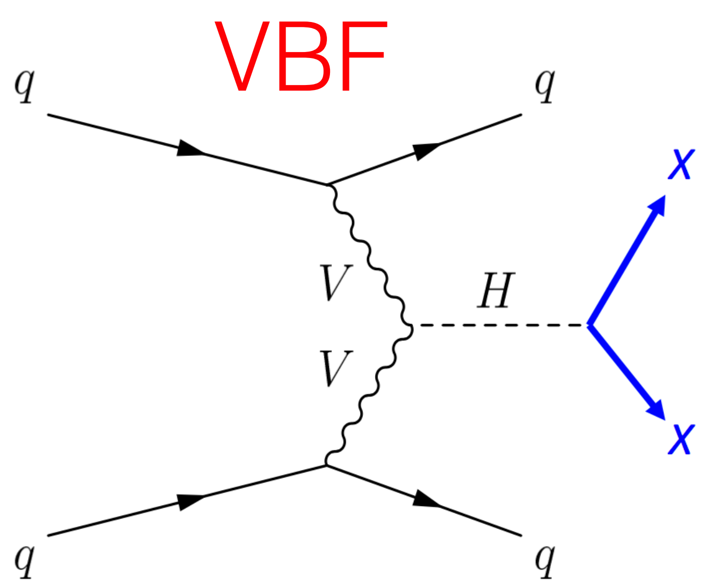
Dijet system with
large rapidity gap - $\Delta\eta(j_1,j_2)$
large dijet mass - m_{jj}

