Light scalar searches at the LHC

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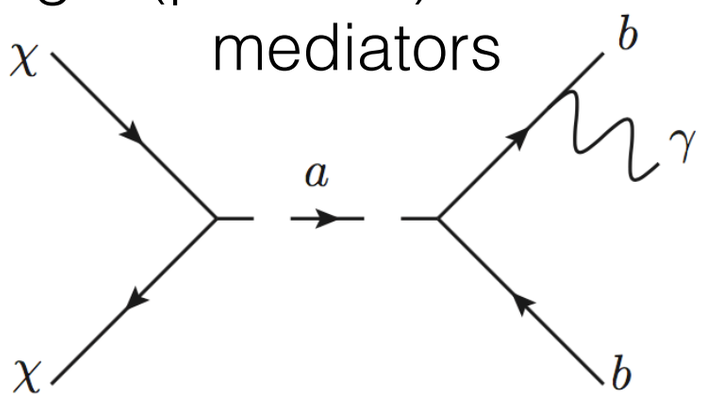
University of Massachusetts Amherst

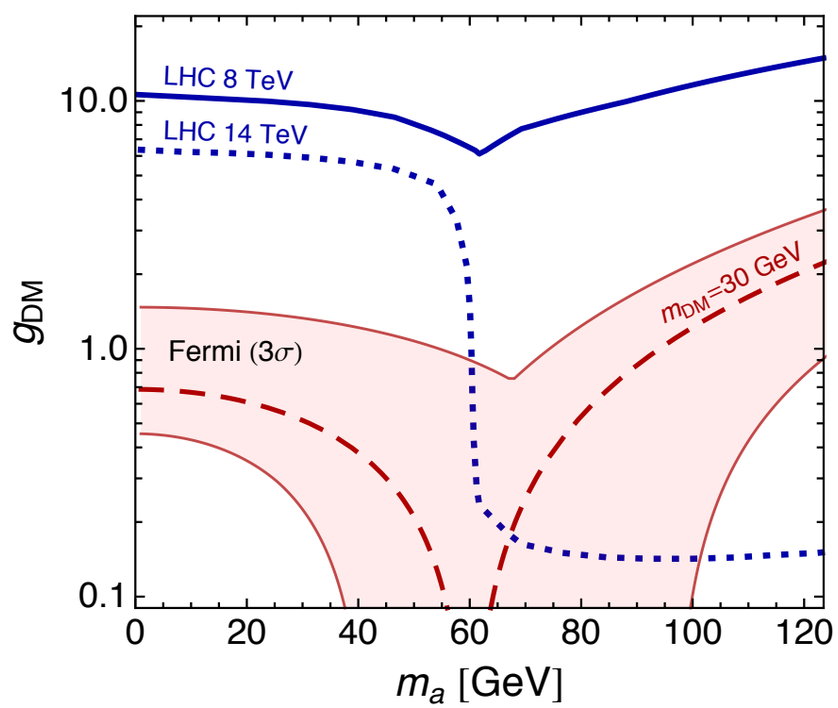
Workshop on Light scalars
Benasque, Spain
April 7th-13th, 2019

Motivations for New Light States

Dark Matter

Light (pseudo-)scalars as mediators

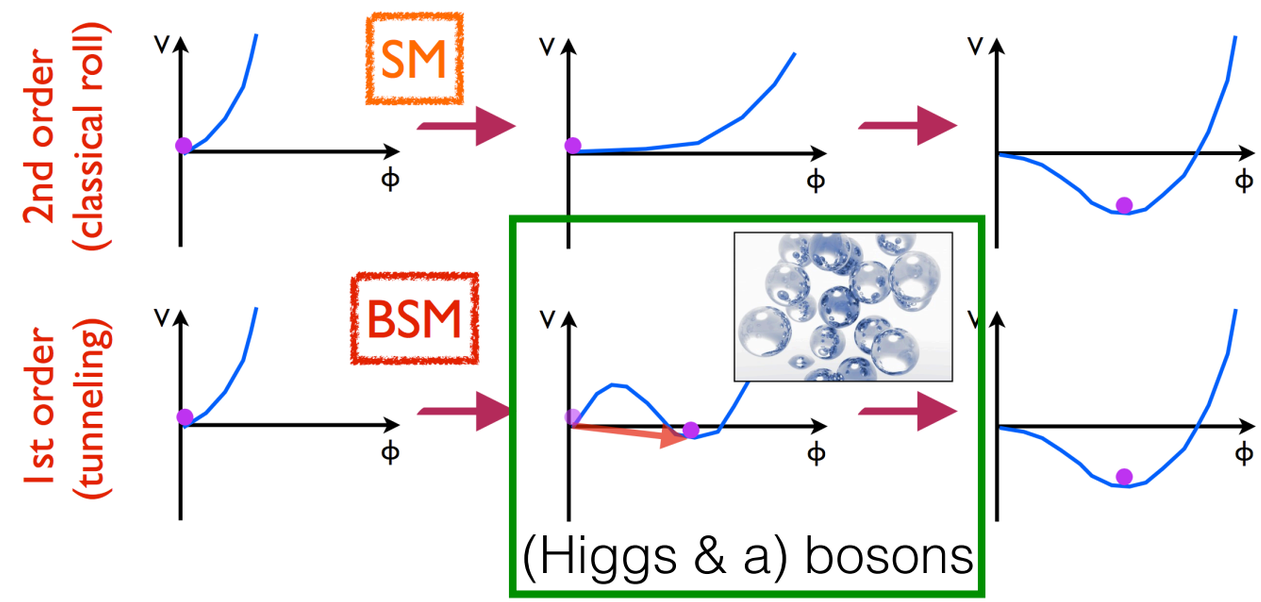




Fermi-LAT 2015
C. Boehm et al. 2014

EW Baryogenesis

EW symmetry breaking as a 1st order phase transition



Profumo, Ramsey-Musolf, Shaughnessy, 2007 and others

Naturalness

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

Strong CP problem

Axion-like-particles
Bauer, Neubert, Thamm 2017, 2018

Searches for light scalars at the LHC

- Several searches at the LHC target light scalars
  - Covers both CP odd and even states → referred to as *a-bosons* here

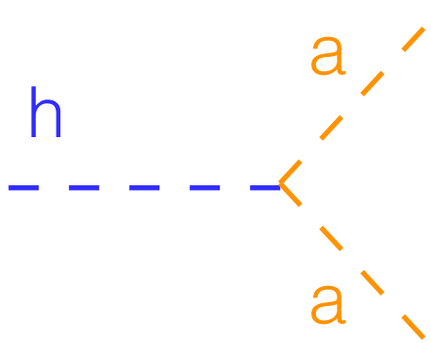
- Several strategies pursued

Exotic decays of the Higgs boson

New opportunity since the Higgs discovery to search for Higgs portals

→ Searches for on-shell decays with $m_a \sim 0.25$ - 60 GeV

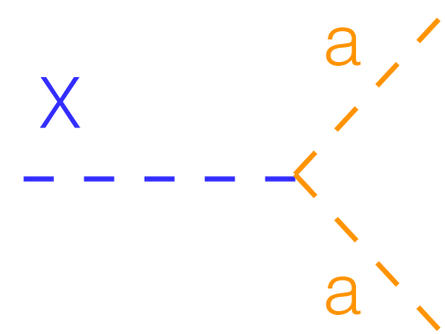
→ Explore displaced decays for cases where light scalar is long lived



$m_h = 125$ GeV

$m_a \sim 0.5$ - 60 GeV

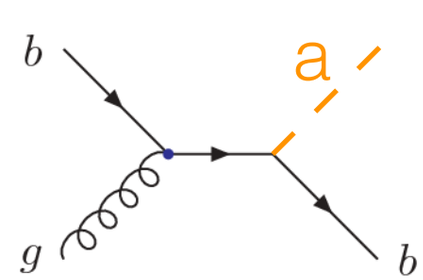
Searches for light states in the decays of new heavy particles

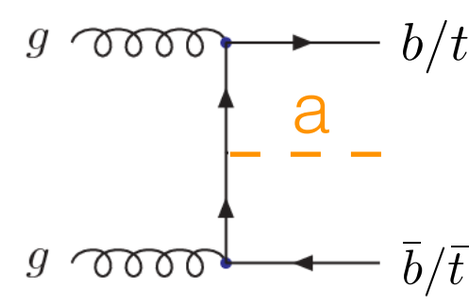


$m_X > m_h$

$m_a < m_X/2$

Search for light state production directly



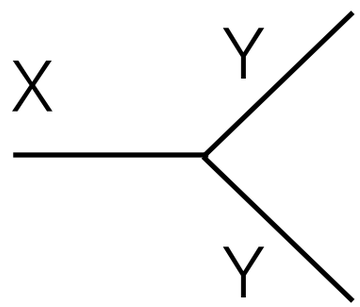


and many other examples

Challenges to Search for Light Scalars at the LHC

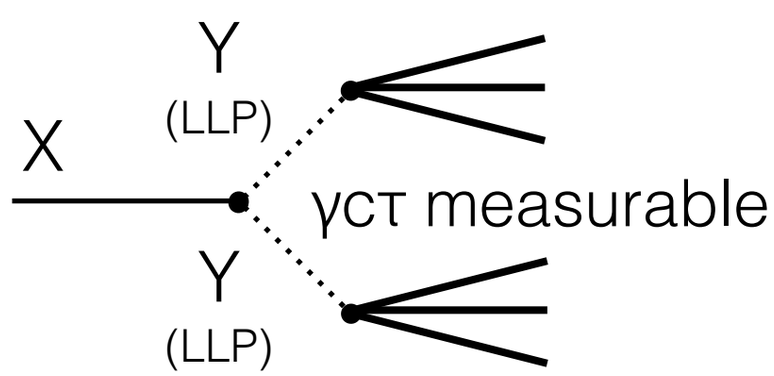
Reconstruction

Light states often result in low p_T and overlapping decay products



$\Delta R(Y,Y) \sim 2\, m_X / p_{TX}$

May be long-lived particle (LLP) → displaced decay



→ these signatures require dedicated techniques

Trigger

Often suffer from inadequate or low efficiency triggers

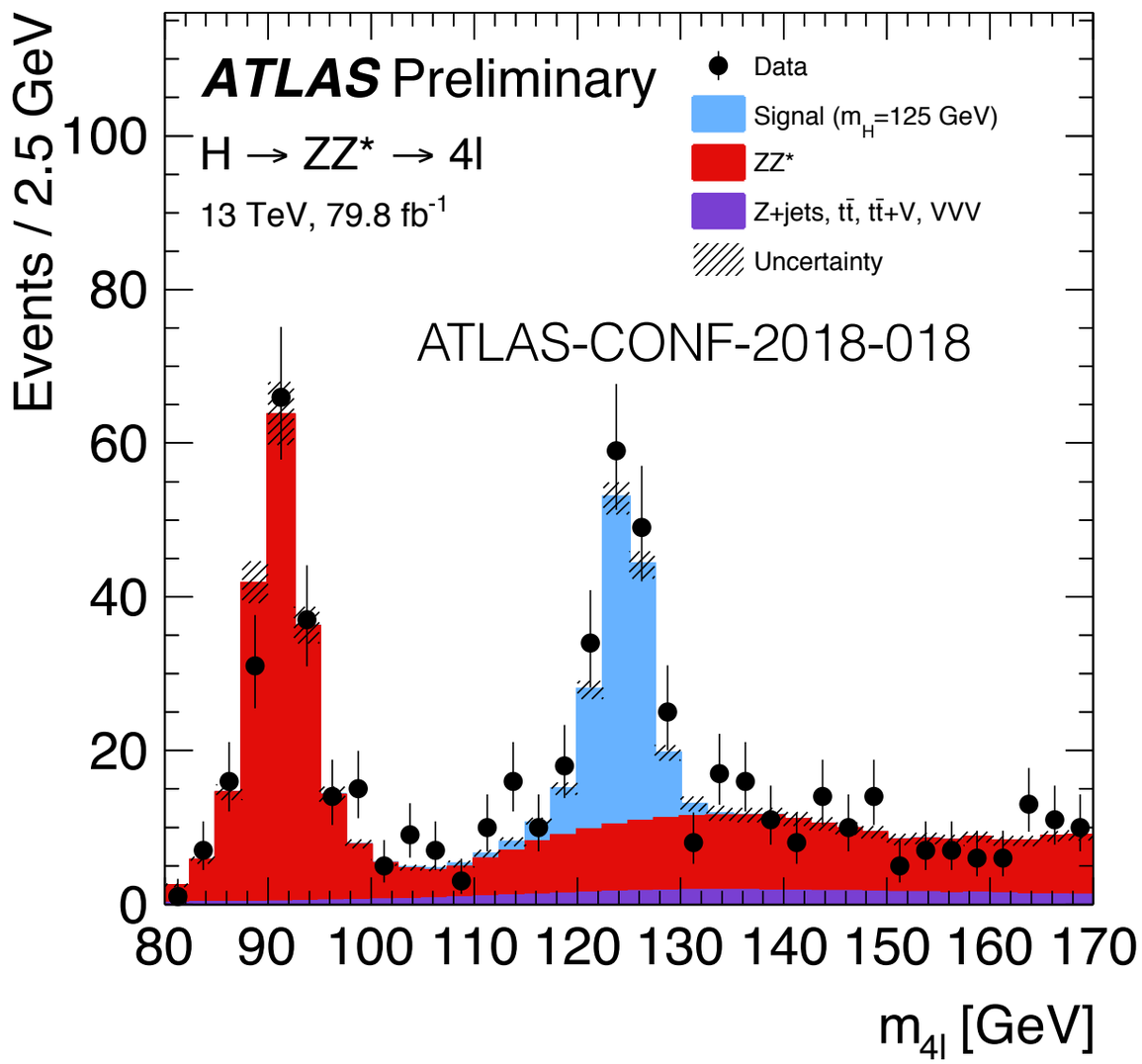
→ requires dedicated triggers or possible solution is to explore final states in association with other objects

Backgrounds

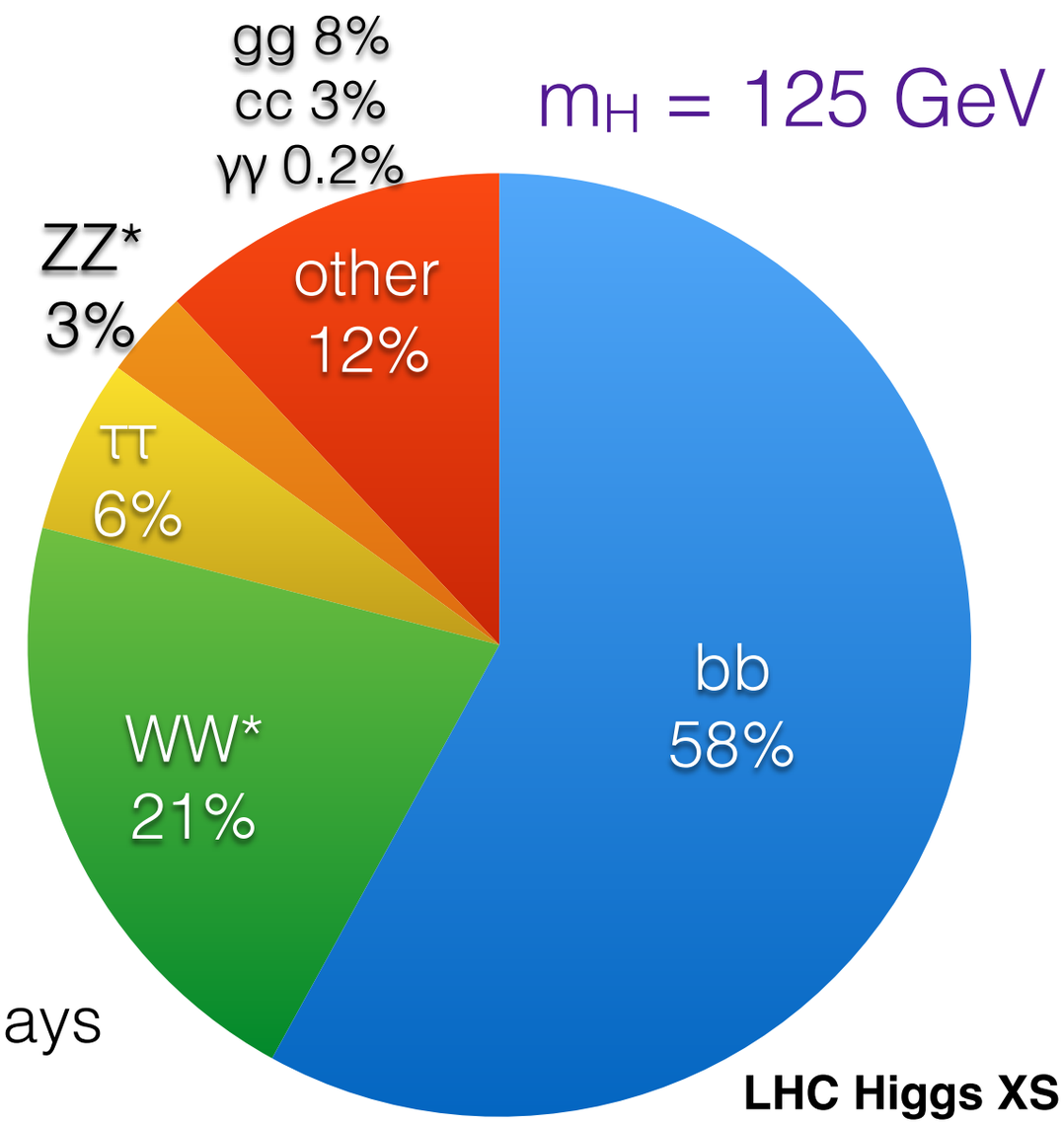
Large backgrounds from SM processes at low p_T

May also have unconventional signatures with non-collision backgrounds e.g. noise, instrumental effects, beam halo …

Higgs Boson Decays



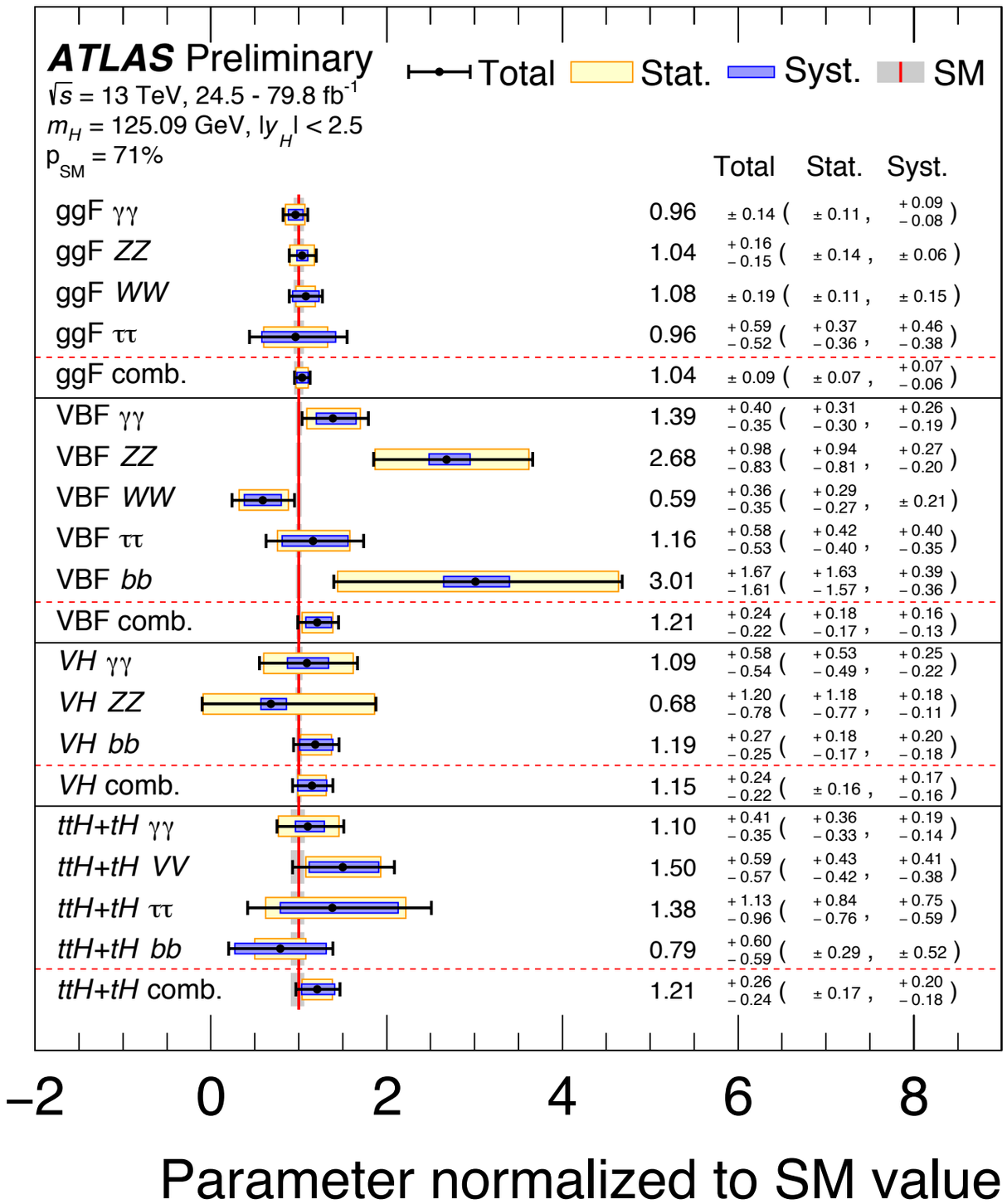
Higgs boson branching ratios in the SM



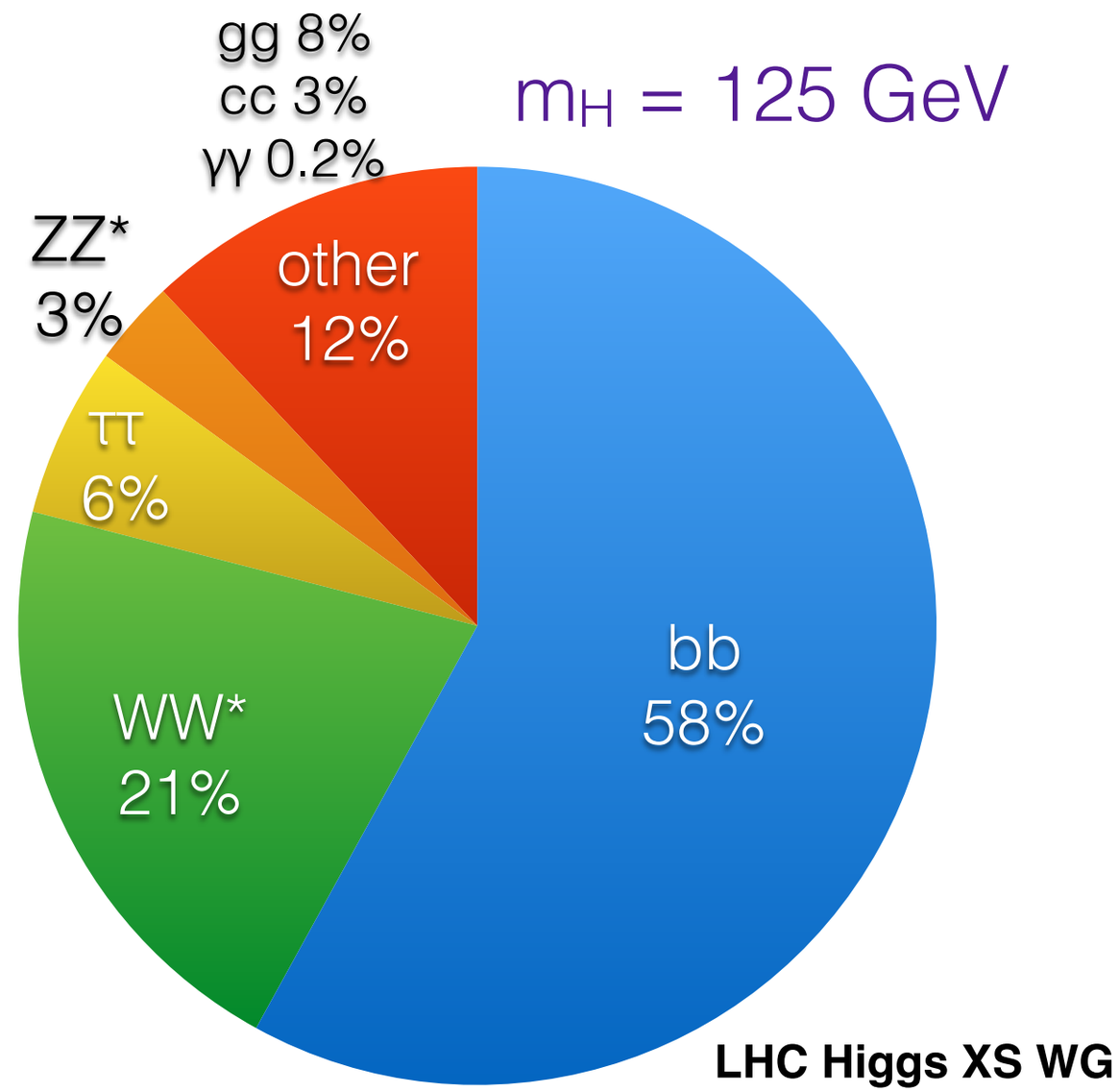
- Higgs boson observed as a resonance in several decay channels
- Many BSM theories predict additional decays
  - Higgs Portal models of dark matter
  - Theories of Neutral Naturalness
  - Models with an extended Higgs sector e.g. 2HDM+S, NMSSM

SM Higgs Boson Decays

ATLAS-CONF-2019-005



Higgs boson branching ratios in the SM

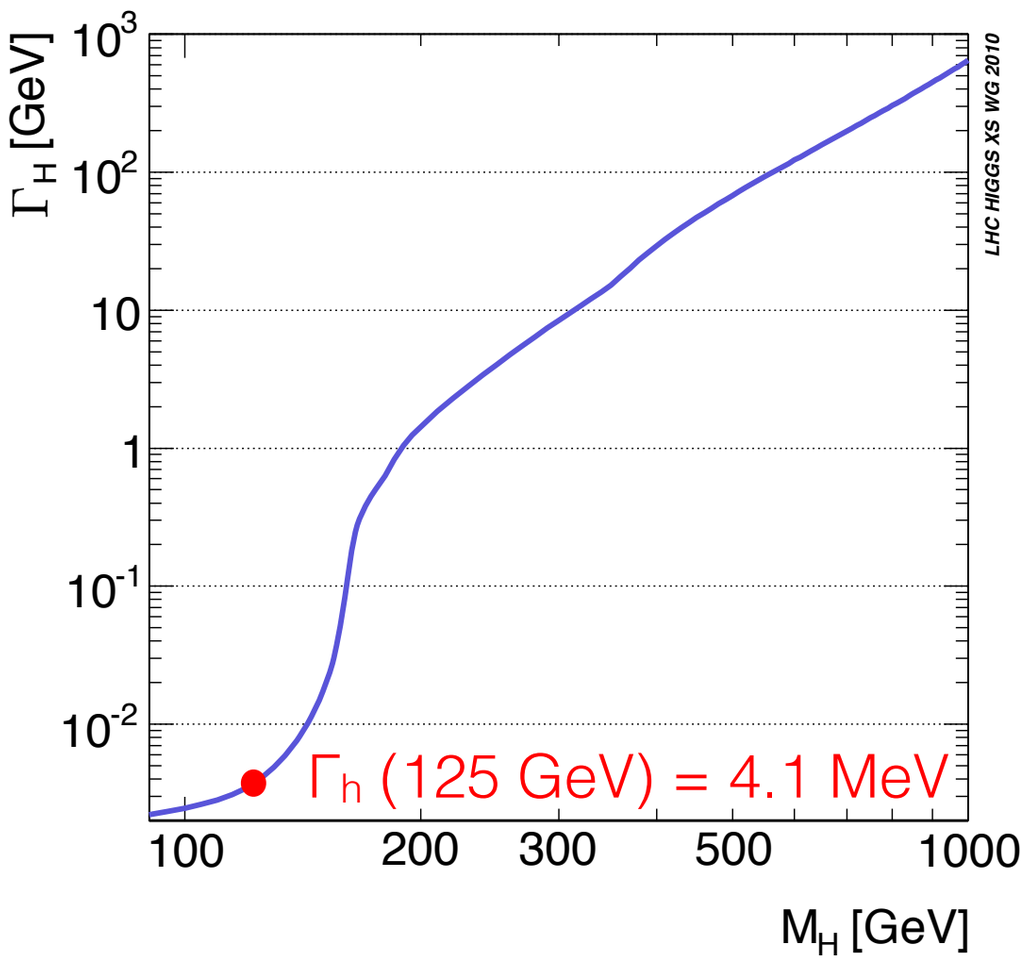


Available measurements are only able constrain BSM decays to ≲ 22%

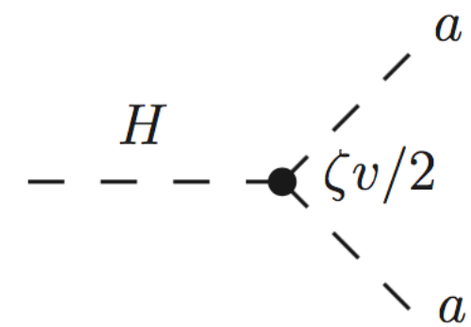
Exotic Higgs Decays

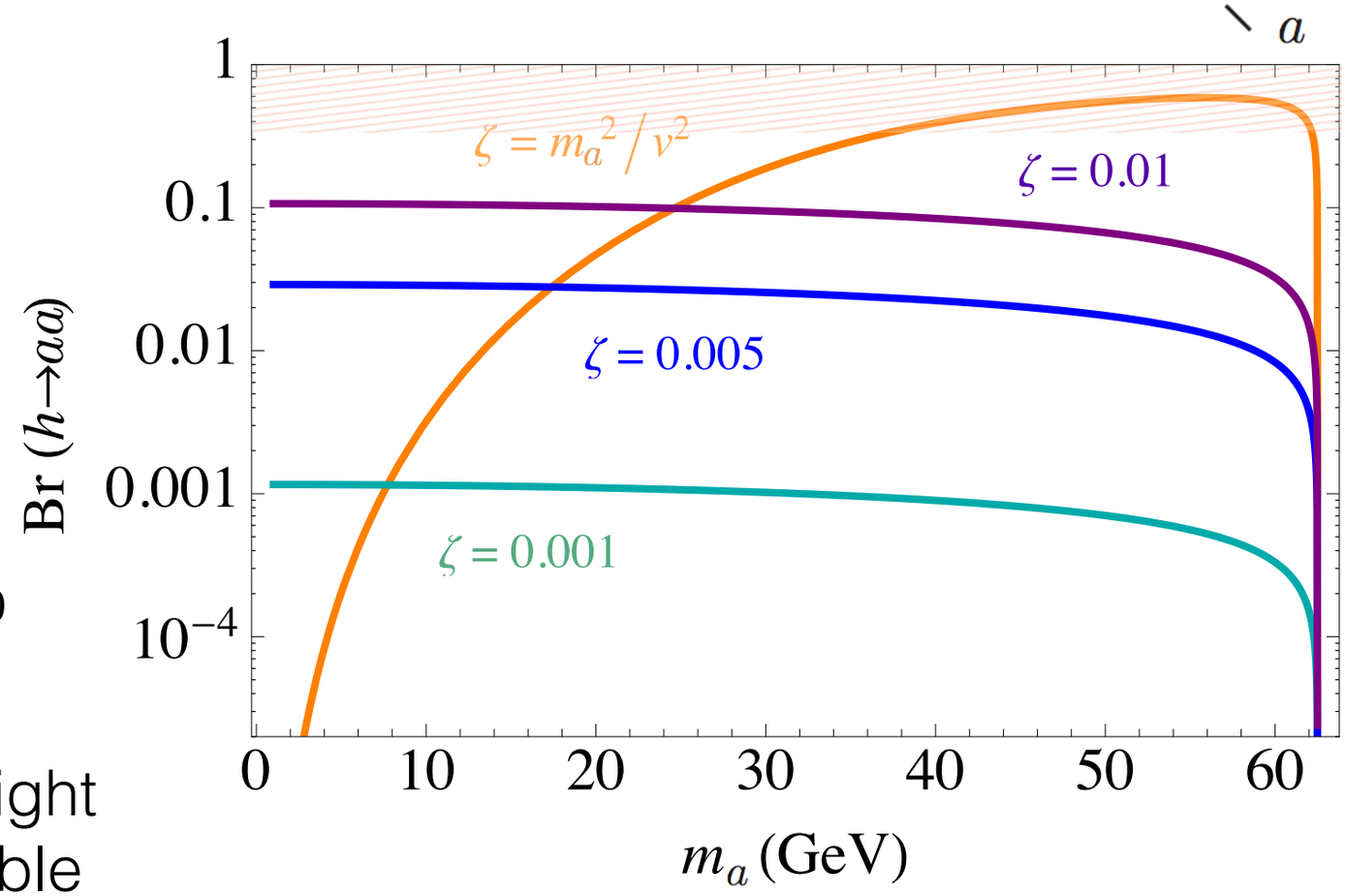
Higgs decays in the SM are suppressed by small Yukawa couplings, loops, or multi-body phase space

