15th LHCHXS working group workshop
CERN, December 10-12 2018

WG3: Exotic Higgs decays subgroup report

CMS: Cecile Caillol (Wisconsin-Madison)

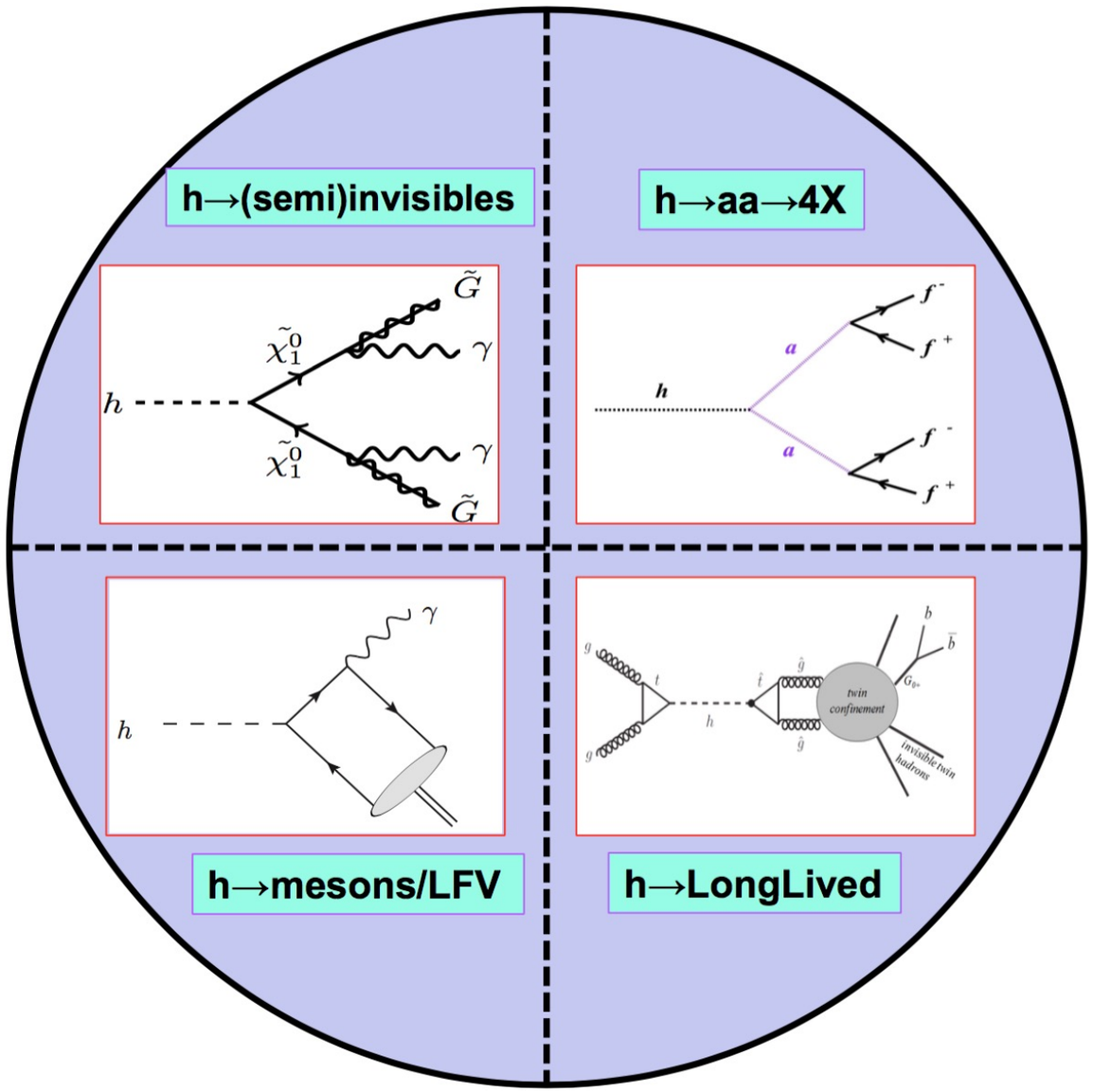
ATLAS: Ljiljana Morvaj (Stony Brook)

LHCb: Lorenzo Sestini (INFN Padova)

Theory: Zhen Liu (Fermilab), Jessie Shelton (UIUC)

Introduction

- Will give an overview of recent progress in theory and experiment in the exotic Higgs decays subgroup

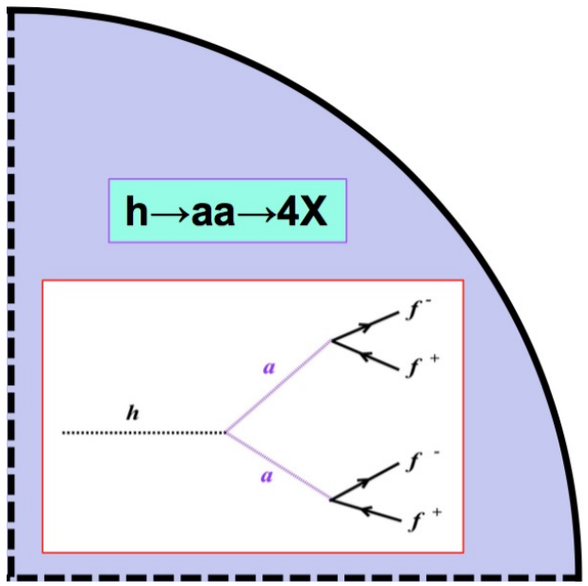


- Current constraint from fits to Higgs parameters is about **Br(H→BSM) < 26%**

  (ATLAS-CONF-2018-031)

  ➡ **Still a lot of space for new physics in Higgs decays!**

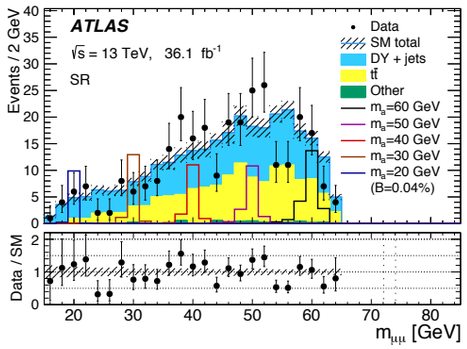
H→aa→xxyy

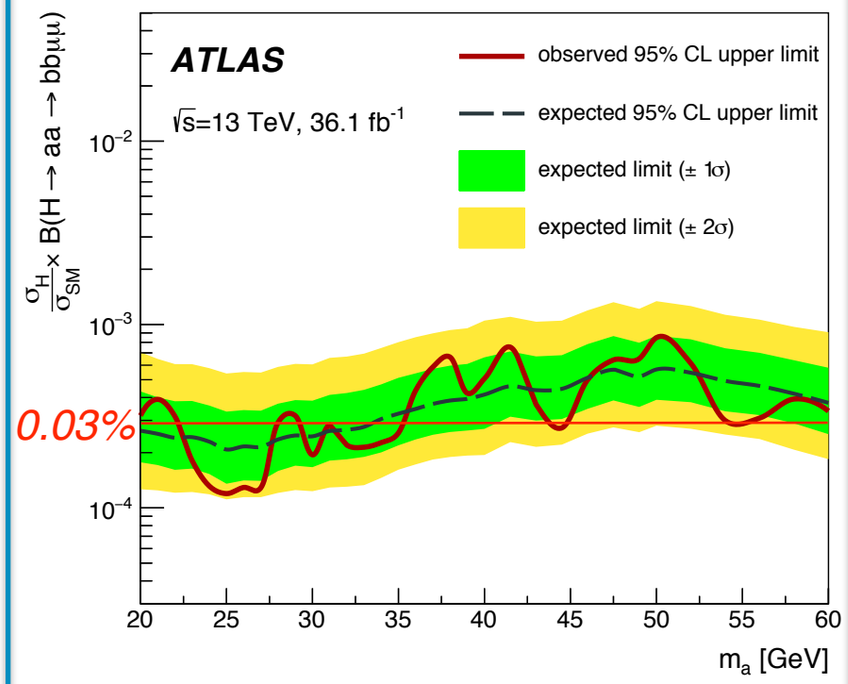


H→aa→2b2μ

arXiv:1807.00539

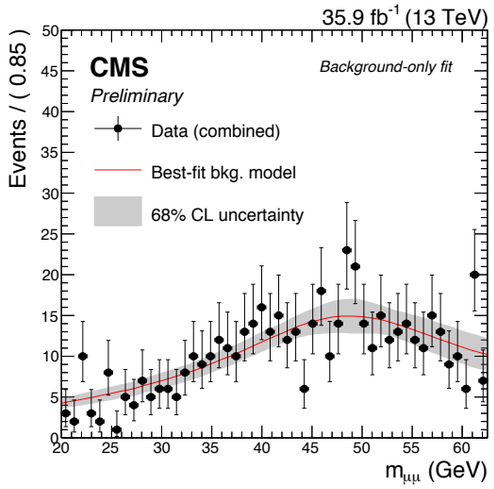
- First ATLAS bb$\mu\mu$ result
- Cut-and-count analysis, scan $m_{\mu\mu}$ in multiple bins

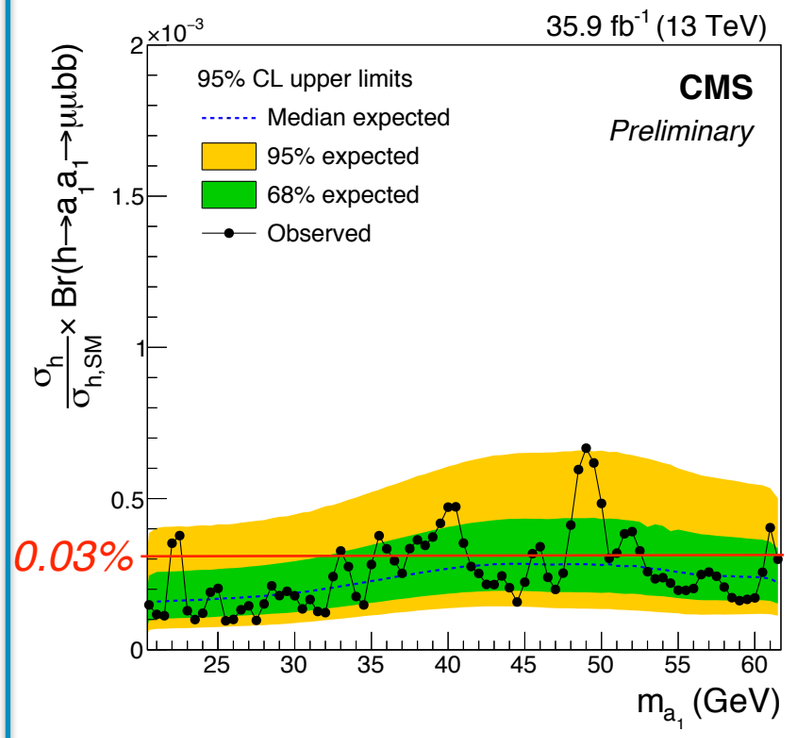


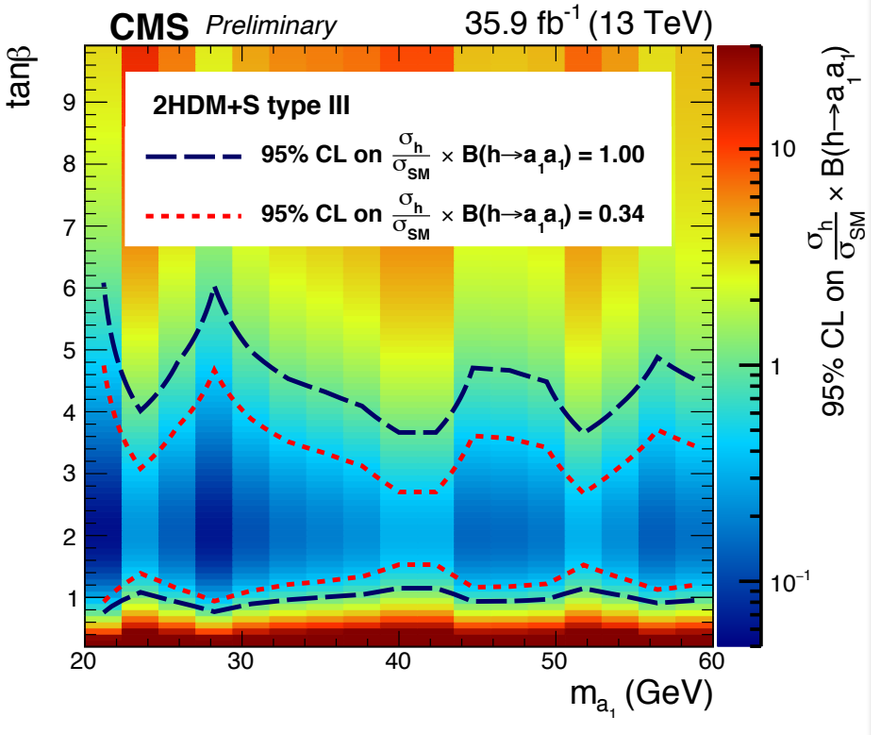


- Update of 8 TeV analysis
  - Using several categories of b-tagged events: loose-tight, tight-tight, tight-medium
  - Extend down to m_a = 20 GeV
- Unbinned fit to $m_{\mu\mu}$