W/Z→qq: medium σ
medium S/B

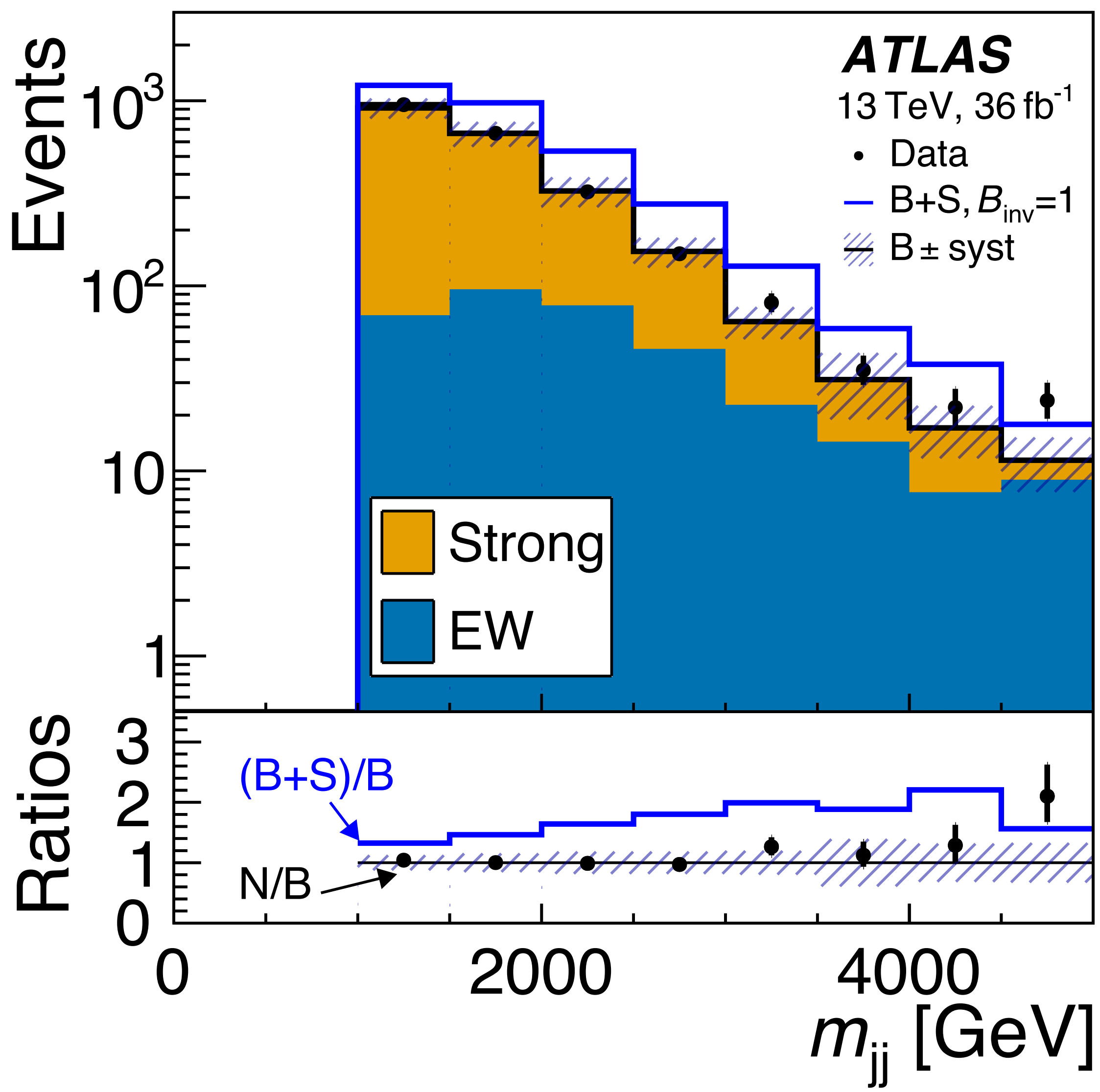
resolved or boosted jets



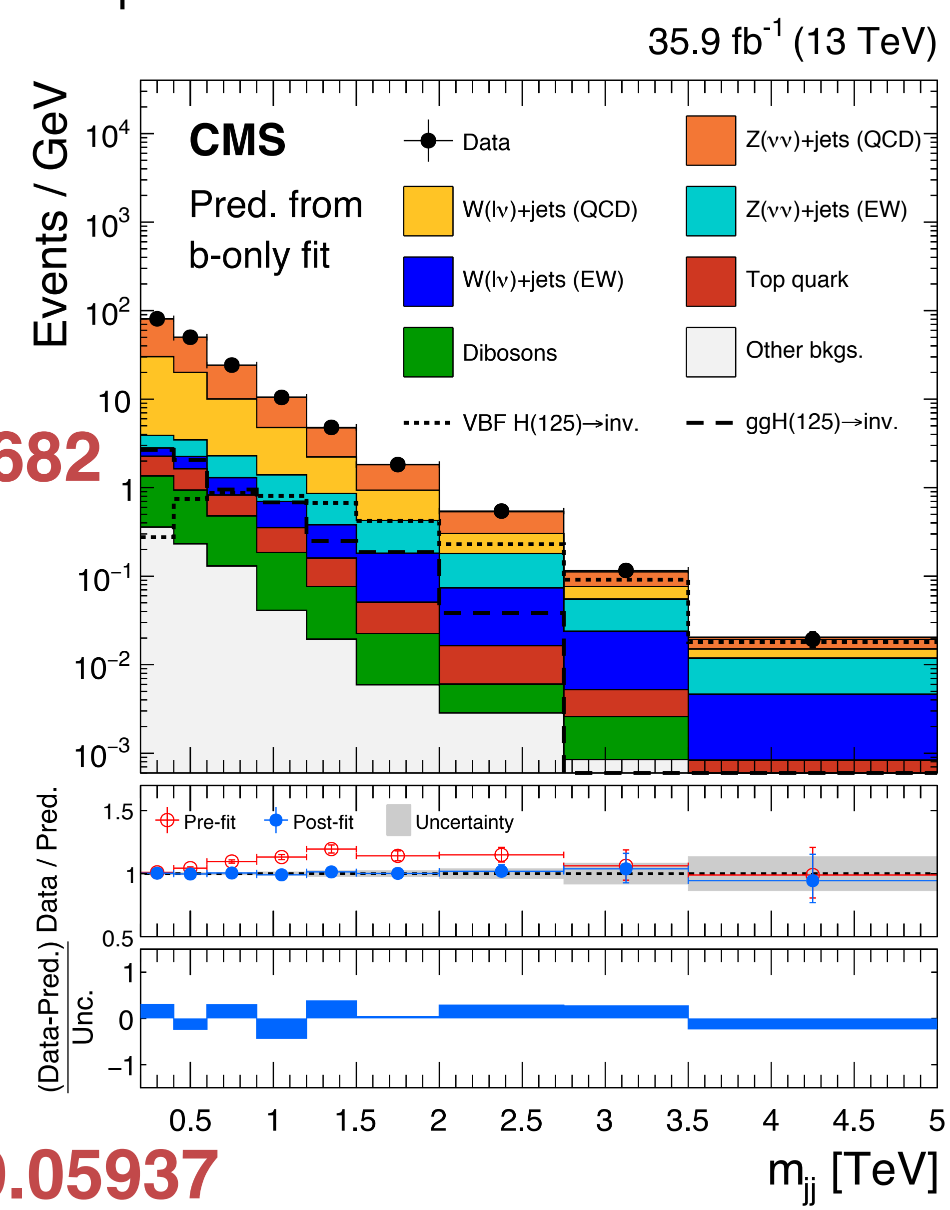
Invisible Decays



- Strategy → focus on VBF - most sensitive
  - Search for dijet events with large rapidity gap $\Delta\eta(j_1,j_2)$ and large mass m_{jj} & MET
  - Major challenge for trigger
- Large backgrounds, mainly Z and W bosons -split into strong and EW components