Dominant decay to b-quarks suppressed by tiny coupling $y_b \sim 0.017\ v/2$



Simple example:
one new scalar

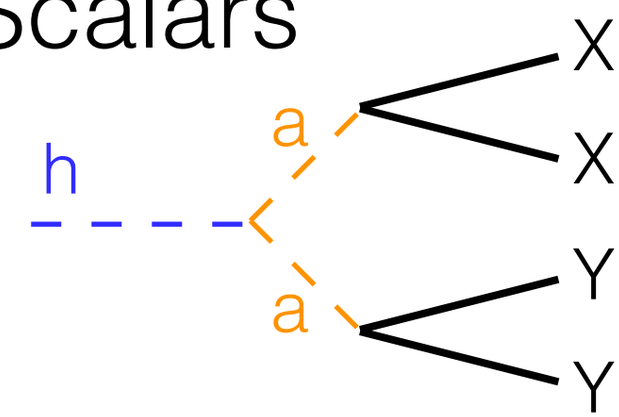




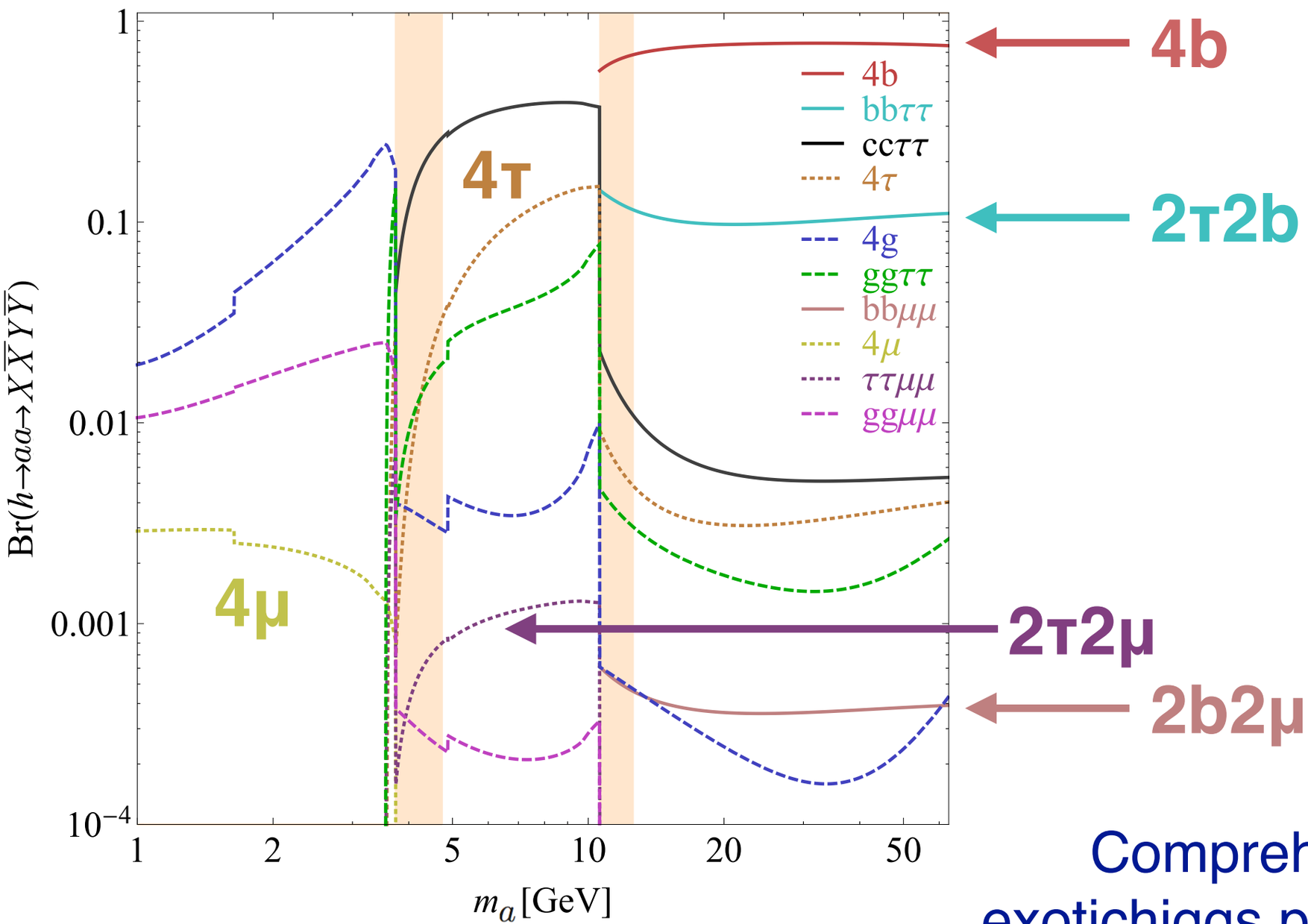
even a small coupling to another light state can open up additional sizable decay modes

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

Higgs Decays to Light (Pseudo-)Scalars



b-jets and taus
largest BR



adding muons
small BR

pair Br:SM Yukawas

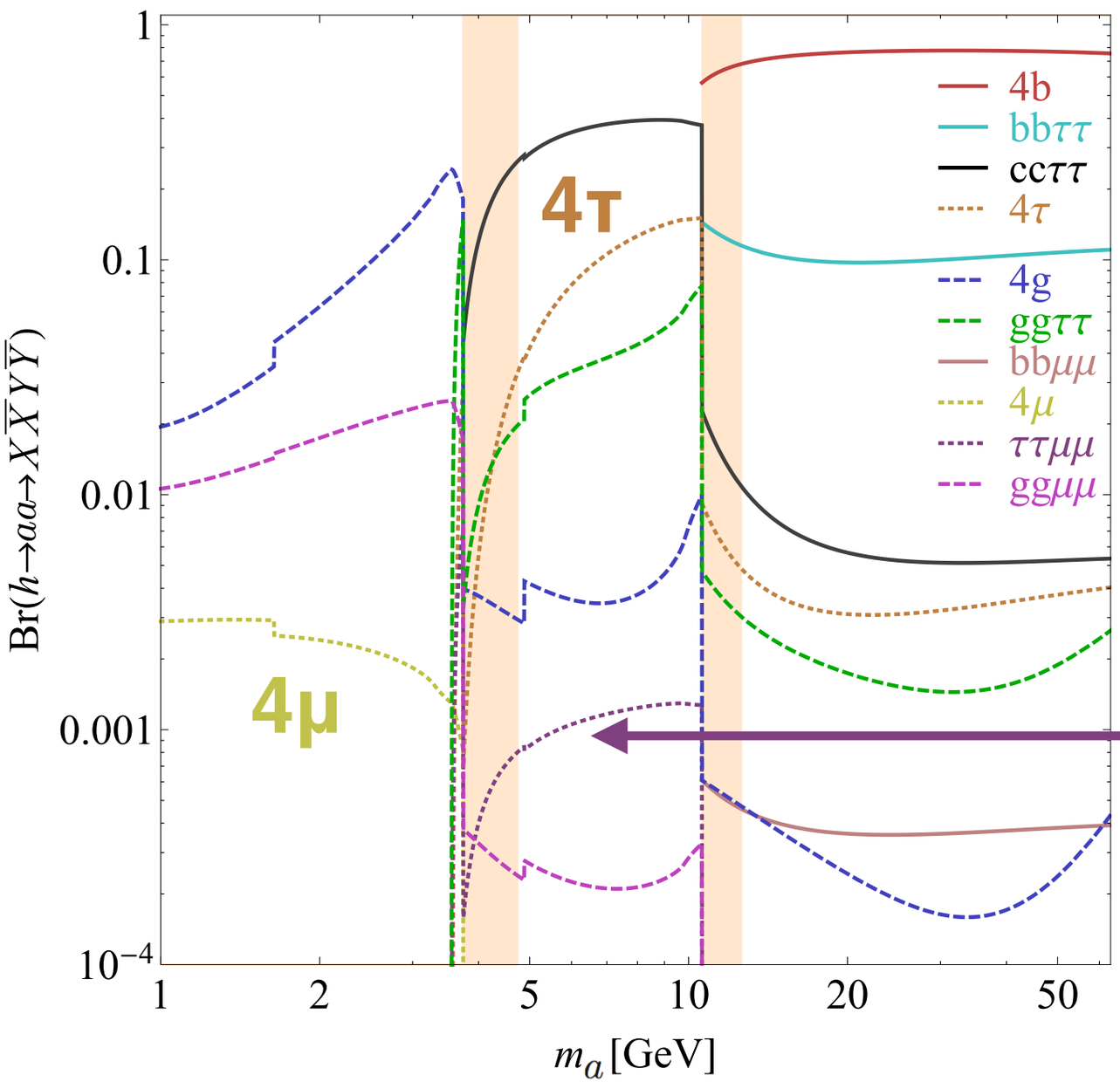
Example benchmark SM+S model

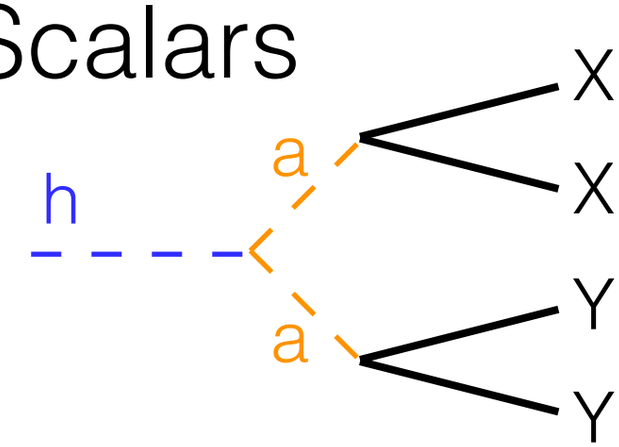
Comprehensive review
exotichiggs.physics.sunysb.edu

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

Higgs Decays to Light (Pseudo-)Scalars

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

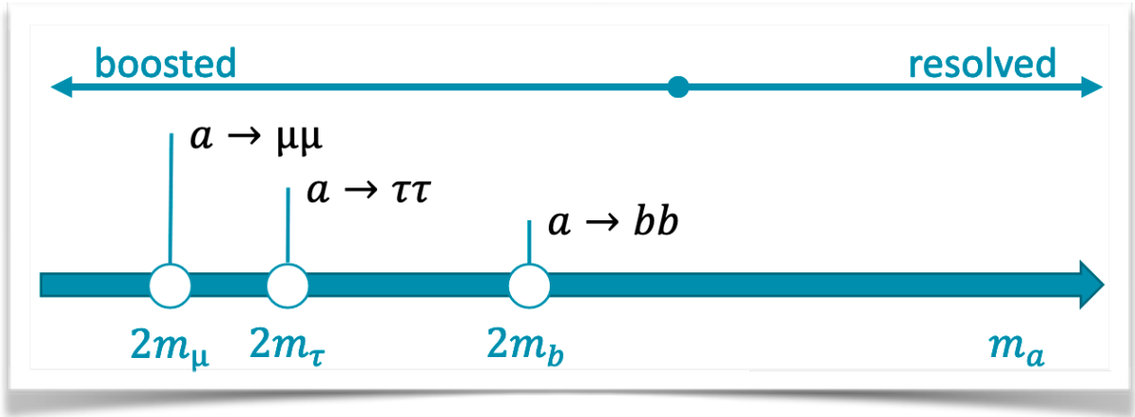




4b

2τ2b

b-jets and taus
largest BR



2τ2μ

2b2μ

adding muons
small BR

pair Br:SM Yukawas

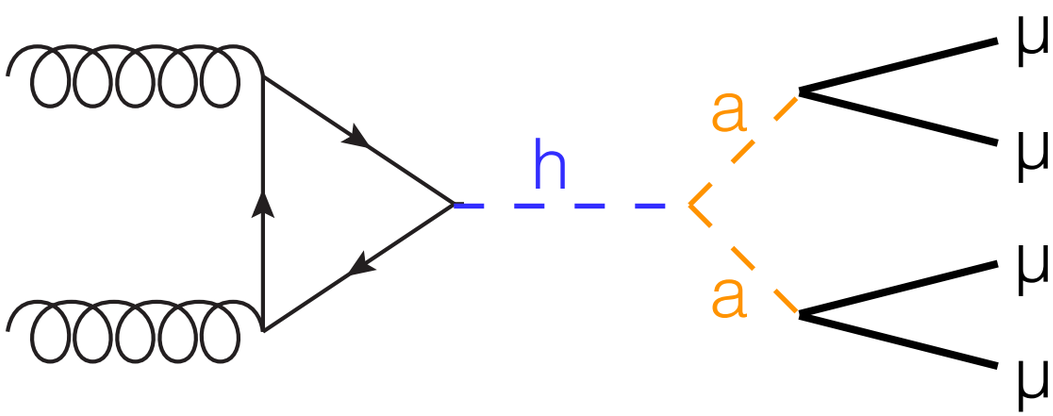
Example benchmark SM+S model

Comprehensive review
exotichiggs.physics.sunysb.edu

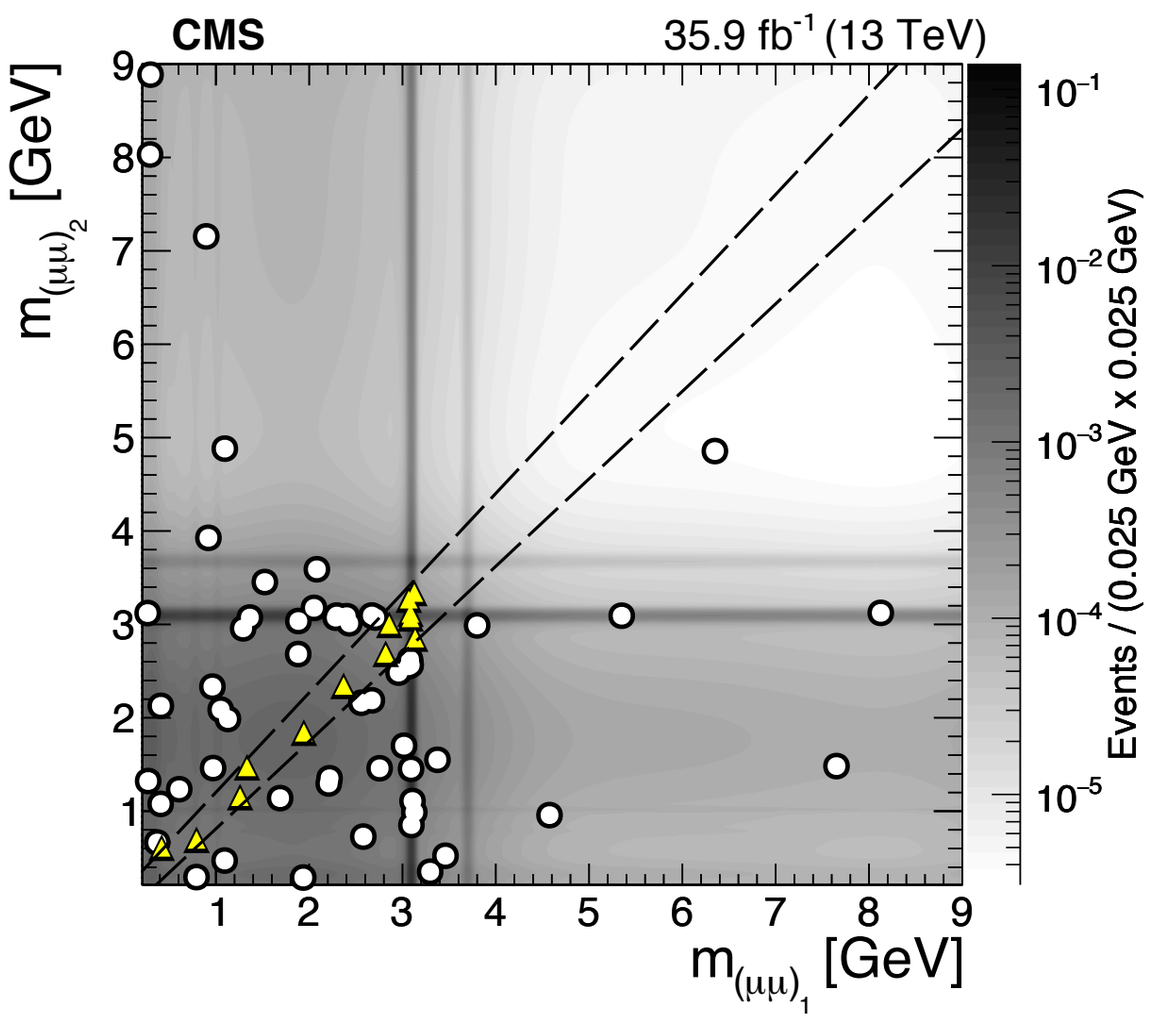
Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

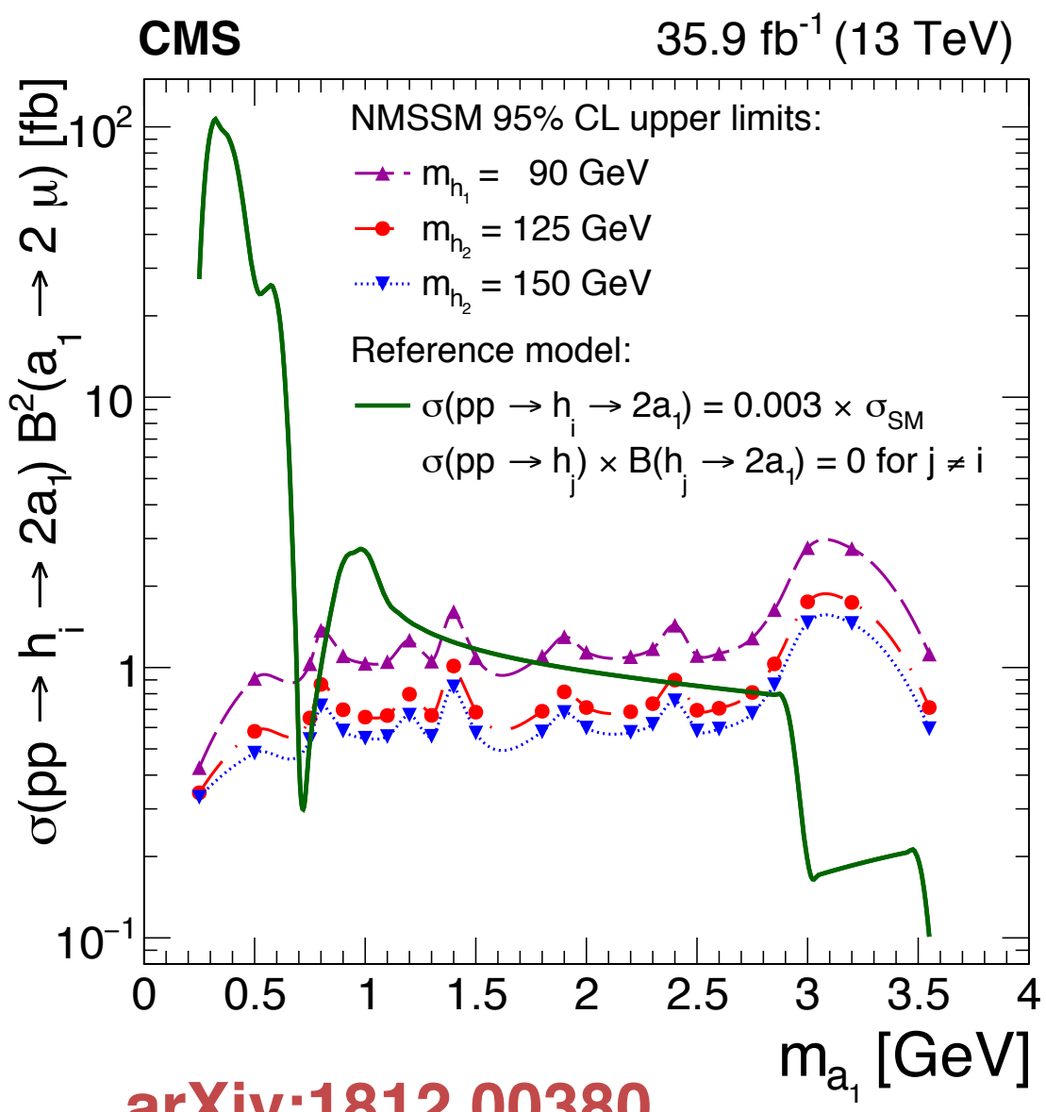
Higgs to Light Scalars: h→2a→4μ

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

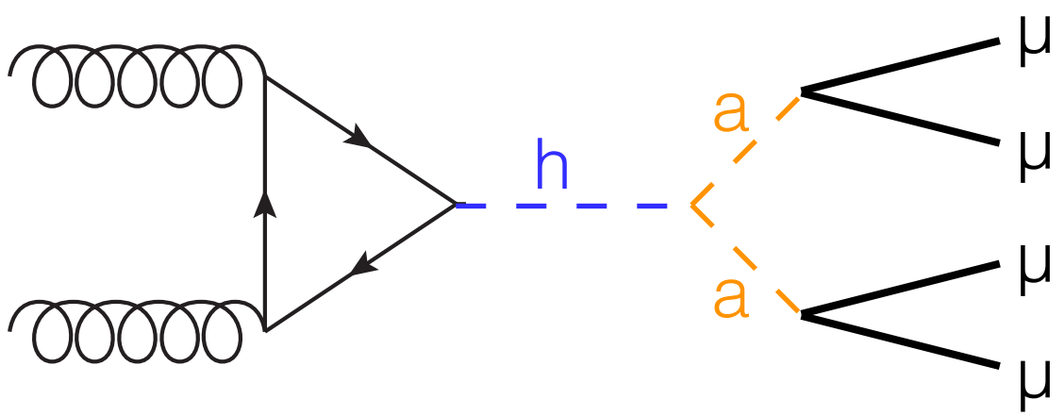




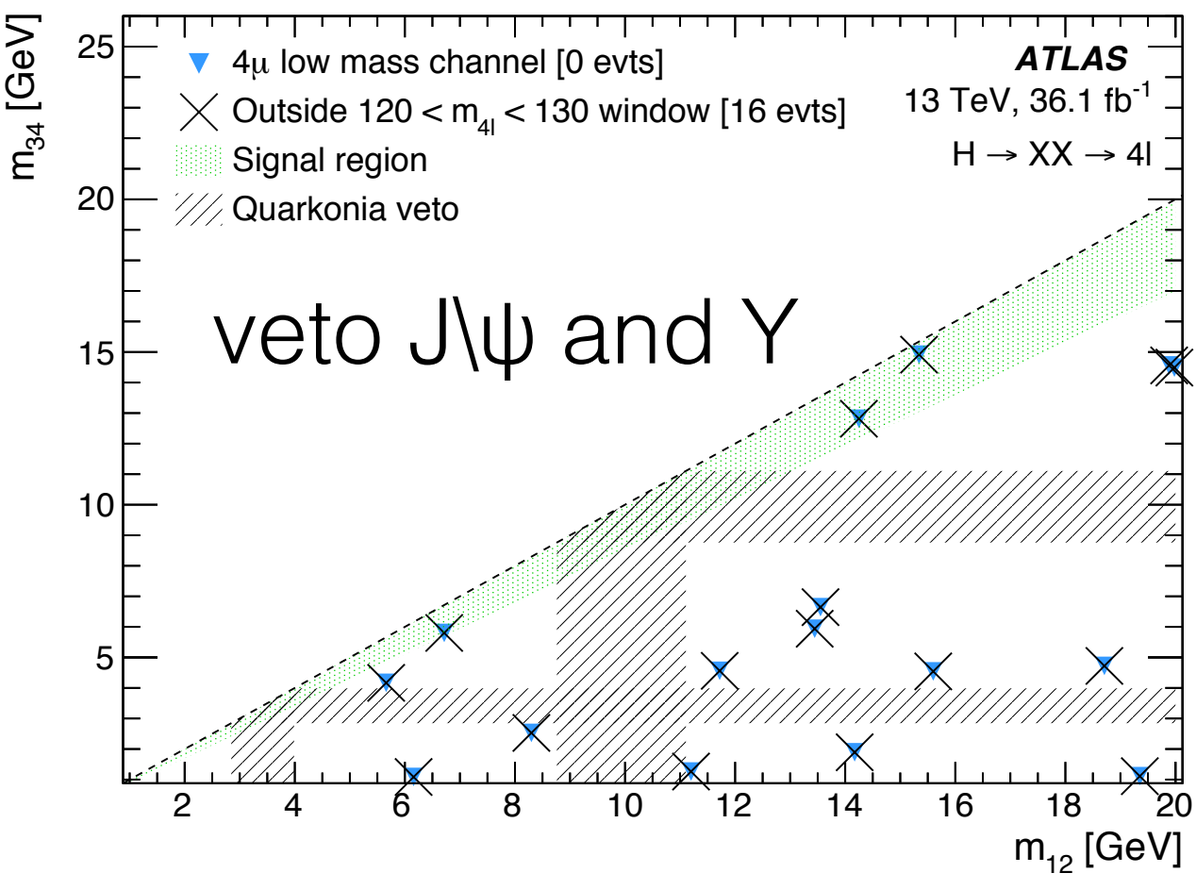
arXiv:1812.00380

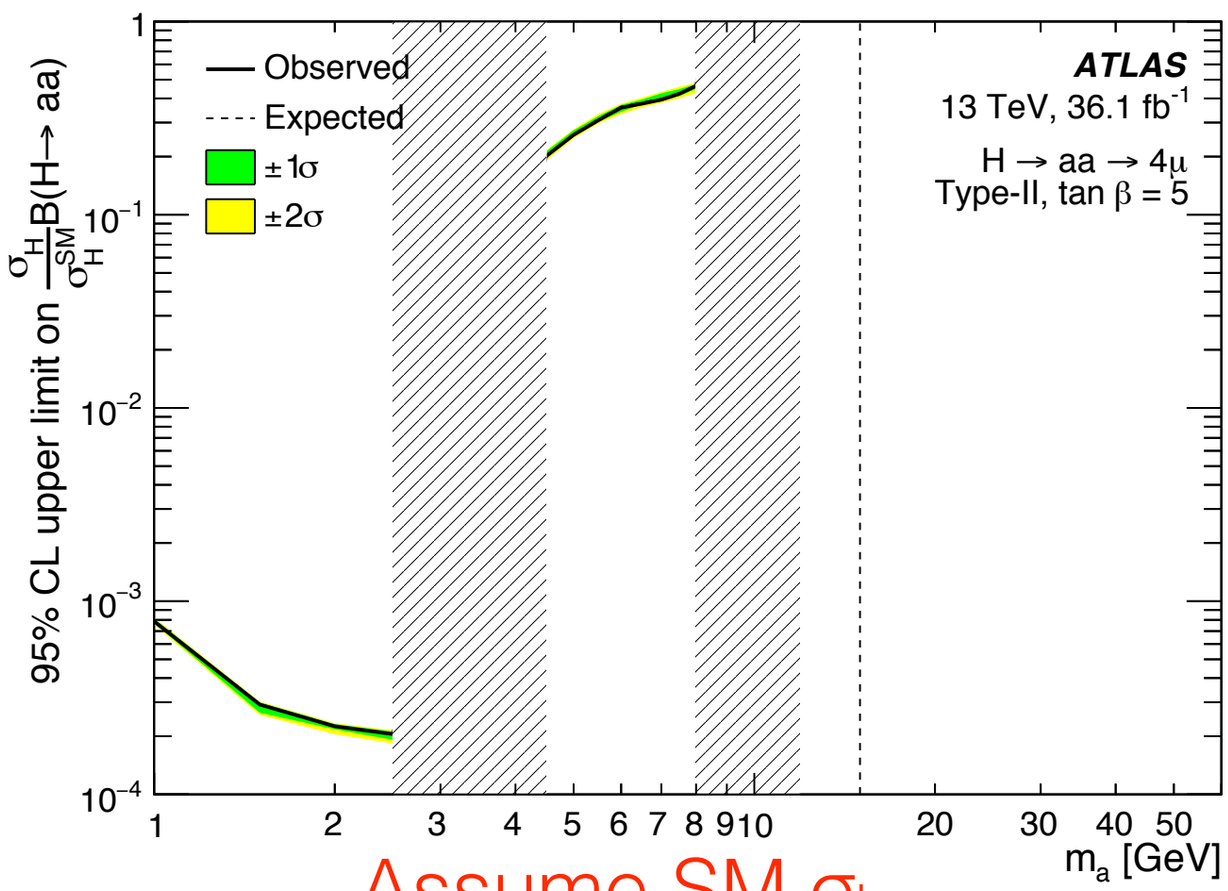
Higgs to Light Scalars: h→2a→4μ

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)



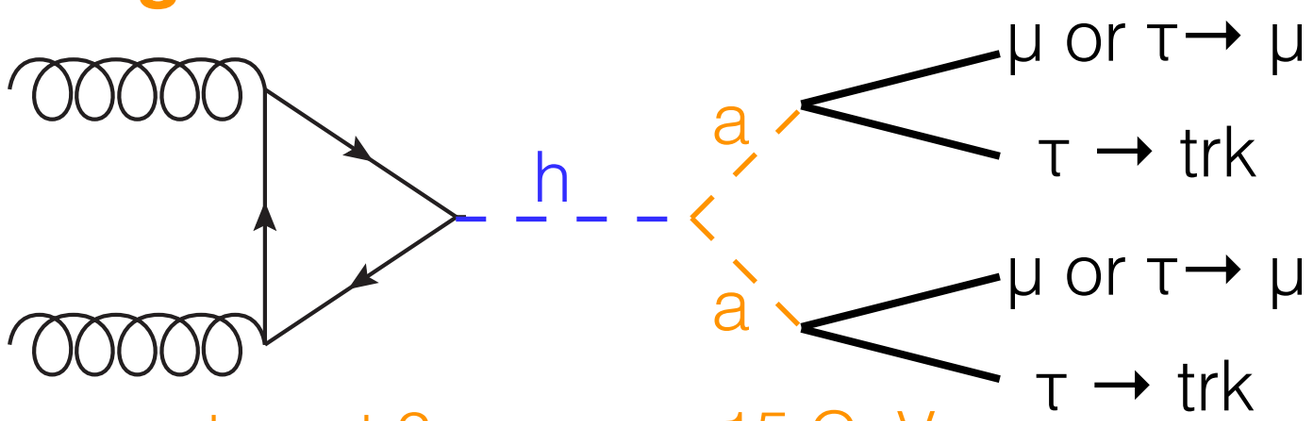


Assume SM σ_h

JHEP 06 (2018) 166 arXiv:1802.03388

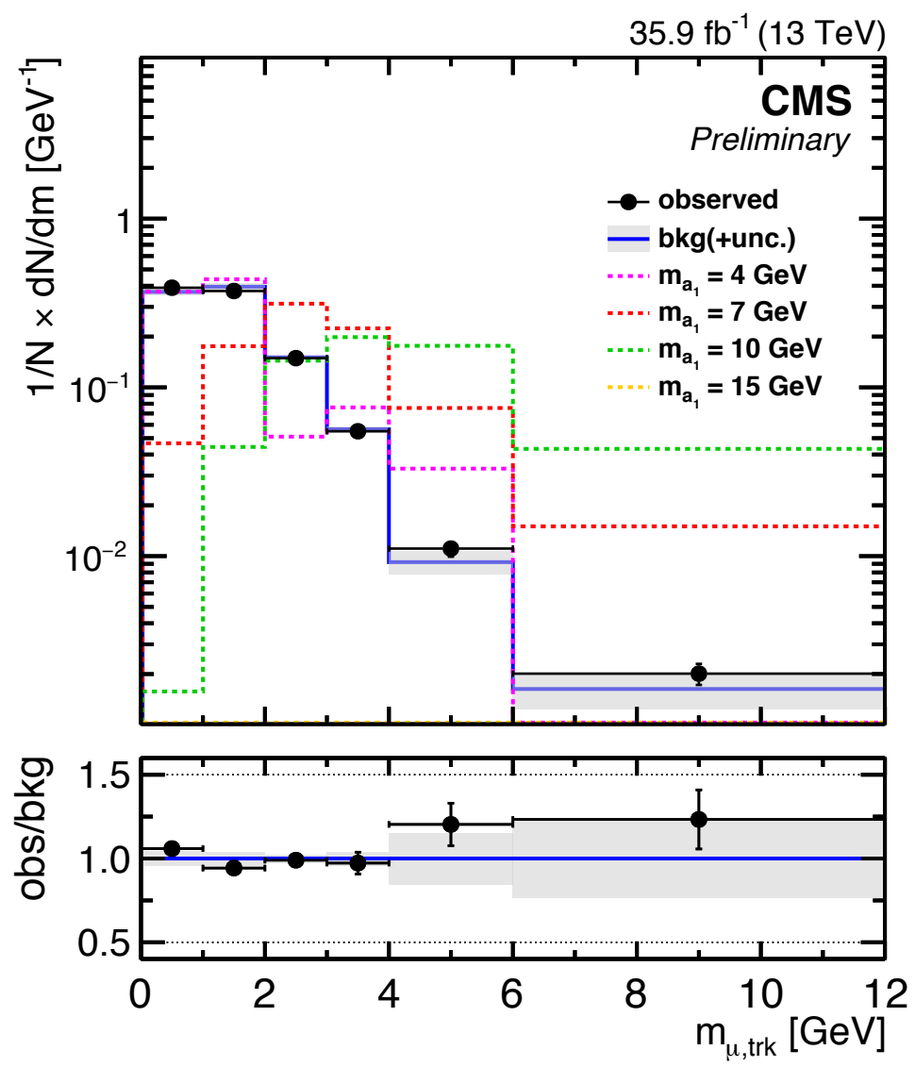
Higgs to Light Scalars: h→2a→2μ2τ or 4τ

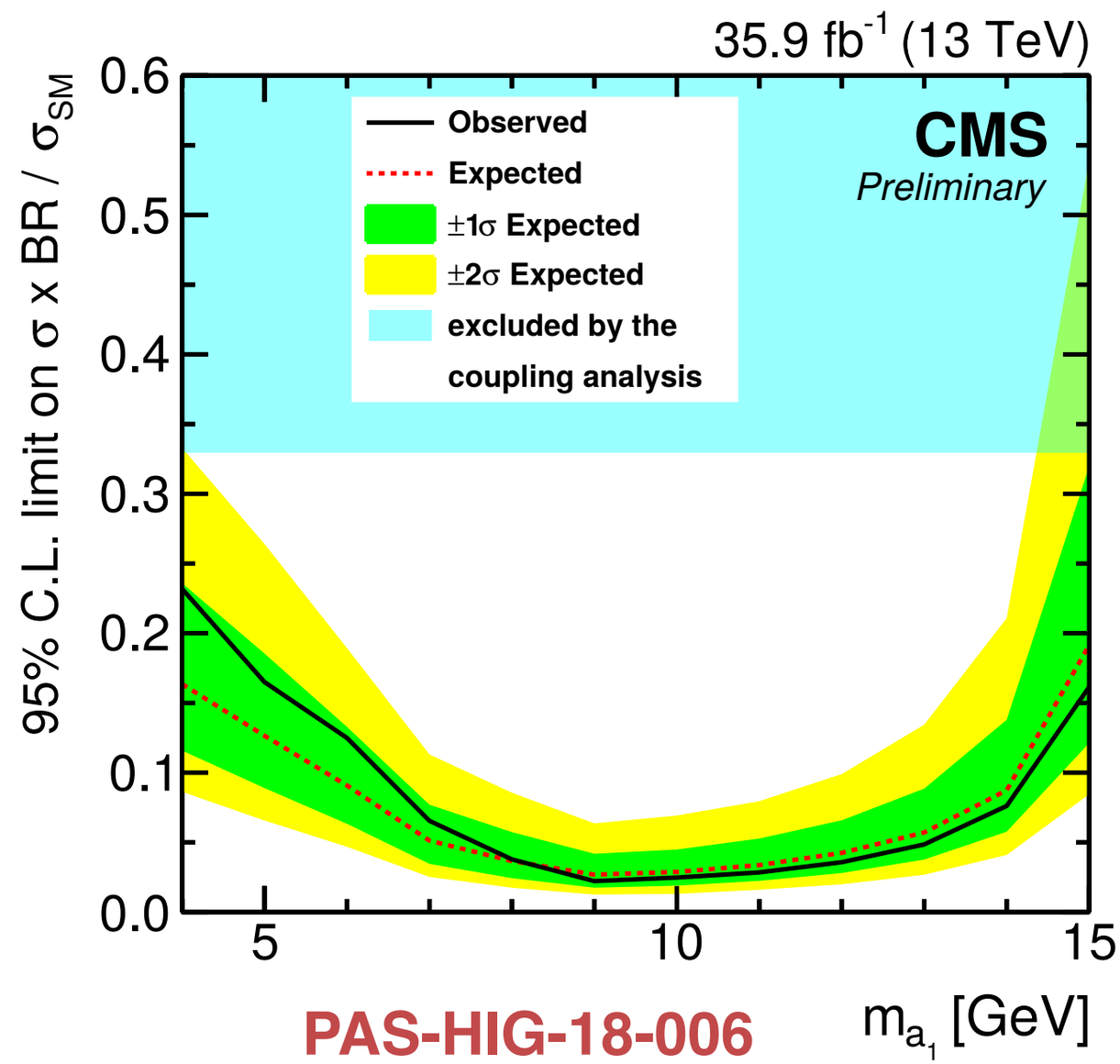
Signal



target $2m_\tau \lesssim m_a \lesssim 15$ GeV

- Strategy
  - Events with 2 same-sign charge muons and 2 tracks
  - 2D search in $m_1(\mu,trk)$ $m_2(\mu,trk)$ plane
- Main backgrounds QCD multijets - b-jets