HIG-18-011-pas



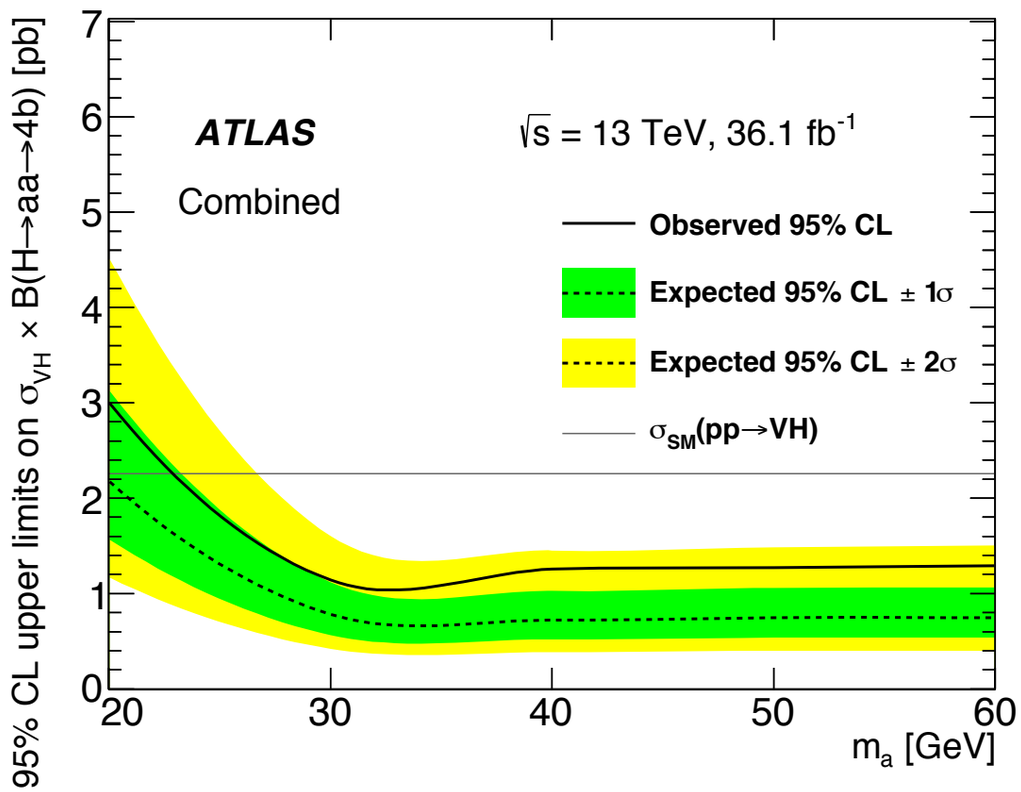




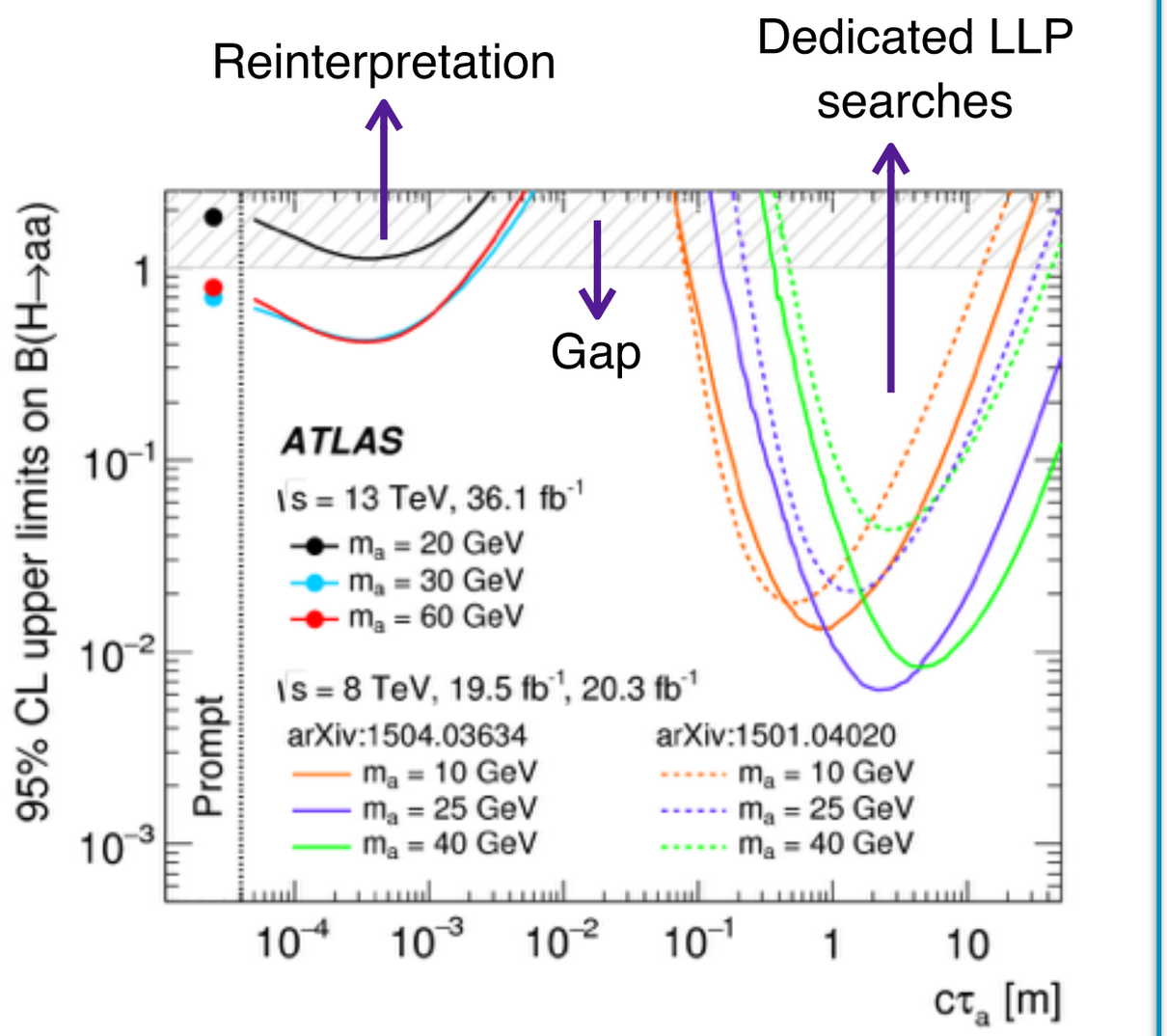
H→aa→4b

JHEP10(2018)031

- Update of 13 TeV 4b analysis with 36 fb^{-1}
  - VH production - add ZH (lep-lep) category
  - Improved analysis technique: train BDT for each m_a - better sensitivity for low m_a



- Reinterpretation of the prompt analysis for slightly displaced signals
  - Explore the transition between prompt and long-lived searches

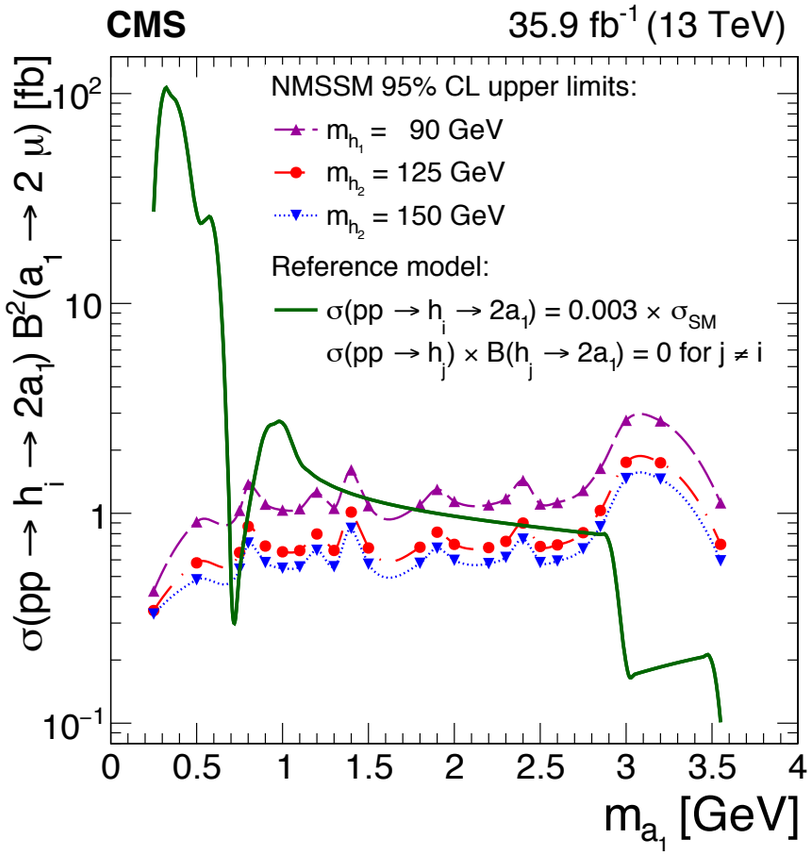


H→aa→4μ

arXiv:1812.00380

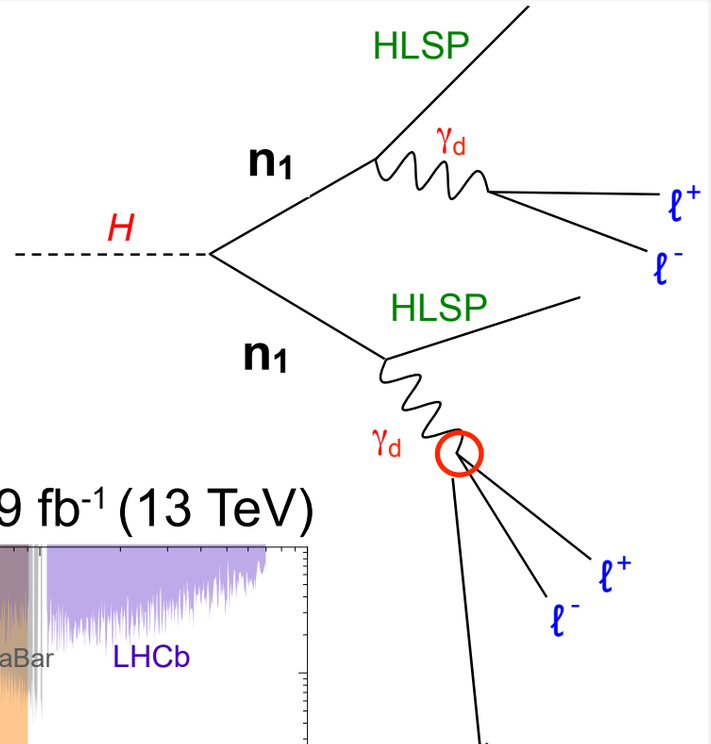
- Probing **$0.25 < m_a < 8.5$ GeV**
- New trigger with increased sensitivity to displaced vertices
- Interpretation in 2 models:

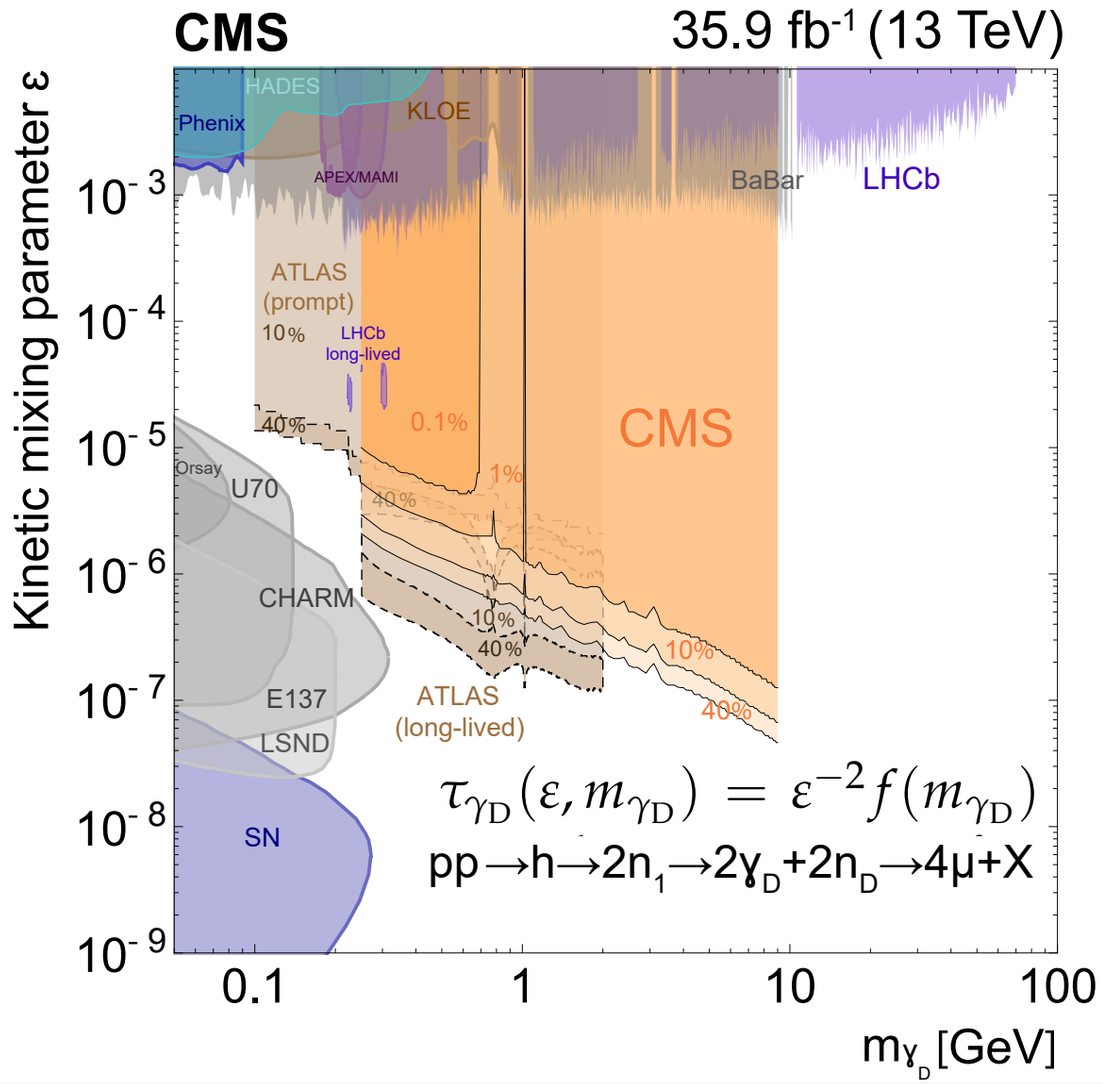
NMSSM: tanβ = 20



Dark SUSY scenario

- ATLAS 8 TeV:
  - prompt: 1511.05542
  - long-lived: 1409.0746



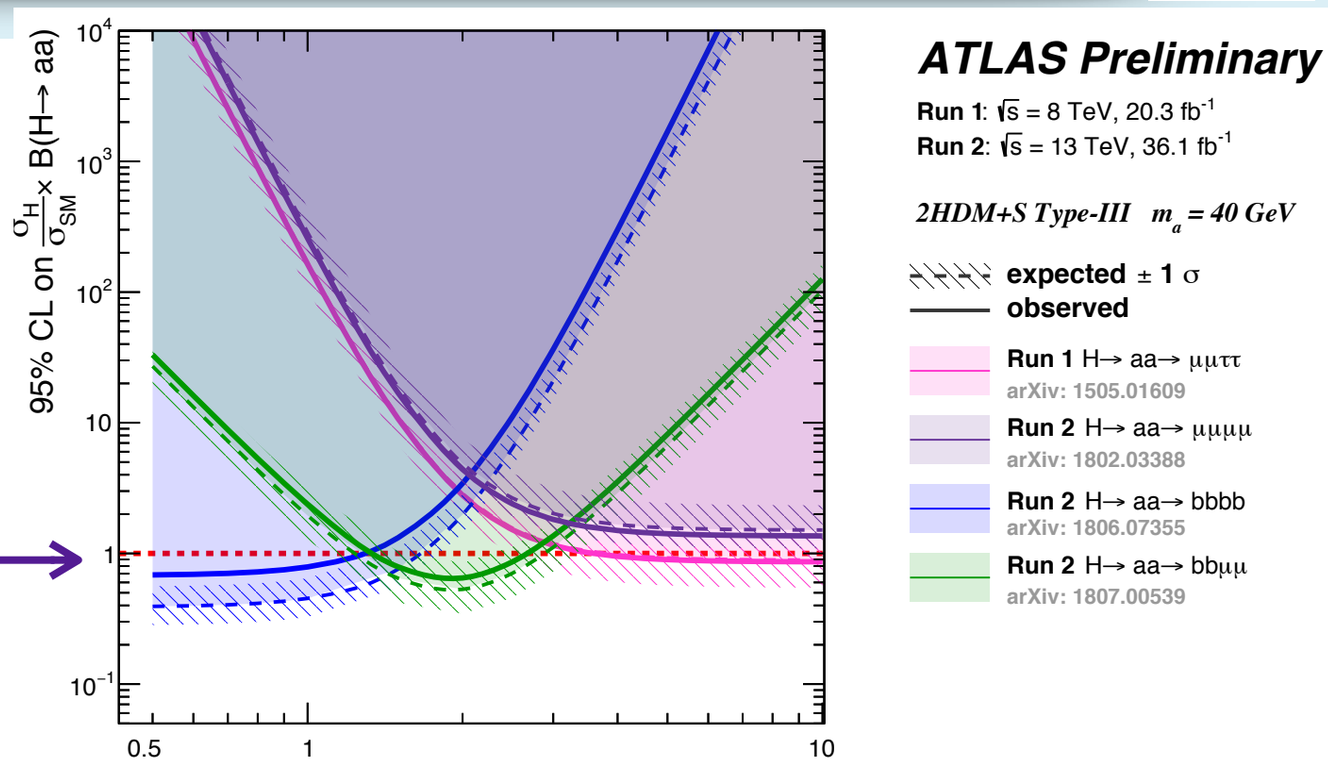


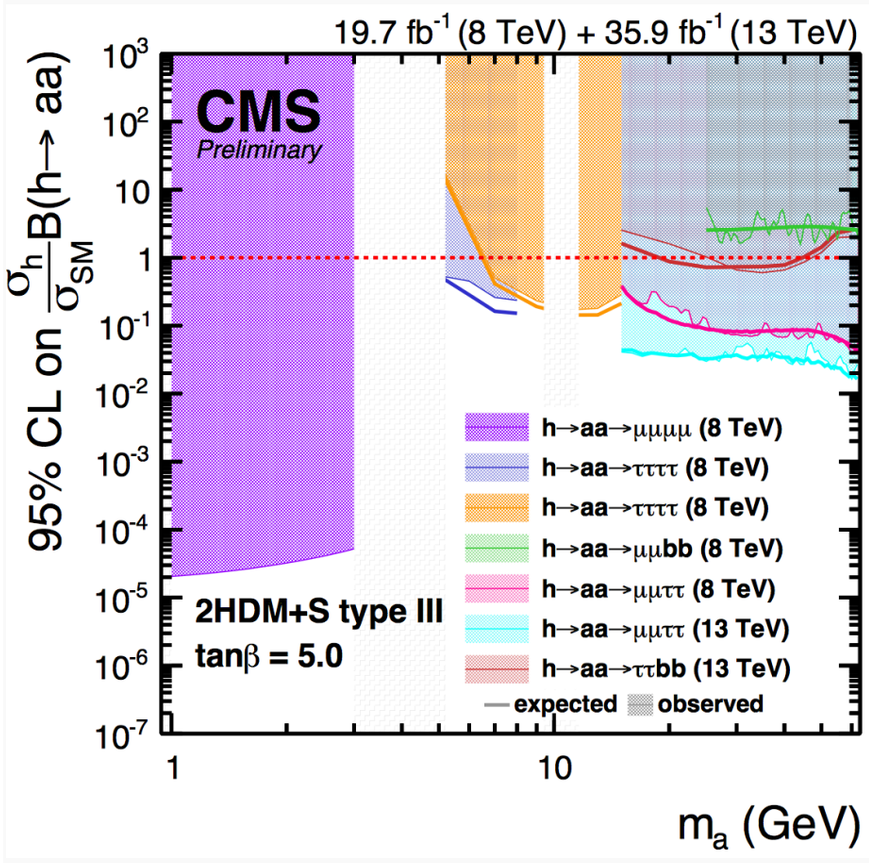
Coupling to SM via kinetic mixing ε

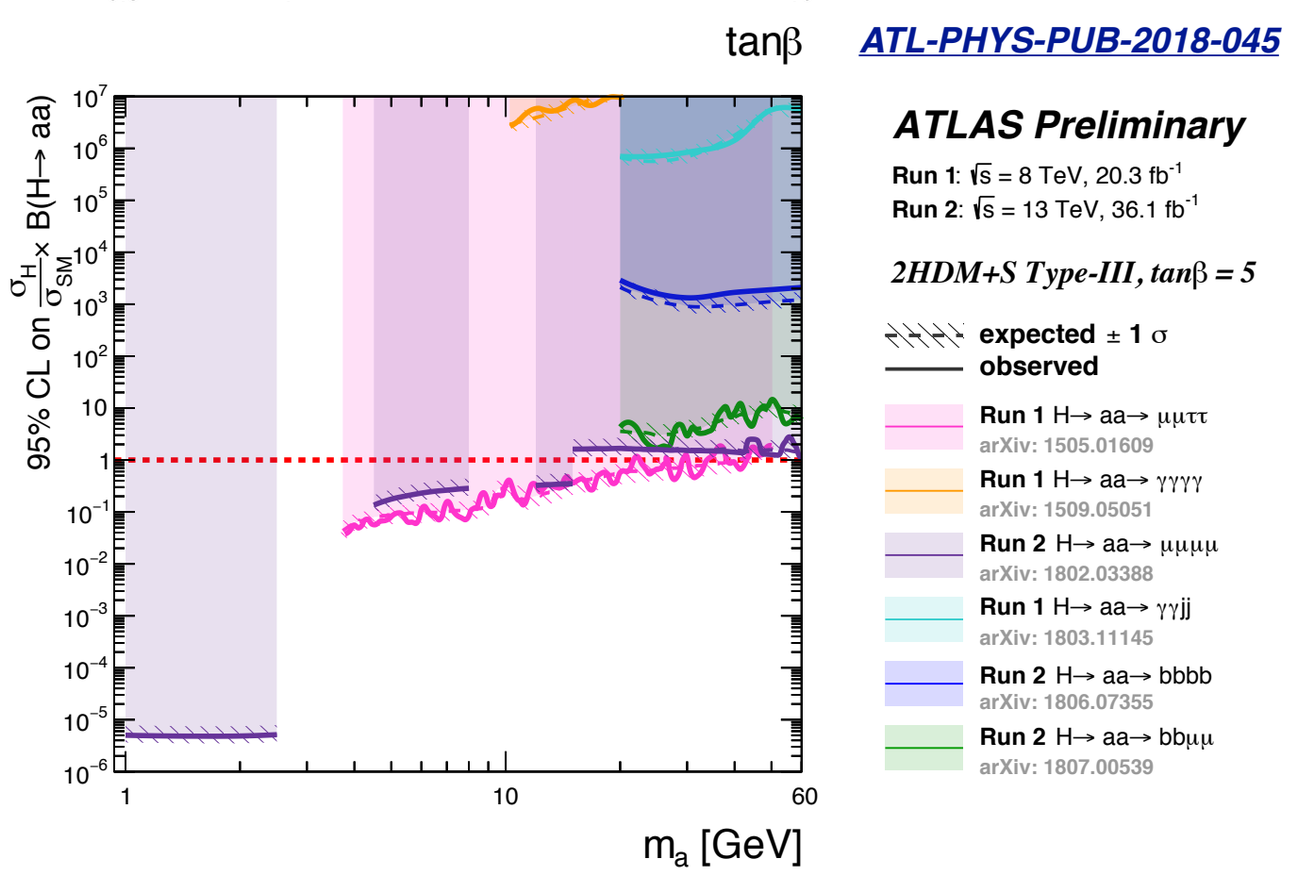
Covering up to $c\tau_{\gamma_D} = 100\,\mathrm{mm}$

H→aa summary

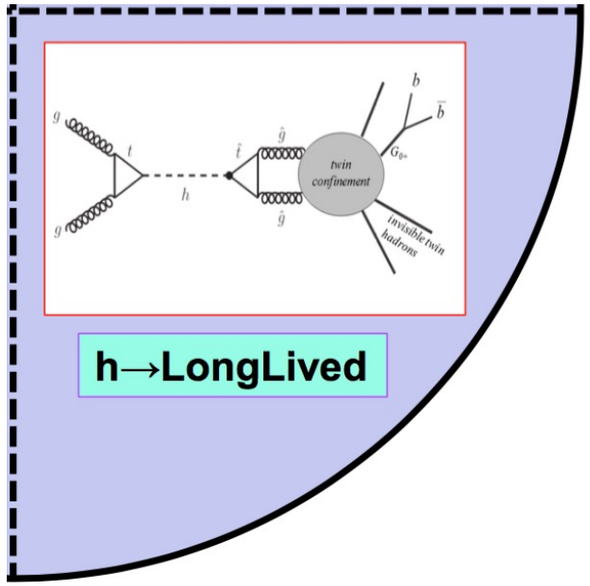
- **New**: ATLAS summary plots
  - Showing the limits also in the quarkonia regions (using calculations from JHEP3(2018)178)
  - Nice complementarity of different channels for different tanβ values







H→LLP

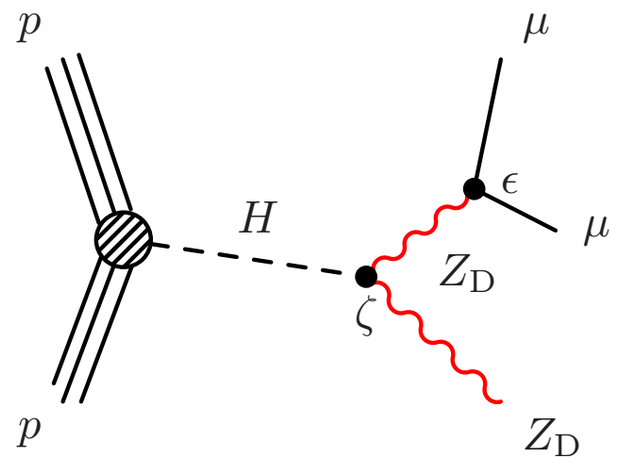

g
g
t
h
t̄
g̃
g̃
twin confinement
b
b̄
G_tw
invisible twin hadrons
h→LongLived

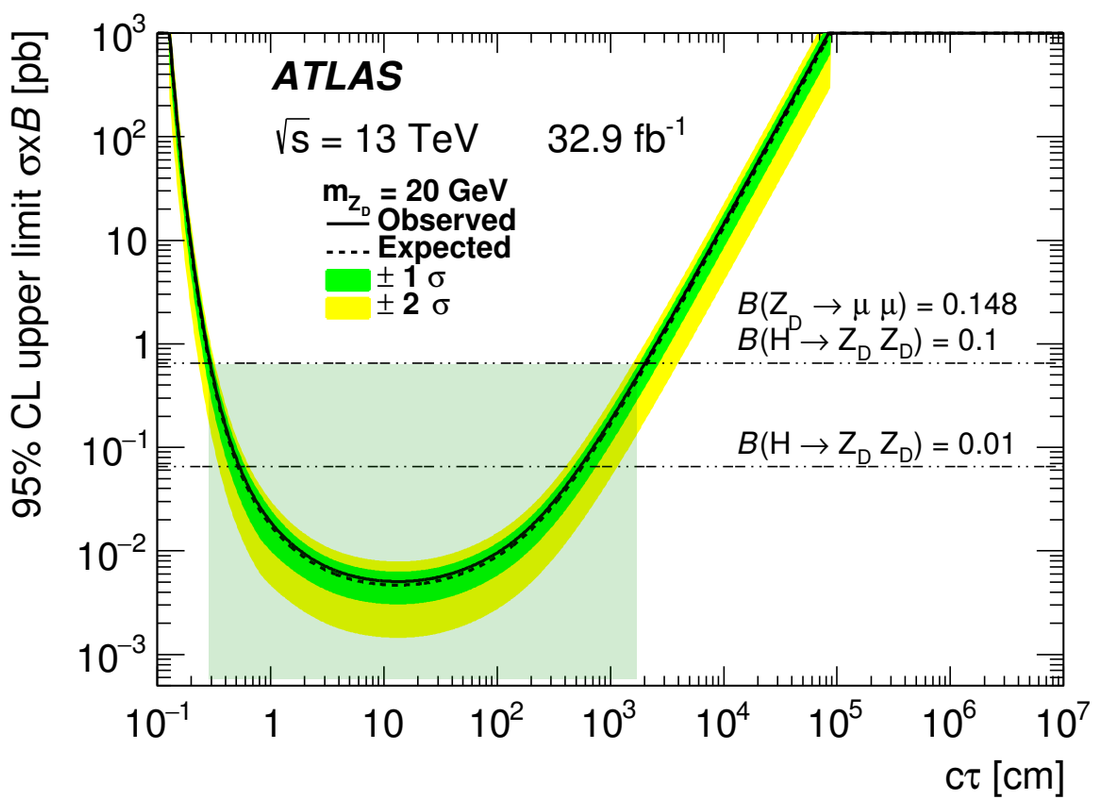
H→displaced muons

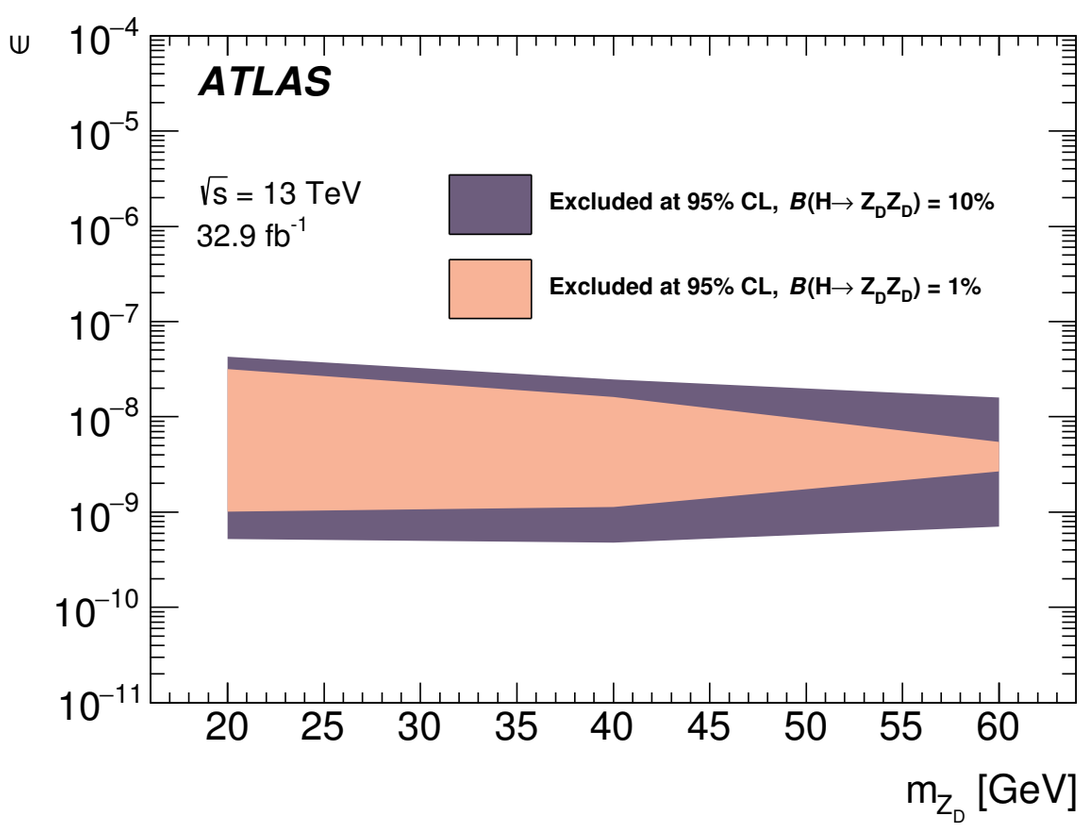
arXiv:1808.03057

- Searching for displaced vertices (DV) using tracks of identified muon
  - ATLAS allows detection of dimuon DVs within a large decay volume
  - Low backgrounds

Hidden sector motivation/interpretation



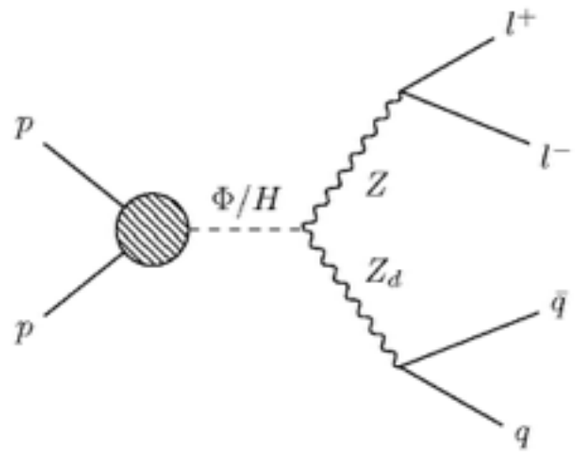


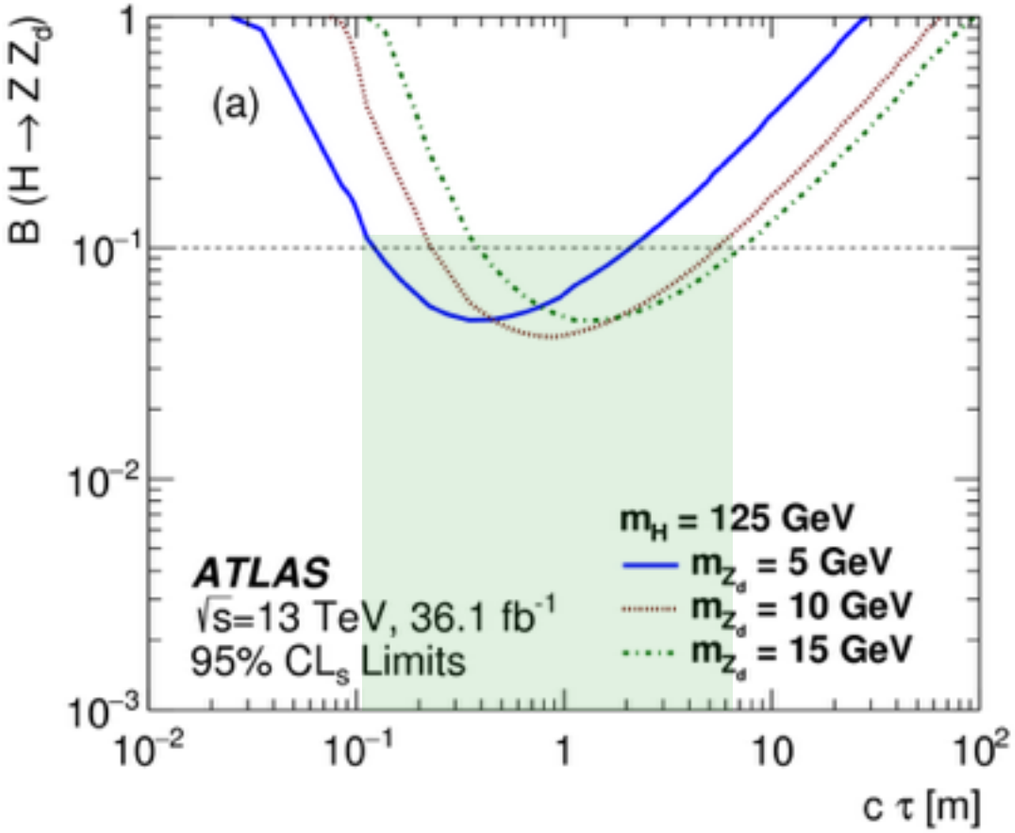


H→displaced jets

arXiv:1811.02542

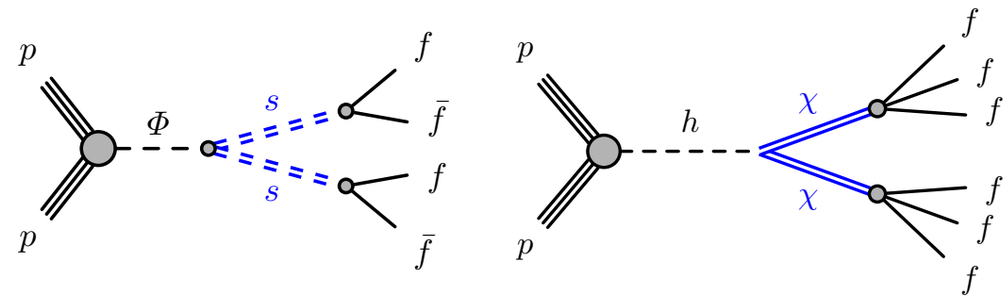
- LLPs decaying to jets in hadronic calo