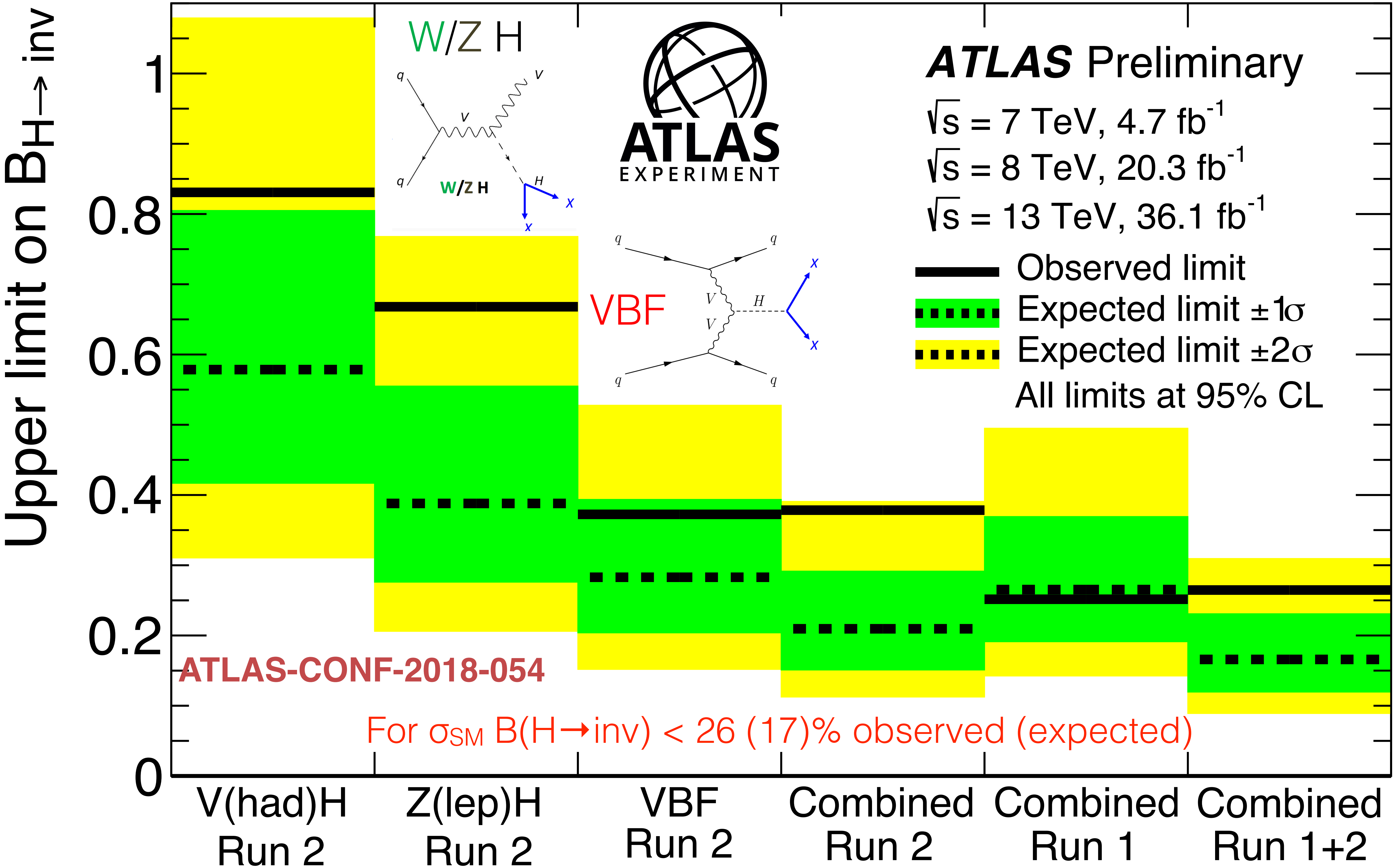


arXiv:1809.06682



arXiv:1809.05937

Invisible Decays Summary

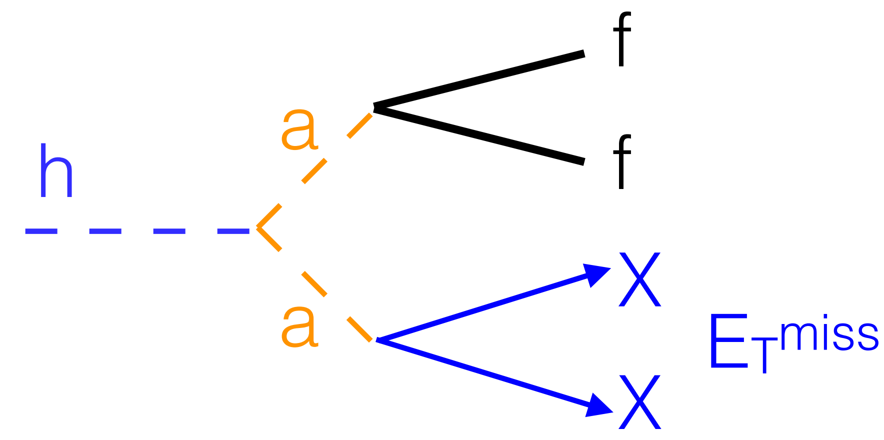


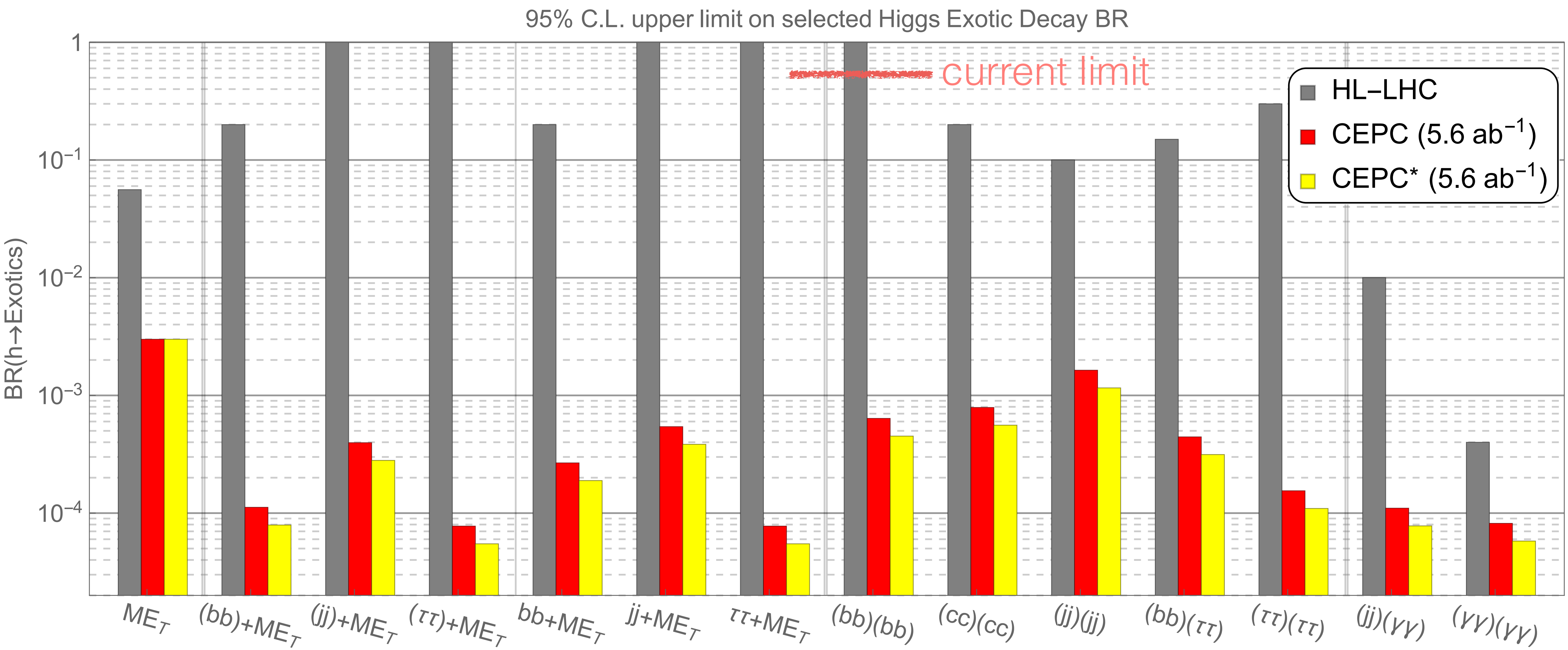
similar results from CMS arXiv:1809.05937

Future Prospects

Projections to HL-LHC and especially to future colliders shows major gains in sensitivity