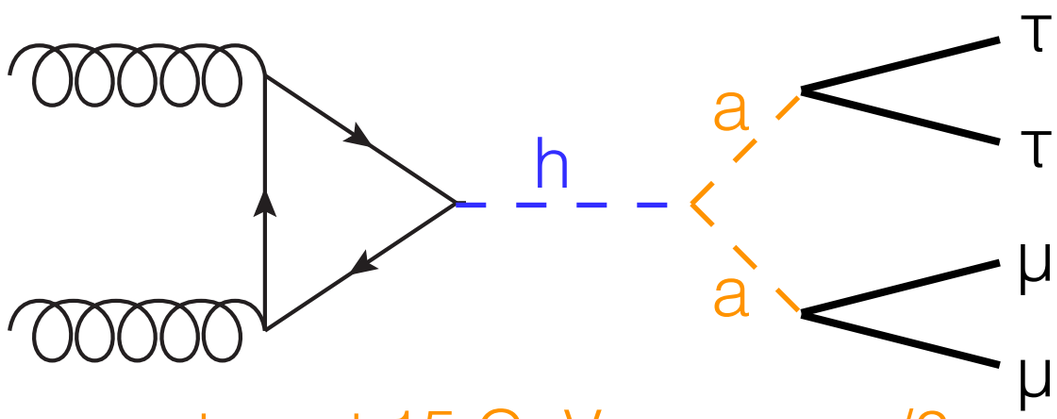




PAS-HIG-18-006

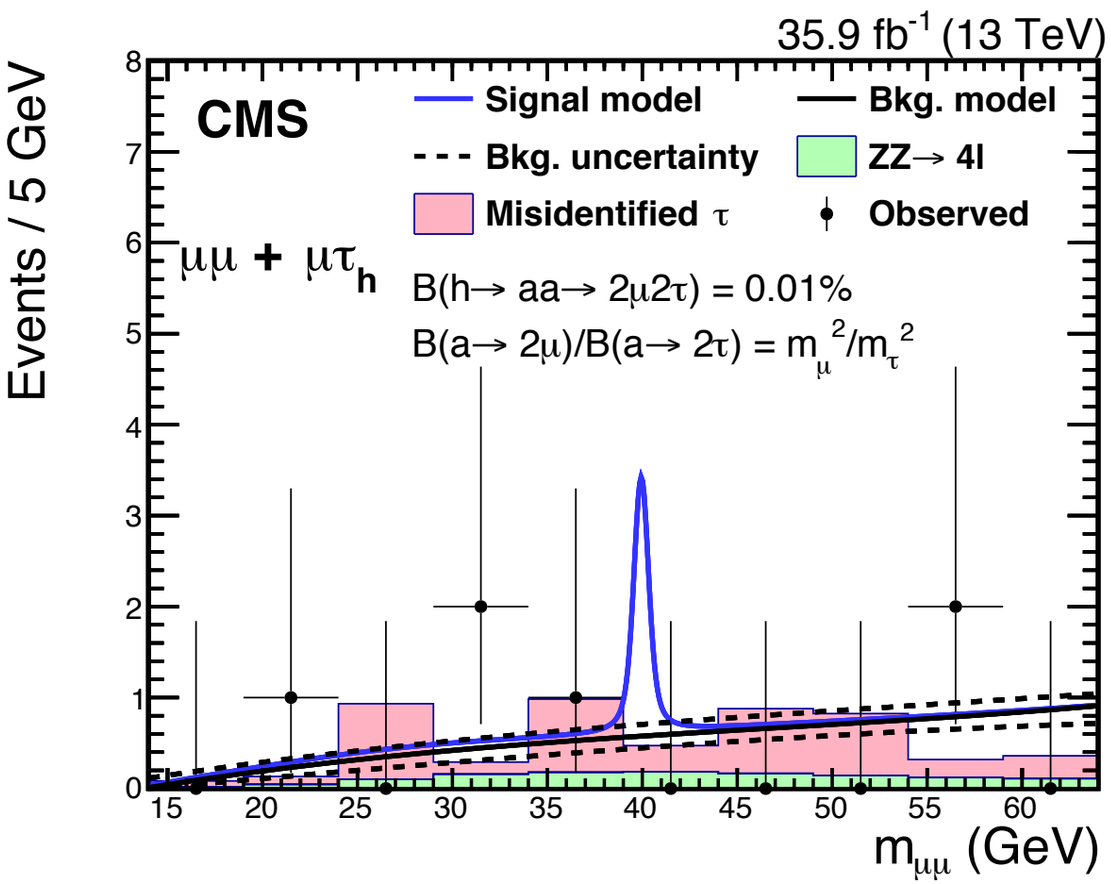
Higgs to Light Scalars: h→2a→2μ2τ

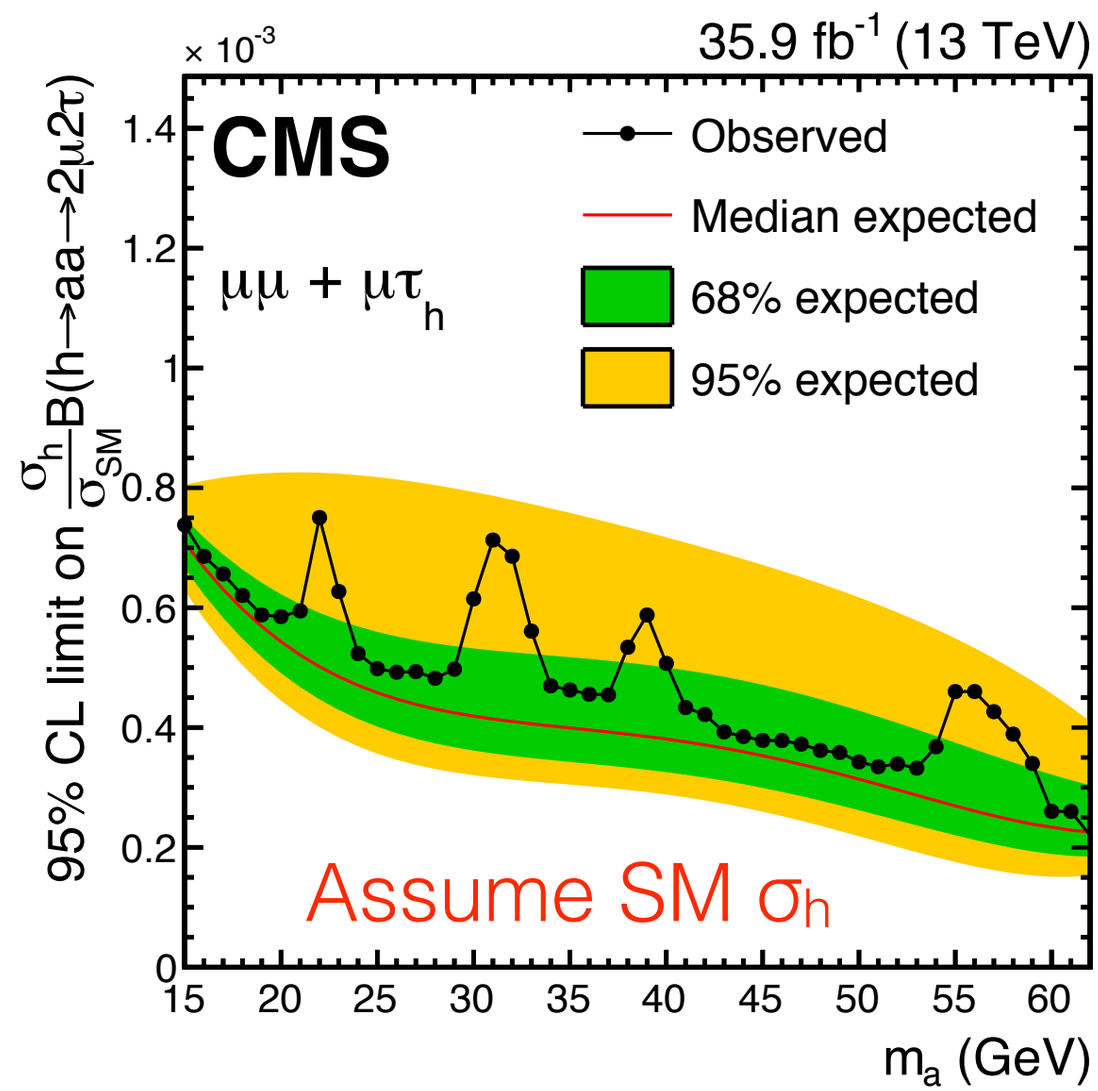
Signal



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

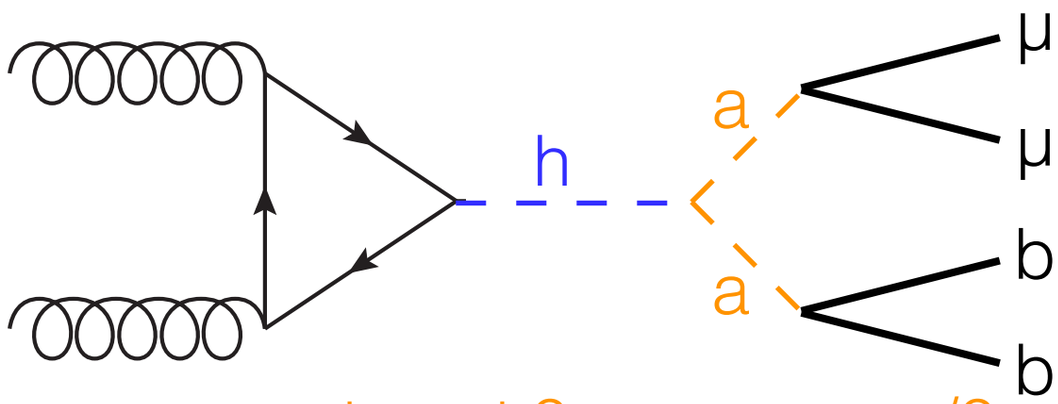




JHEP 11 (2018) 018 arXiv:1805.04865

Higgs to Light Scalars: h→2a→2μ2b

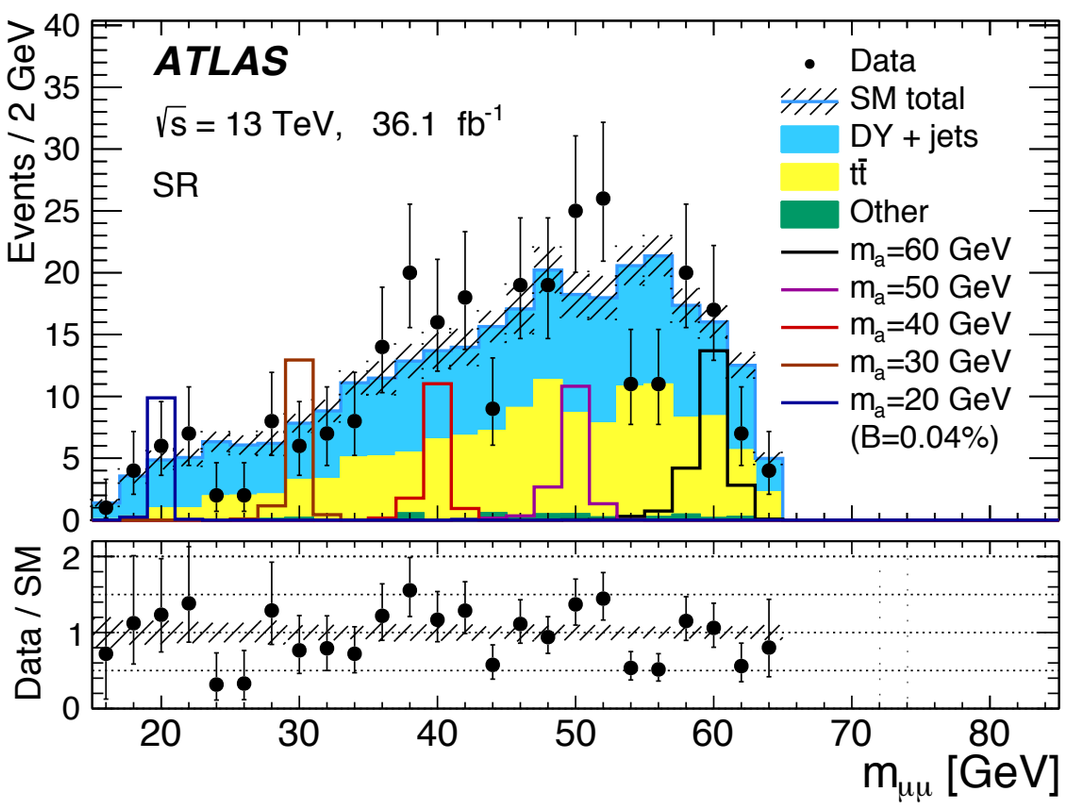
Signal

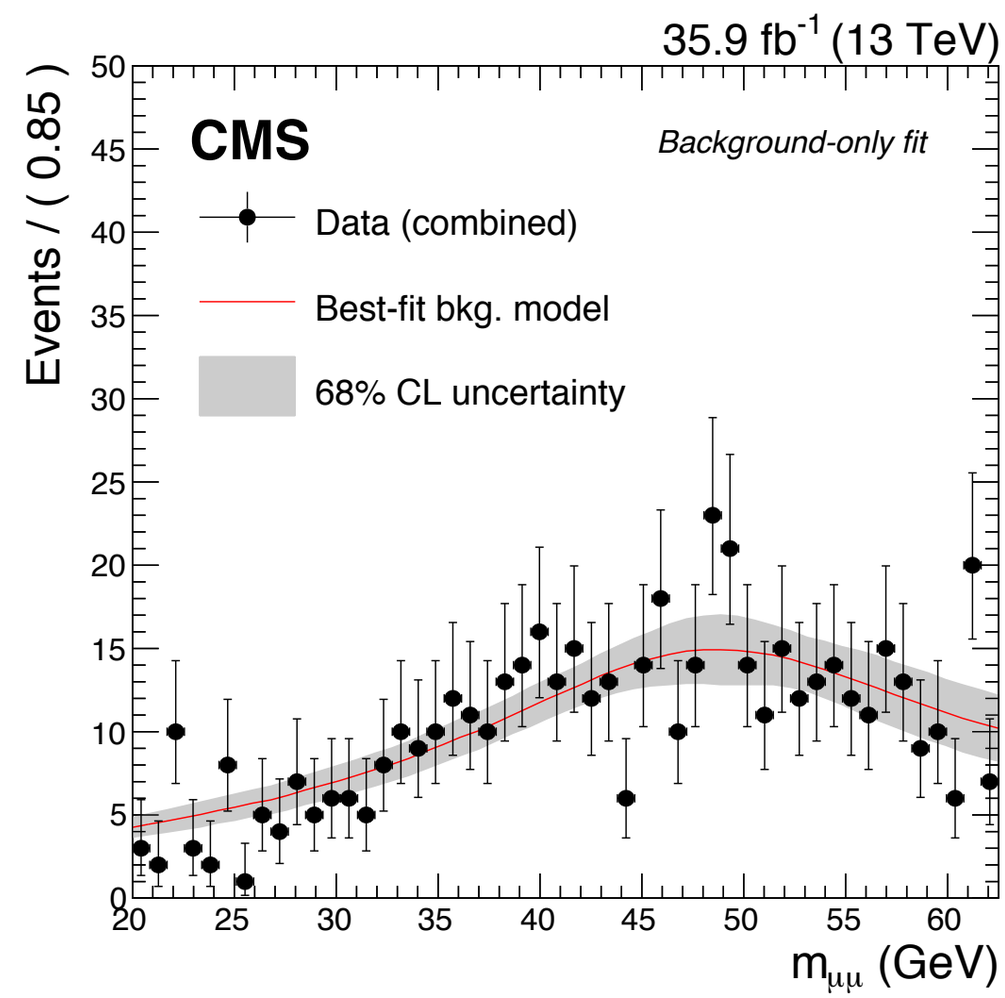


target $2m_b \lesssim m_a \lesssim m_h/2$

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

arXiv:1807.00539

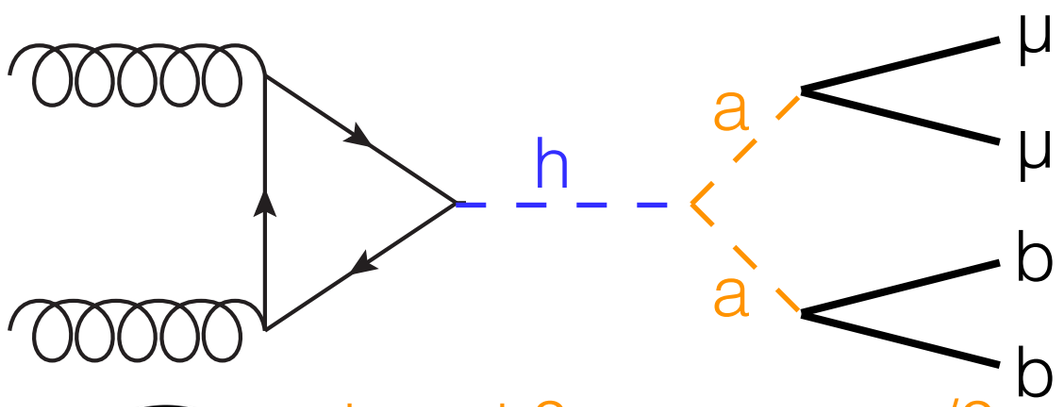




arXiv:1812.06359

Higgs to Light Scalars: h→2a→2μ2b

Signal

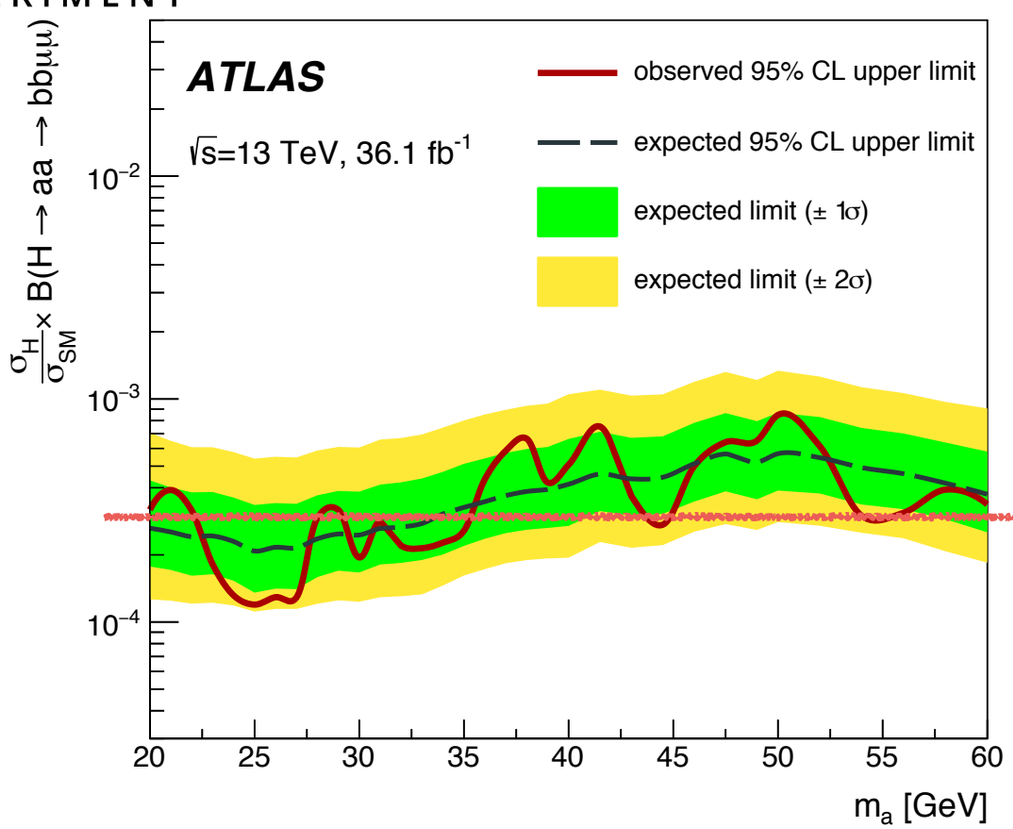


target $2m_b \lesssim m_a \lesssim m_h/2$

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

ATLAS EXPERIMENT

arXiv:1807.00539



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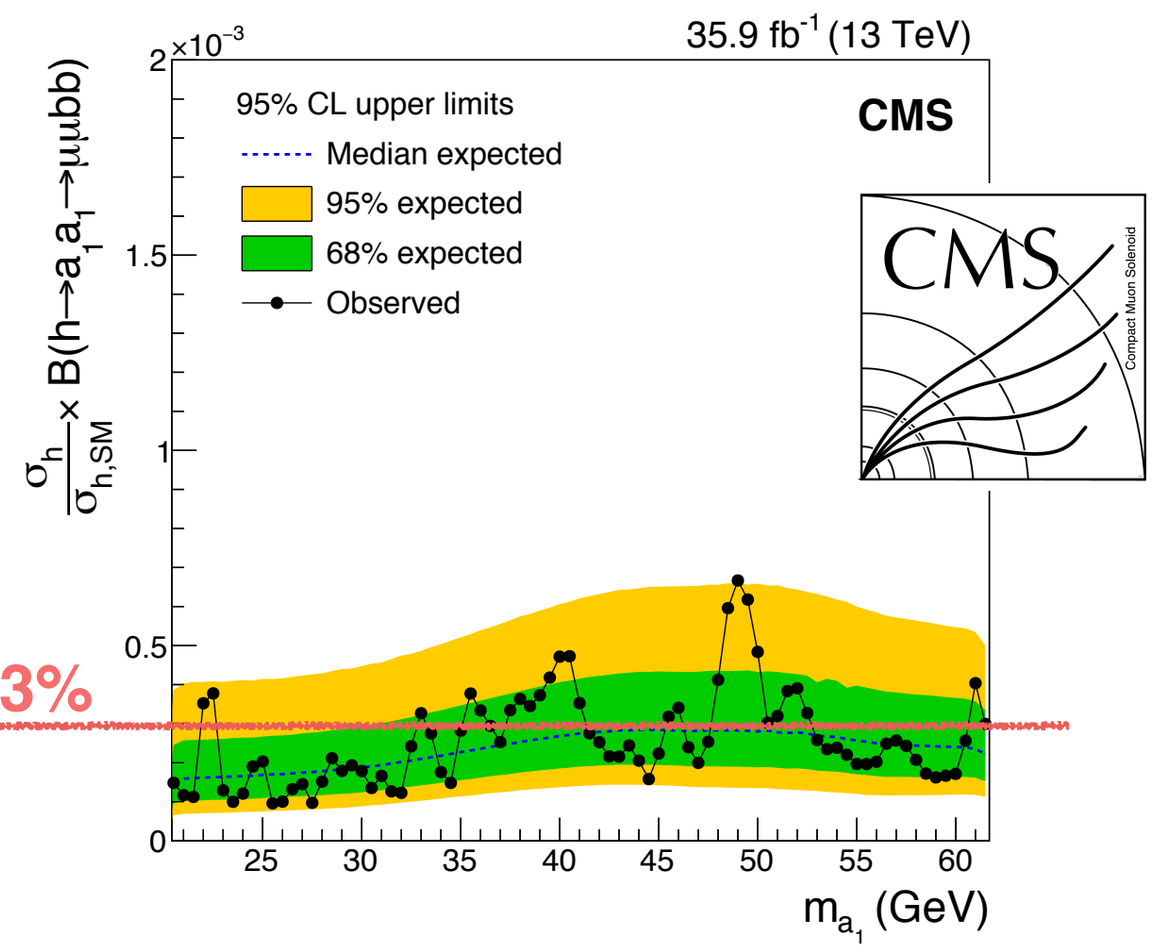


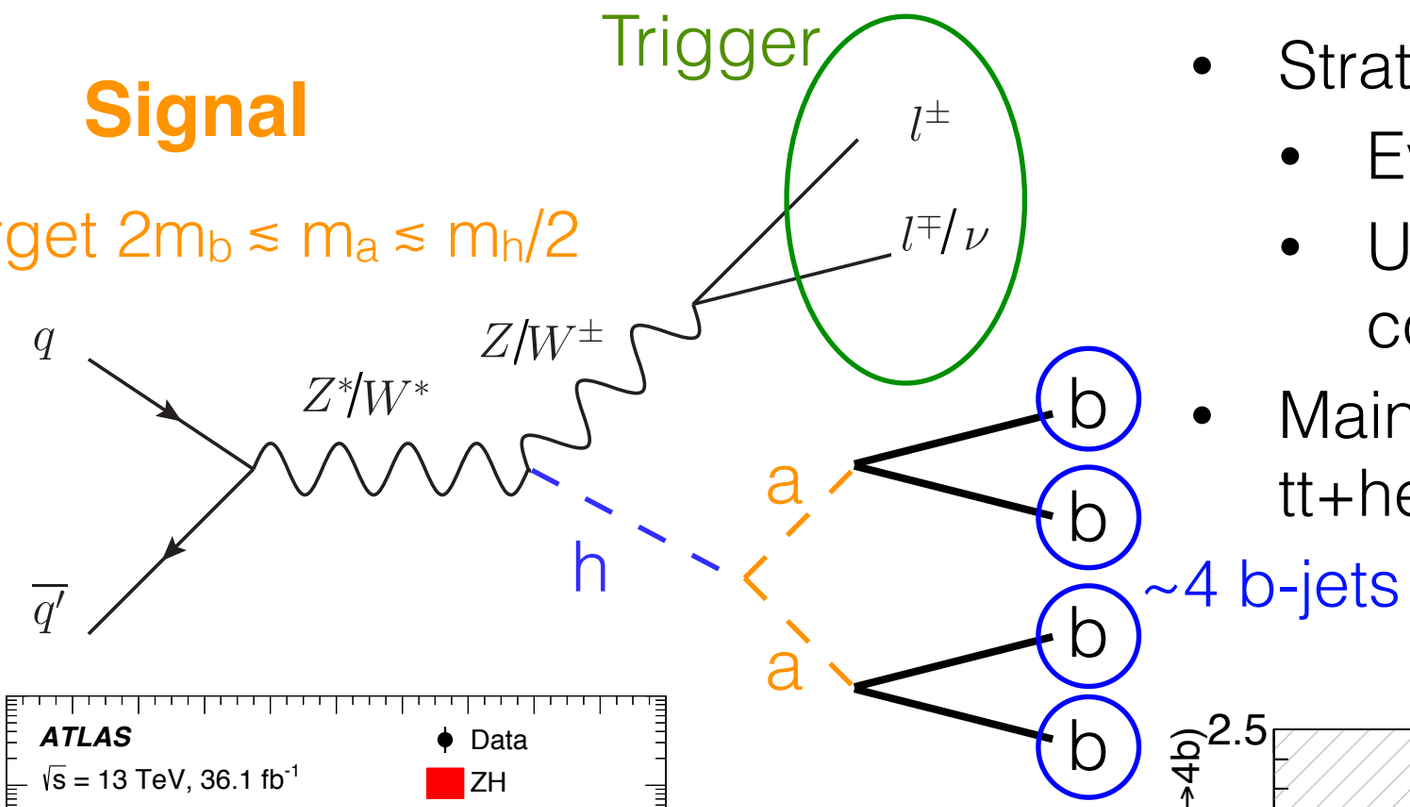
arXiv:1812.06359

Assume SM σ_h

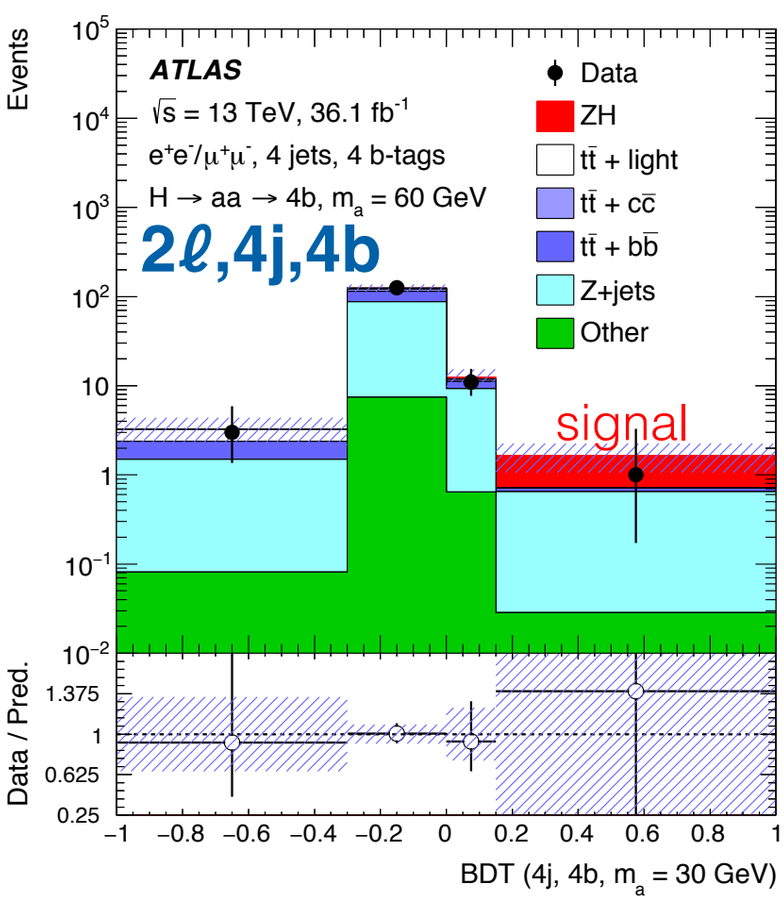
Higgs to Light Scalars: h→2a→4b

Signal

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



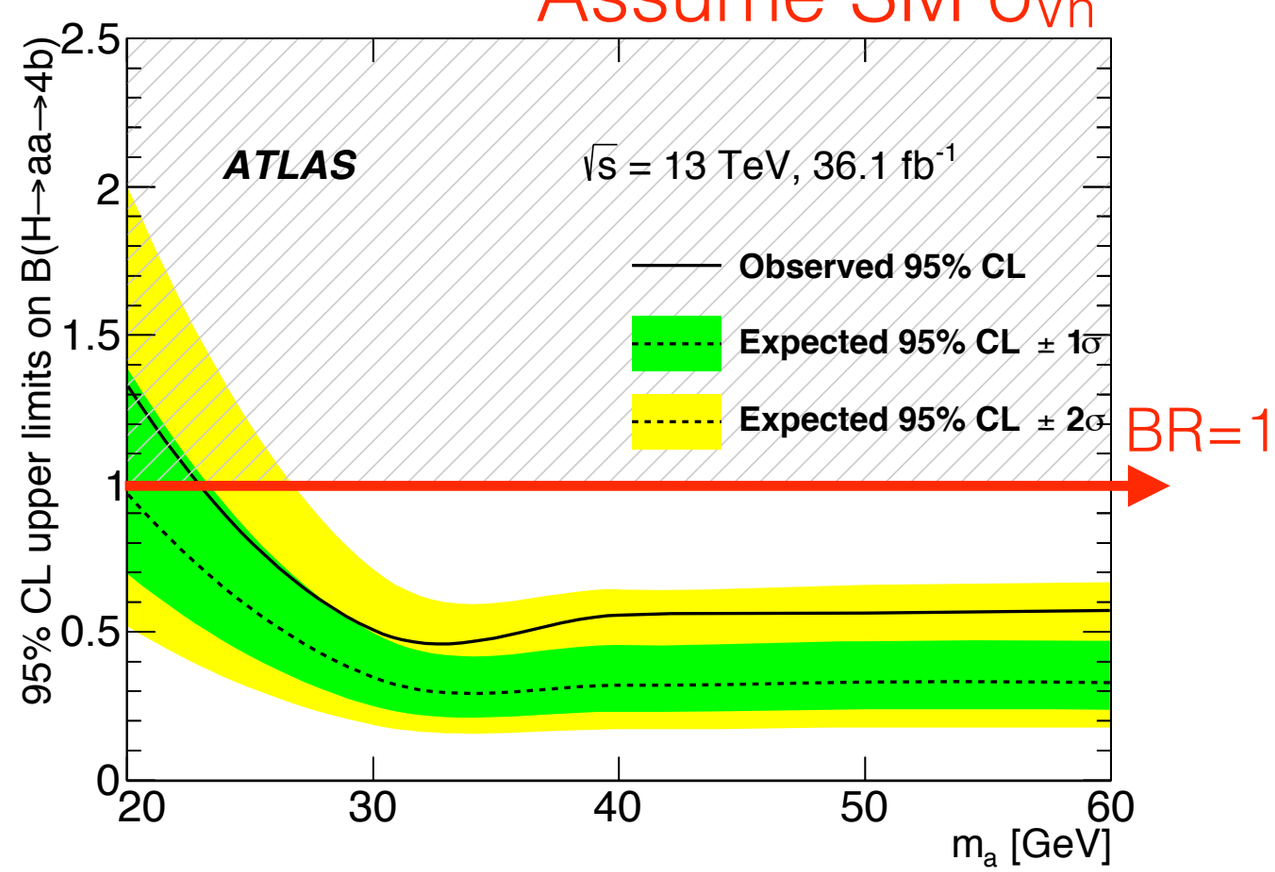
- Strategy
  - Events with 1/2 leptons & 3/4 b-jets
  - Use multivariate technique and complex background modeling
- Main backgrounds Z+heavy flavor & tt+heavy flavor