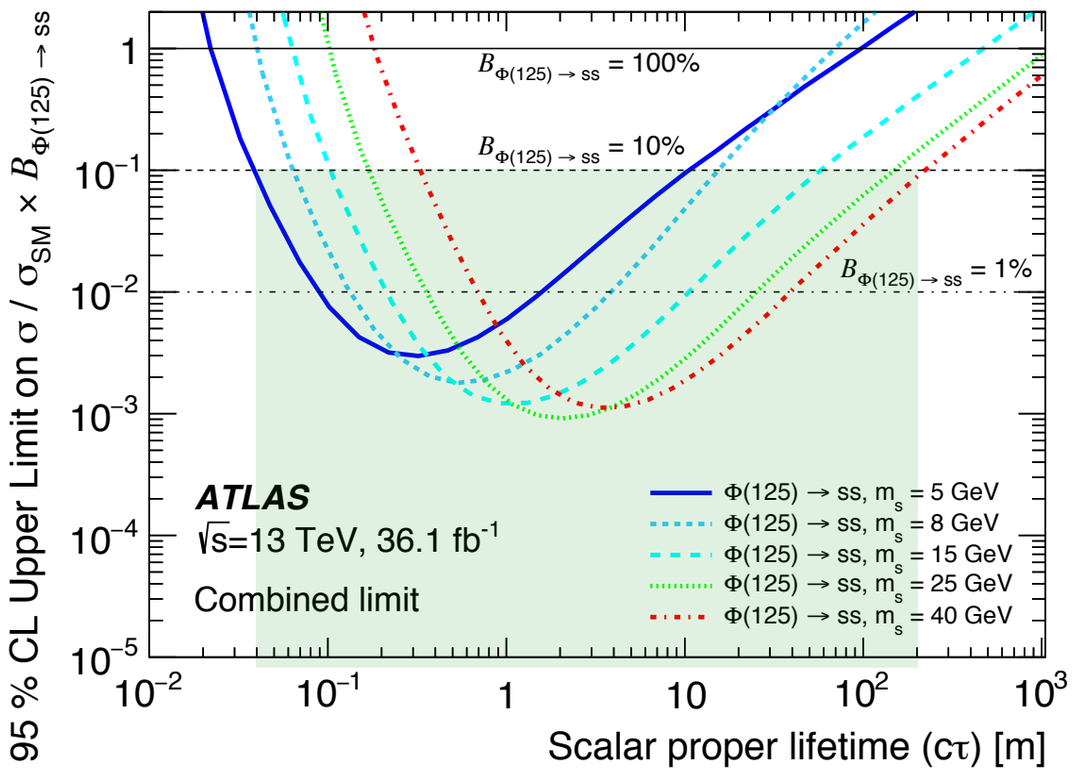




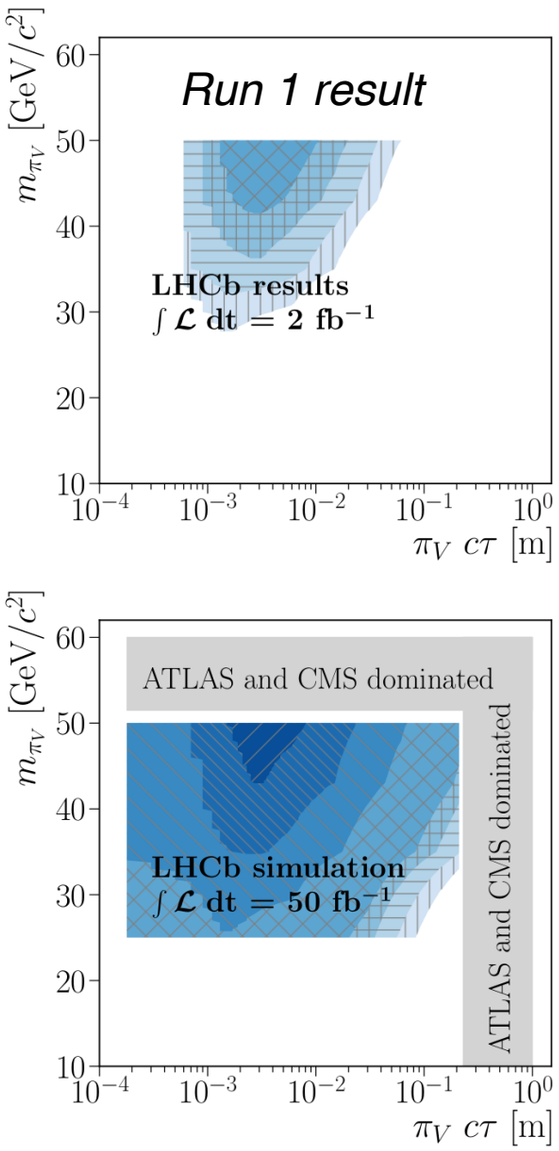
arXiv:1811.07370

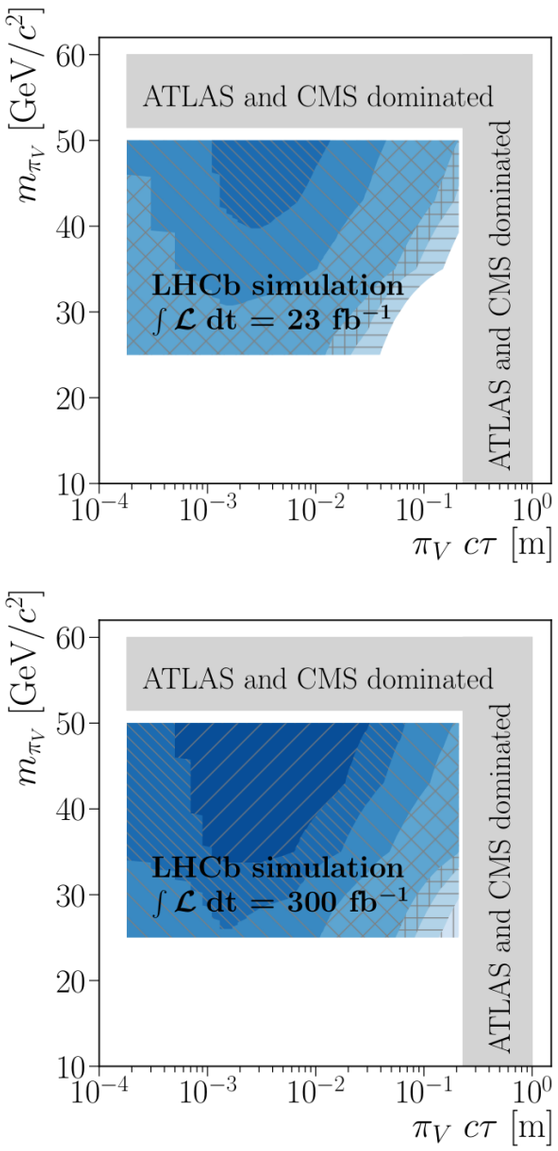
- LLPs decaying into jets in the muon spectrometer
  - 2 DV in MS, 1 DV in MS + 2 prompt jets, 1 DV in MS + MET

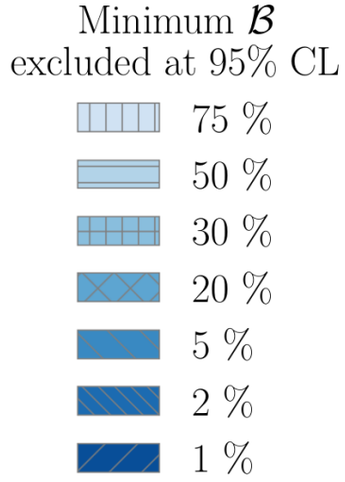




H→LLP prospects







- New conference note prepared for HL-LHC Yellow Paper
- You can find more results at this link: ***link***
  http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/LHCb-CONF-2018-006.html

Projected sensitivities of the search for HV pions decaying hadronically (jet pair) and produced through a Higgs boson exotic decay. Upper limits on Higgs Branching ratio.

Theory: LLP

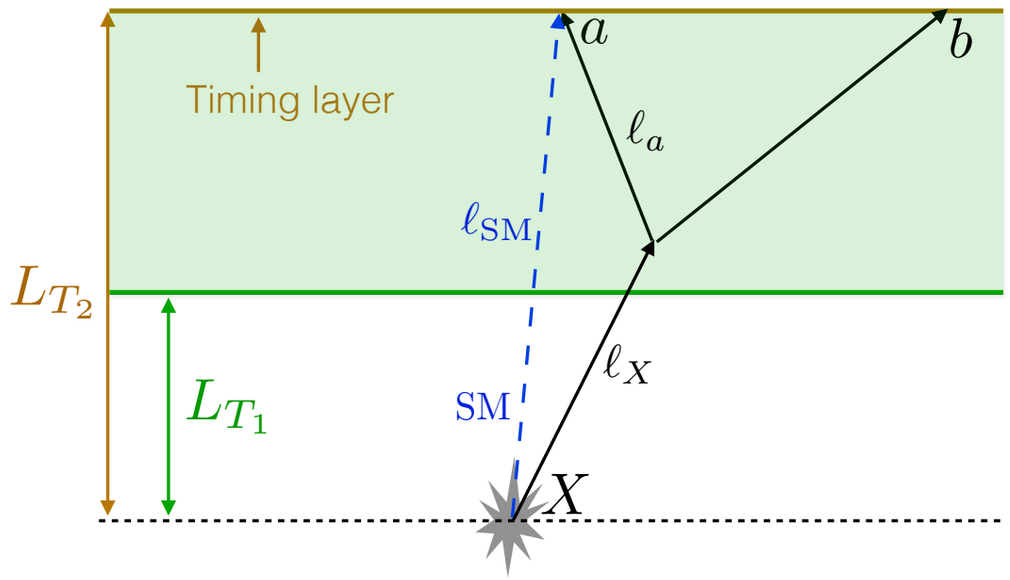
Long-lived particles at the LHC: Catching Them In Time: ***arXiv:1805.05957***

- Jia Liu, Zhen Liu, Lian-Tao Wang

- LLPs (with mass > 10s of GeV) typically have much slower motion
- Signal arrival time (vs. SM reference):

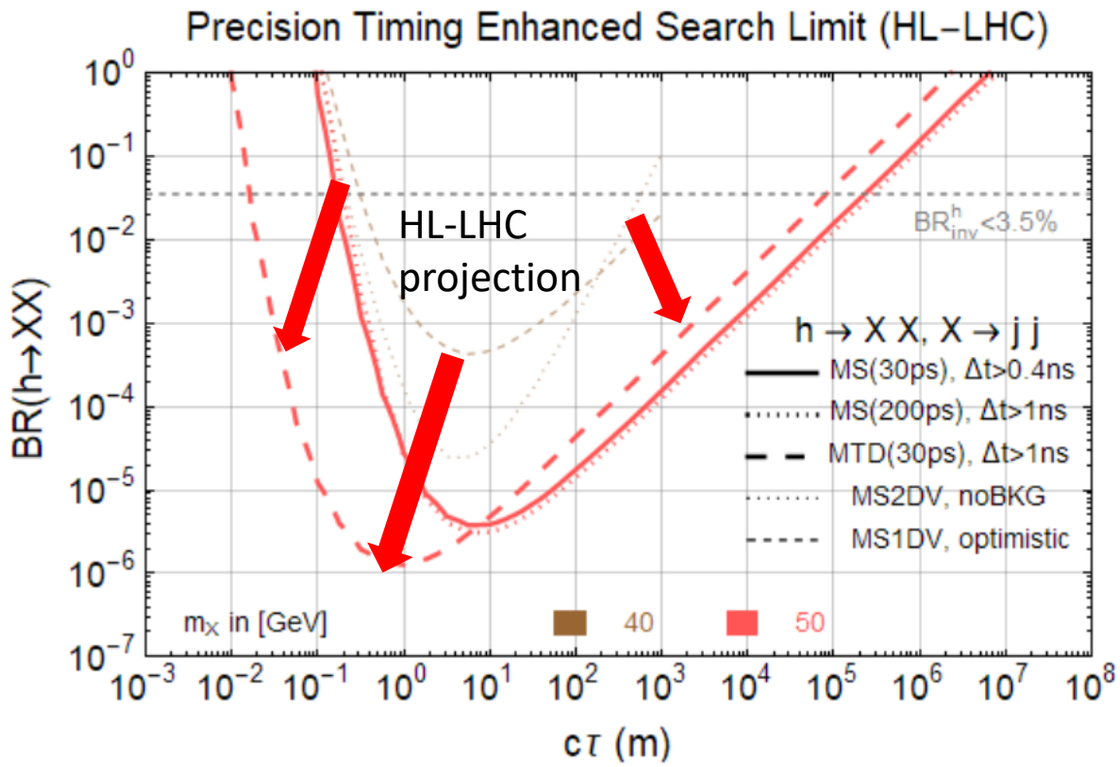
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

$\sim ns$



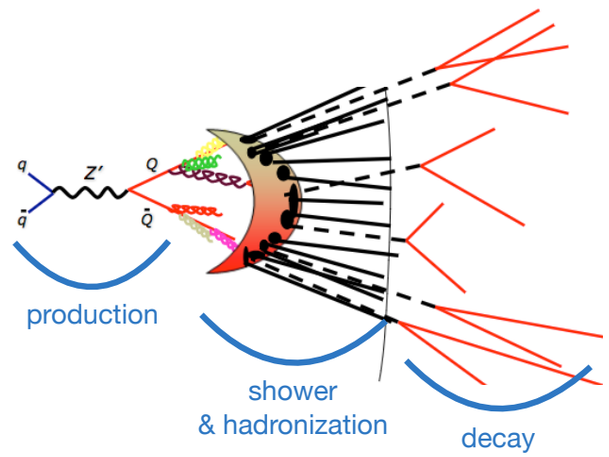
- Assuming ~30 ps timing resolution could be sensitive to ~1% level time delays wrt. SM particles travelling at c
- Projections using the timing information show significant improvement!