Mixed modes largely uncovered at the LHC

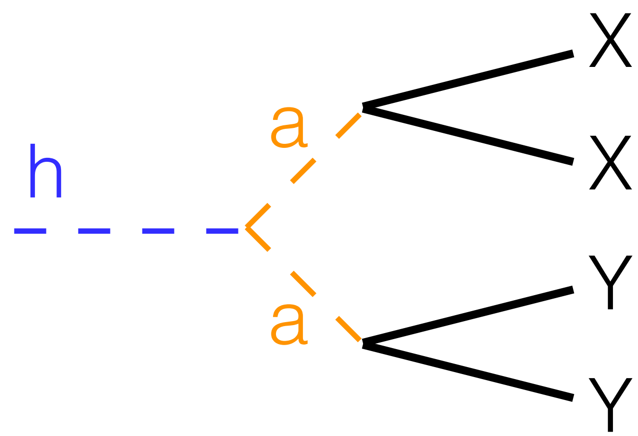




arXiv:1612.09284 and CEPC CDR

BSM Decays and Couplings

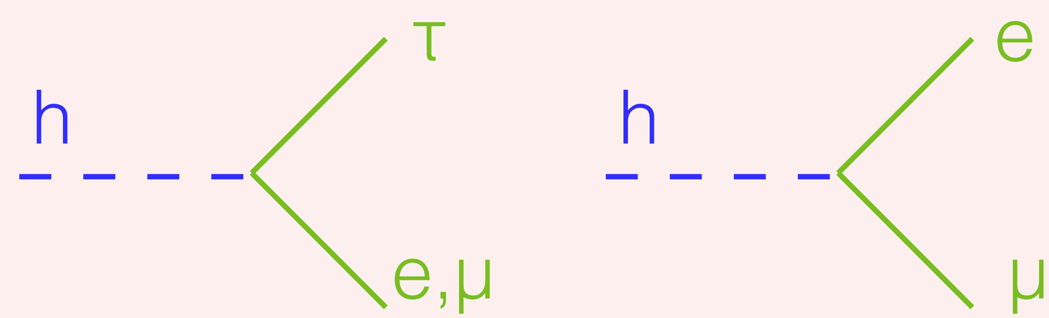
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

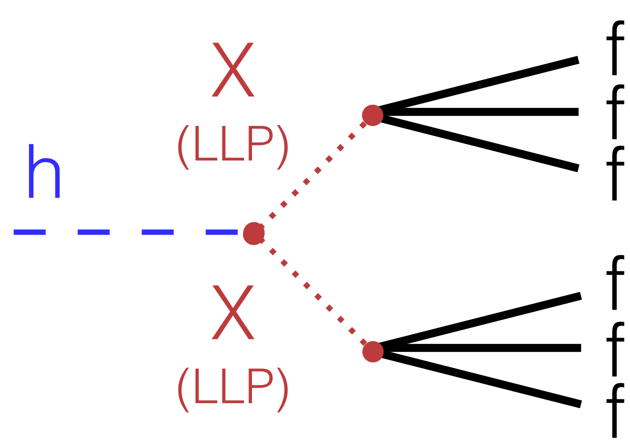
lepton decays



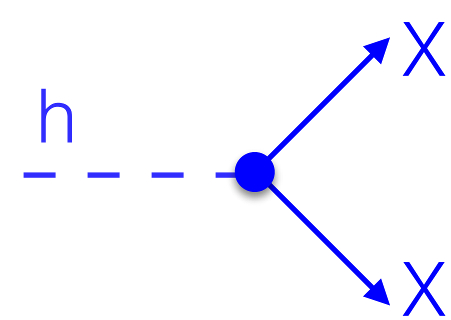
FV in quark sector also considered

Long lived particles (LLP)