Sensitivity driven by 2ℓ

loss in sensitivity at low m_a due to merged jets

Assume SM σ_{Vh}



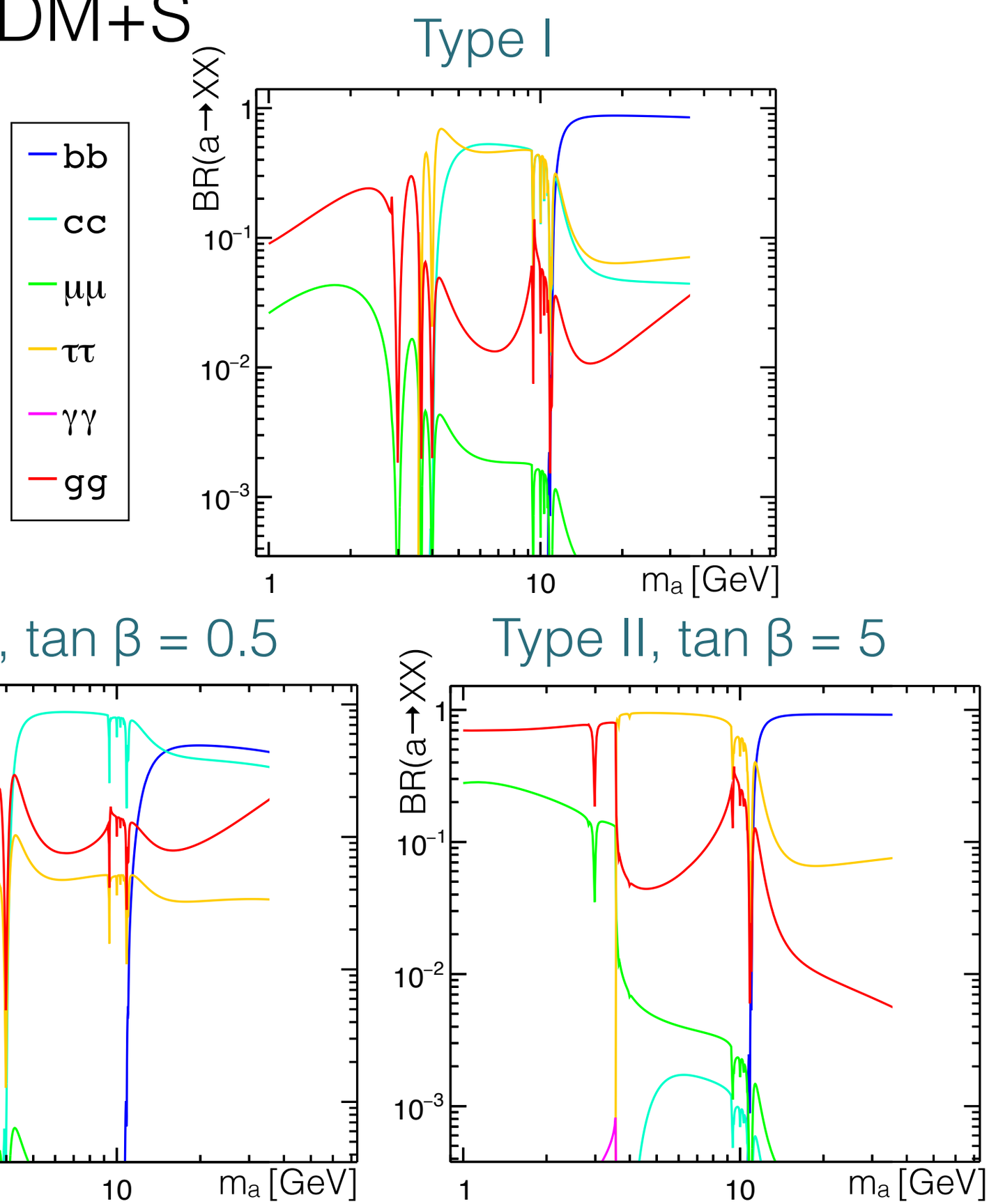
JHEP 10 (2018) 031 arXiv:1806.07355

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
JHEP 3 (2018) 178

From LHC Higgs XS WG on Exotic Decays



2HDM+S Models

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New calculations including quarkonia regions JHEP3(2018)178

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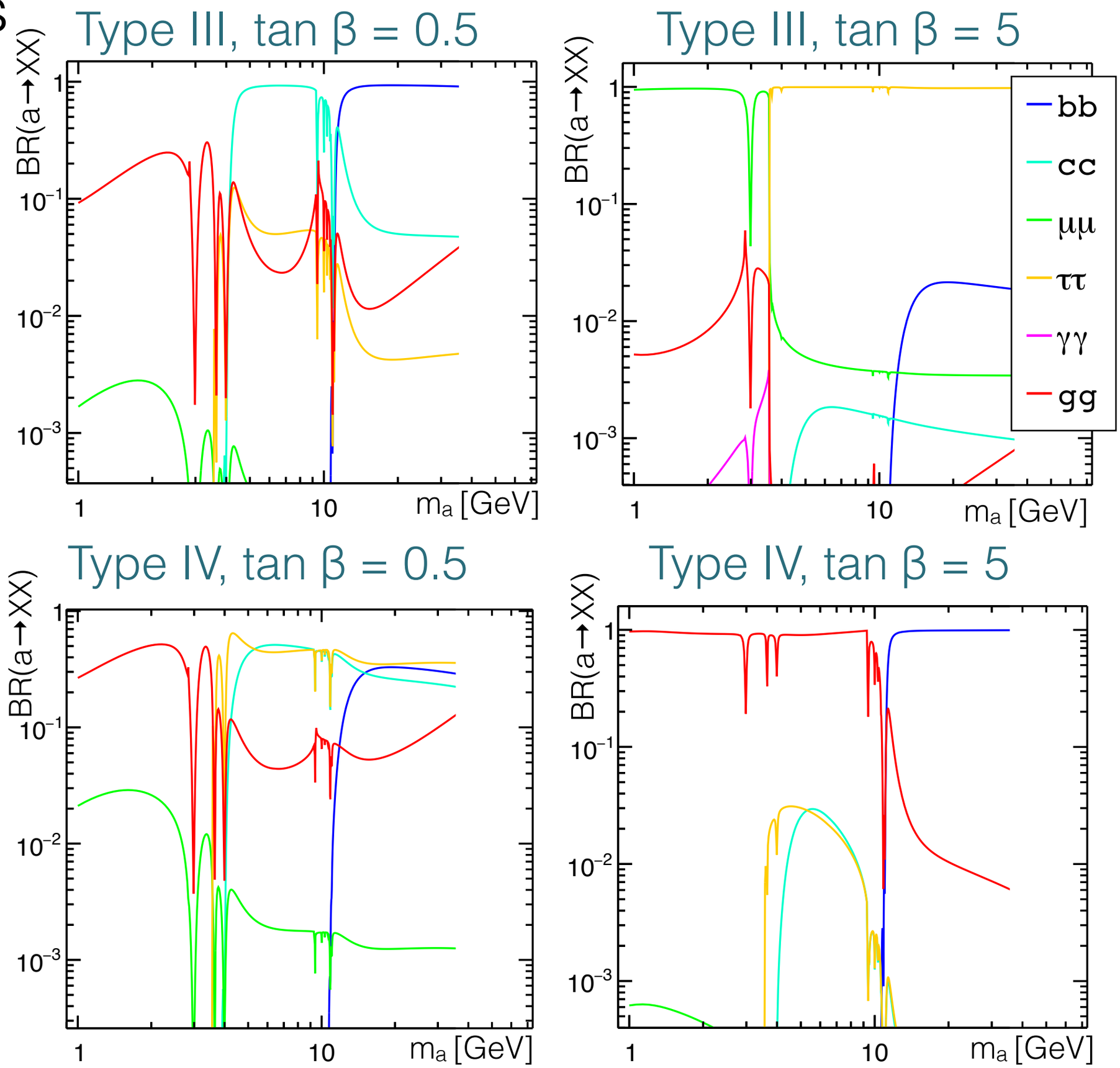
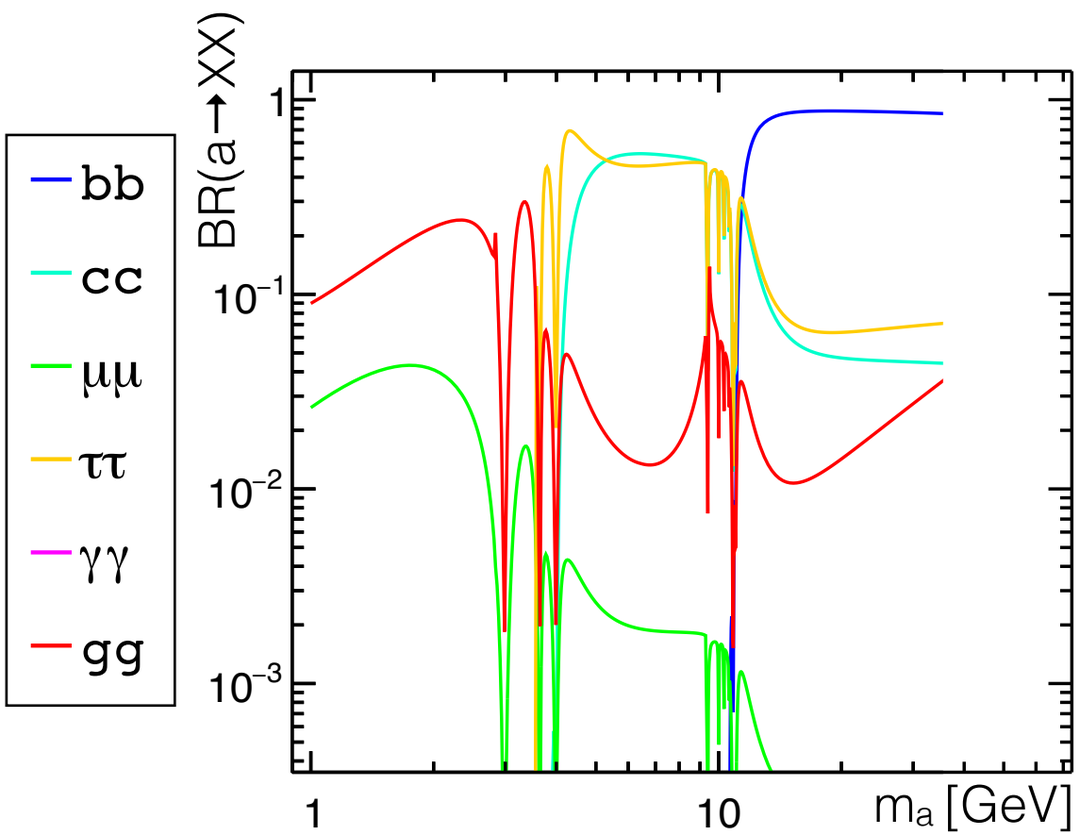


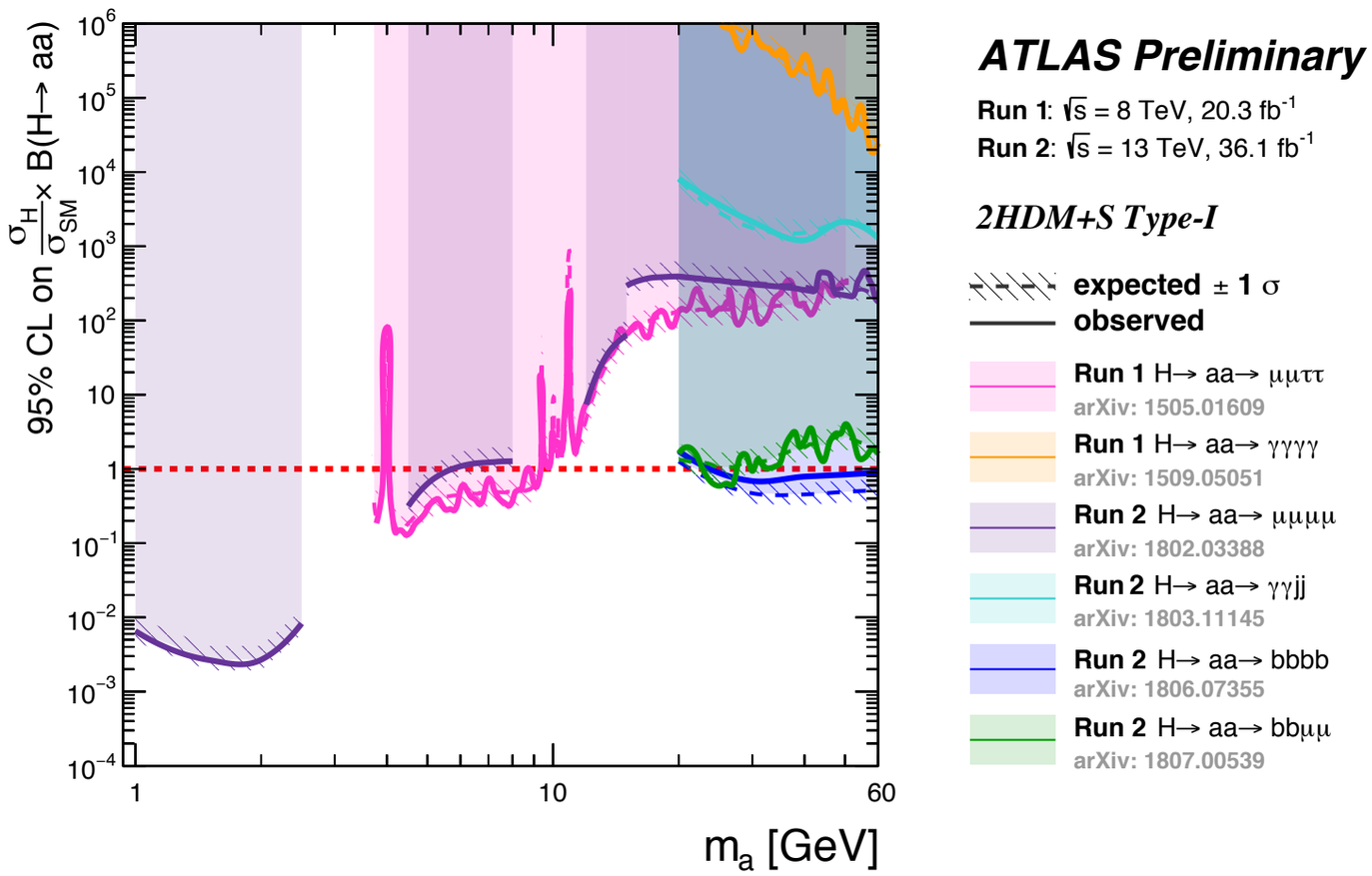
Higgs to Light Scalars: Summary

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

Example benchmark model 2HDM+S Type I



JHEP3(2018)178



ATL-PHYS-PUB-2018-045

Summary 2HDM+S

- **Type I:** all fermions couple to H_2
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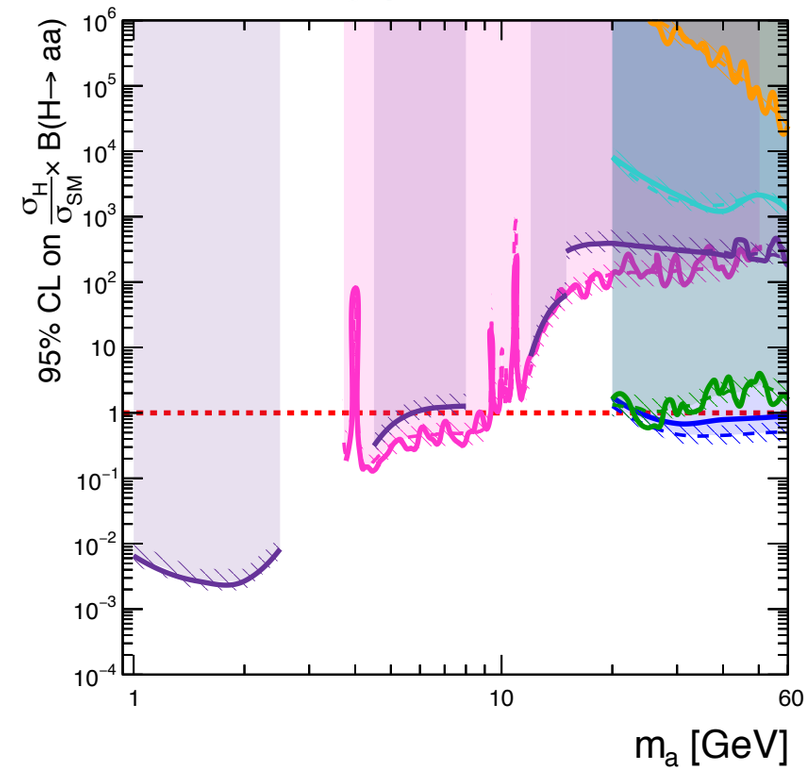
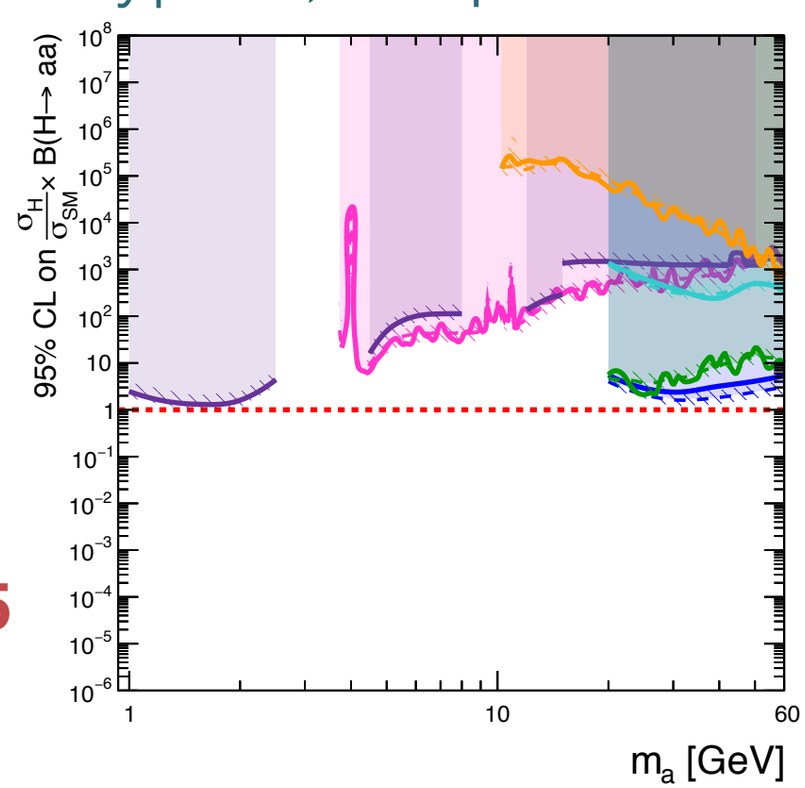
- Type IV: flipped, with u_R, e_R coupling to H_2 and d_R to H_1

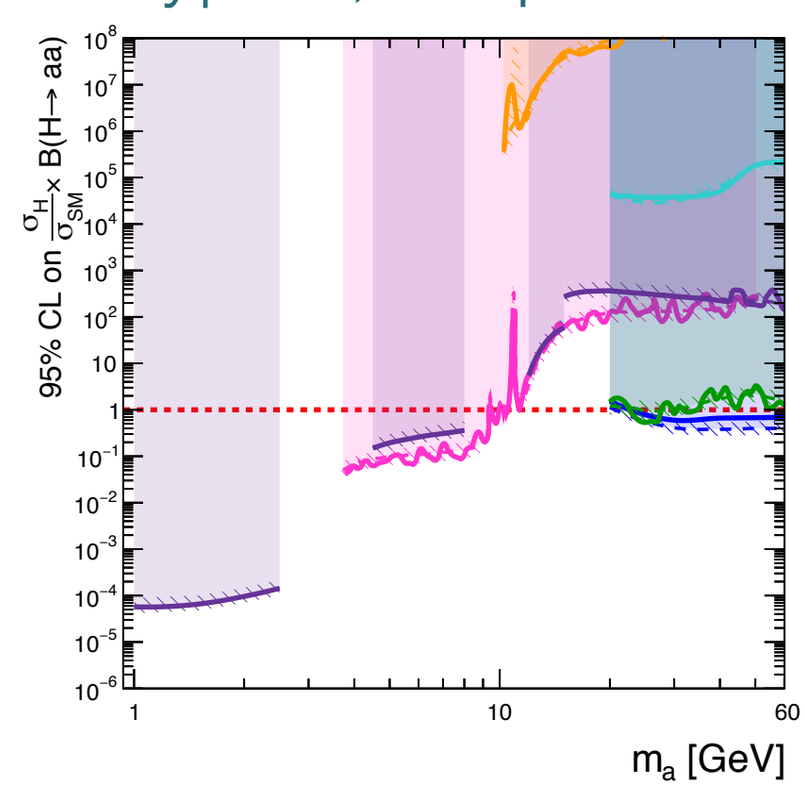
Type I



Type II, tan β = 0.5



Type II, tan β = 5

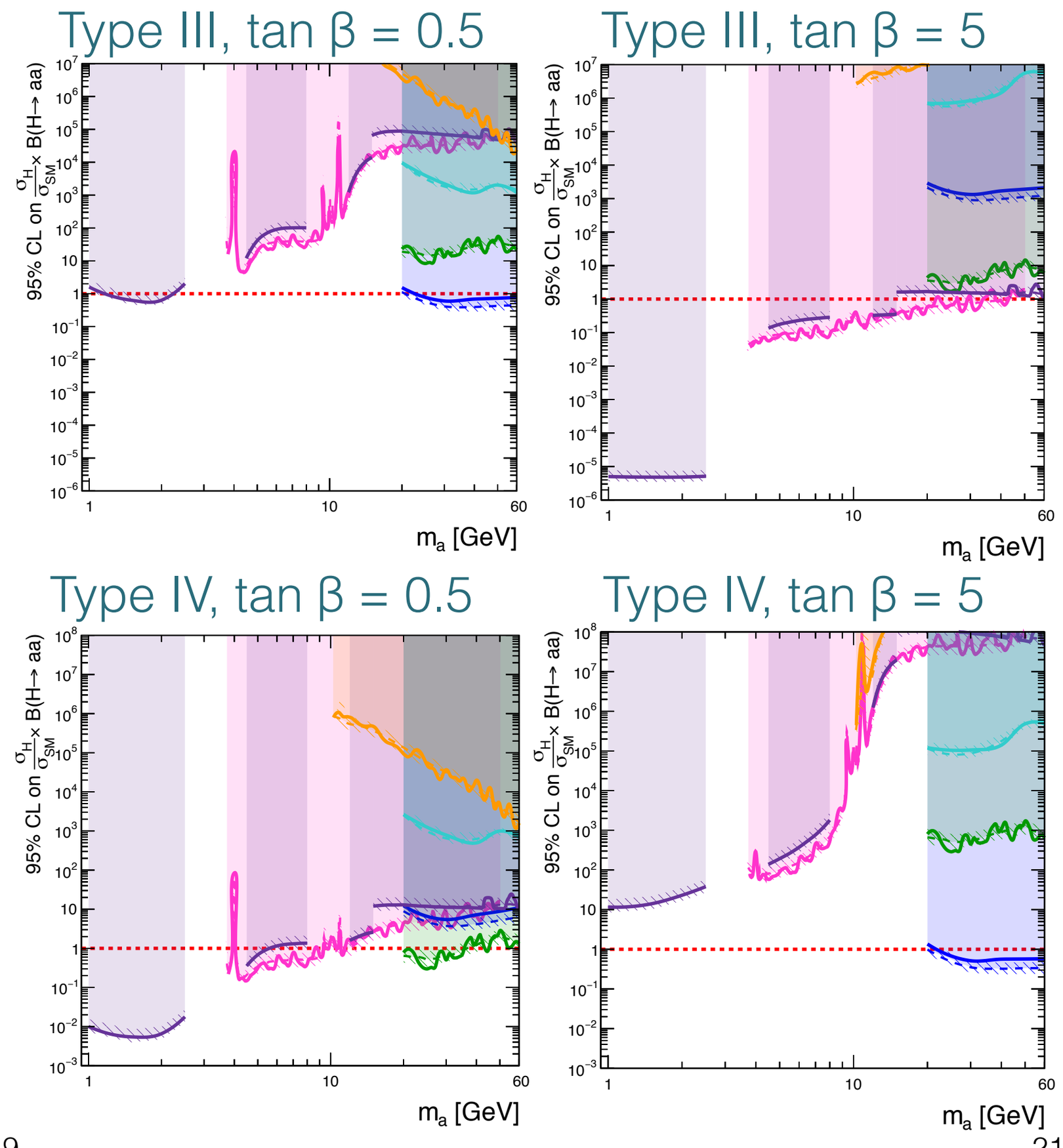


ATLAS EXPERIMENT

ATL-PHYS-PUB-2018-045

Summary 2HDM+S

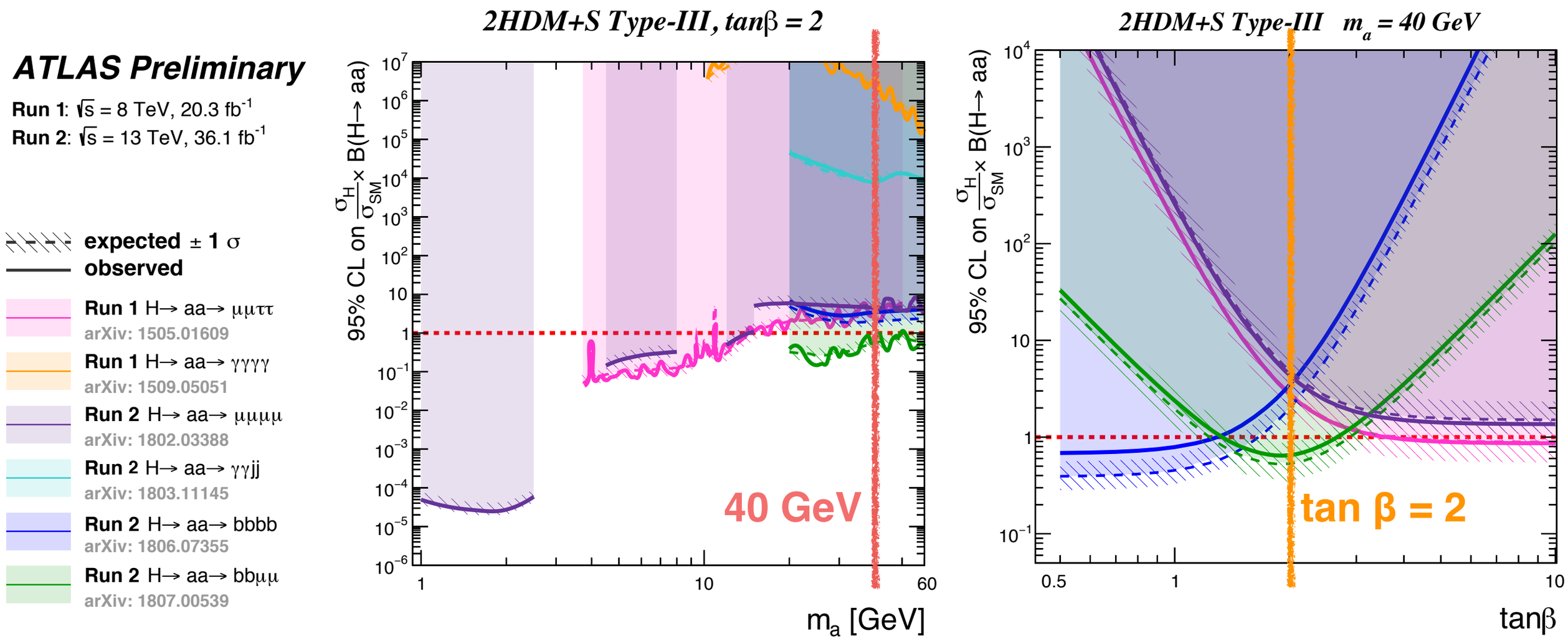
- Type I: all fermions couple to H_2
- Type II: MSSM-like, d_R and e_R couple to H_1, u_R to H_2
- **Type III:** lepton-specific, leptons/quarks couple to H_1/H_2 respectively
- **Type IV:** flipped, with u_R, e_R coupling to H_2 and d_R to H_1



ATLAS EXPERIMENT

ATL-PHYS-PUB-2018-045

Higgs to Light Scalars: Summary



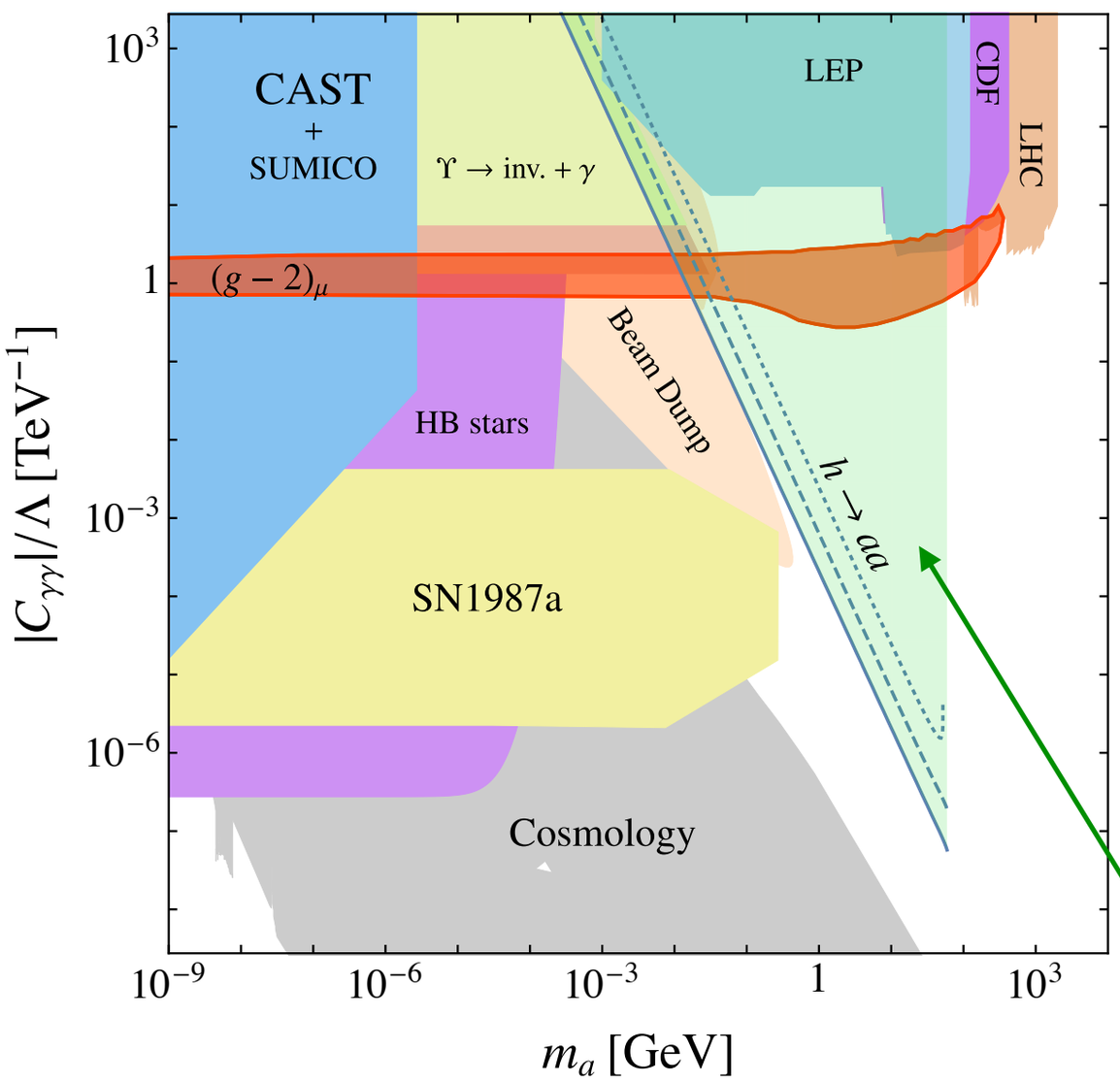
ATL-PHYS-PUB-2018-045

Analyses starting to probe interesting region
→ stay tuned for updates with full 13 TeV dataset