ATLAS MS LLP search (without timing) ***arXiv:1811.07370***



Theory: dark showers

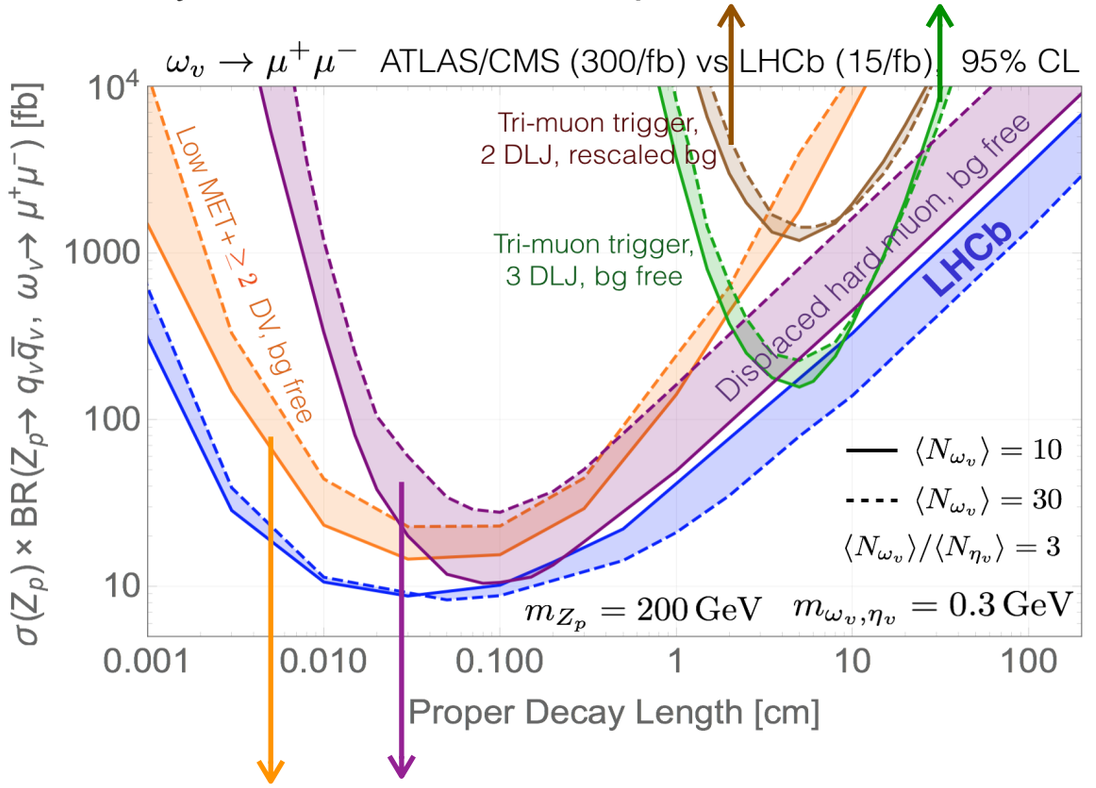
- Largely unexplored territory
  - Hidden valley scenarios exhibiting confinement
  - Long-lived light hidden hadrons produced in showering process



- **Dark showers chapter in the upcoming LHC LLP white paper**
  - Simon Knapen, Jessie Shelton, and Dong Xu
  - Production mechanisms, decays, phenomenological models…

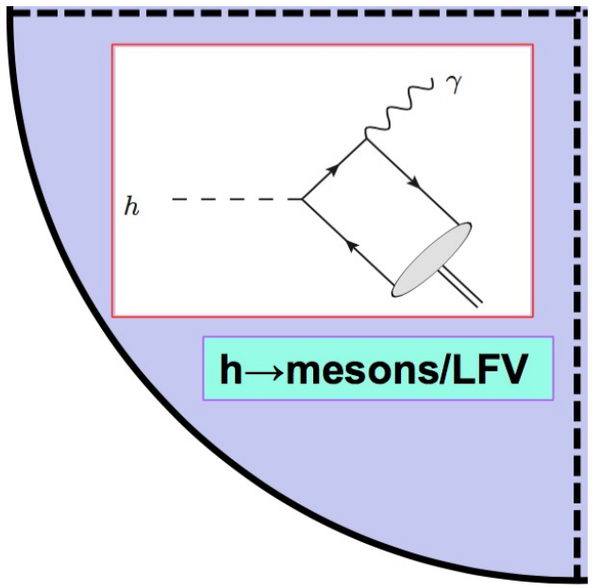
- **Searching for Confining Hidden Valleys at the LHC(b)**: ***arXiv: 1708.05389***
  - Aaron Pierce, Bibhushan Shakya, Yuhsin Tsai, Yue Zhao
  - LHCb: excellent vertex reconstruction, trigger, mass resolution, PID => ideal for soft long-lived particles

Projected bounds from displaced muon searches



Modified ATLAS MET+DV search

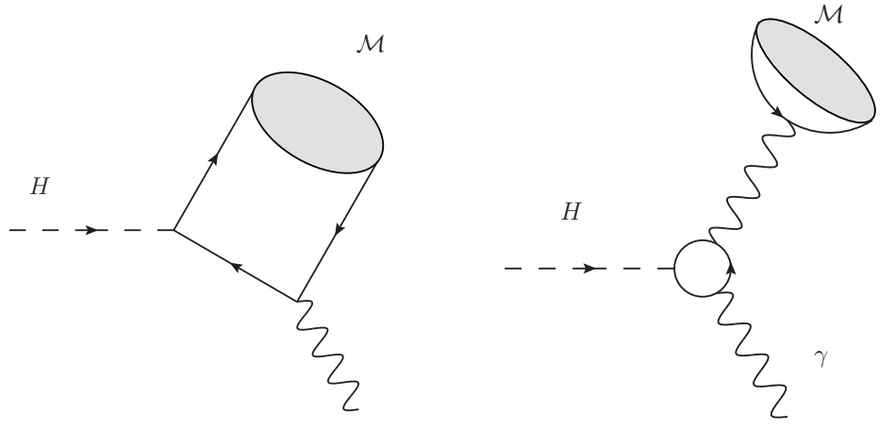
H→mesons/LFV



H-> J/ψy, ψ(2s)y, Υ(nS)y

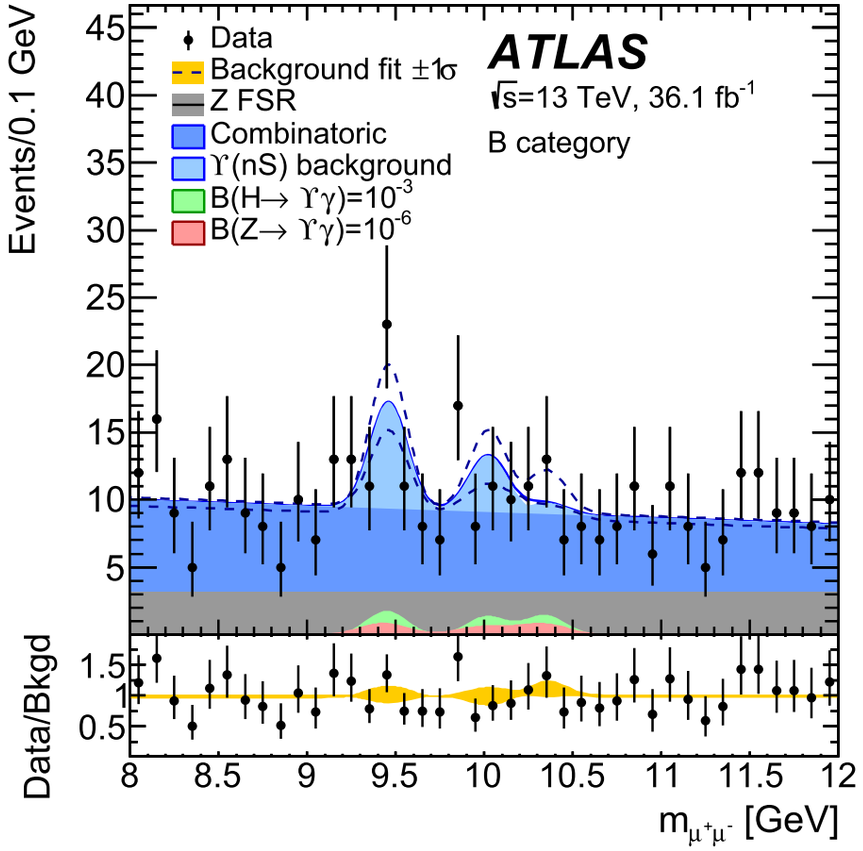
Phys. Lett. B 786 (2018) 134

- Allows access to 1st and 2nd generation Yukawa couplings
  - Currently direct evidence exists only for 3rd generation couplings



- Standard Model Predictions:
  - $\mathcal{B}(H \to J/\psi\gamma) = (2.99 \pm 0.16) \times 10^{-6}$†
  - $\mathcal{B}(H \to \psi(2S)\gamma) = (1.03 \pm 0.06) \times 10^{-6}$†
  - $\mathcal{B}(H \to \Upsilon(1S)\gamma) = (5.2^{+2.0}_{-1.7}) \times 10^{-9}$†

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[10^{-4}]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi\,(2S)\,\gamma)\,[10^{-4}]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[10^{-4}]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.5}_{-1.4}$	5.7

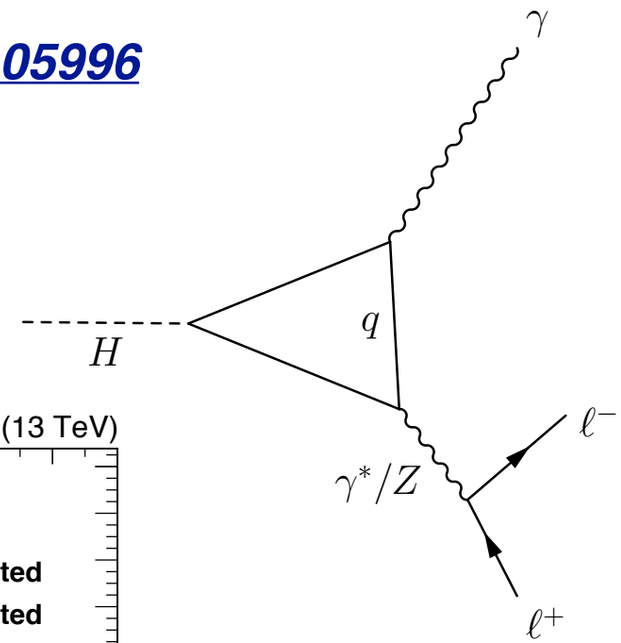


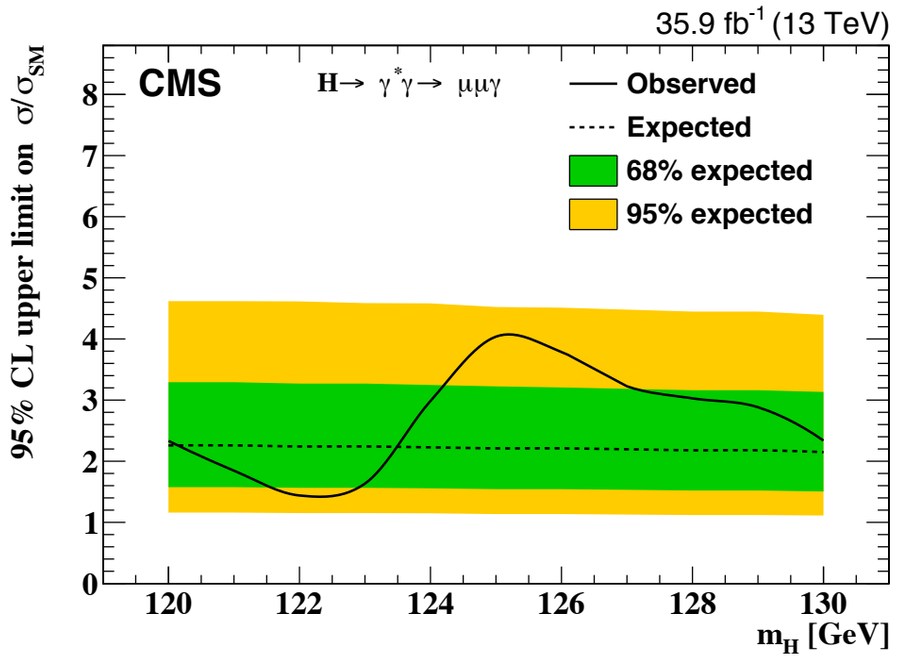
- Still 2-5 orders of magnitude above SM predictions

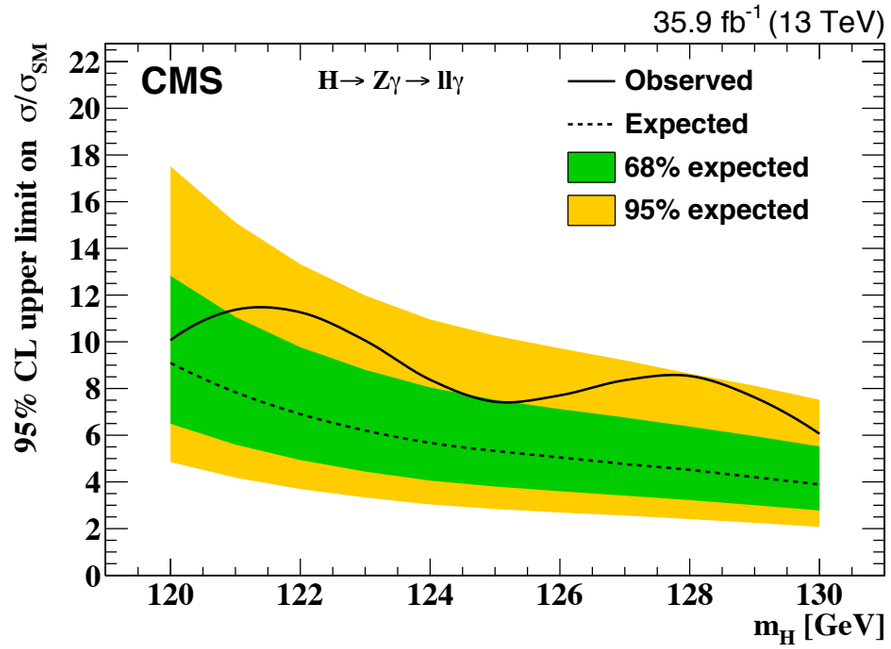
H→llγ

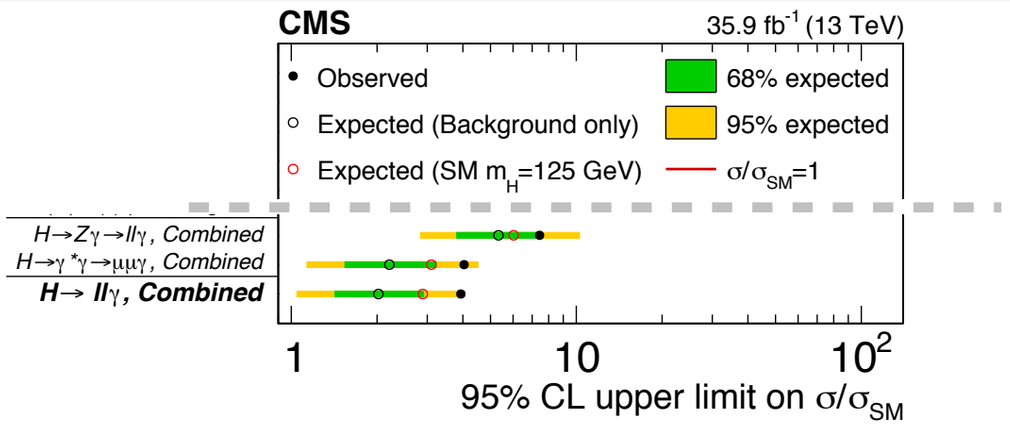
- Measurement of rare decays of SM Higgs: **arXiv:1806.05996**

$$\frac{\mathcal{B}(\mathrm{H} \to \gamma^{*}\gamma \to \mu\mu\gamma)}{\mathcal{B}(\mathrm{H} \to \gamma\gamma)} = (1.69 \pm 0.10)\%, \quad \frac{\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma \to \mathrm{e^{+}e^{-}}\gamma/\mu\mu\gamma)}{\mathcal{B}(\mathrm{H} \to \gamma\gamma)} = (2.27 \pm 0.14)\%$$









➡ Combined limit (observed): 4 x SM

- ATLAS 36 fb-1: 6.6 (5.5) x SM obs (exp)

Theory: ffy

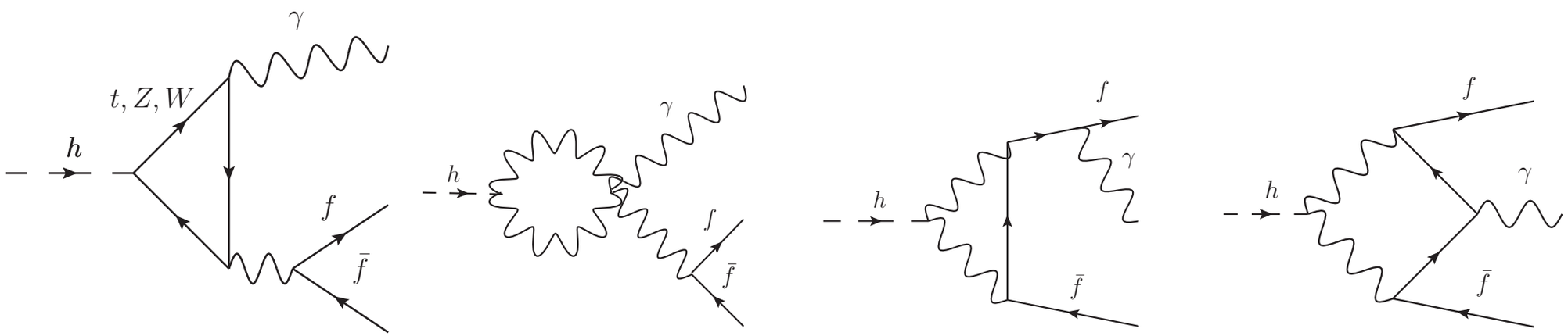
Higgs to ff+\gamma

Radiative Decays of the Higgs Boson to a Pair of Fermions *arXiv:1704.00790*

Tao Han (Pittsburgh U. & Tsinghua U., Beijing & CICQM, Beijing), Xing Wang (Pittsburgh U.)