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



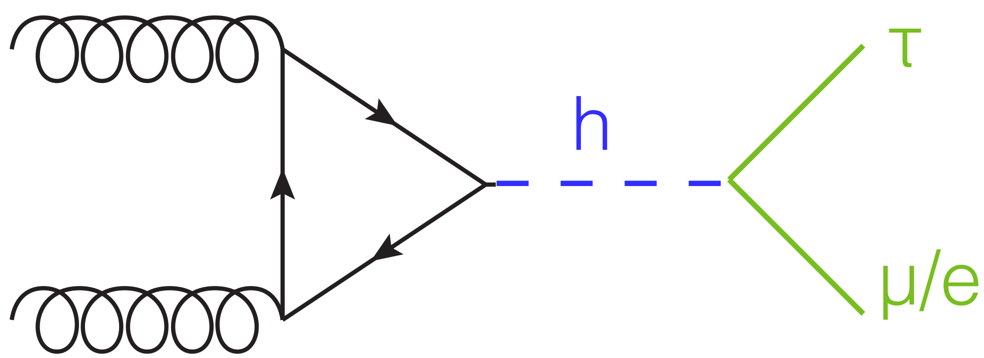
Invisible Decays



X gives E_T^{miss} signature

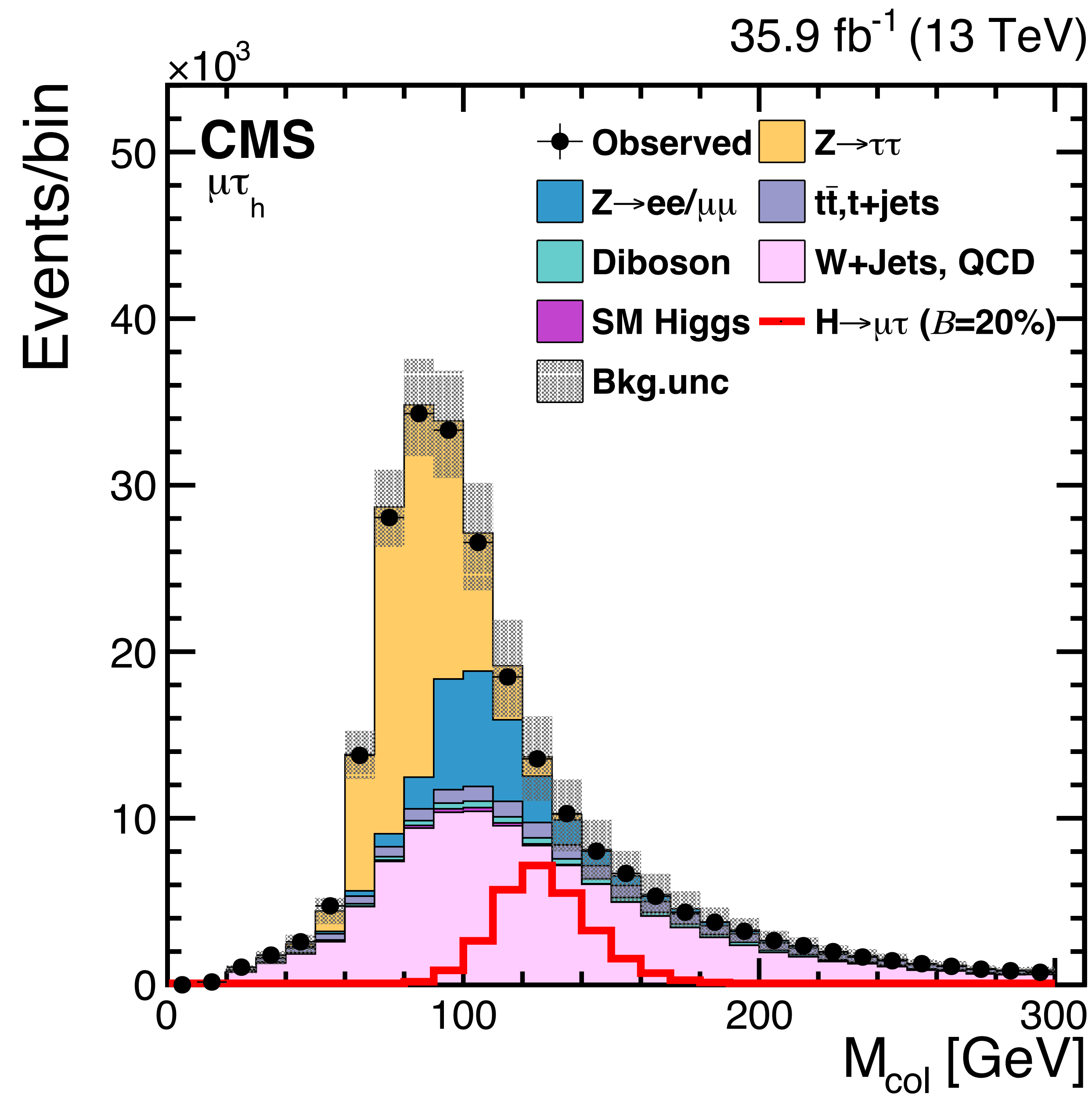
Flavor Violating Couplings: Lepton Decays

Signal



JHEP 06 (2018) 001 arXiv:1712.07173

- Strategy
  - Search for $\ell\tau$ in multiple decay modes for the tau ($\ell\tau_\ell$, $\ell\tau_{had}$)
  - Multivariate analysis including collinear mass distribution
- Large backgrounds, mainly $Z\rightarrow\tau\tau$

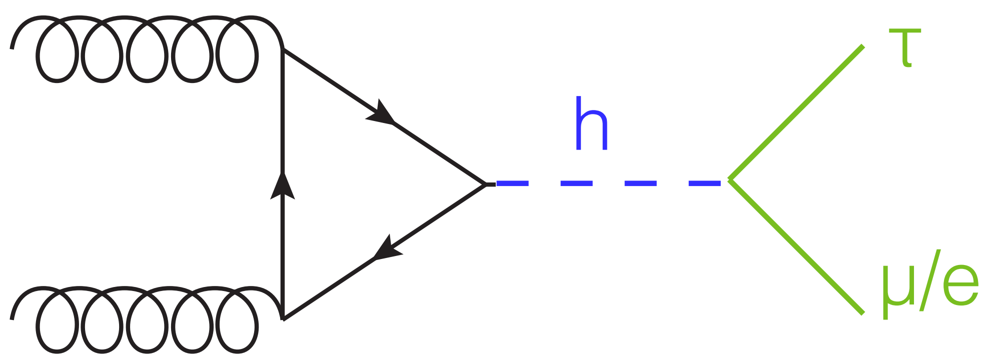


13 TeV: $Br(H\rightarrow\mu\tau)<0.25\%$ (0.25% expected)

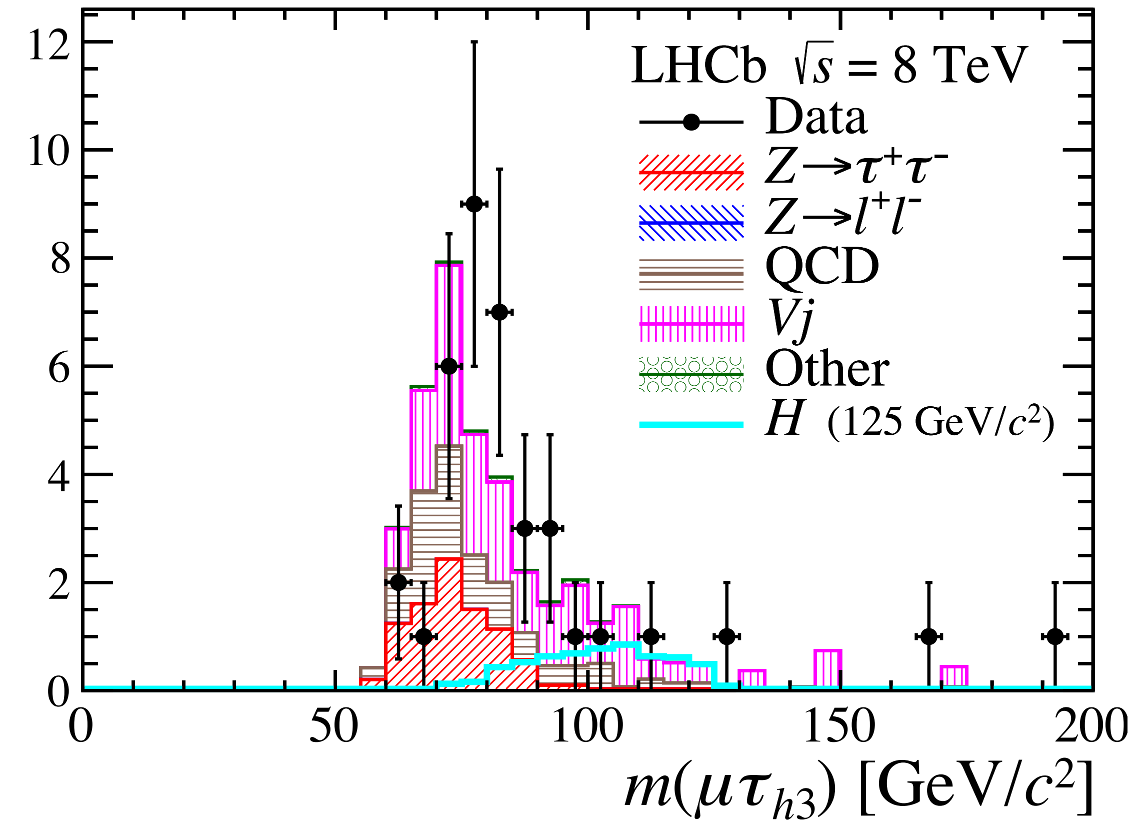
$Br(H\rightarrow e\tau)<0.61\%$ (0.37% expected)