Axion-Like Particles (ALPs) at the LHC

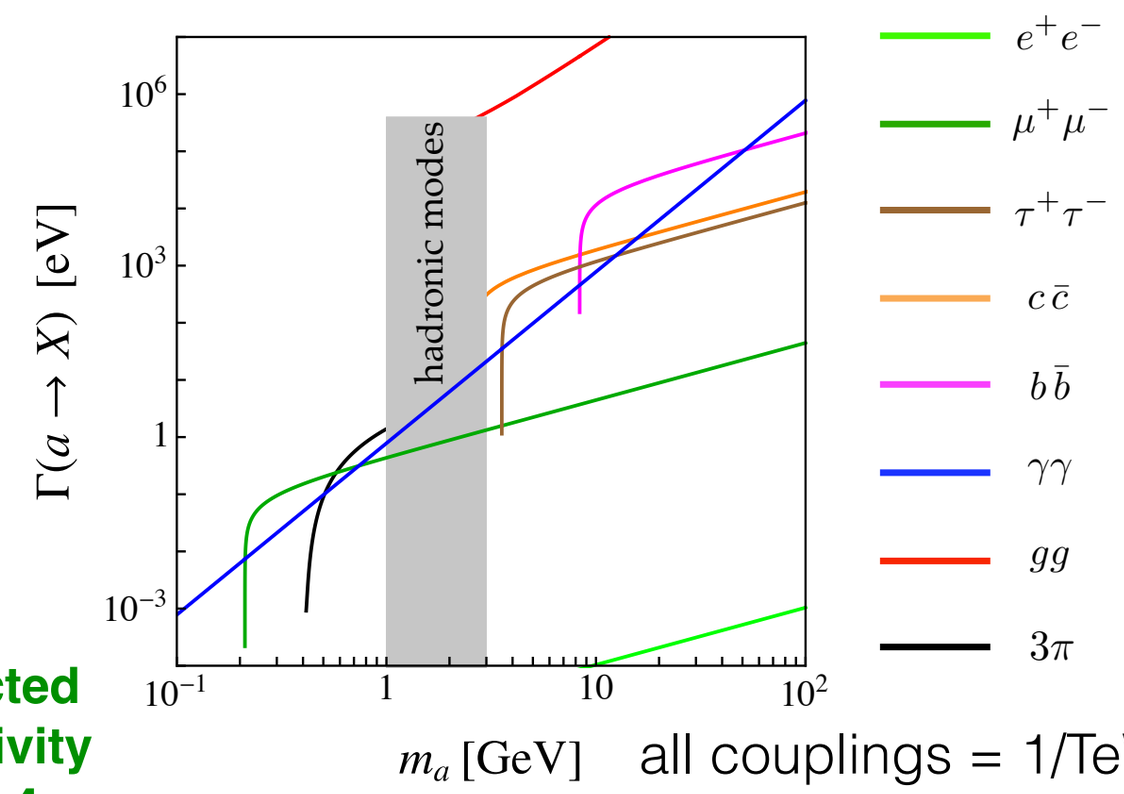
Couplings of an axion-like particle a to the SM can be described by a SM effective field theory

$$\frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C'_{ah}}{\Lambda^2}\,m_{a,0}^2\,a^2\phi^\dagger\phi \qquad\qquad e^2\,C_{\gamma\gamma}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$



Expected sensitivity of h→4γ with 300 fb^{-1}

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

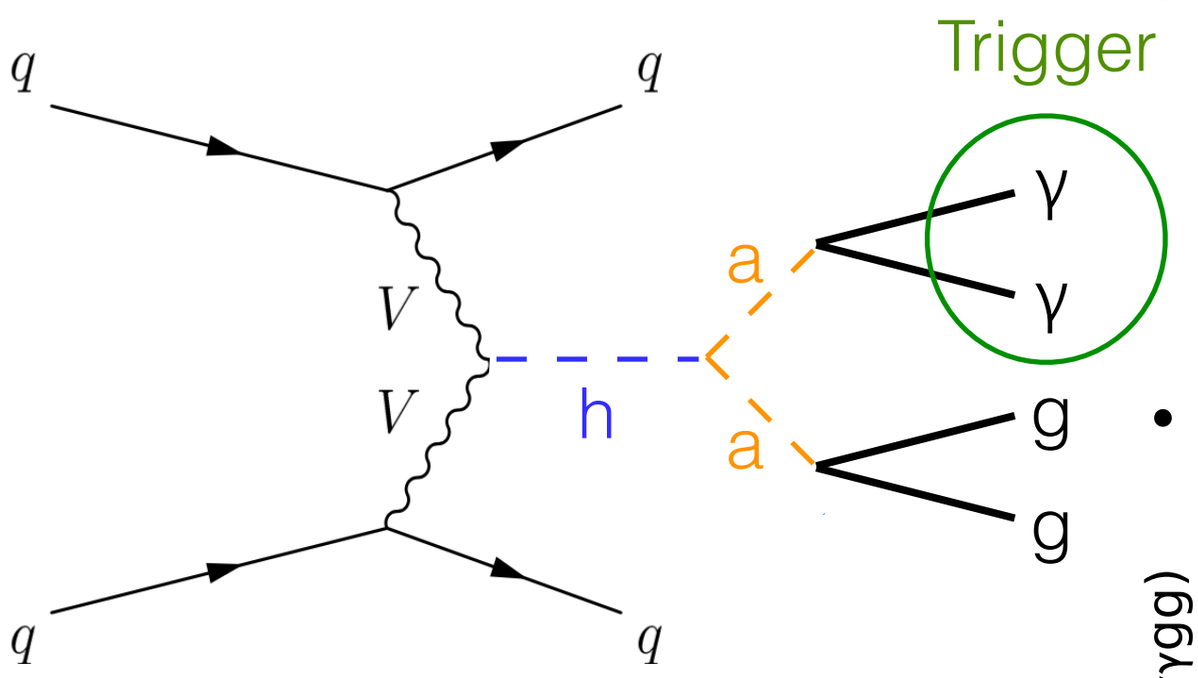


all couplings = 1/TeV

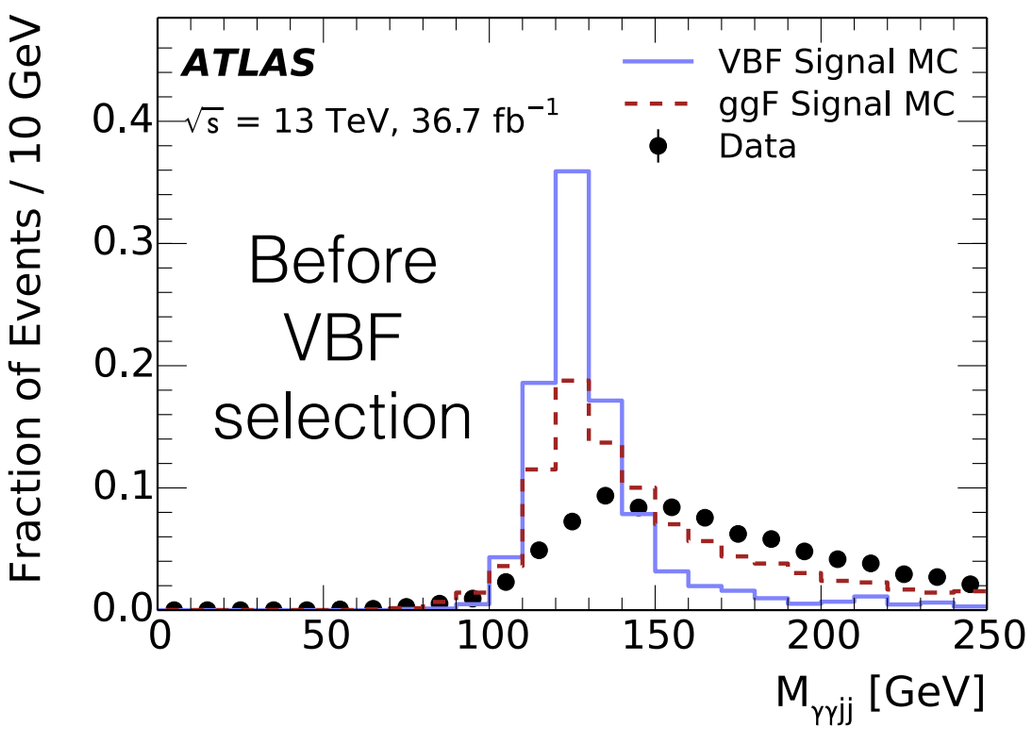
[Bauer, Neubert, Thamm: 1704.08207, 1708.00443, 1808.10323 (+Heiles)]

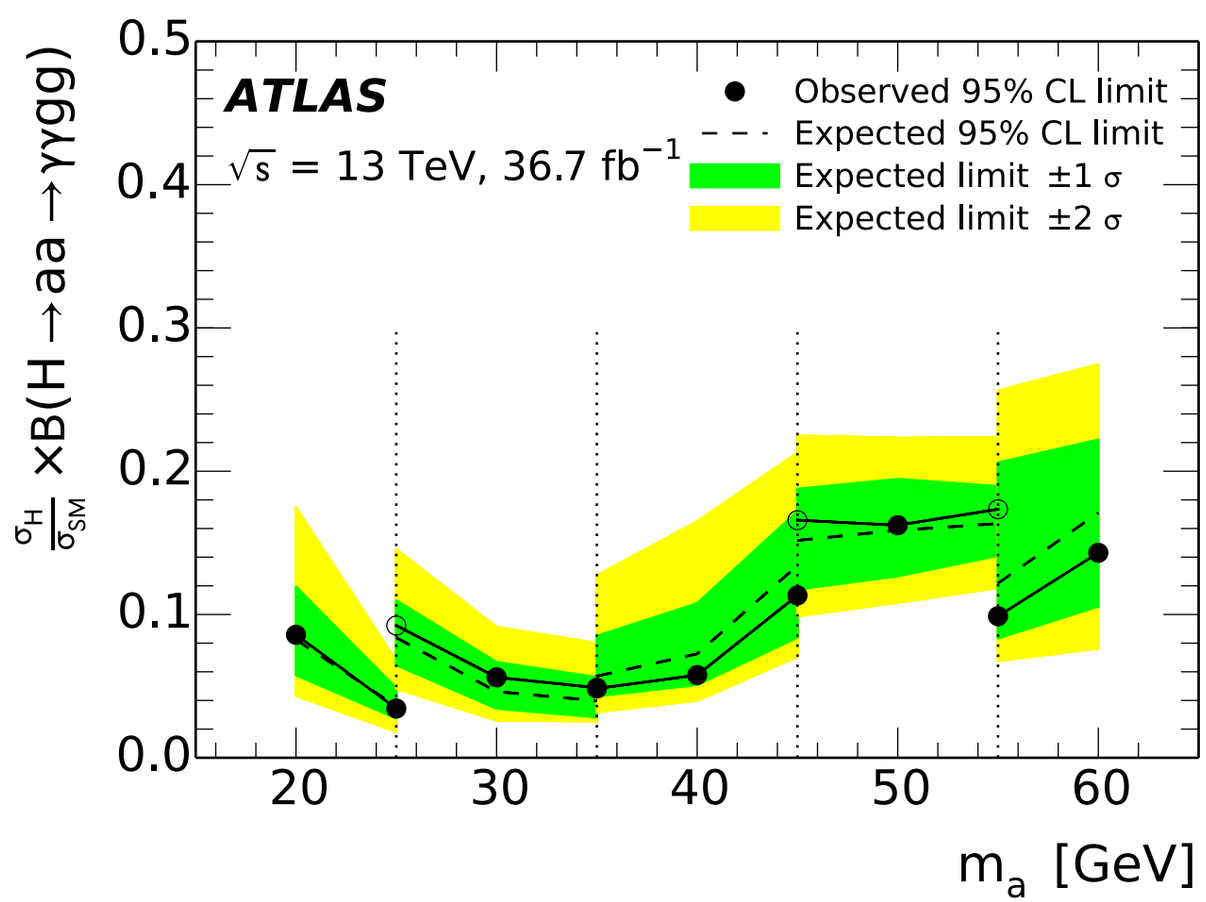
ALP-like Signatures: h→2a→2γ2j

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



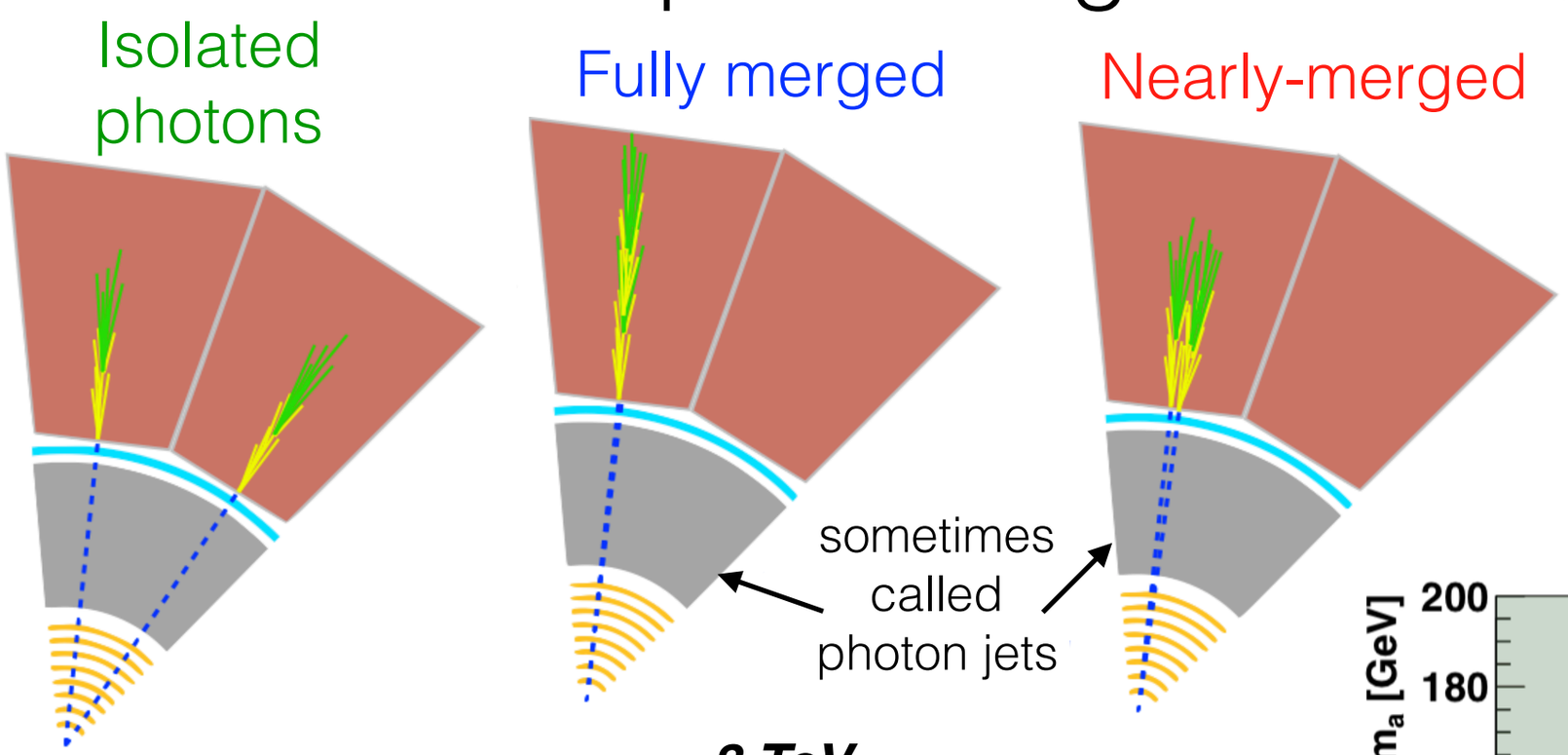
- Strategy
  - VBF selection: 2 jets with large rapidity gap $\Delta\eta(j_1,j_2)$ & large mass m_{jj}
  - Select 2 photons and 2 more jets with $m_{\gamma\gamma} \sim m_{jj}$
- Main backgrounds γγ+multiple jets

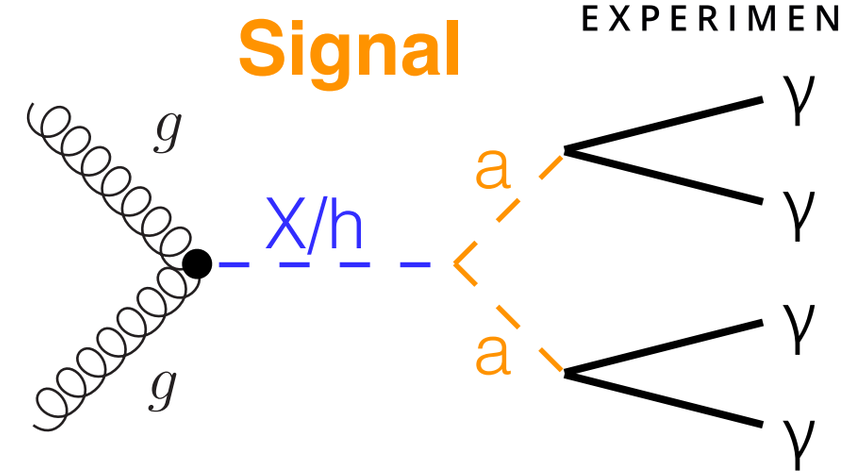




PLB 782 (2018) 750 arXiv:1803.11145

Multi-photon Signatures: h/X→2a→4γ





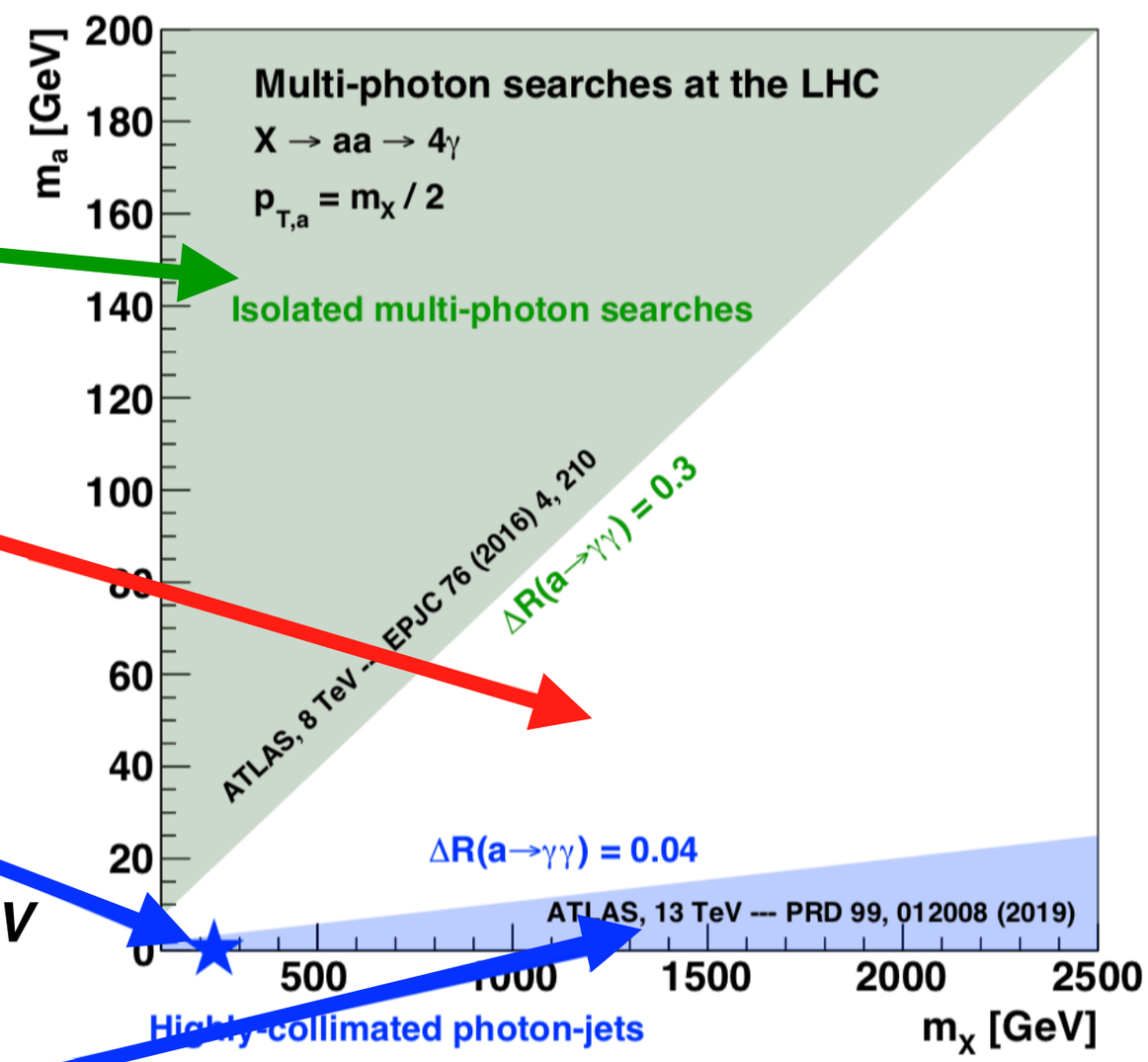
8 TeV
arXiv: 1509.05051
EPJC 76 (2016) 4, 210

Several searches targeting different regimes made possible due to trigger improvements

Not covered

7 TeV, for m_X = 125 GeV
ATLAS-CONF-2012-079

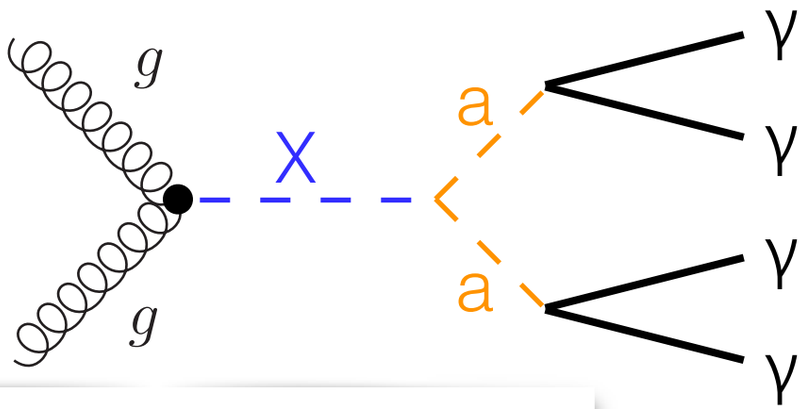
13 TeV, for m_X > 200 GeV
arXiv: 1808.10515
PRD 99, 012008 (2019)

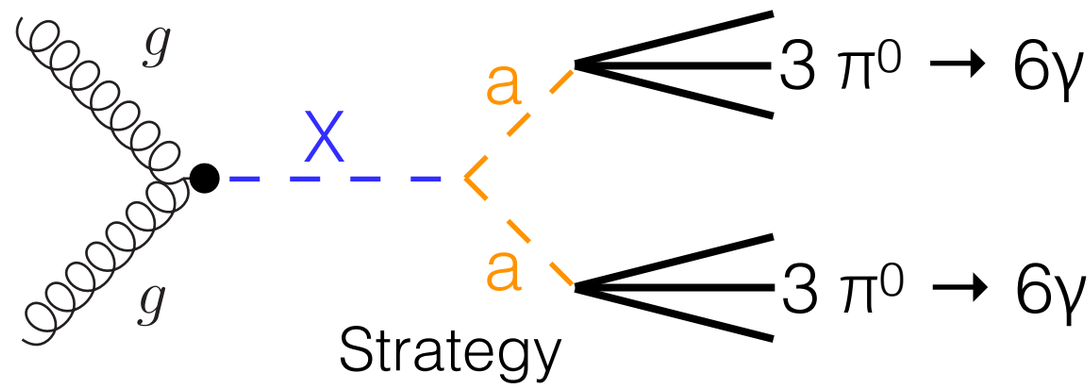


From J. Beacham

Multi-photon Signatures: X→2a→4γ

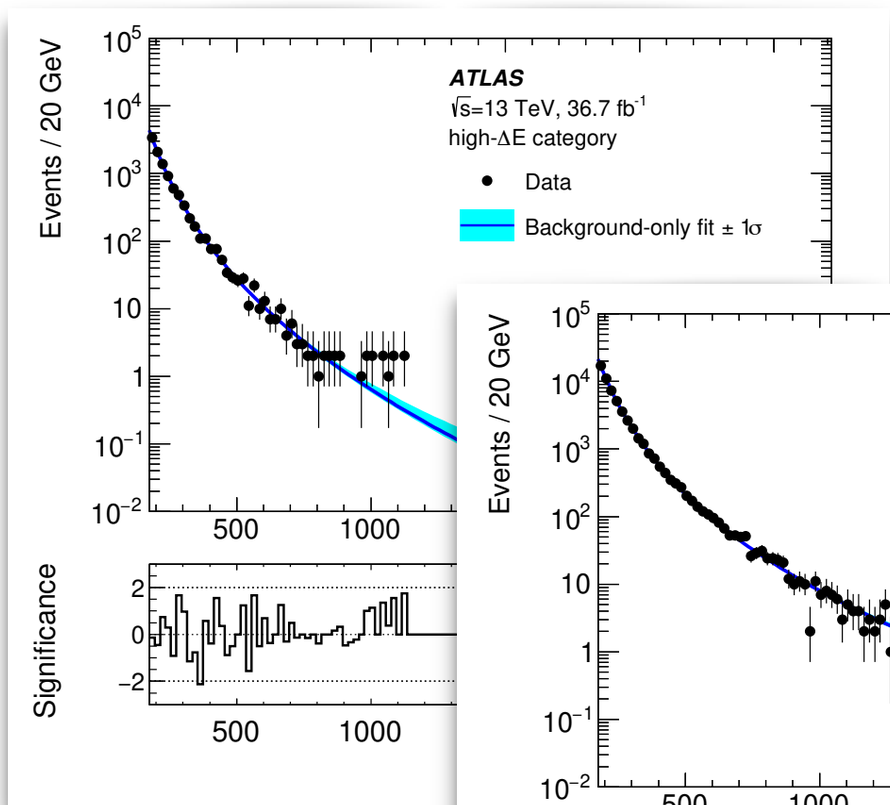
Signal target $0.1 \lesssim m_a \lesssim 10$ GeV for $200 \lesssim m_X \lesssim 2000$ GeV

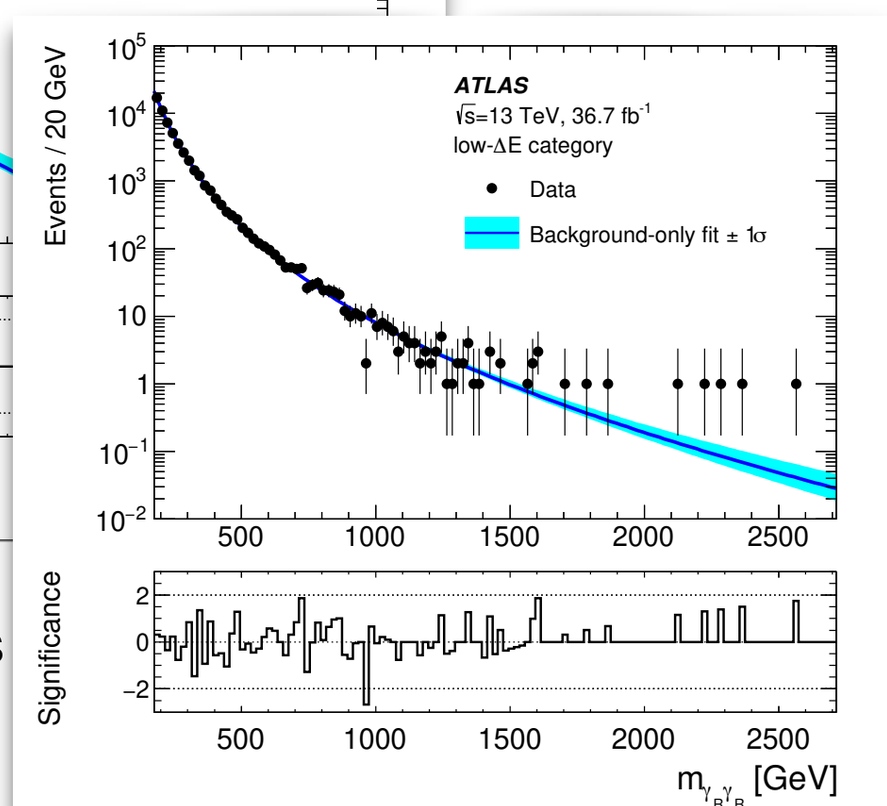


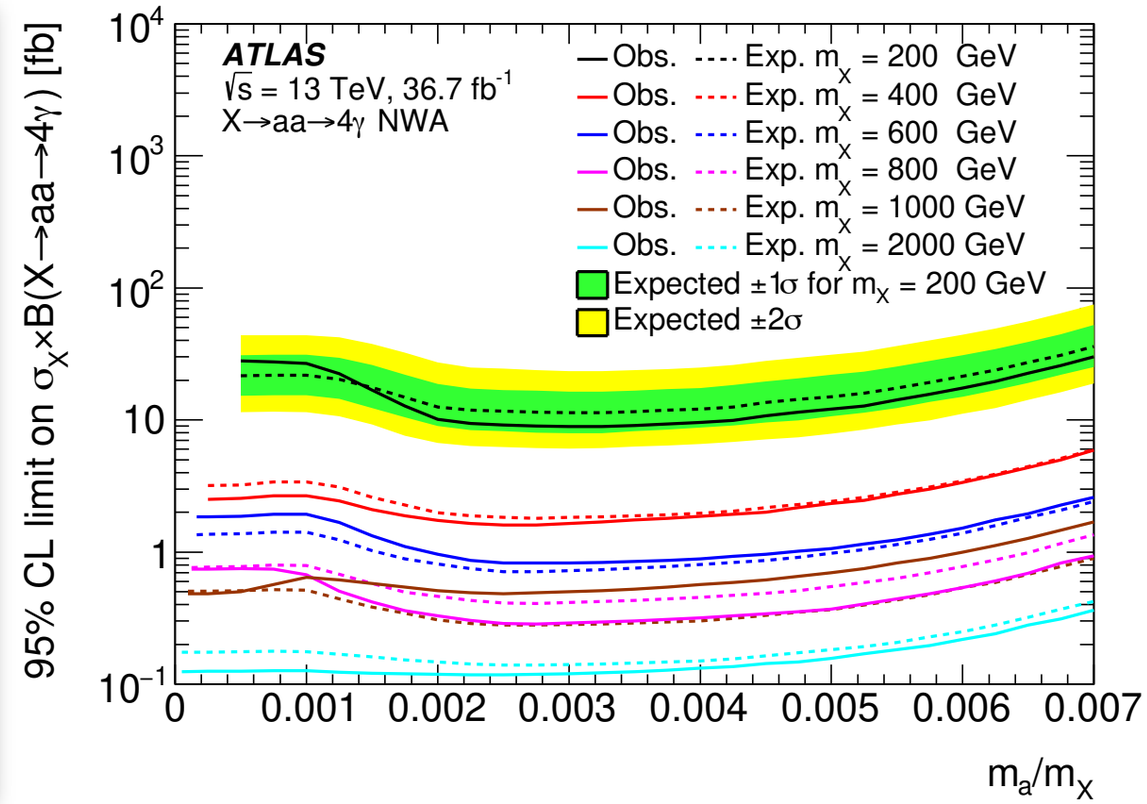


Strategy

- Focus on fully collimated regime multiple photons reconstructed as one photon
- Resonance search in diphoton reconstructed mass $m_{\gamma\gamma}$