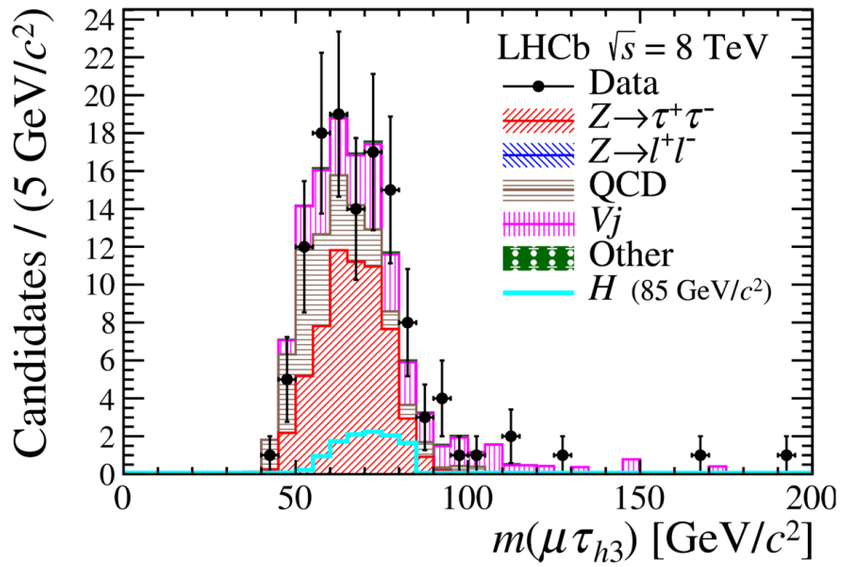
- Complimentary to Higgs decaying into mesons
- Shall we ask for recommendations?

- All the leptonic radiative decays potentially observable at the LHC Run 2 or the HL-LHC
- h→ccγ better than the h→J/ψγ channel in constraining the charm-Yukawa coupling



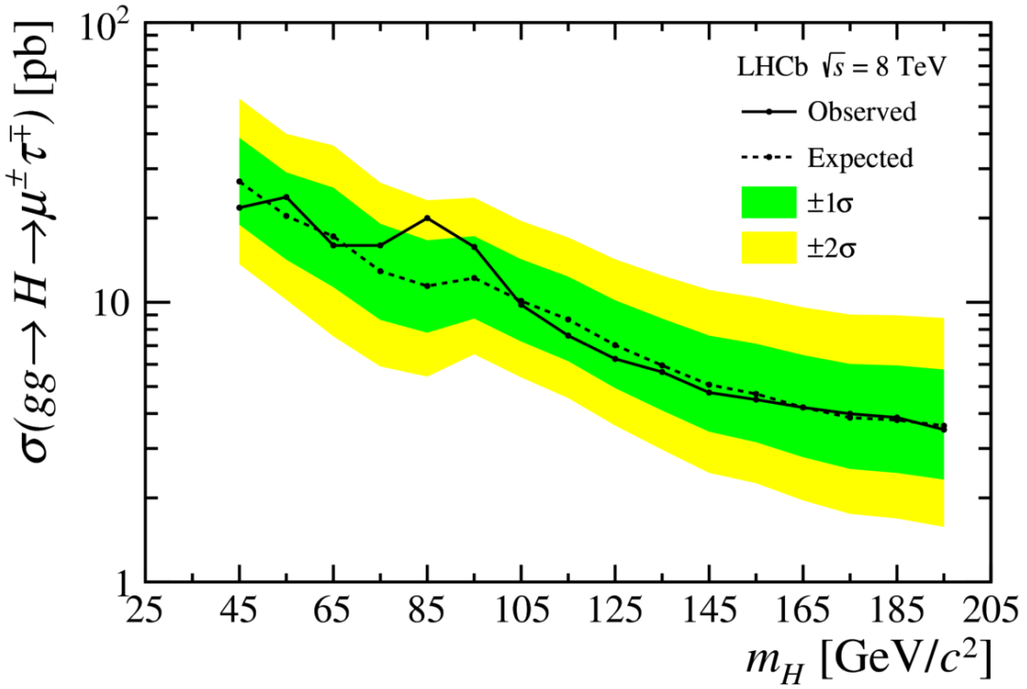
H→LFV

Search for H→τμ in the forward region

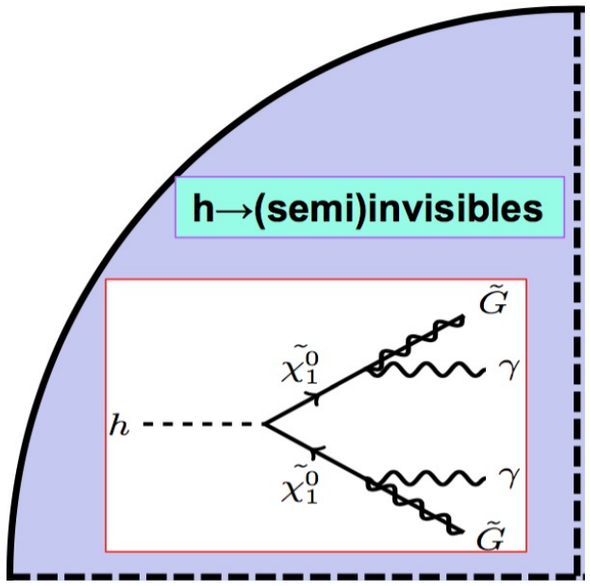


- Search for lepton flavour violating Higgs decay.
- Taus are reconstructed in 4 different decay channels (muon, electron, hadron, 3-hadrons).
- Main background Z→ττ

- Complementary wrt ATLAS and CMS: different phase space region.
- At 125 GeV upper limit BR(H→τμ) <26%
- Accepted for publication on EPJC.



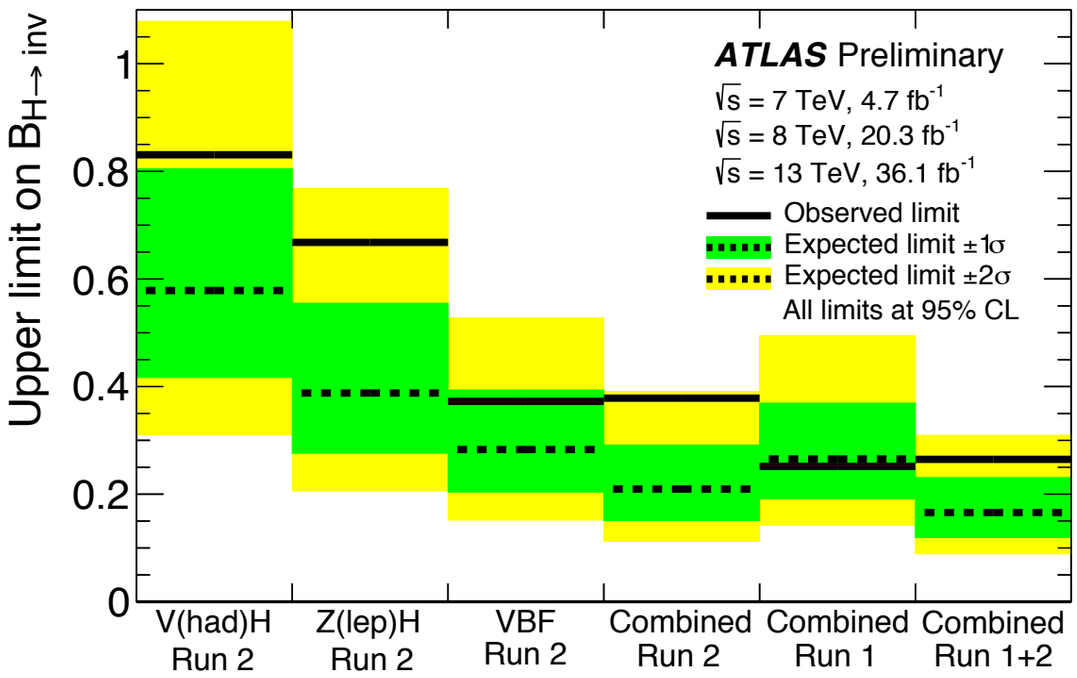
H→(semi)invisible

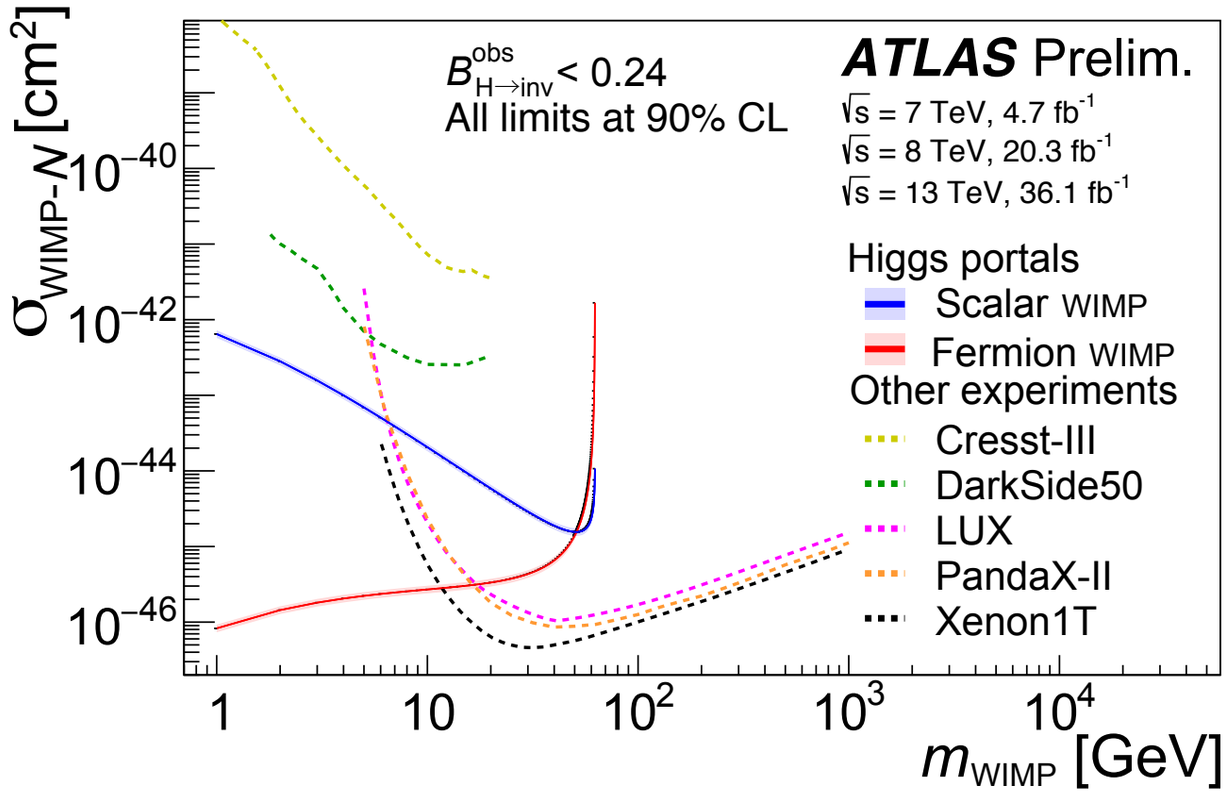


H→invisible

ATLAS-CONF-2018-054

- 7+8+13 TeV combination: **Br(H→inv)<0.24**





Benchmarks

- Started collecting benchmarks on our Twiki
  - Include: motivation, relevant parameter calculations (e.g. Br), MC implementation

2HDM+S + Z_d models: so far used in H→xxyy interpretations

Signature	Motivation	Parameter calculations	MC implementation	Contact
H(125)→aa (ss) →XXYY	1312.4992	Br(a(s)→XX) for plots from the paper, outside of the quarkonia regions plotdata.zip		Stefania Gori, Yiming Zhong
H(125)→aa (ss) →XXYY	1802.02156	BR.tgz. Calculations provide Br(a->xx) values for multiple tan(beta) values and cover also the quarkonia regions. Please read the README.txt to know how to use them.		Ulrich Haisch
H(125)→2Zd→4 lep	1412.0018	Table2 of 1412.0018	hahm_mg	Jessie Shelton, Stefania Gori, David Curtin, Rouven Essig
H(125)→2Hd→4Ad→8 lep	Hto8lepChannel_Stolarski	Table2 of 1412.0018	hahm_mg	Daniel Stolarski
H(125)→aa (ss) → 4y/2j2y				
H(125)→aa (ss) →XXYY/invis	mixture of visible & invisible (DM) decays			

Benchmarks

Higgs up to 8 Leptons

The Platinum Channel: Higgs Decays to as many as 8 Leptons
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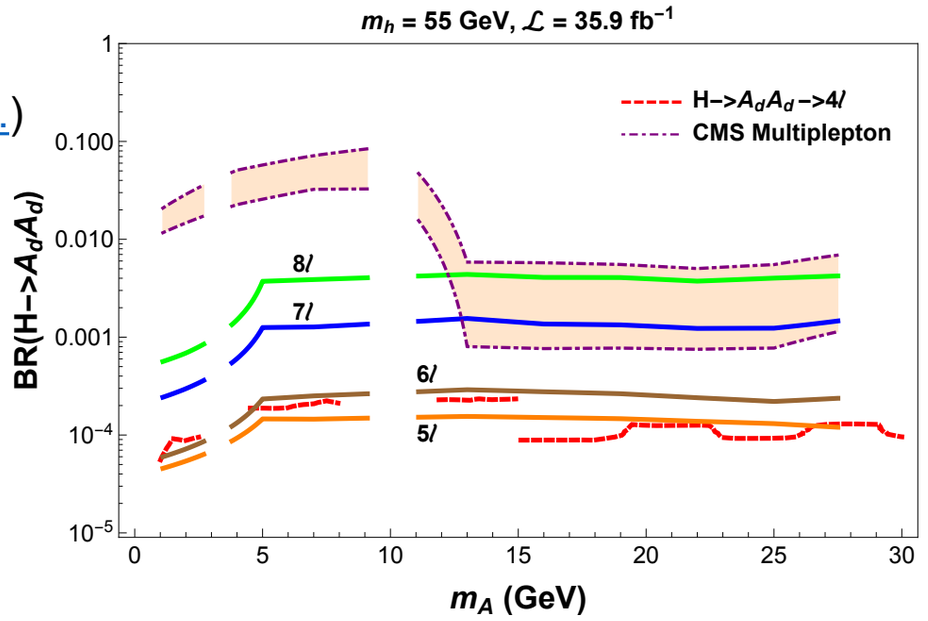
1805.12136

$$H \to h_d h_d \to A_d A_d A_d A_d \to 8f$$



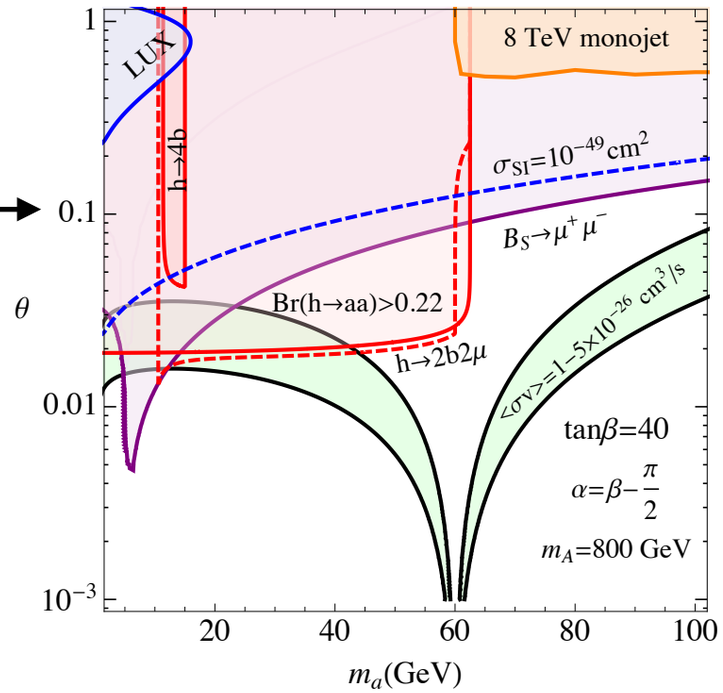
Wish-list from the theory side:)