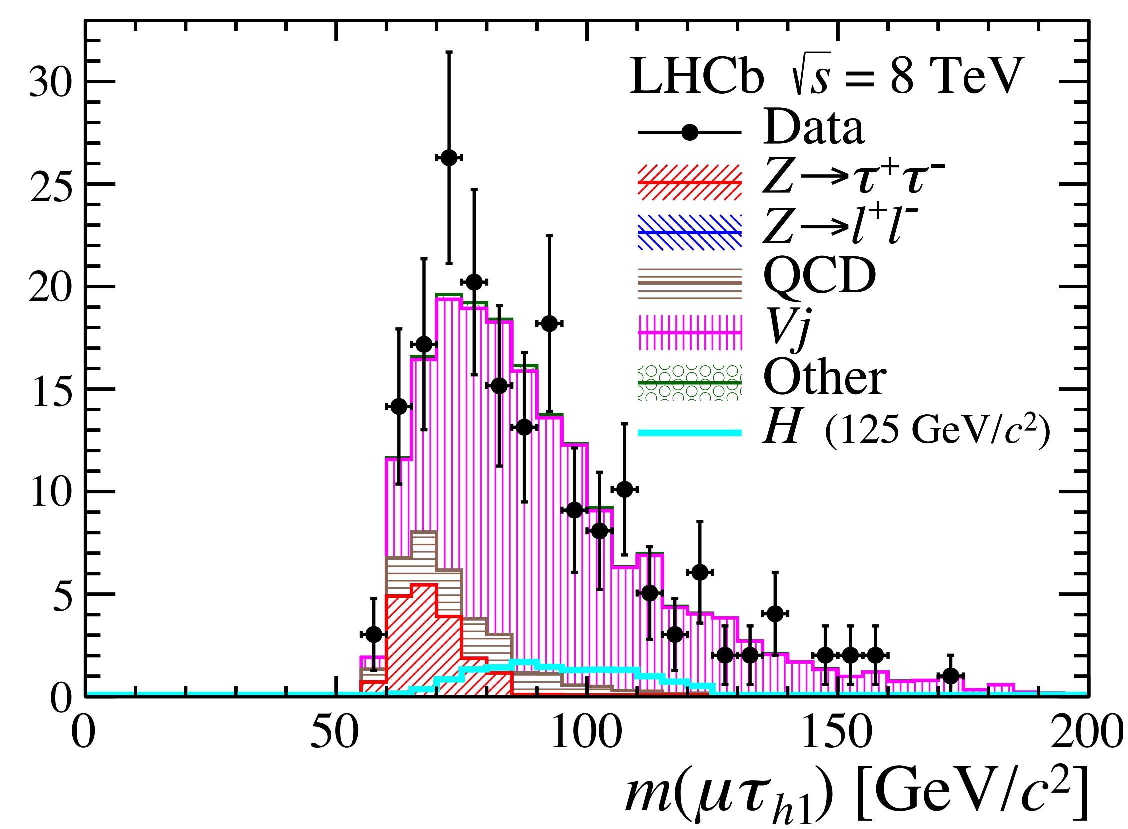
Flavor Violating Couplings: Lepton Decays

Signal



EPJC 78 (2018) 1008 arXiv:1808.07135





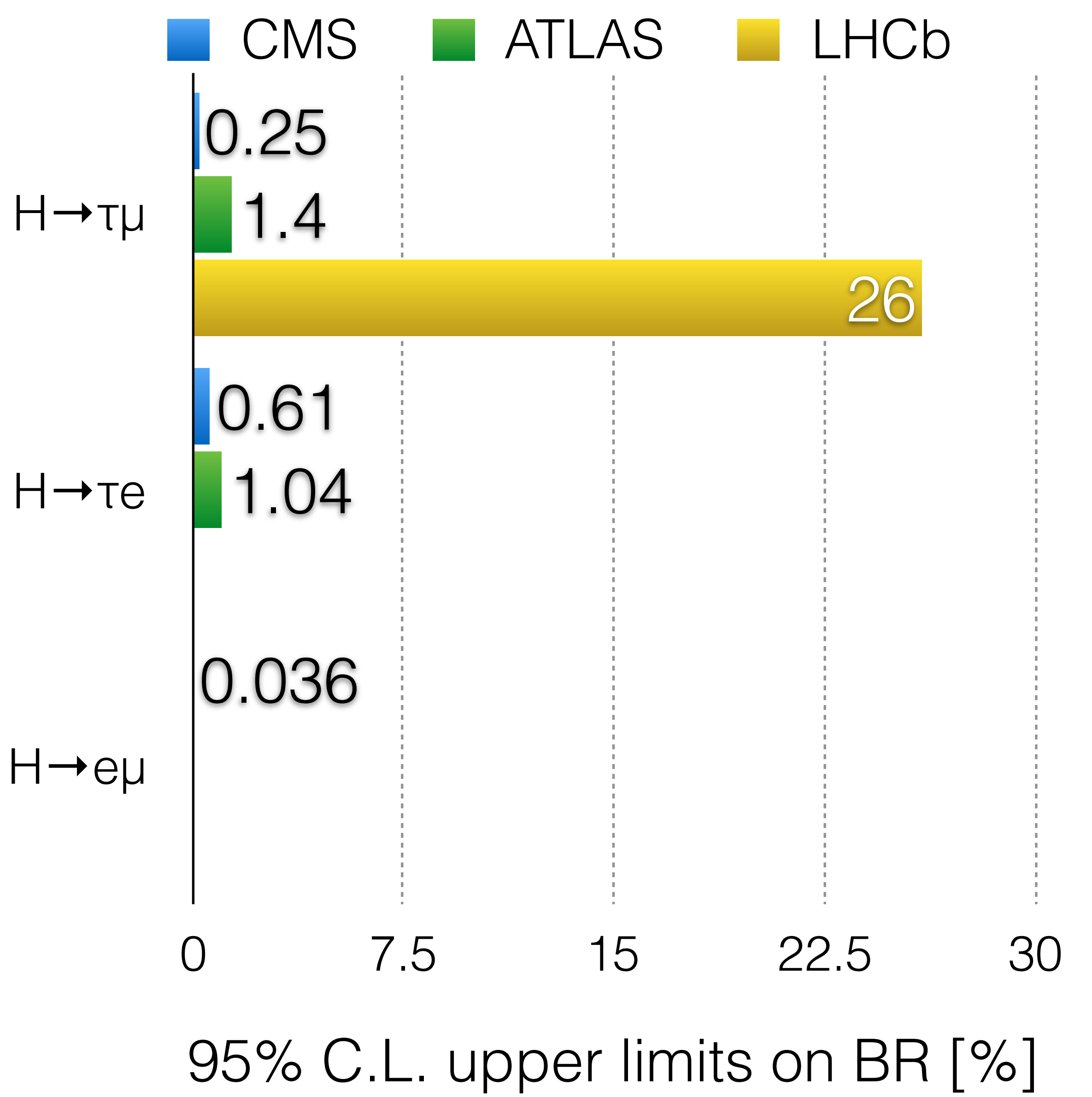
Taus reconstructed in 4 channels ($\ell\tau_e$, $\ell\tau_\mu$, $\ell\tau_{h1}$, $\ell\tau_{h3}$)