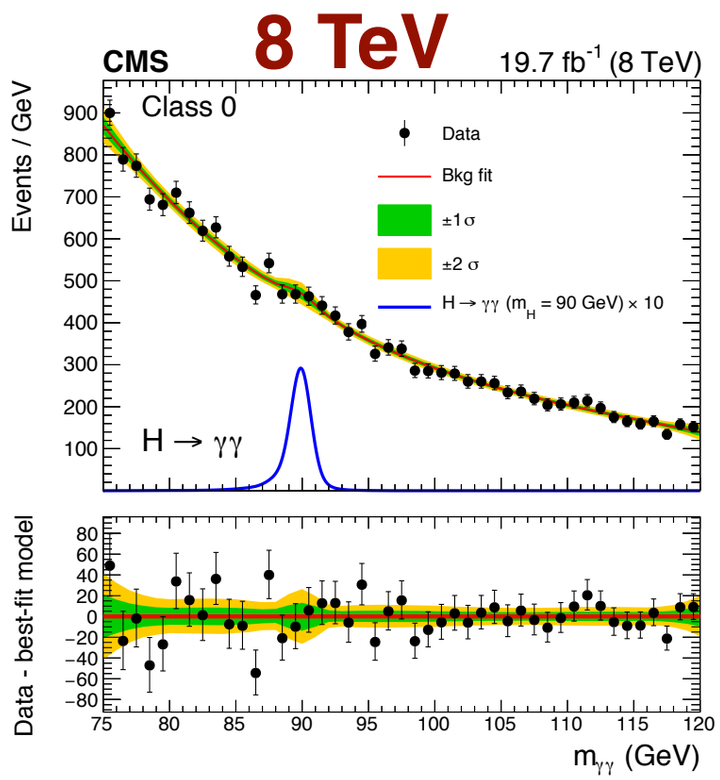


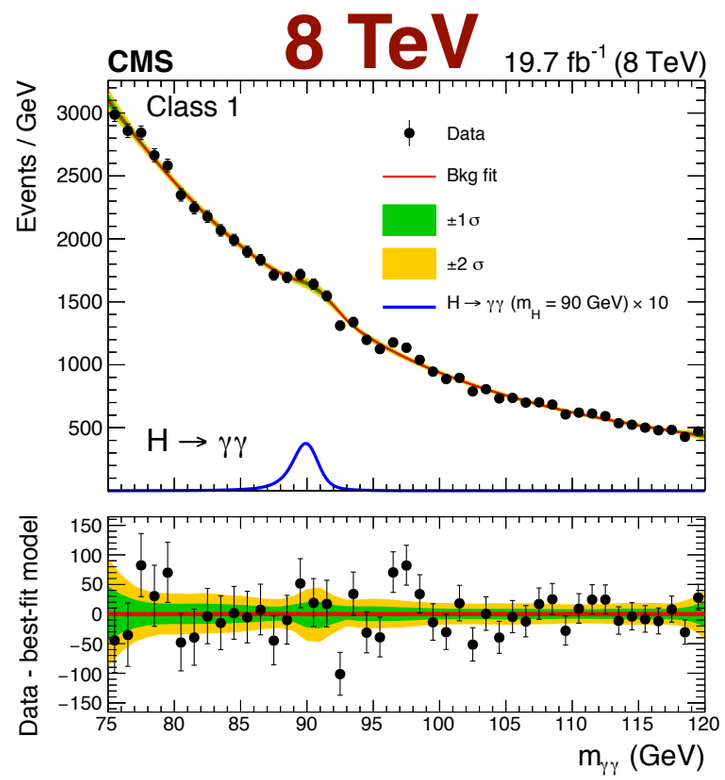


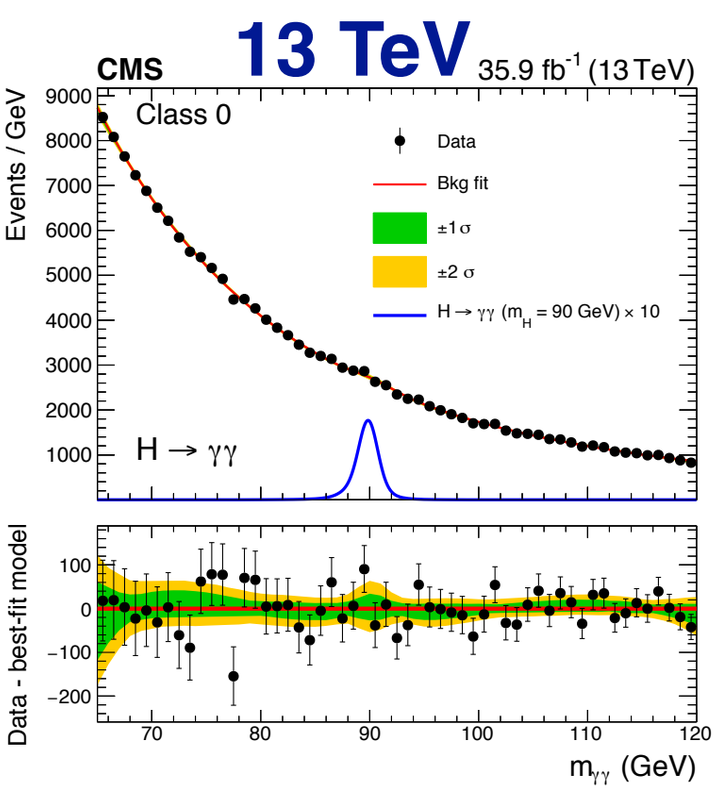
Main backgrounds from 2γ, γj, jj
j→hadronic jet

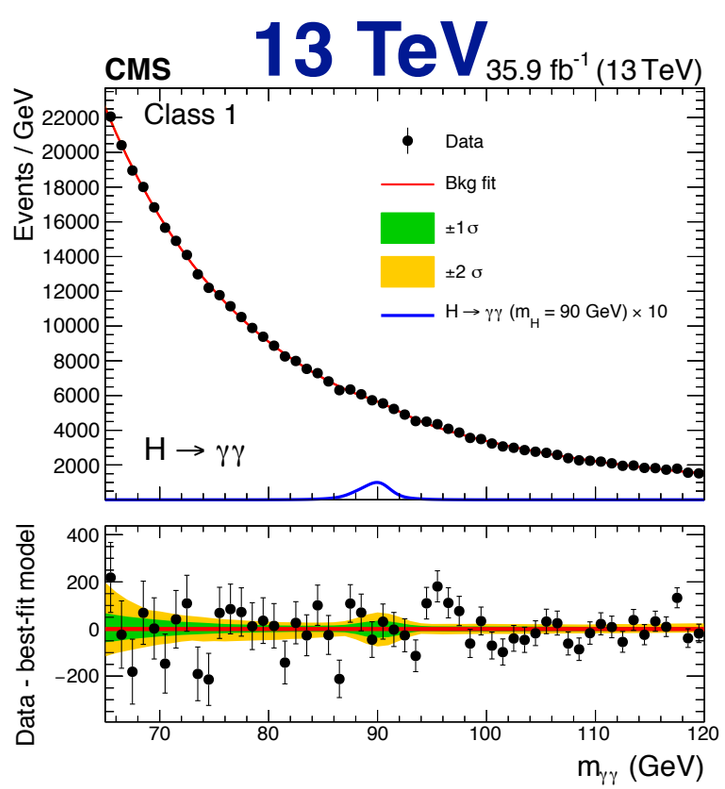
arXiv: 1808.10515, PRD 99, 012008 (2019)

Direct searches: a→2γ



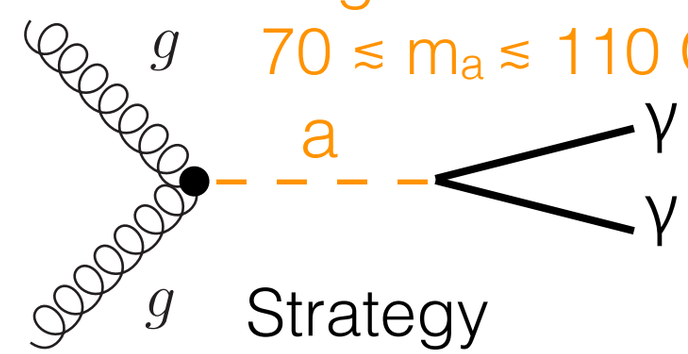






Signal

target
$70 \lesssim m_a \lesssim 110$ GeV



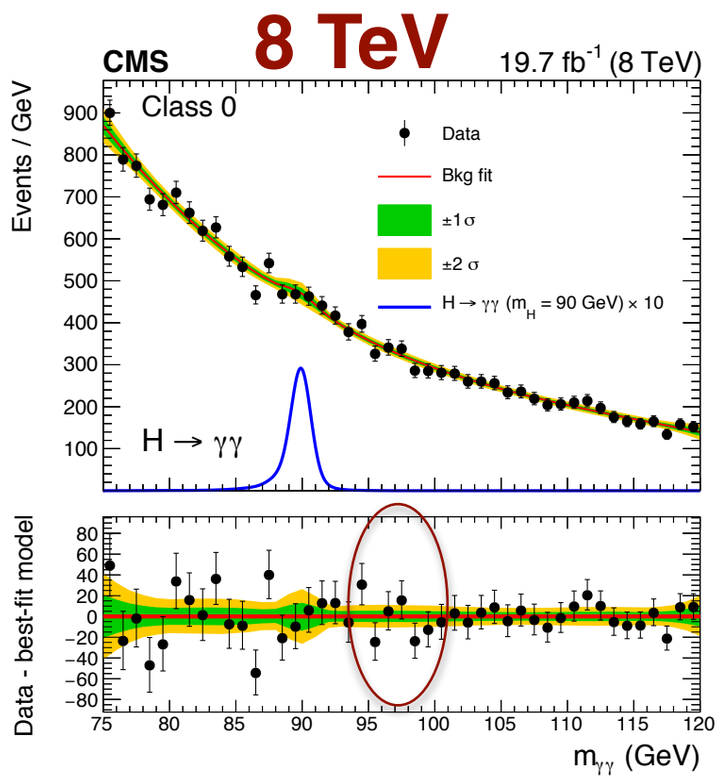
Strategy

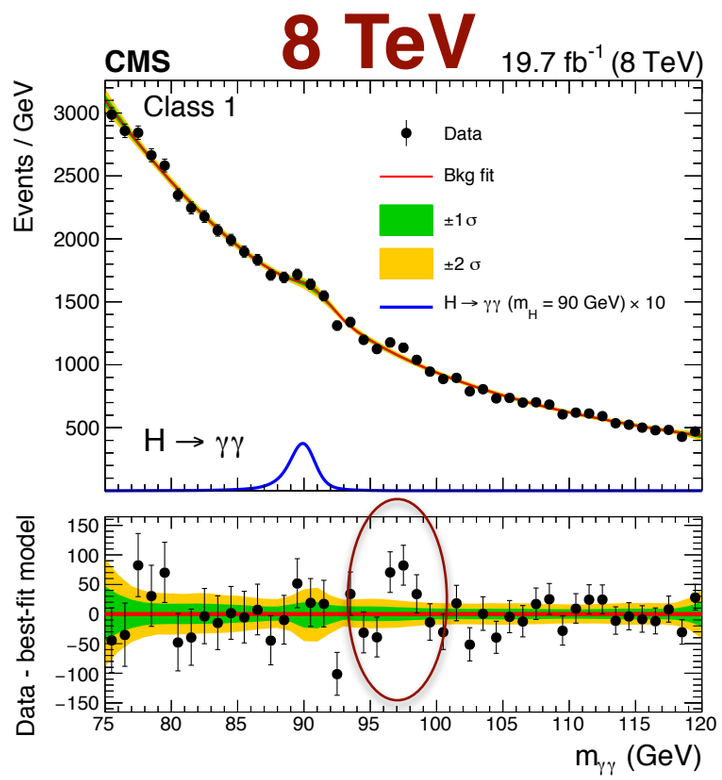
- Search for a→2γ resonance in diphoton reconstructed mass $m_{\gamma\gamma}$
- Categorize events according to expected sensitivity - use kinematic properties and mass resolution of γγ-system & γ ID variables

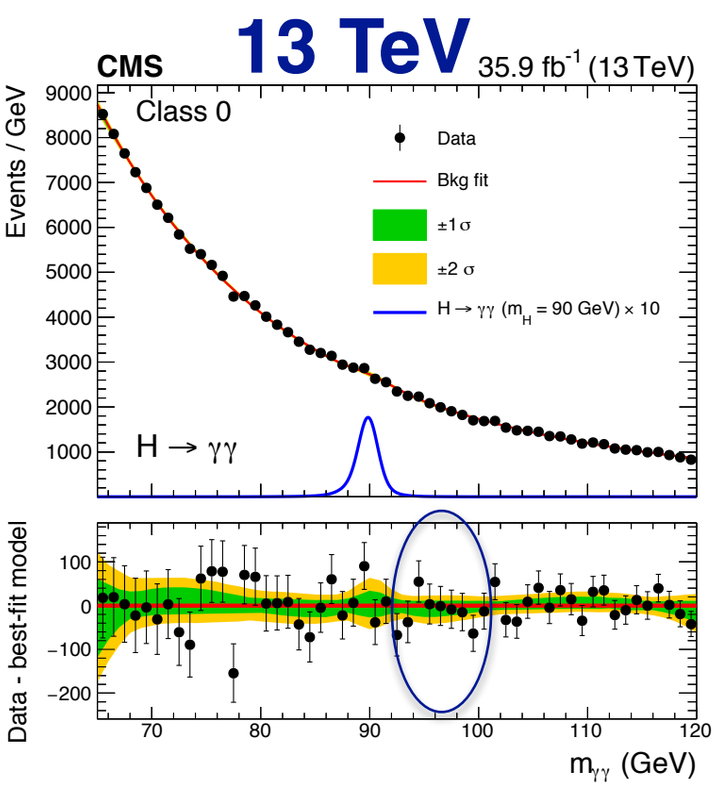
Main backgrounds from 2γ, γj, jj
j→hadronic jet

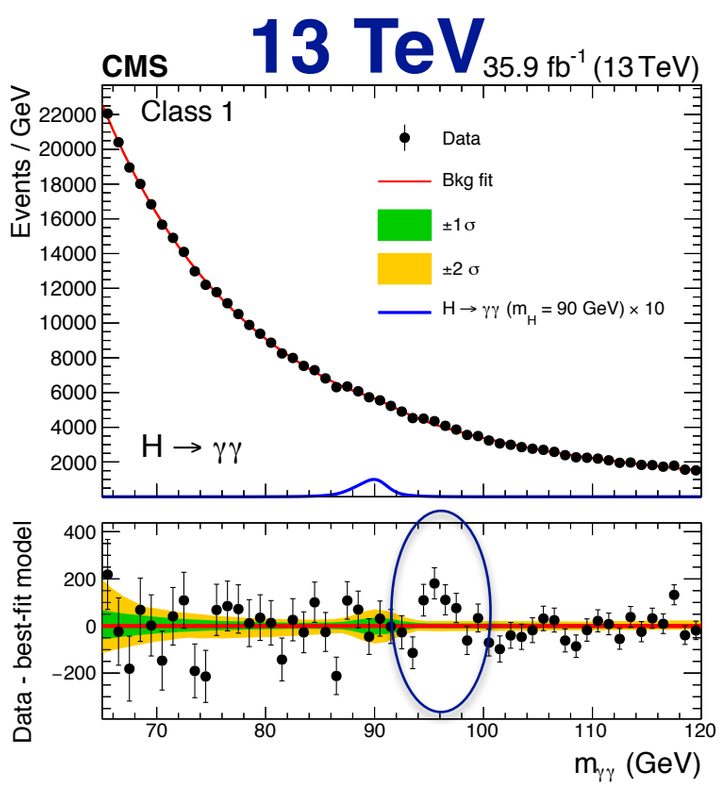
 arXiv: 1811.08459

Direct searches: a→2γ









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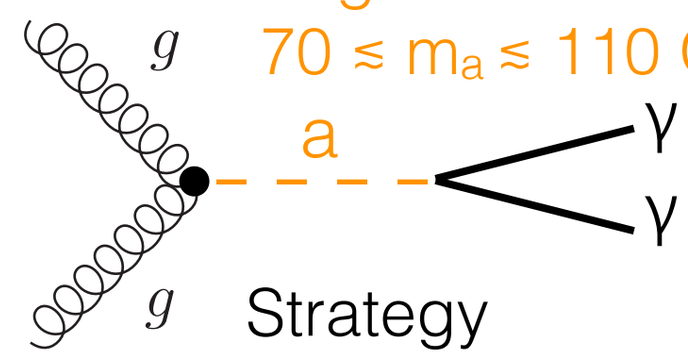

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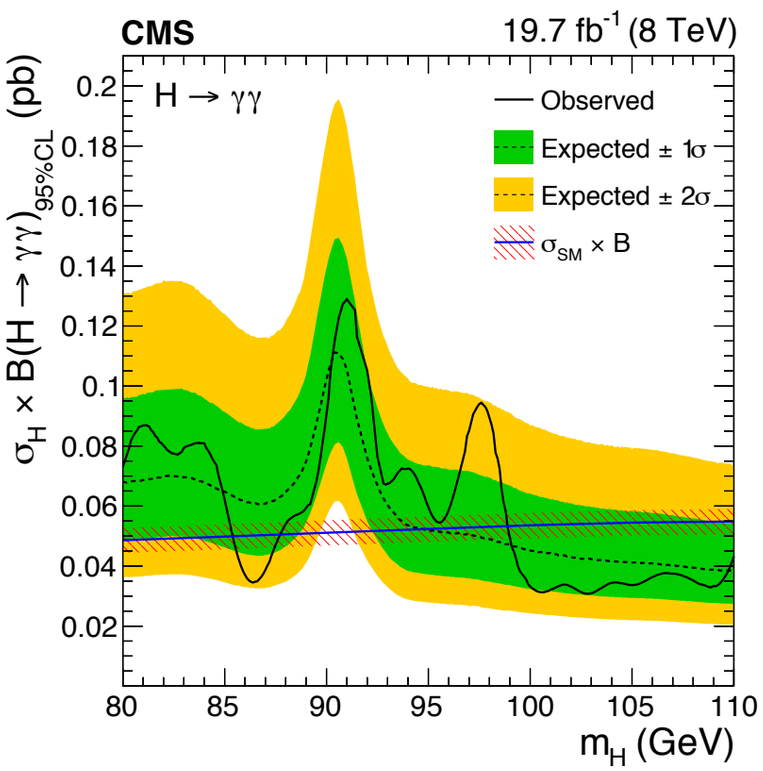
Slight excess observed maximal around $m_{\gamma\gamma}$ ~ 95.3 GeV with 2.8 (1.3) σ of local (global) significance

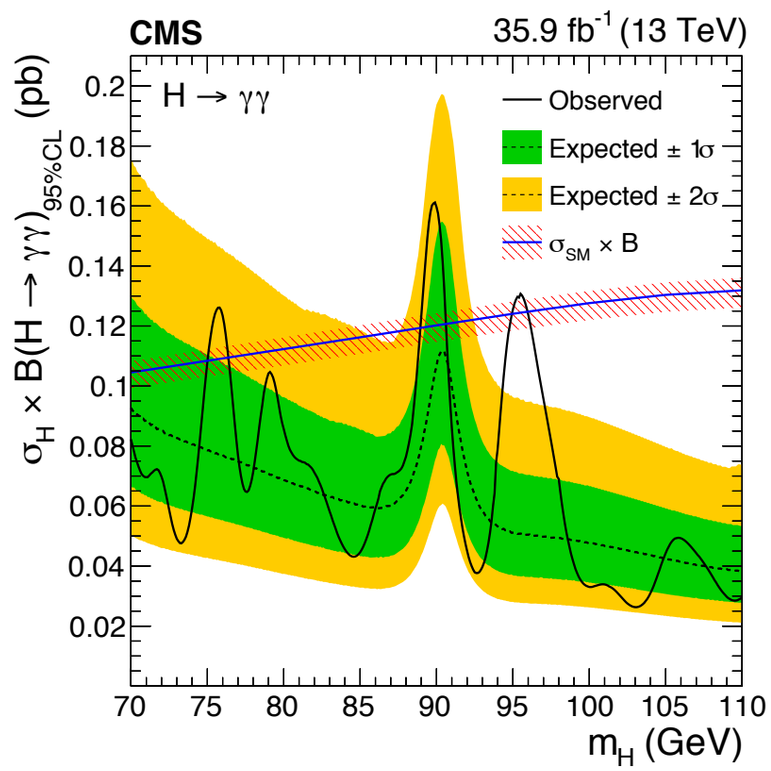
arXiv: 1811.08459

Direct searches: a→2γ

8 TeV



13 TeV



arXiv: 1811.08459

Signal

target
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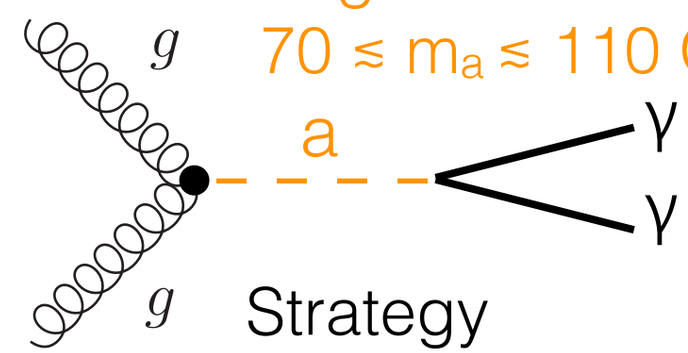

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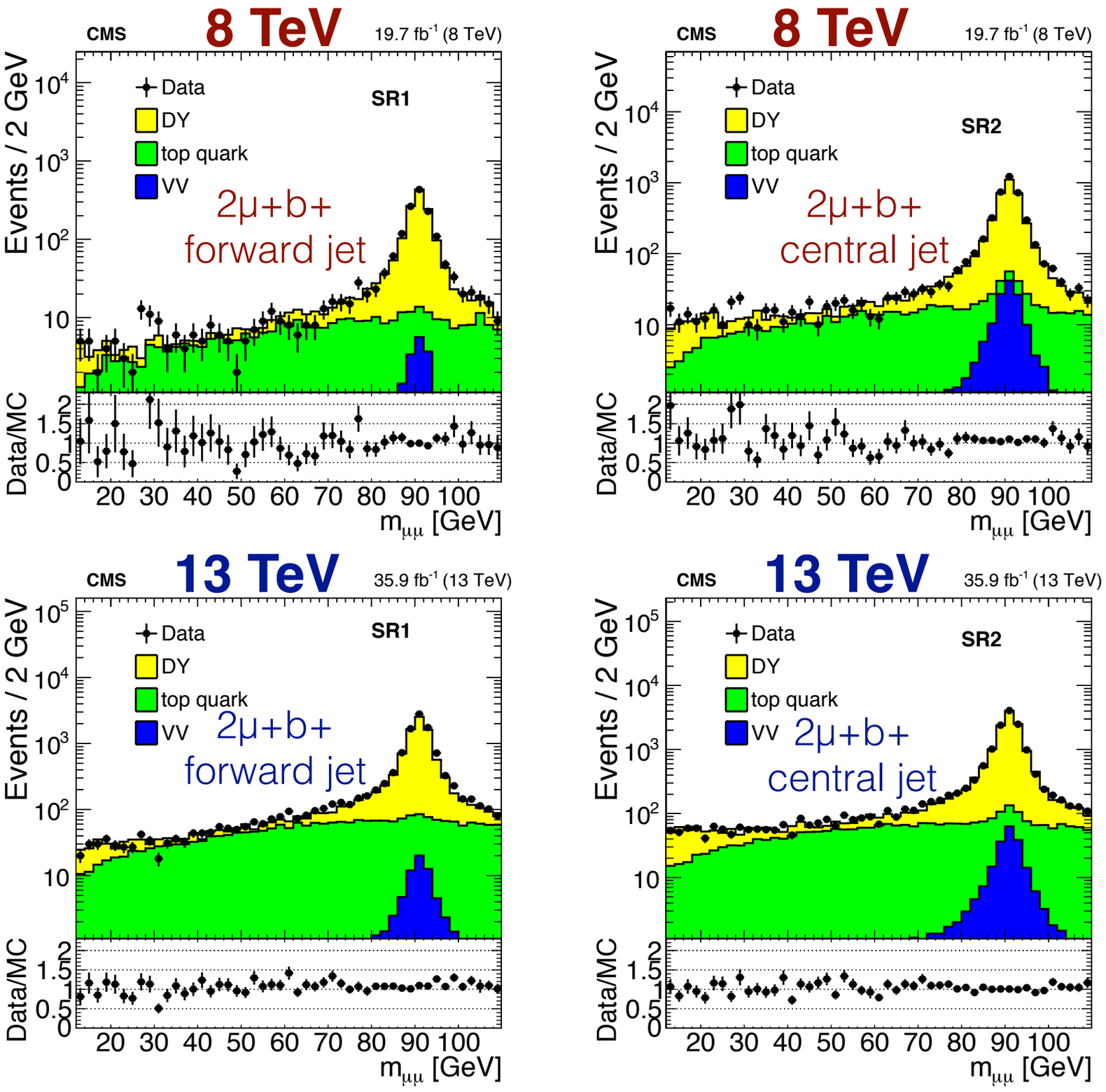
Direct searches: a→2μ + b-jets



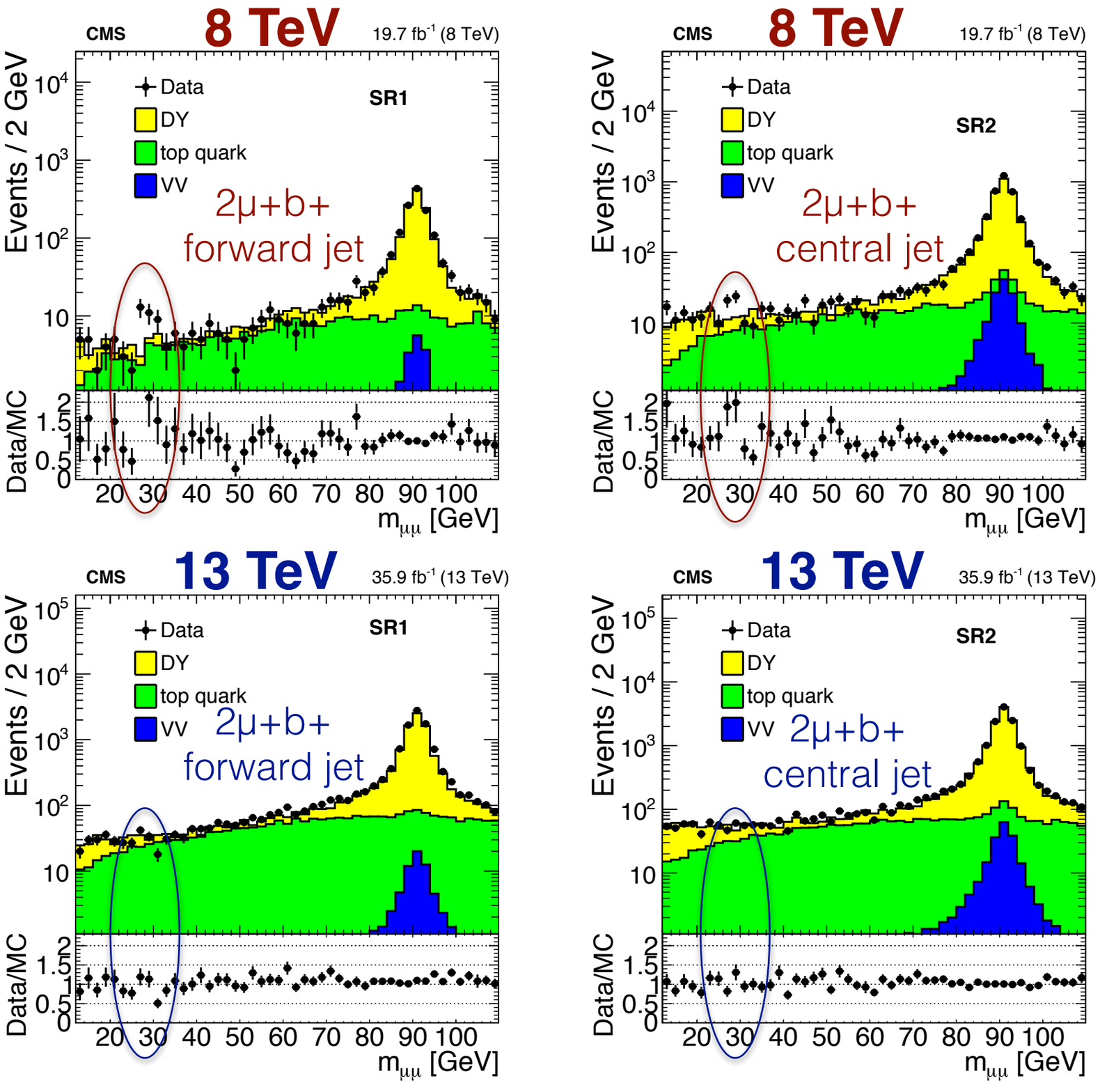
Strategy

- Search for a→2μ in association with b-jet and an additional jet
- Two samples based on additional jet
  - Forward $|\eta_j| > 2.4$
  - Central $|\eta_j| < 2.4$

Main backgrounds from low mass Drell-Yan and top quark pairs

JHEP 11 (2018) 161, arXiv: 1808.01890

Direct searches: a→2μ + b-jets



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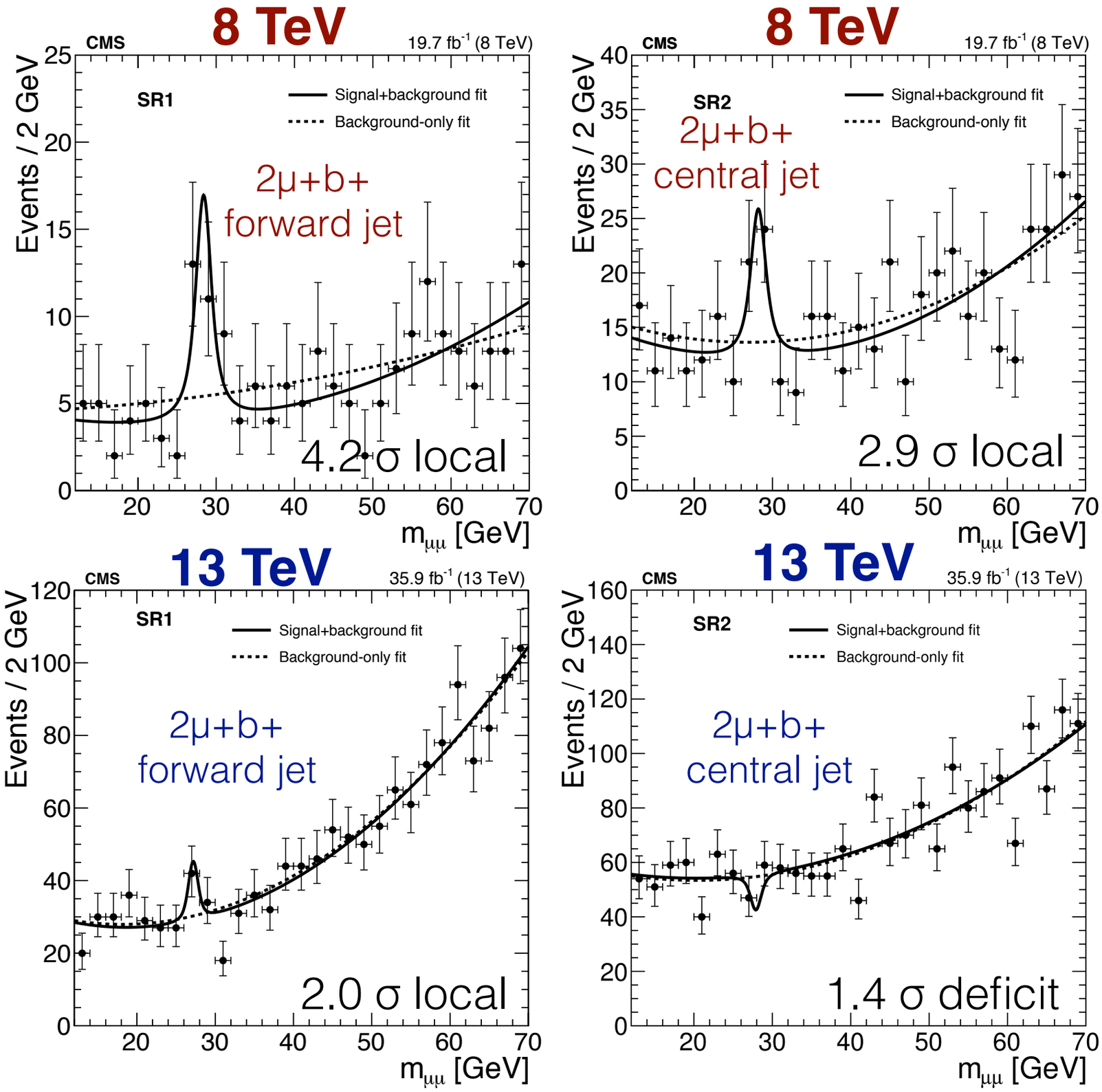
  - Central $|\eta_j| < 2.4$

Main backgrounds from low mass Drell-Yan and top quark pairs

Slight excess observed around $m_{\mu\mu} \sim 28$ GeV in 8 TeV data, especially in 2μ+b+ forward jet sample

JHEP 11 (2018) 161, arXiv: 1808.01890

Direct searches: a→2μ + b-jets



- Strategy
  - Search for a→2μ in association with b-jet and an additional jet
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- Slight excess observed around $m_{\mu\mu} \sim 28$ GeV in 8 TeV data, especially in 2μ+b+ forward jet sample