Signature	Motivation	Parameter calculations	MC Implementation	Contact
H(125)→aa (ss) →XXYY	1312.4992	Br(a(s)→XX) for plots from the paper, outside of the quarkonia regions plotdata.zip		Stefania Gori, Yiming Zhong
H(125)→aa (ss) →XXYY	1802.02156	BR.tgz. Calculations provide Br(a >xx) values for multiple tan(beta) values and cover also the quarkonia regions. Pleas read the README.txt to know how to use them.		Ulrich Haisch
H(125)→2Zd→4 lep	1412.0018	Table2 of 1412.0018	hahm_mg	Jessie Shelton, Stefania Gori, David Curtin, Rouven Essig
H(125)→2Hd→4Ad→8 lep	Hto8lepChannel_Stolarski	Table2 of 1412.0018	hahm_mg	Daniel Stolarski
H(125)→aa (ss) → 4y/2j2y				
H(125)→aa (ss) →XXYY/invis	mixture of visible & invisible (DM) decays			

Benchmarks

- H→aa→SM/DM
  - Can we come up with a benchmark where the mediator could decay to both DM and SM and then show all the constraints together?
- Meaningful model for H→4y/2j2y
  - ALPs? e.g. 1708.00443

arXiv:1404.3716



Wish-list from the experiment side:)

Signature	Motivation	Parameter calculations	MC implementation	Contact
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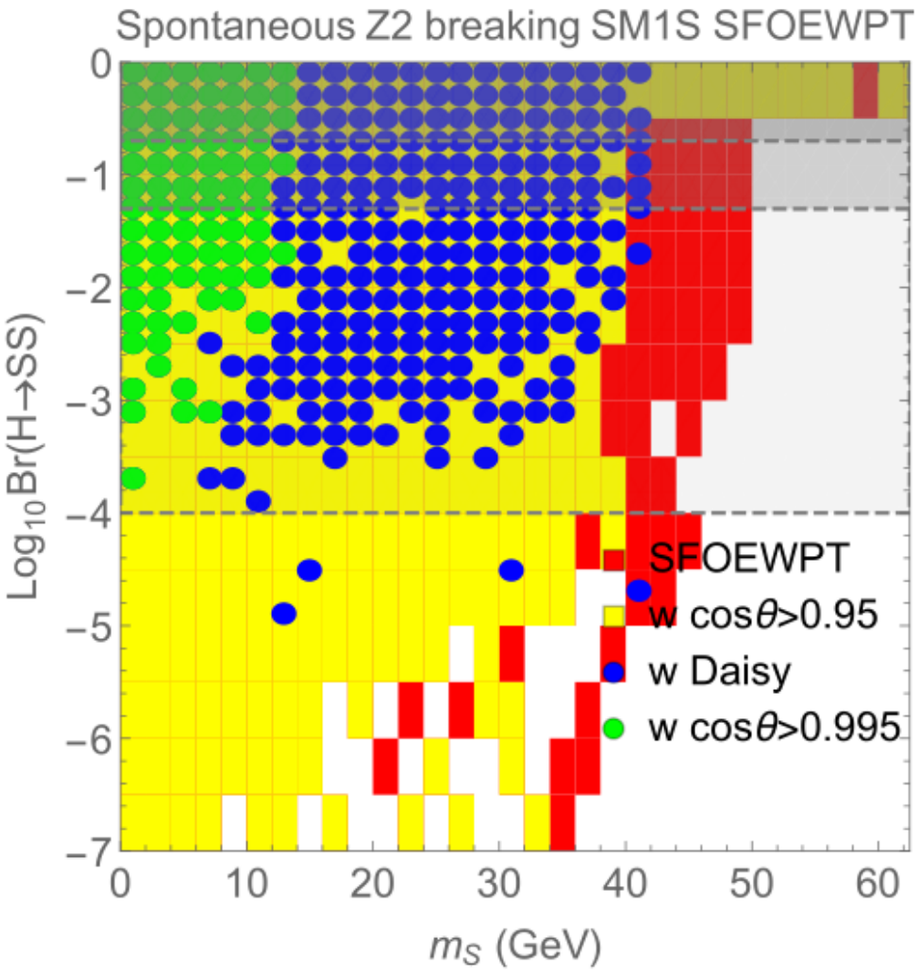
H→ss benchmark

- Ongoing study by M. Carena, Z. Liu, Y.K. Wang;
- Ongoing study by J. Shelton,
  Jonathan Kozaczuk and Michael Ramsey-Musolf
- H→SS decays is well-motivated from the point of view of strongly first order electroweak phase transition;
- Successful EWPT predicts (in a general class of spontaneous Z2 breaking singlet extension of the SM) sizable amount of the H→SS branching fraction and can be tested at the LHC.

expecting paper early next year and recommendations coming after.

Preliminary results by M. Carena, Z. Liu, Y.K. Wang



Blue and green points are to be tested by the exotic decay program.
Yellow regions covered by HL-LHC Higgs precision program.

Summary & plans

- Rich programme of signatures ongoing in experiments
- **Strong interest in reinterpreting prompt searches into LL signals** to see ”how far we get” without a dedicated analysis and where the gaps are
  - Some nice examples already there (H→aa→4b), plan to do more for future results in H→aa
- **Thinking about new benchmark scenarios/signatures**
  - Especially ones that will benefit from the increased dataset (H→8 lep)
  - New benchmarks for interpretation of existing (& future) searches: H→4y/2j2y & H→aa→SM/DM
- **Preparing for HL-LHC**:
  - Developments in dark showers
  - Prospects for LLPs with upgraded detectors (e.g. timing) need studies by experiments
- See also our Twiki to-do list

Backup

Backup

Ongoing analyses

- Long Lived Particles program (Run II):
  - ➔ Updated search for displaced di-jet resonances
  - ➔ Search for lepton flavour violating LLP
- Prompt di-jet scalar resonance searches (b and c di-jets)
- New trigger lines for Run III (di-jets, di-electrons, di-photons)

H->ϕy, ρ y

- 36 fb^{-1} @13 TeV

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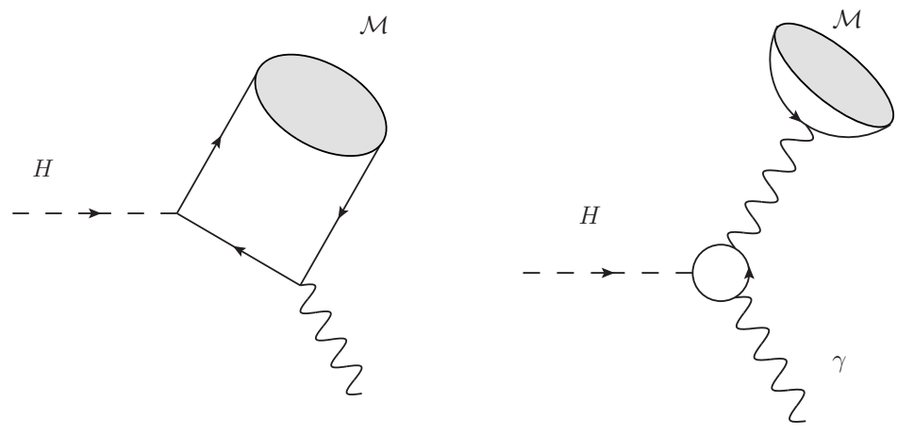
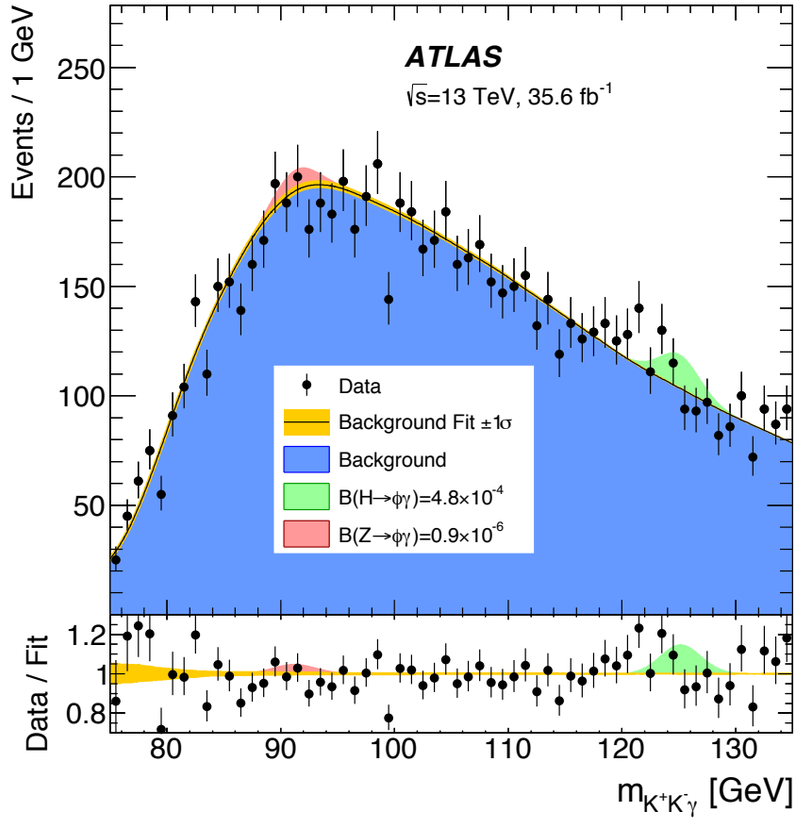


- SM predictions:
  - $\mathcal{B}(H \to \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$
  - $\mathcal{B}(H \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$

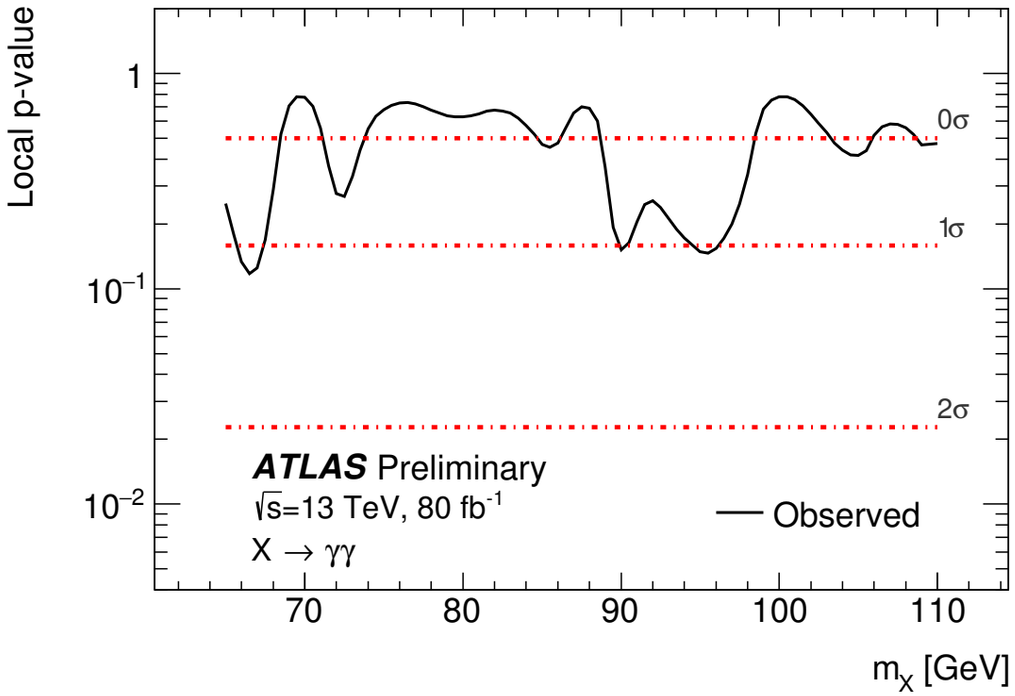
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-4}]	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)$ [10^{-6}]	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)$ [10^{-4}]	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)$ [10^{-6}]	33^{+13}_{-9}	25