Complementary to ATLAS & CMS probing different phase space region

13 TeV: Br(H→μτ)<26%

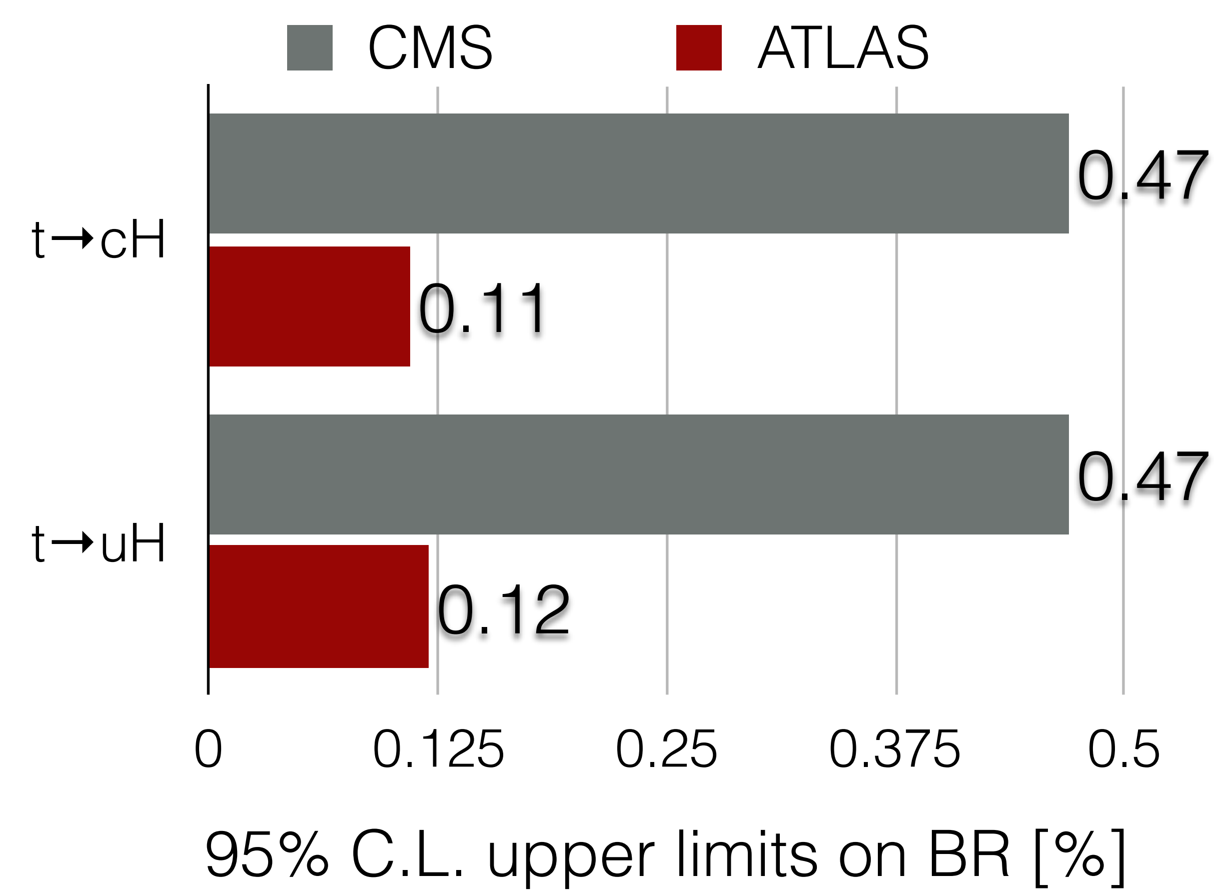
Flavor Violating Couplings Summary

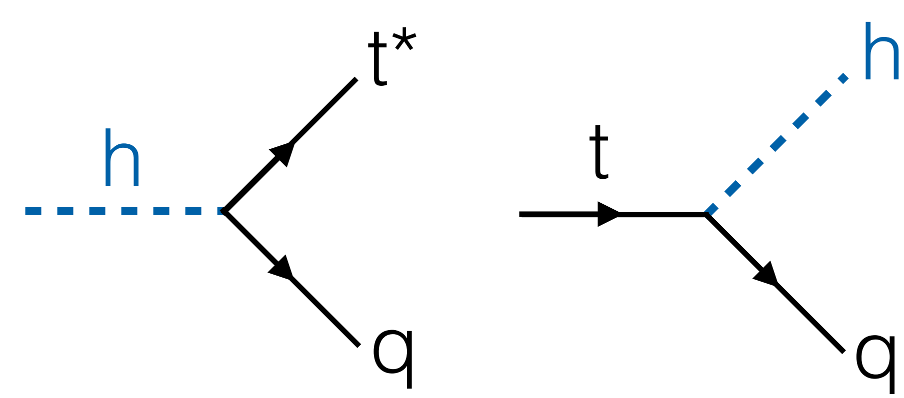
Lepton Couplings



CMS arXiv:1502.07400, arXiv:1607.03561, arXiv:1712.07173
ATLAS arXiv:1508.03372, arXiv:1601.03567, arXiv:1604.07737
LHCb: arXiv:1808.07135
CMS arXiv:1410.2751, arXiv:1610.04857, arXiv:1712.02399
ATLAS arXiv:1403.6293, arXiv:1509.06047, arXiv:1812.11568