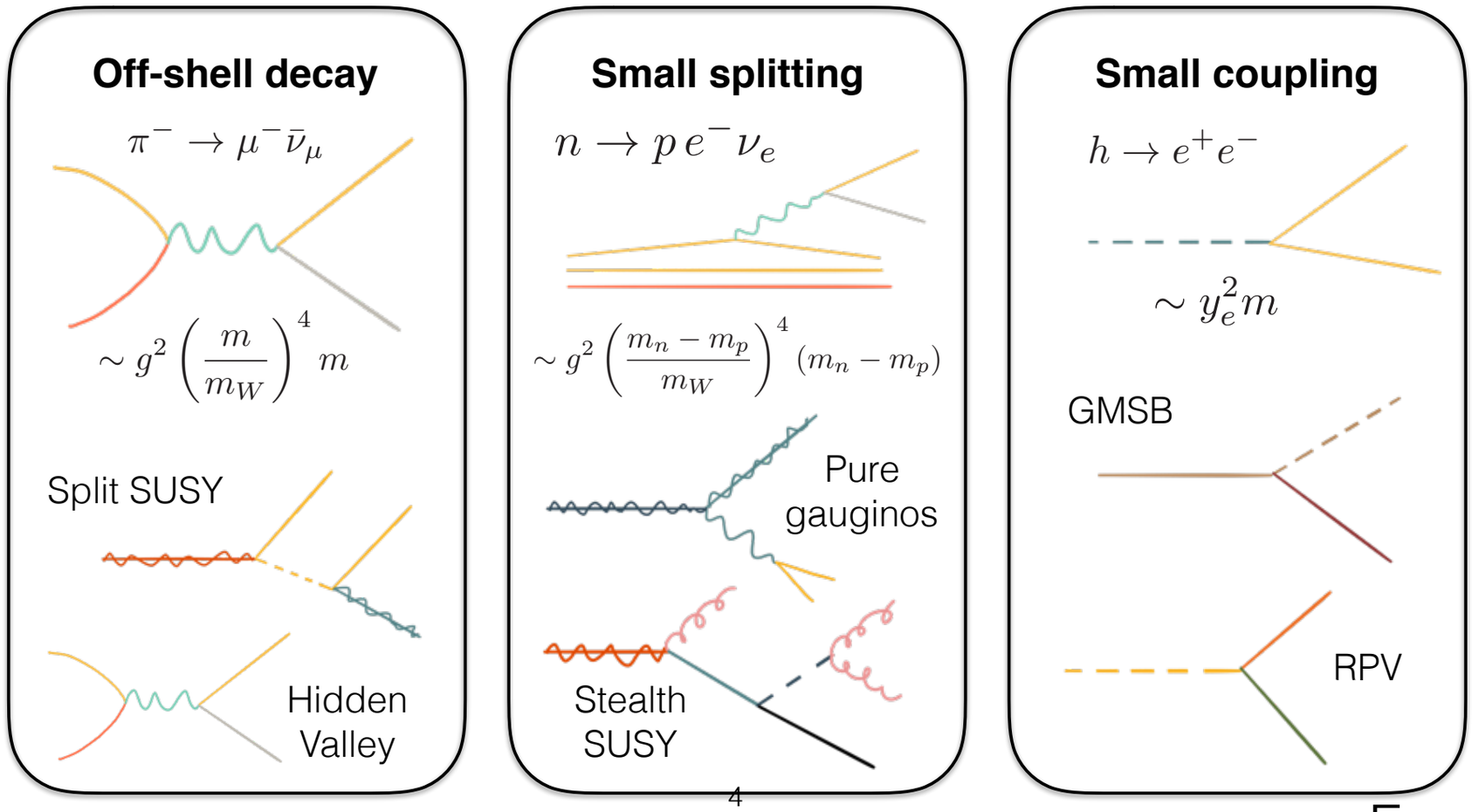
JHEP 11 (2018) 161, arXiv: 1808.01890

Motivating Long Lived Particles

LLPs are generic in SM & BSM

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

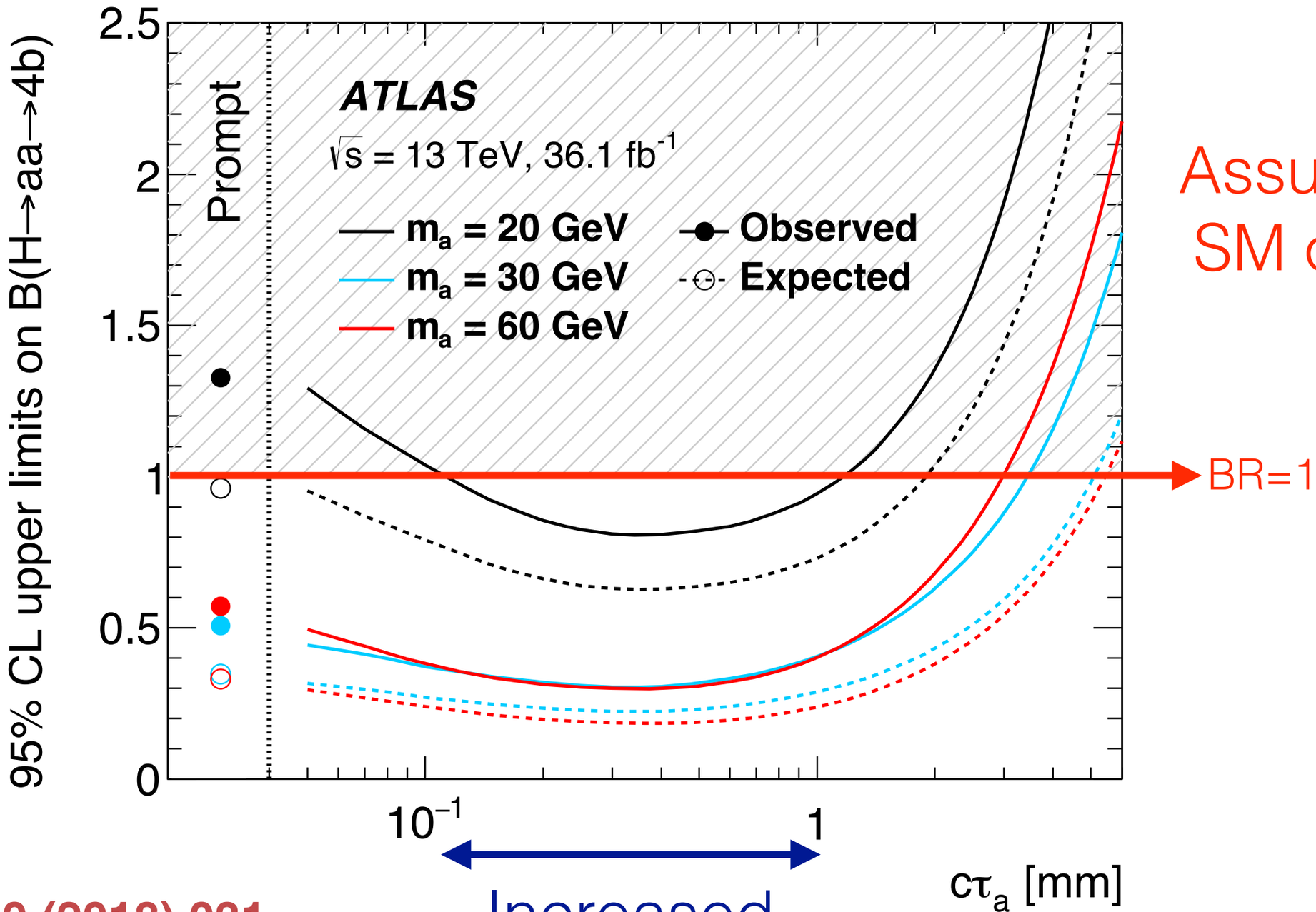
E.g. small couplings, hierarchy of scales



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]

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

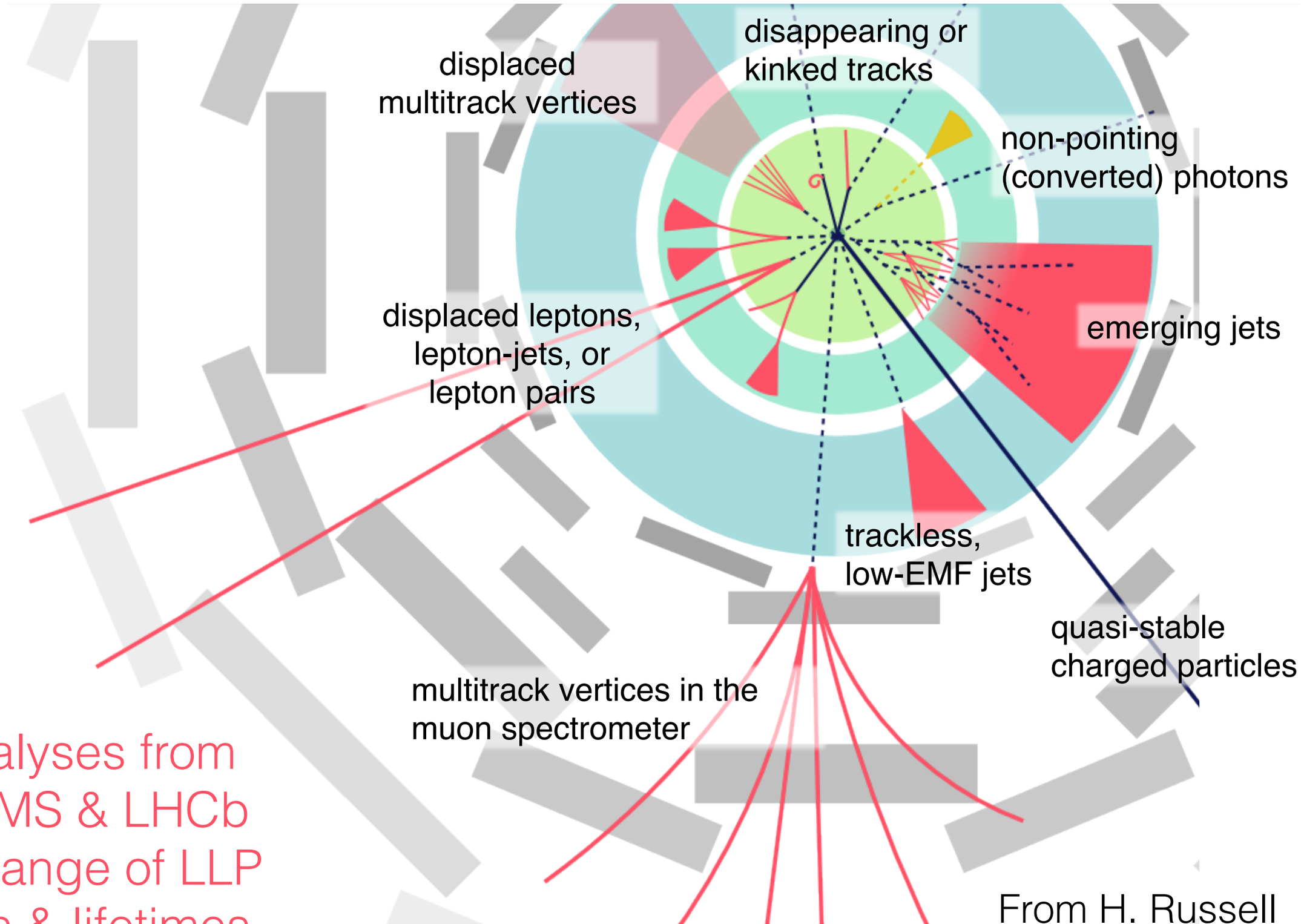


Assume SM σ_{VH}

JHEP 10 (2018) 031
arXiv:1806.07355

Increased b-jet acceptance

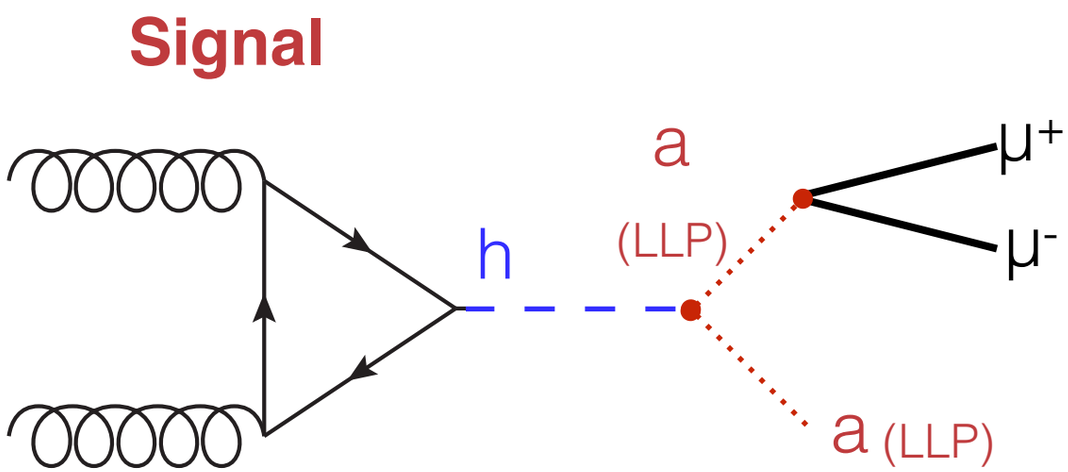
LLP Experimental Signatures



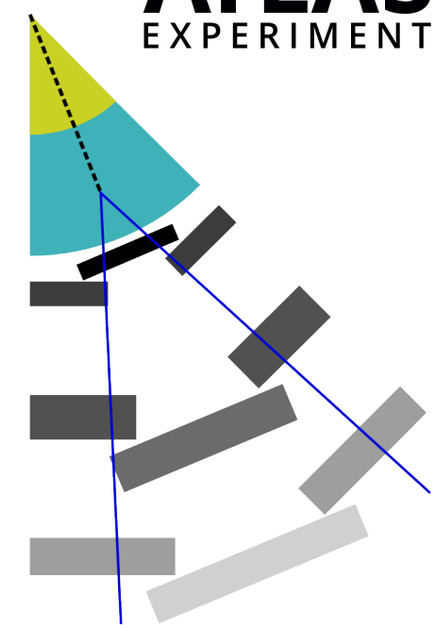
Many analyses from ATLAS, CMS & LHCb targeting range of LLP signatures & lifetimes

From H. Russell

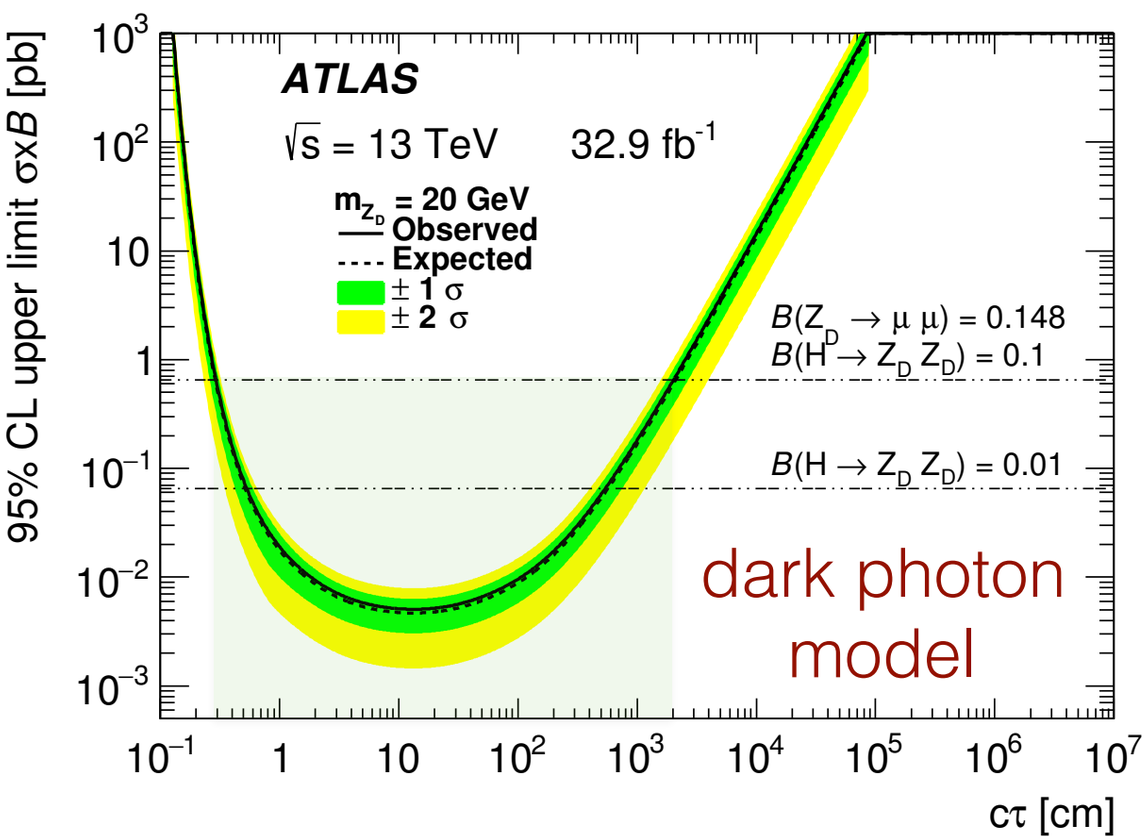
Long Lived Decays: h → displaced muons

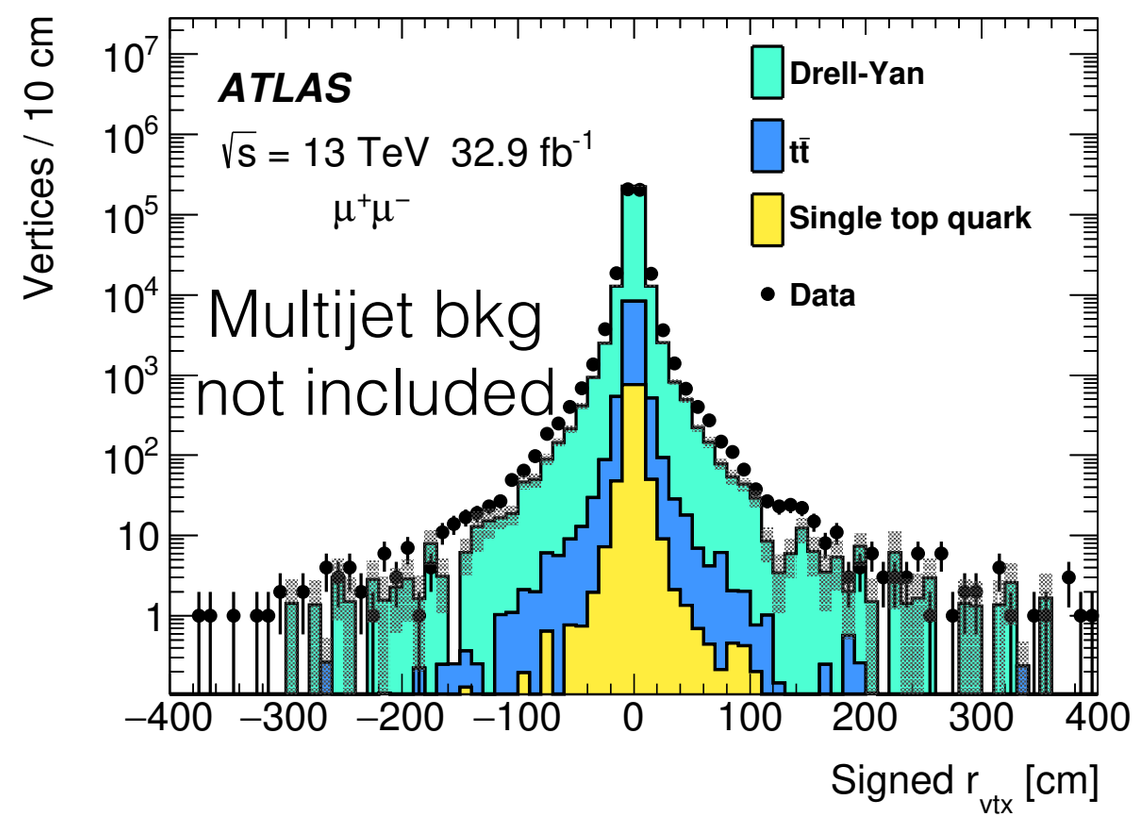


- Strategy
  - Search for displaced vertices (DV) in the muon system
  - No tracks in inner detector
- Low backgrounds



In ATLAS can detect dimuon DVs in large decay volume

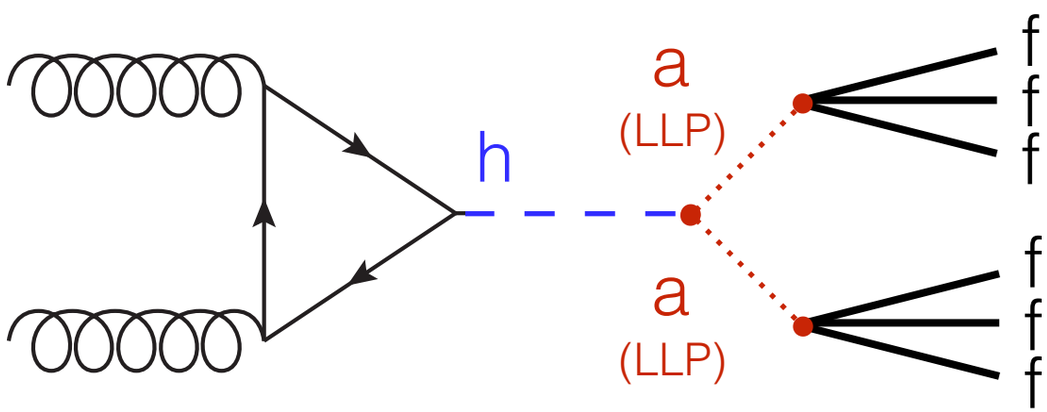




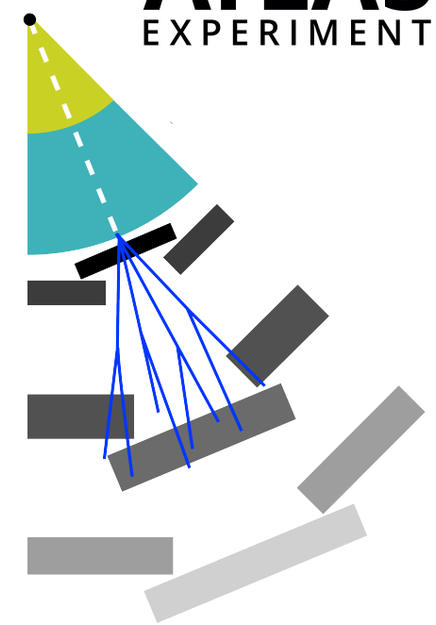
Phys. Rev. D 99, 012001 (2019) arXiv:1808.03057

LL Decays: h → displaced jets in muon system

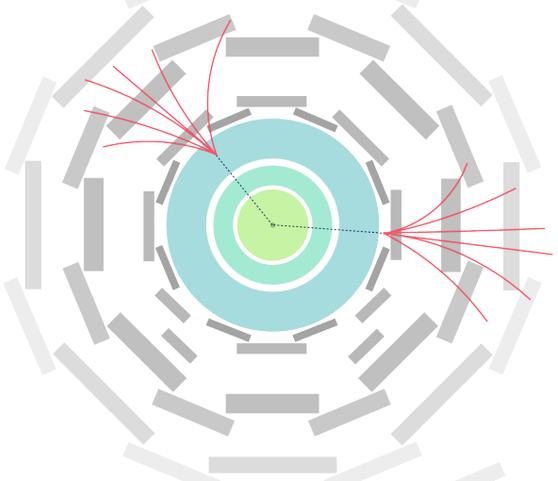
Signal



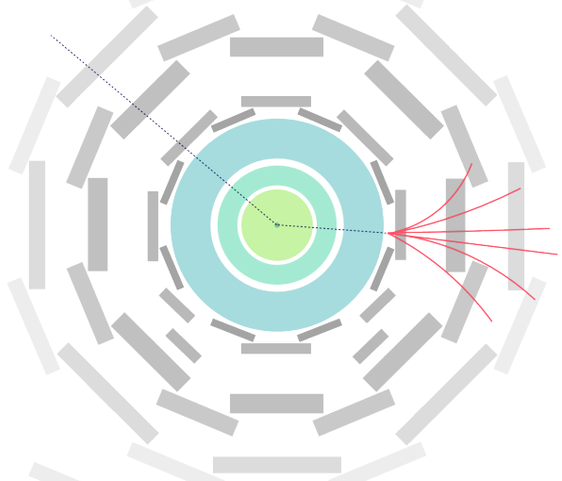
- Strategy
  - Search for multitrack displaced vertices in muon system
  - No tracks in inner detector nor calorimeter signals



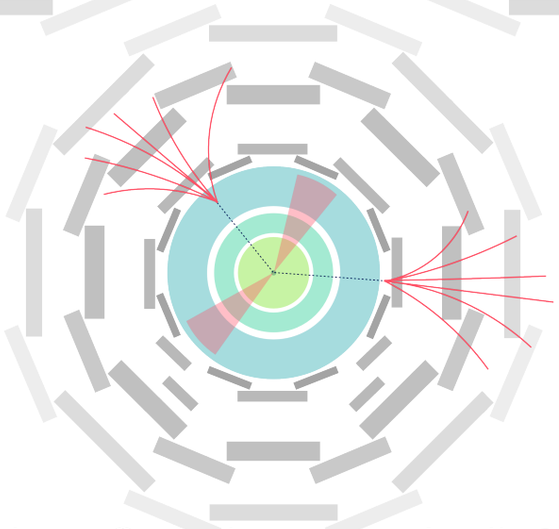
2 DVs

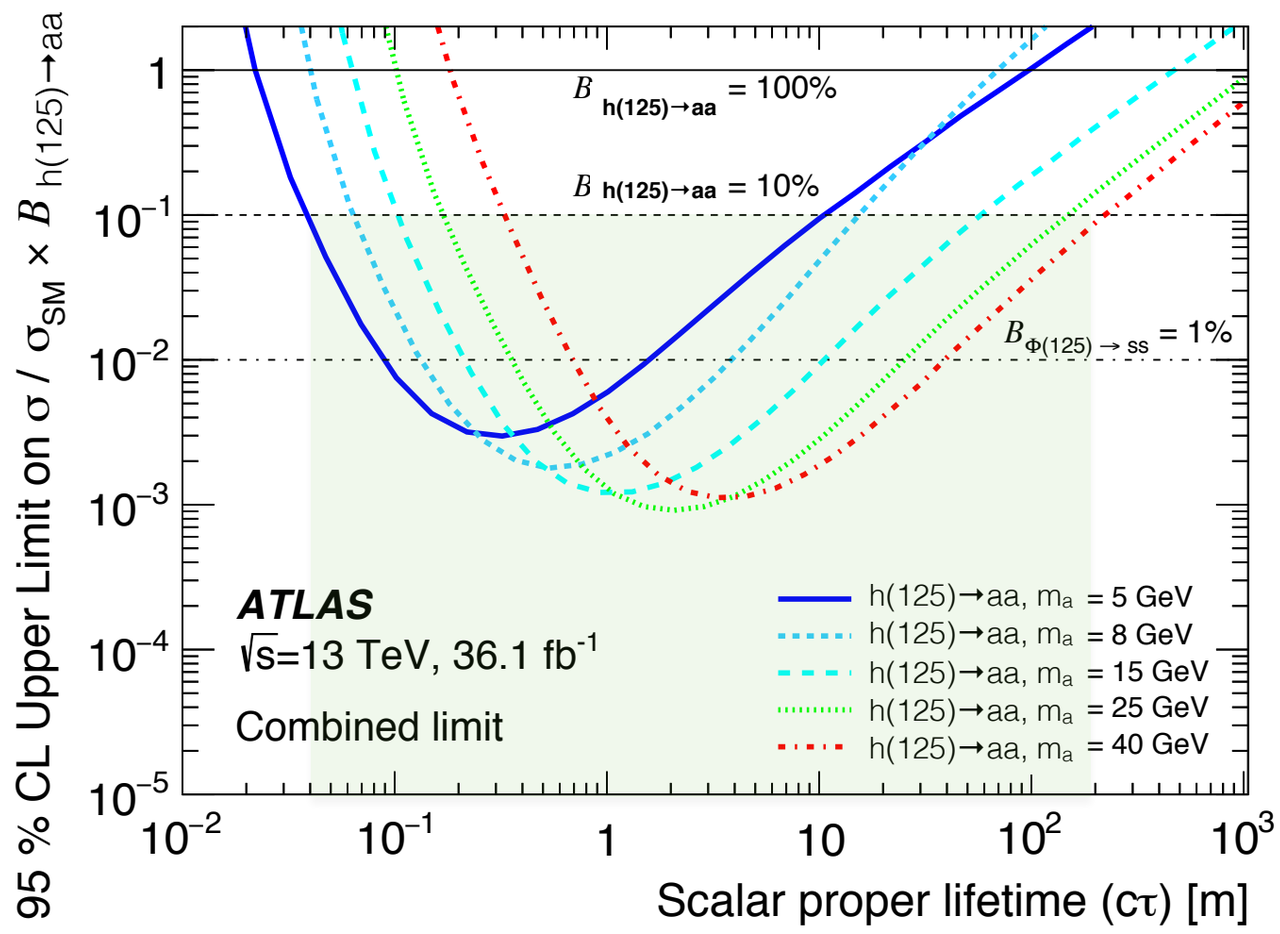


1 DV + MET



2 DVs + 2 prompt jets

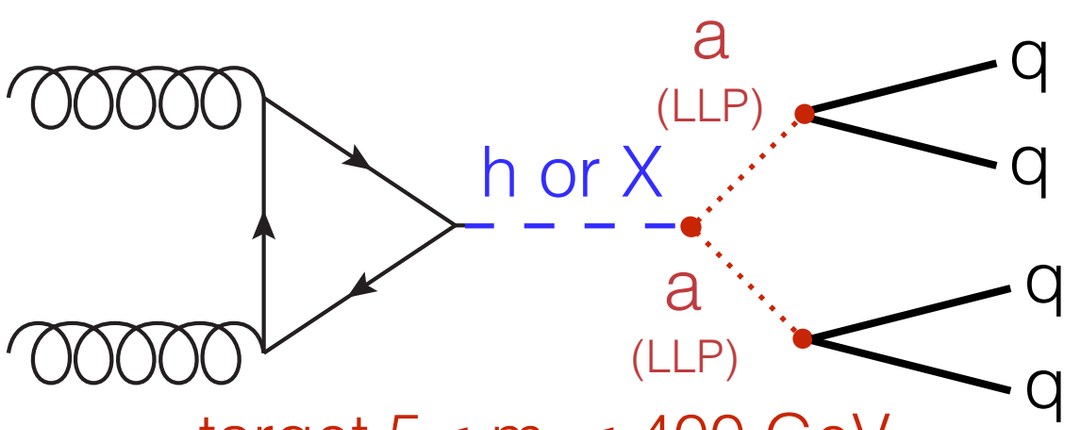




PRD 99, 052005 (2019), arXiv:1811.07370

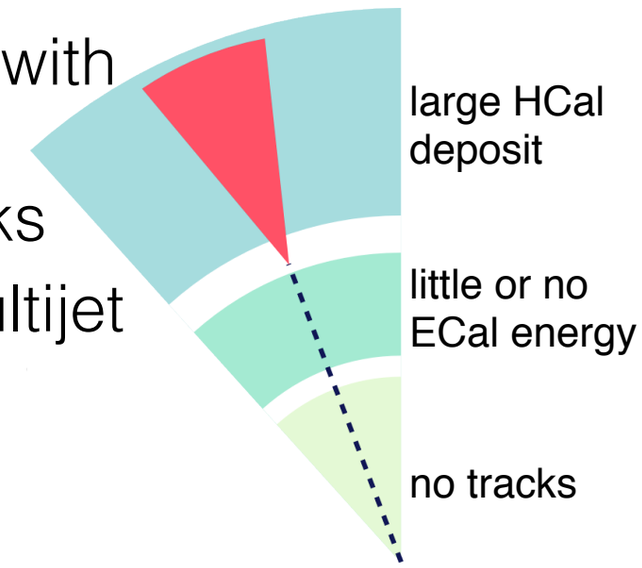
LL Decays: h → displaced jets in calorimeter

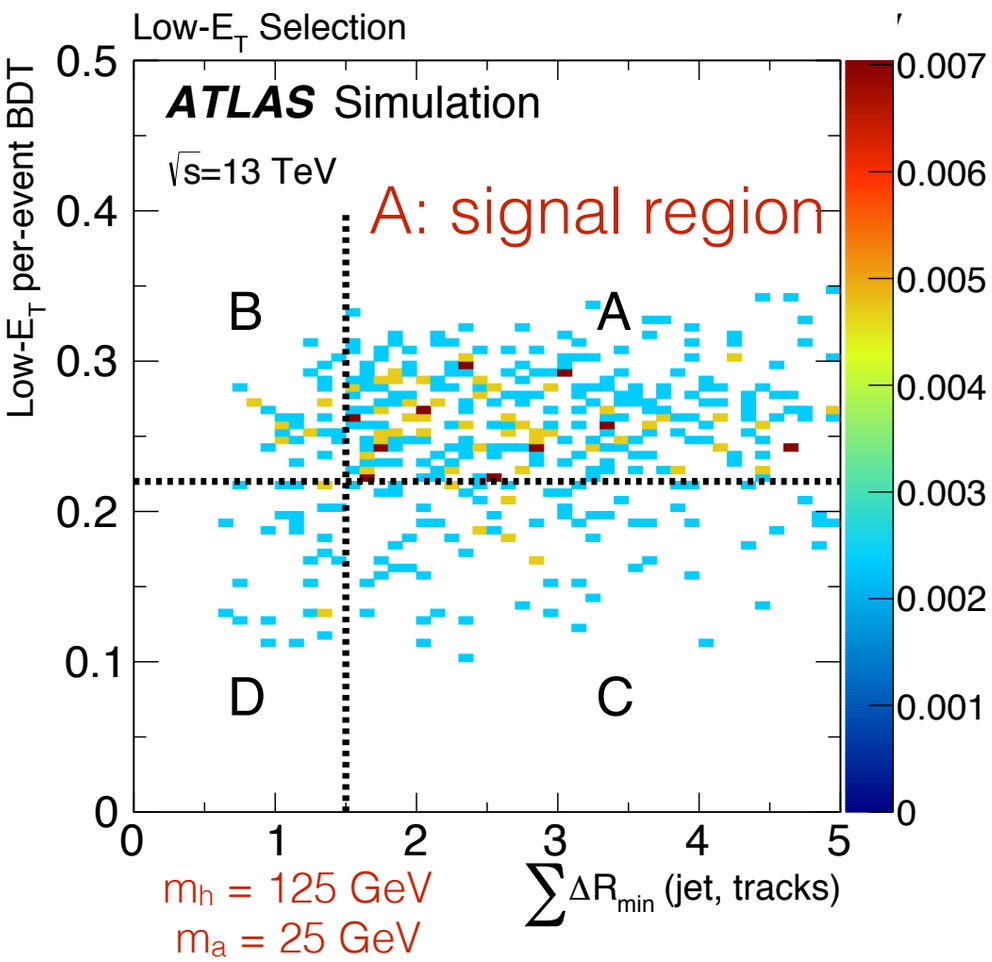
Signal

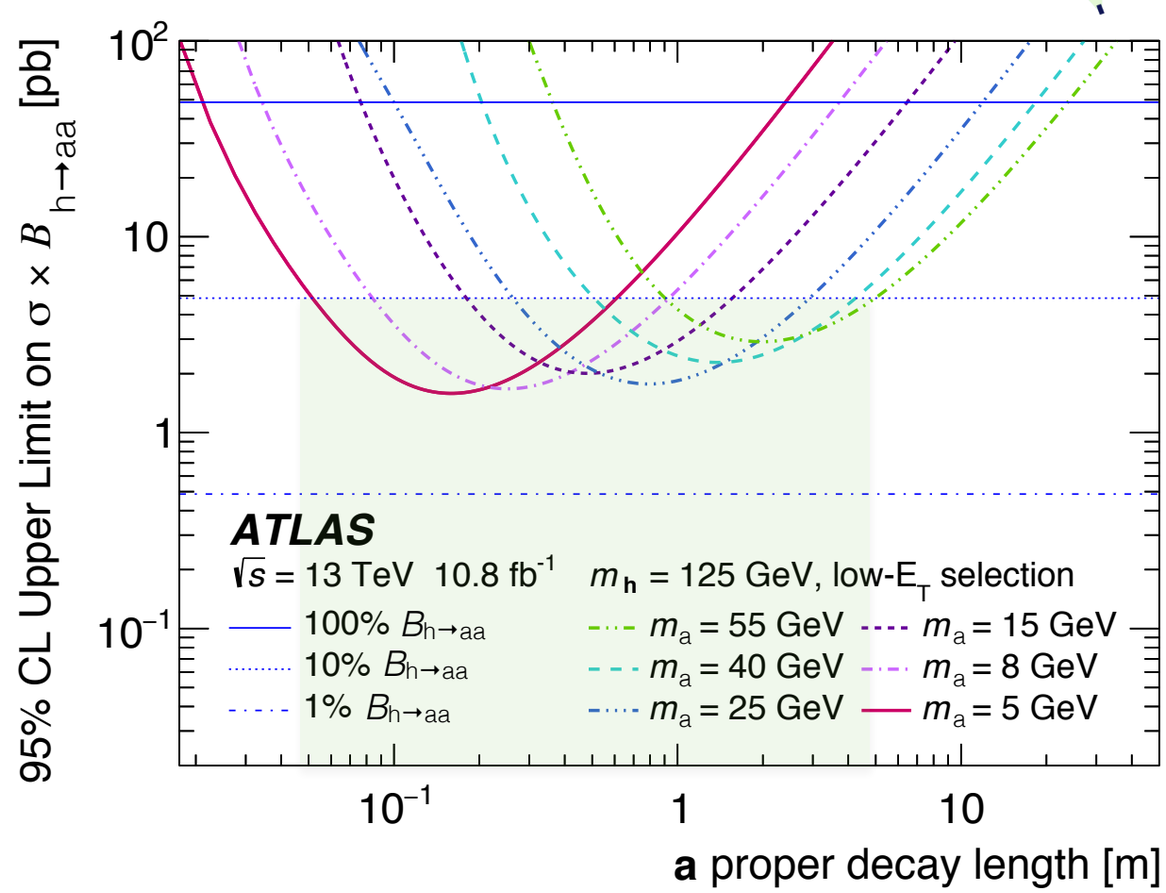


target $5 \lesssim m_a \lesssim 400$ GeV
for $125 \lesssim m_X \lesssim 1000$ GeV