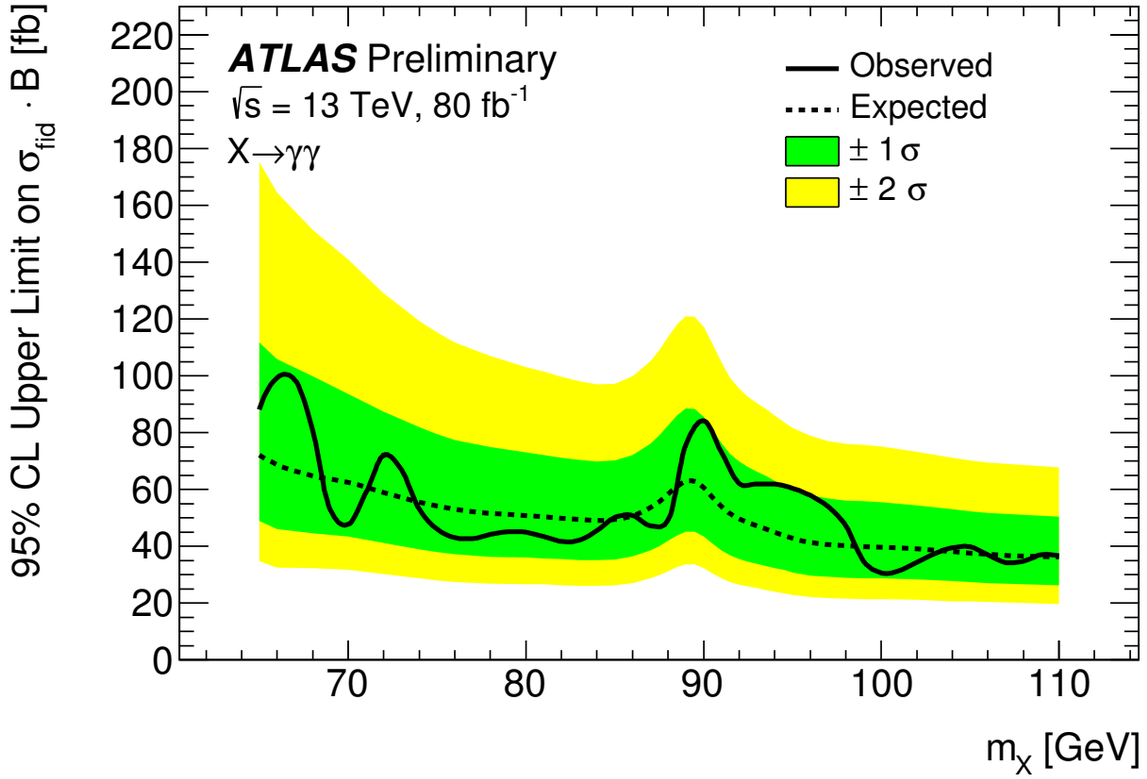


Low-mass yy

- 80 fb^{-1} @13 TeV

ATLAS-CONF-2018-025

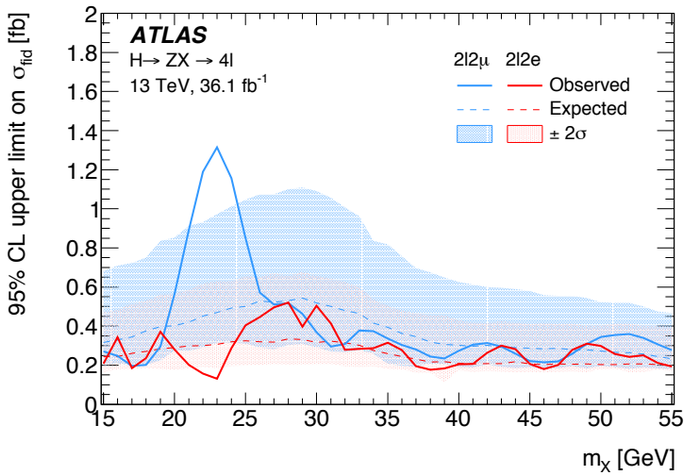


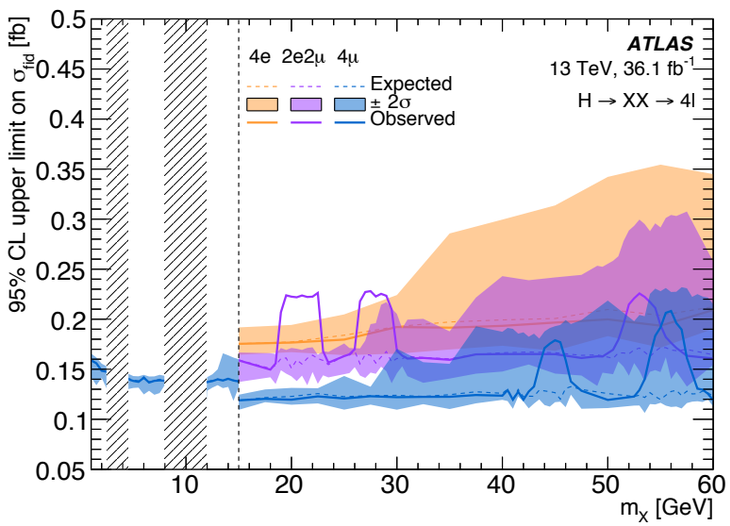


H-> aa -> XXYY

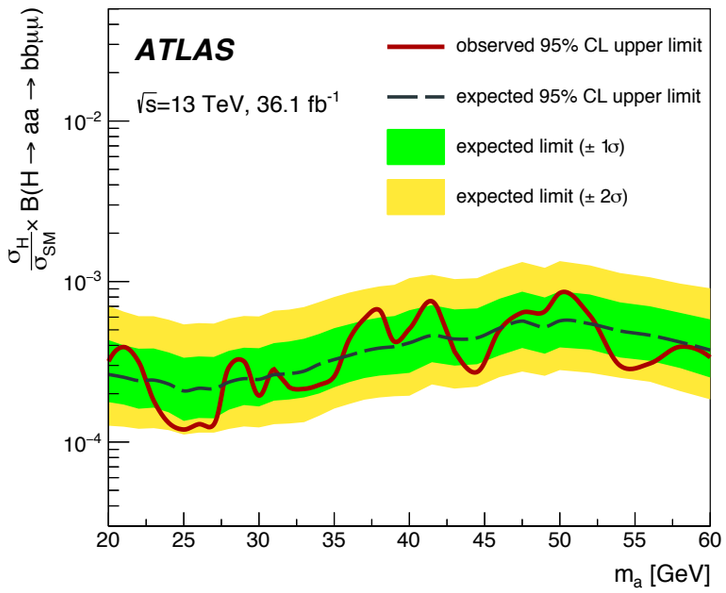
- 36 fb^{-1} @13 TeV

h→ZdZd→4lep

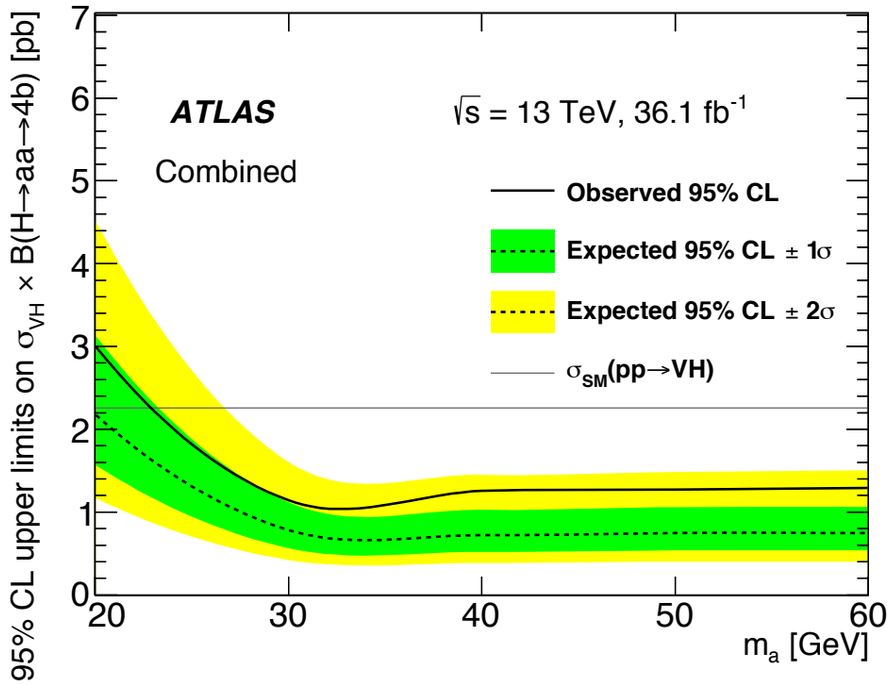




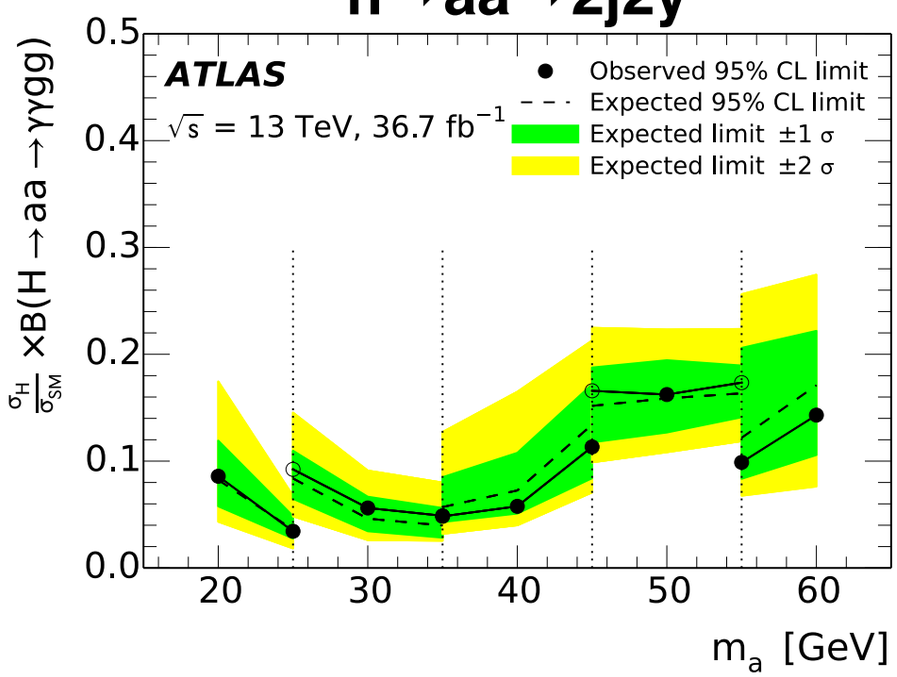
h→aa→2b2*μ*



h→aa→4b

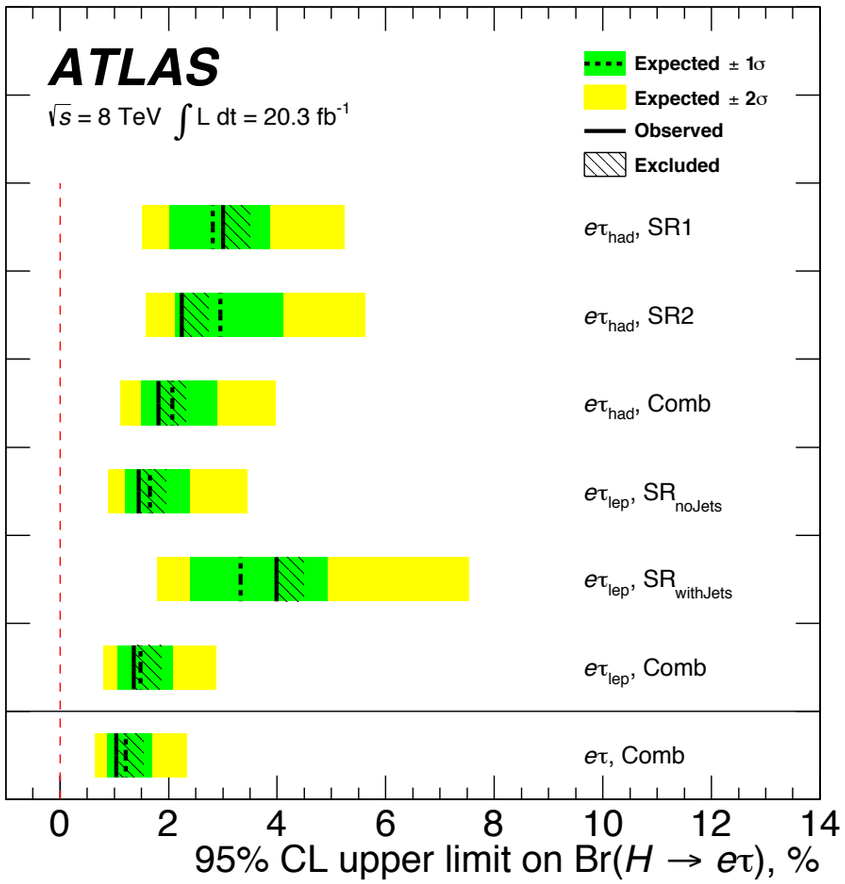


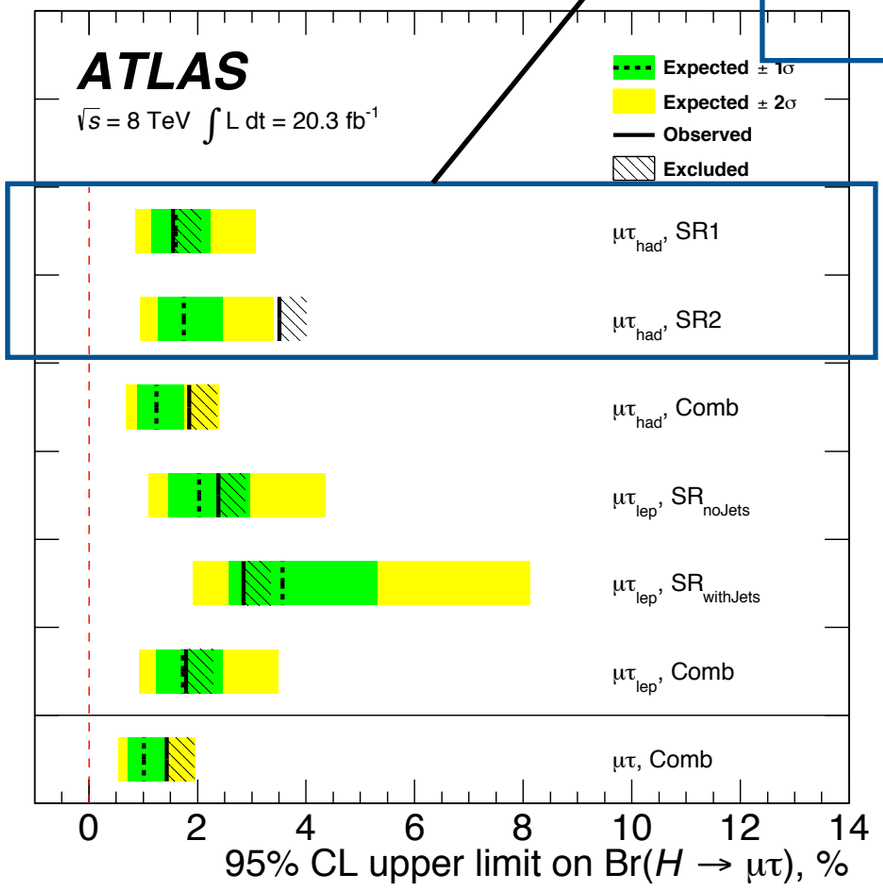
h→aa→2j2y

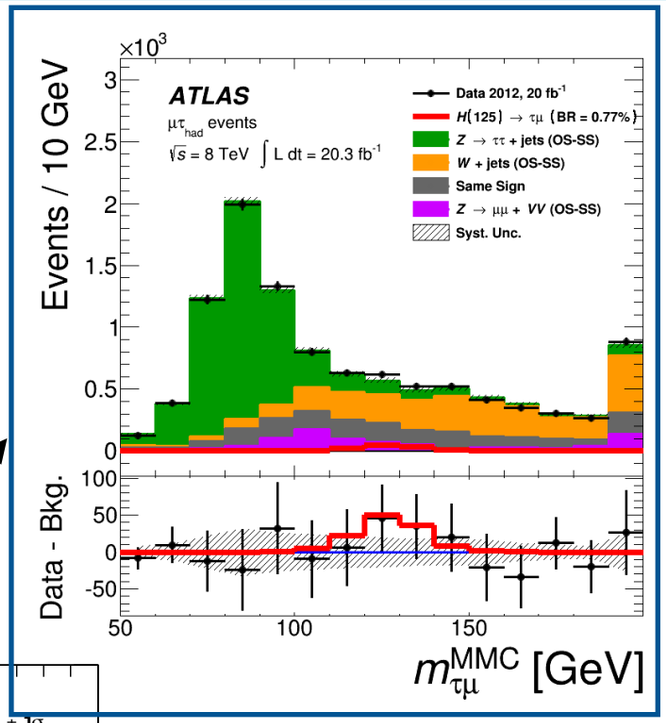


H->e/μ tau

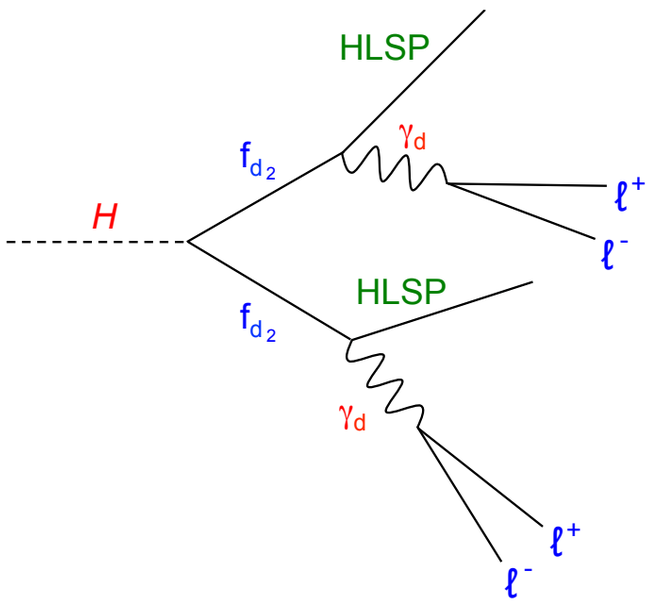
1604.07730



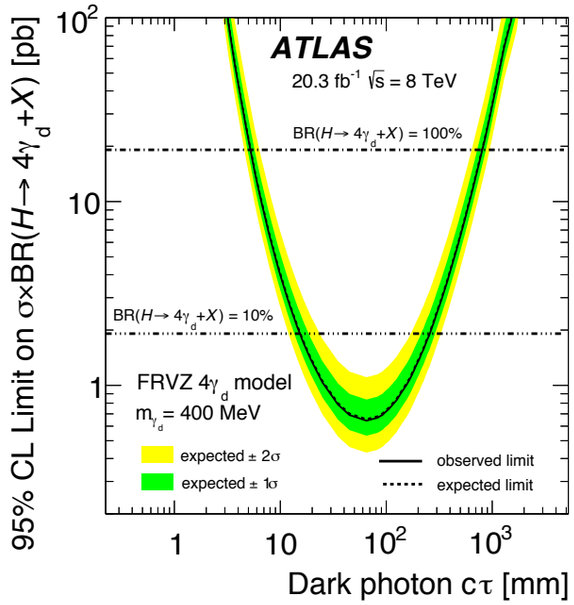




Lepton jets



arXiv:1409.0746



arXiv:1511.05542