Quark Couplings



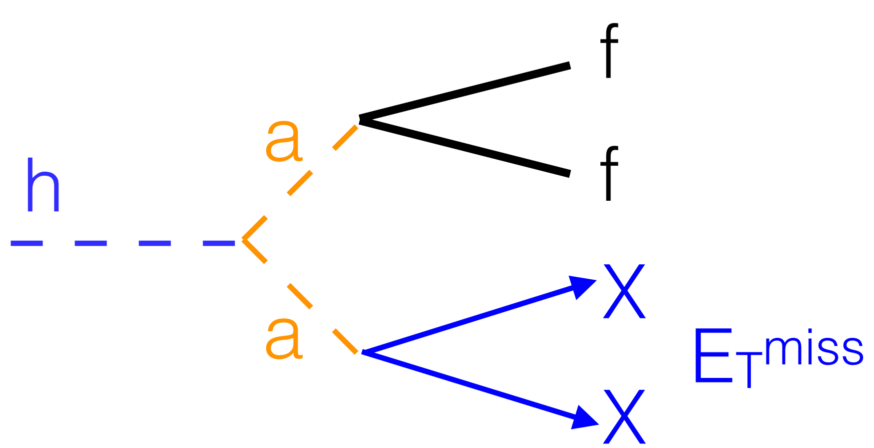


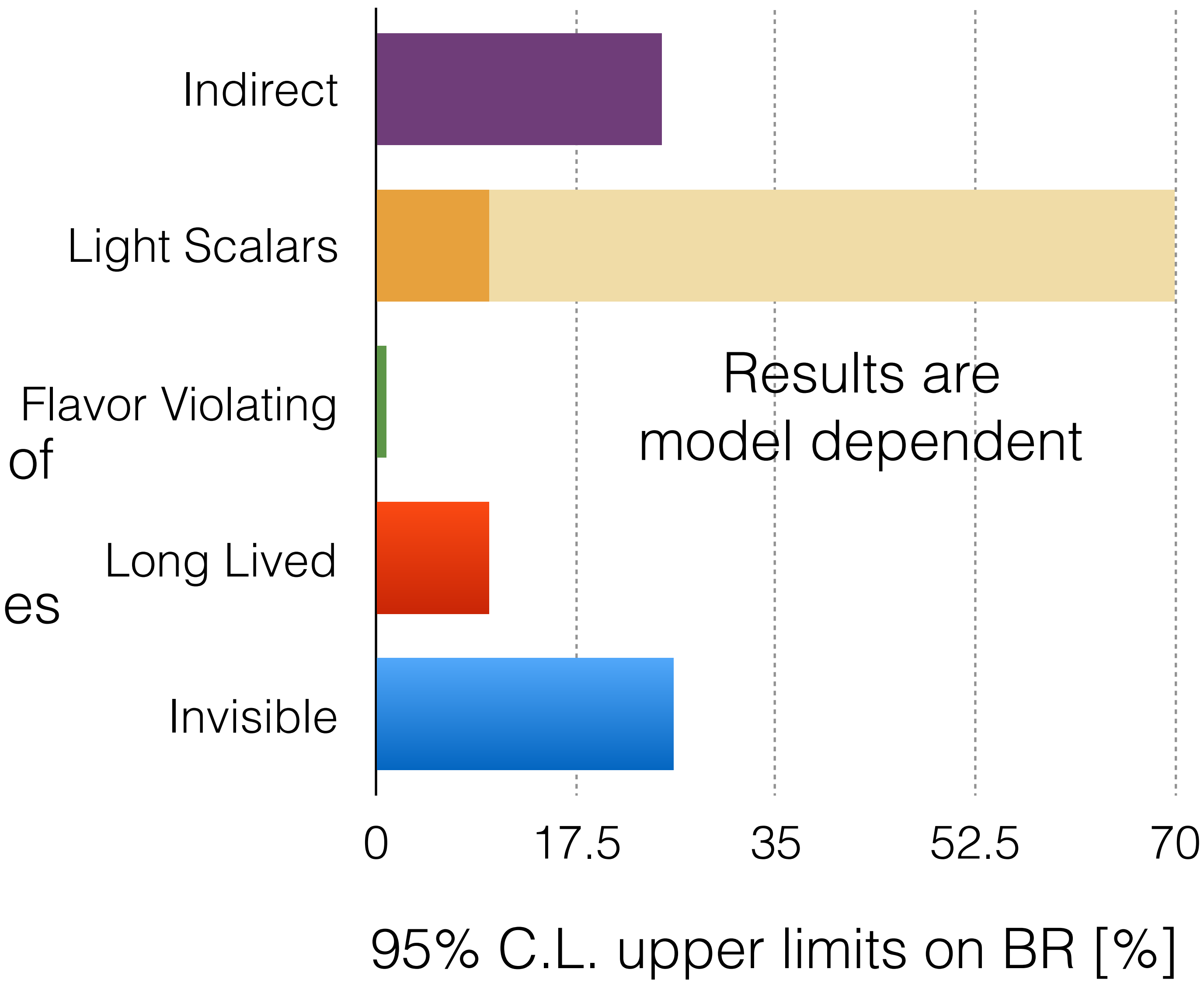
Both are sensitive to $|Y_{tq}|^2+|Y_{qt}|^2$

ATLAS arXiv:1812.11568

Summary & Outlook

- Program of dedicated searches for non-standard decays of the Higgs boson ongoing
  - New light resonances
  - Long lived particles
  - Flavor violating couplings
  - Invisible decays
- Signatures motivated by broad range of phenomenology
- Need to continue to explore possibilities in as many channels as possible to cover full spectrum
  - For example: gaps in LLPs, mixed decays





More results expected soon with full 13 TeV dataset