- Strategy
  - Search narrow jets with low ECal energy & no associated tracks
- Main backgrounds multijet and beam-induced



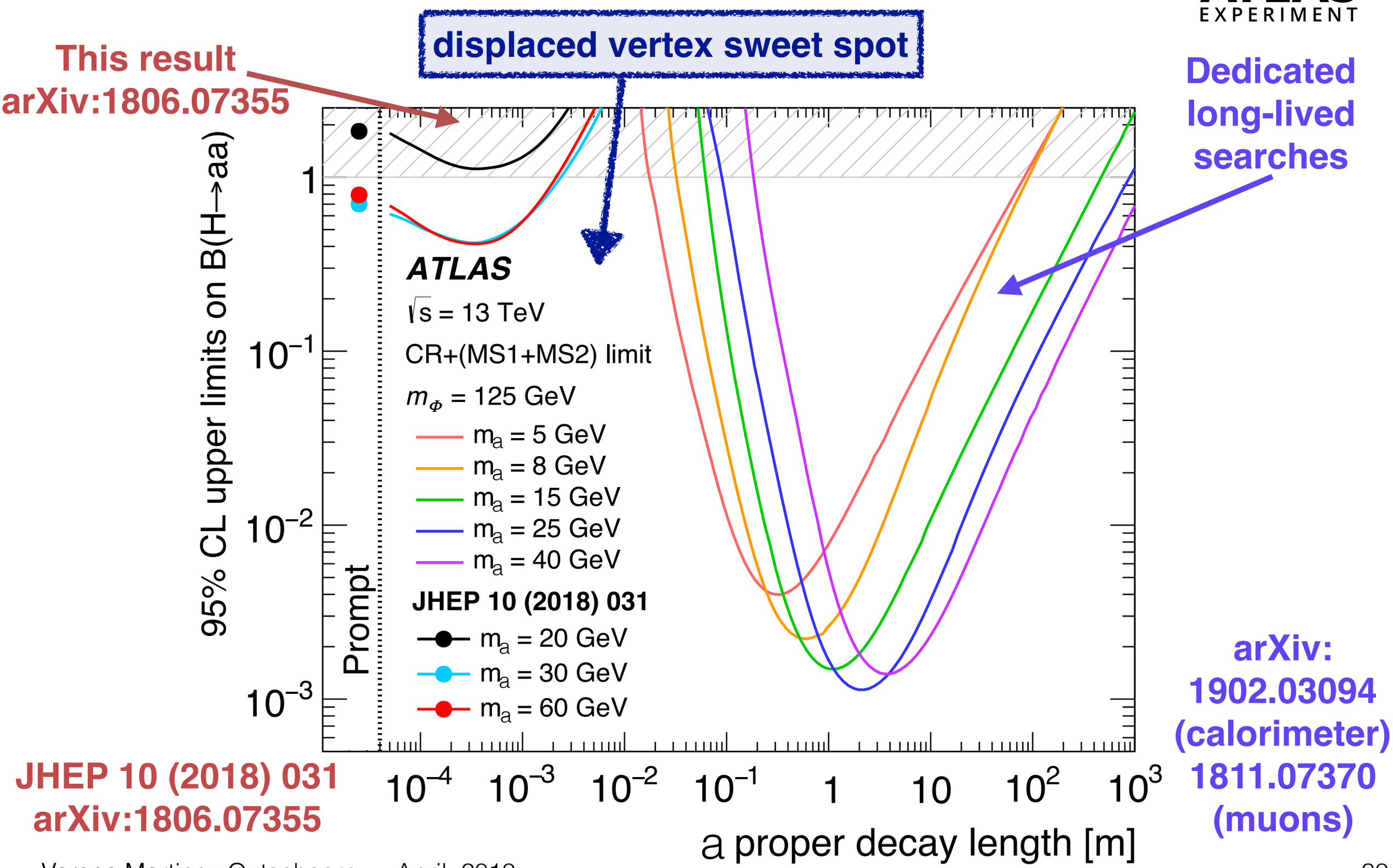




arXiV 1902.03094

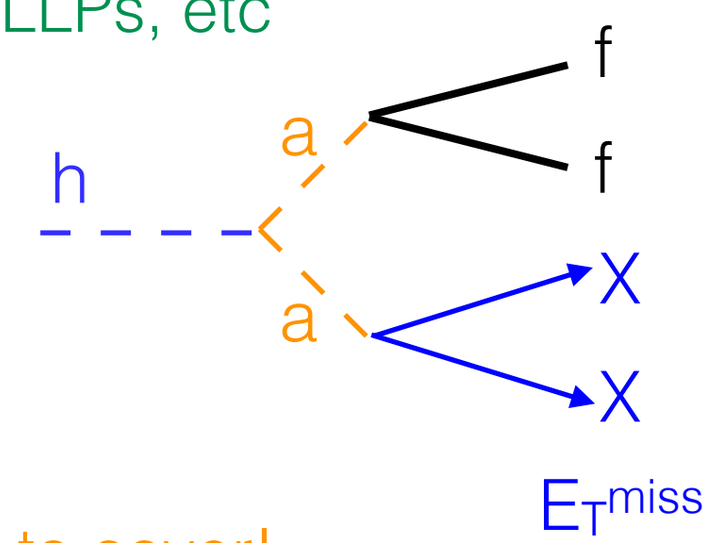
Related analysis with Z + displaced jet in backup

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



Summary & Outlook

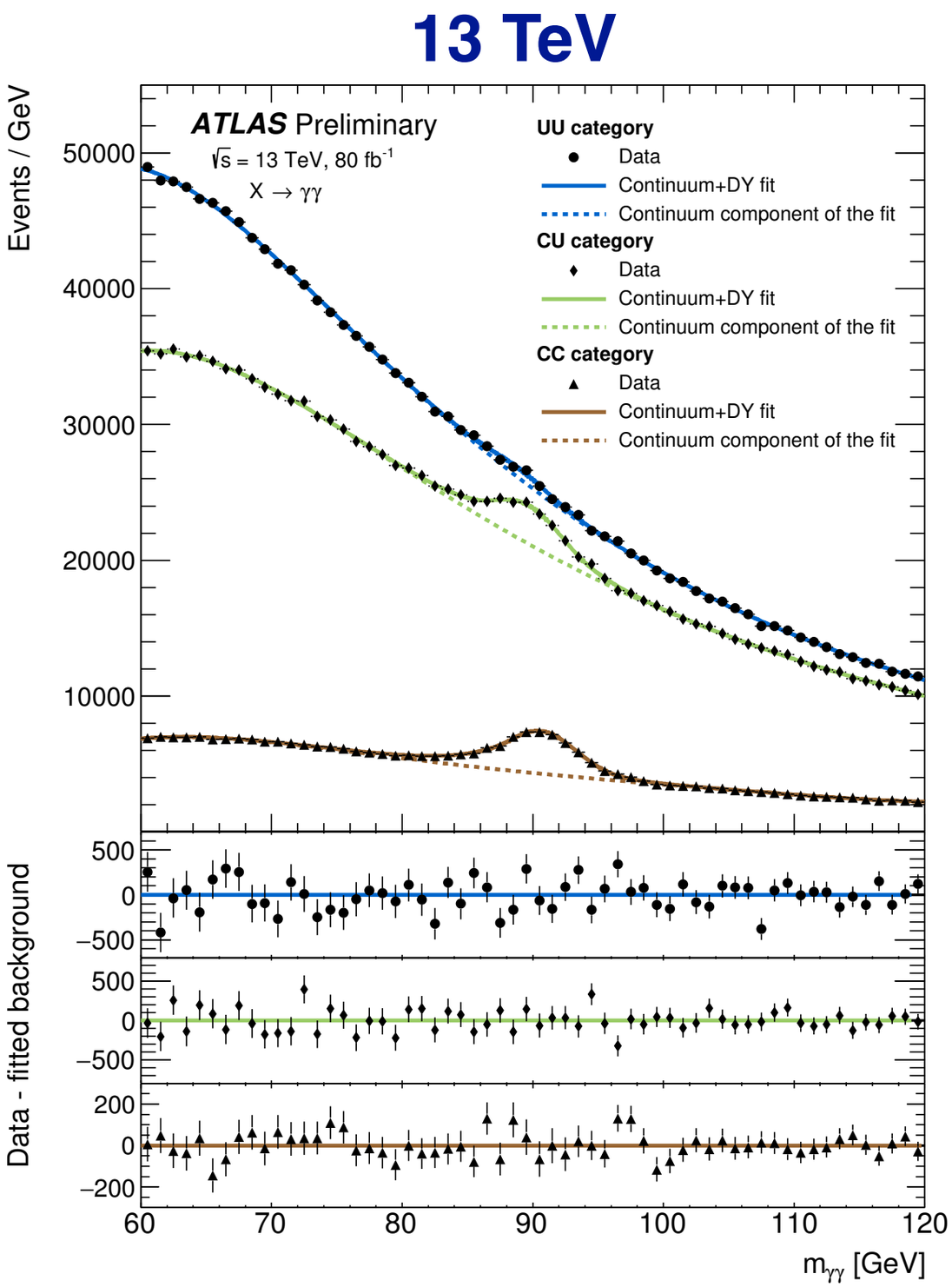
- Program of searches for light scalar states at the LHC
  - New light resonances
  - Long lived particle signatures
- Several strategies pursued
  - Exotic decays of the Higgs boson
  - Light states produced in the decays of new heavy particles
  - Direct or associated production of light states
- Need to continue to explore possibilities to cover full spectrum of options
  - Uncovered channels & regions of phase space, gaps in LLPs, etc
  - Invisible decays → already being explored at the LHC
  - Mixed decays → largely uncovered so far
  - Other production channels e.g. tta
- Signatures motivated by broad range of phenomenology
  - Benchmark models are very useful to guide analyses
  - Please let us know if you have suggestions for scenarios to cover!



More results expected soon with full 13 TeV dataset

BACKUP

Direct searches: a→2γ



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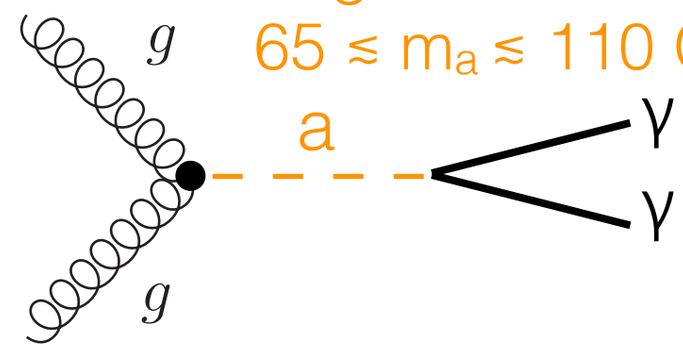
Signal



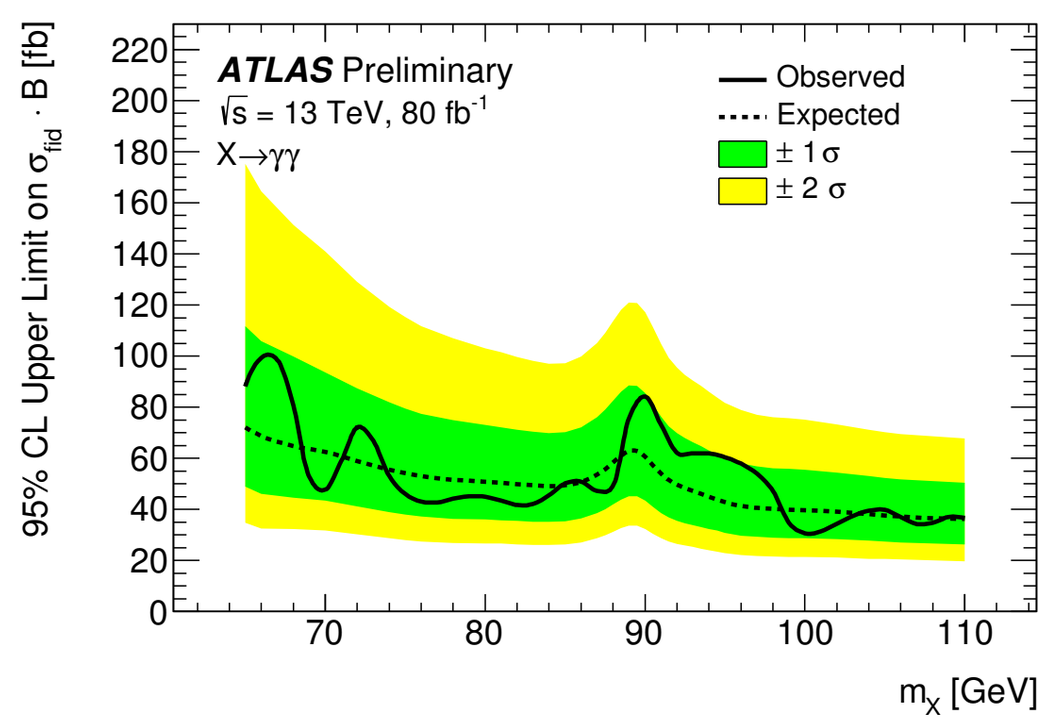
target
$65 \lesssim m_a \lesssim 110$ GeV

Strategy

- Search for a→2γ resonance in diphoton reconstructed mass $m_{\gamma\gamma}$
- Categorize events based on conversions

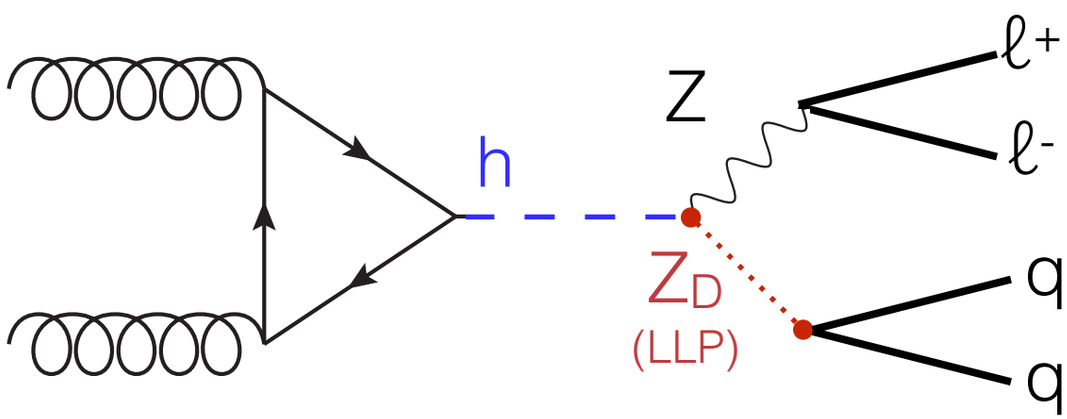
Main backgrounds: γγ, γj, jj j→hadronic jet

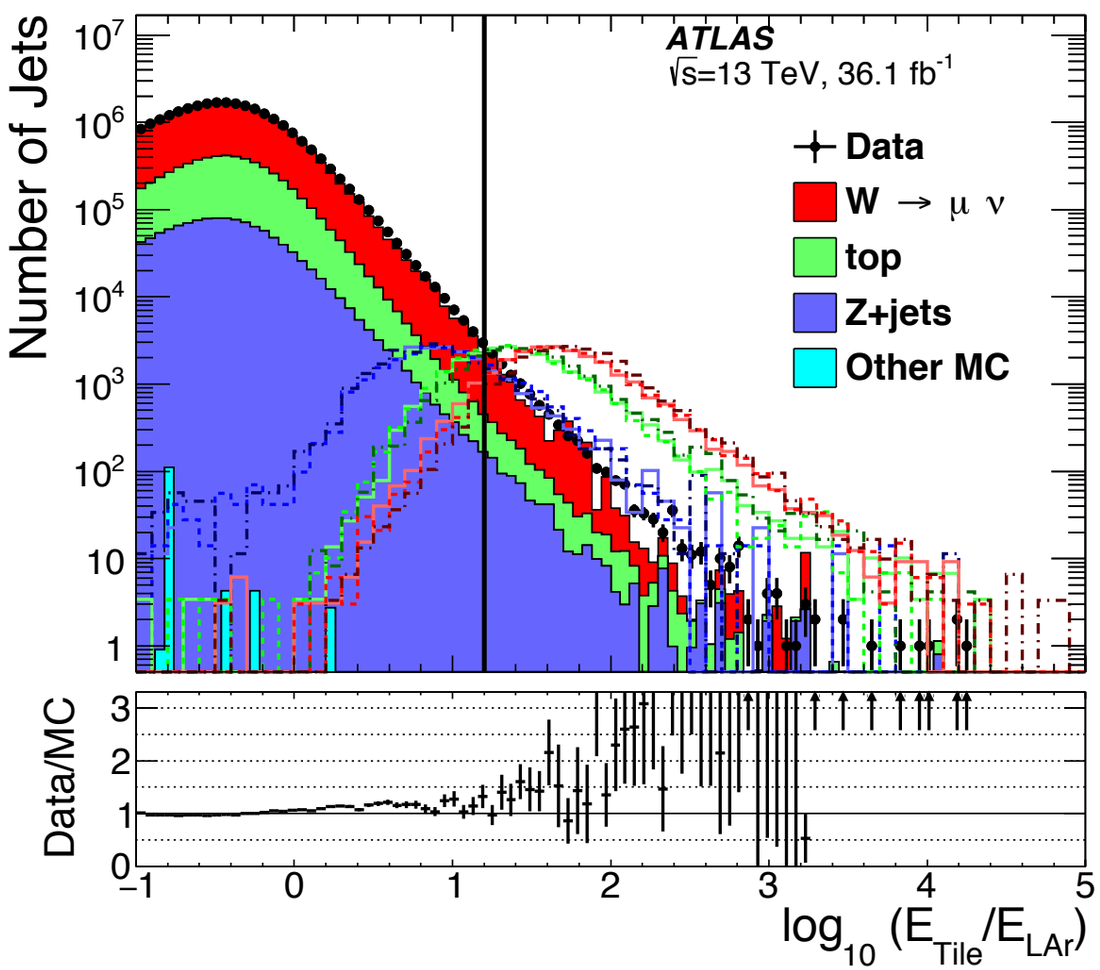
No significant excess observed



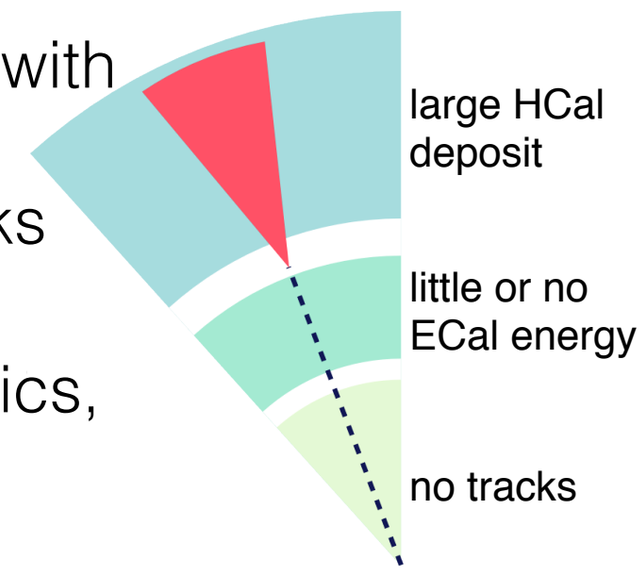
LL Decays: h → Z+displaced jet in calorimeter

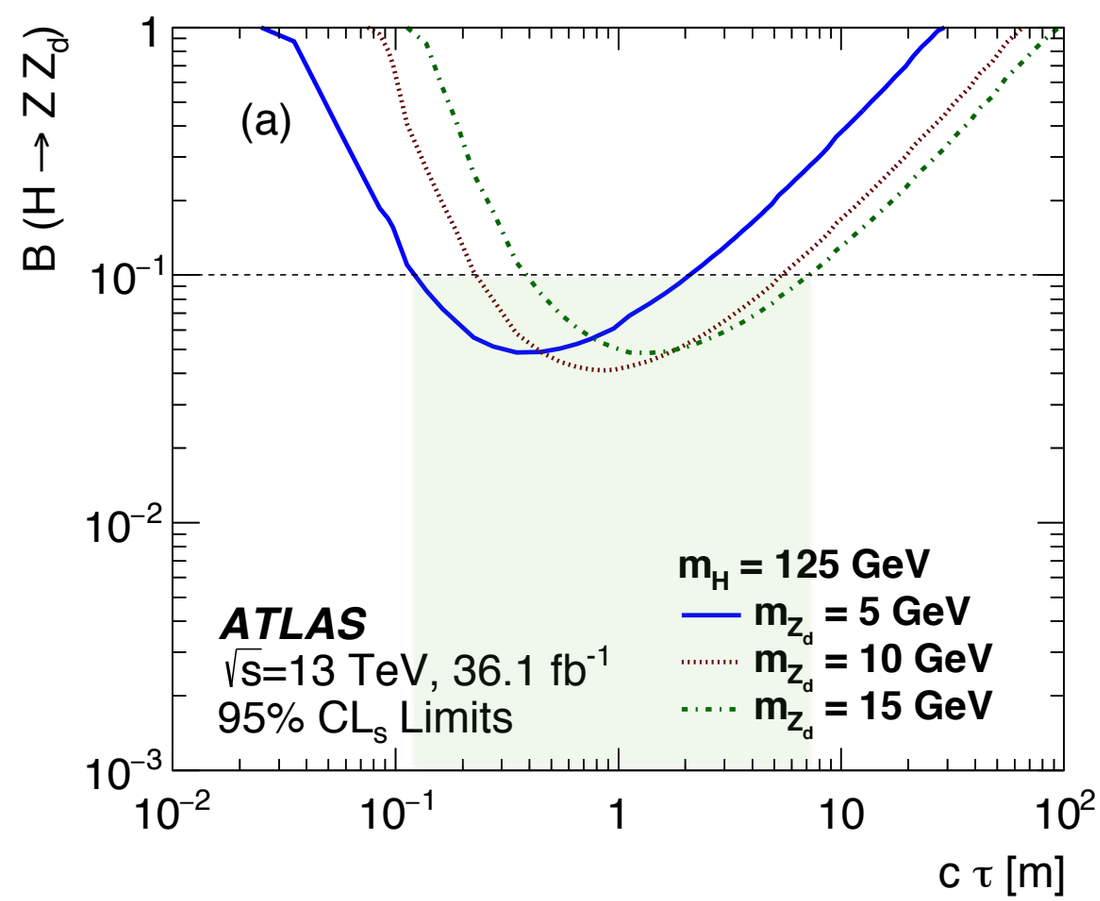
Signal





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

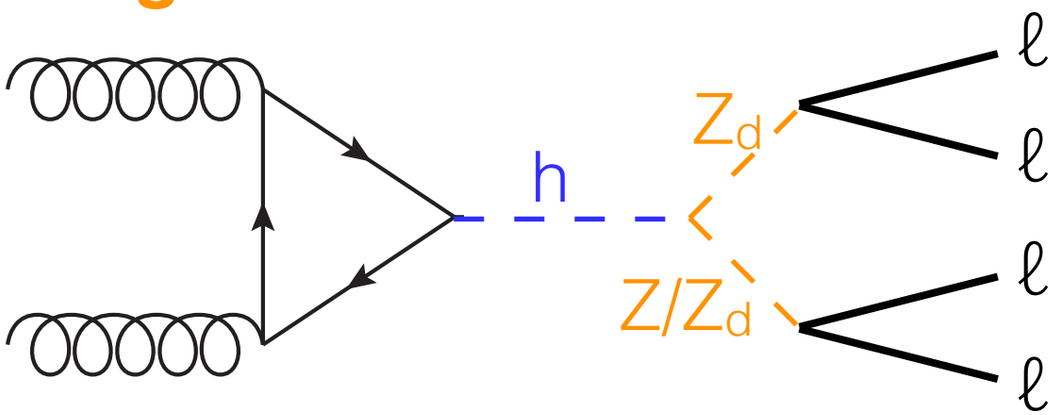


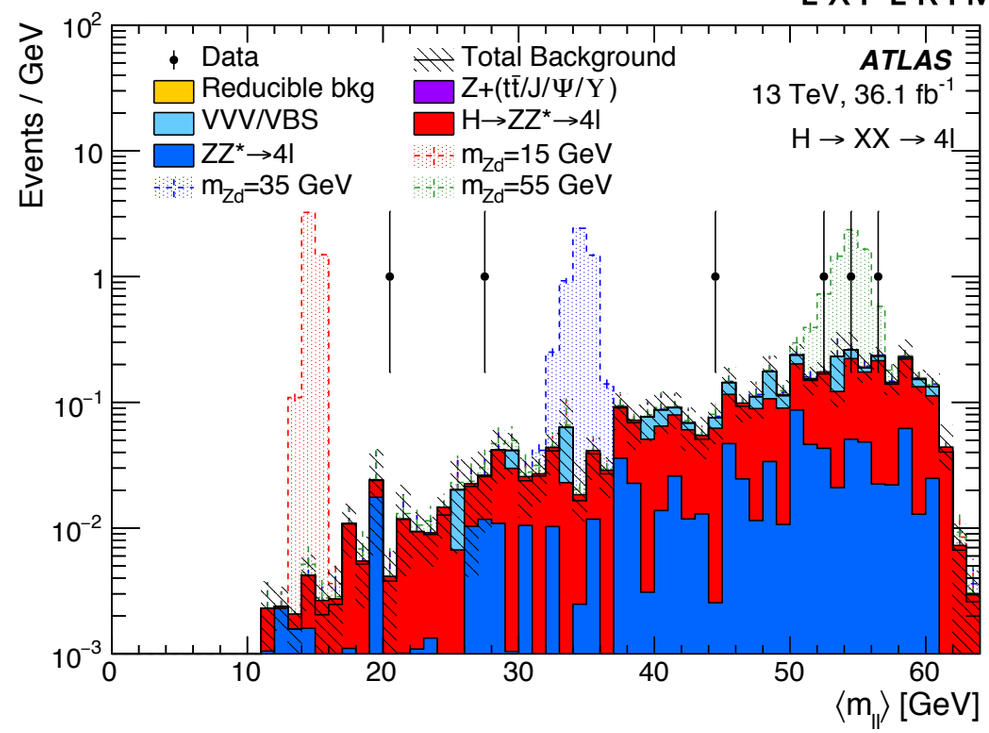


arXiv:1811.02542

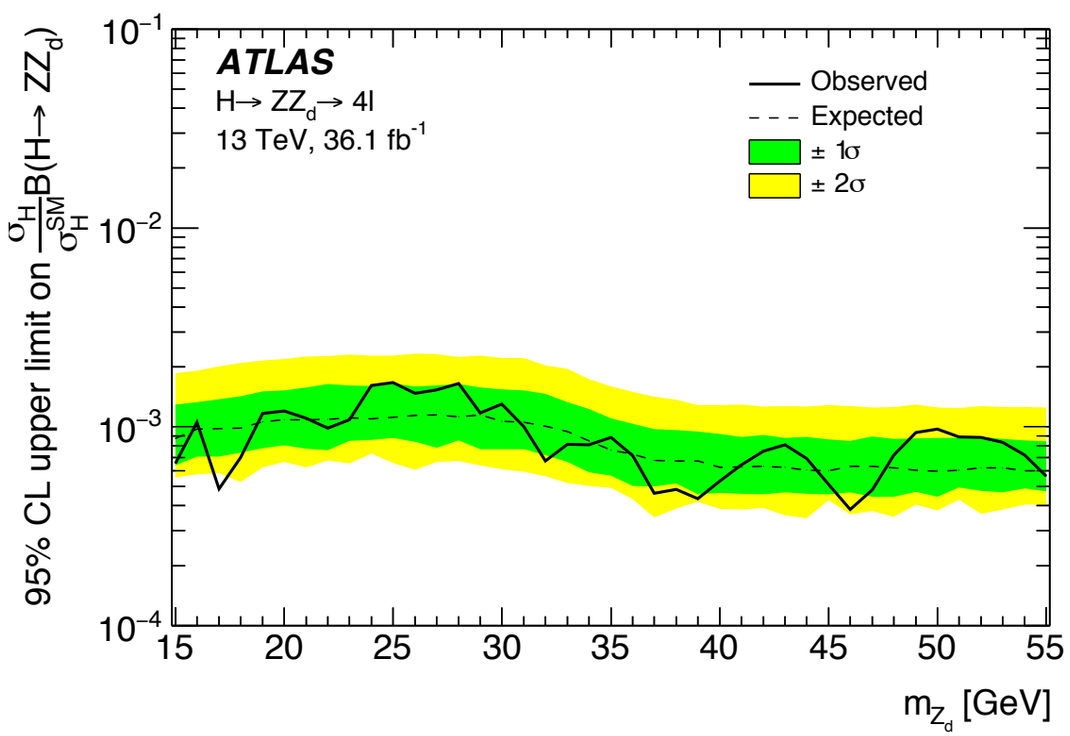
Z-Dark Signatures: $h \rightarrow Z_d Z_d \rightarrow 4\ell$

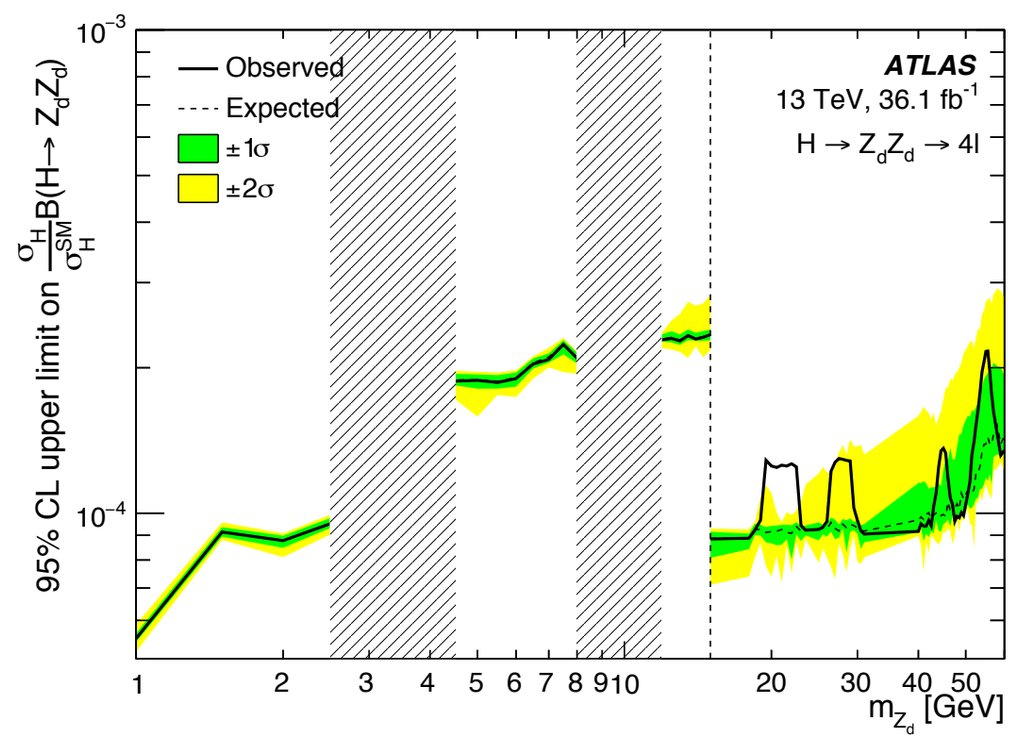
Signal





- 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