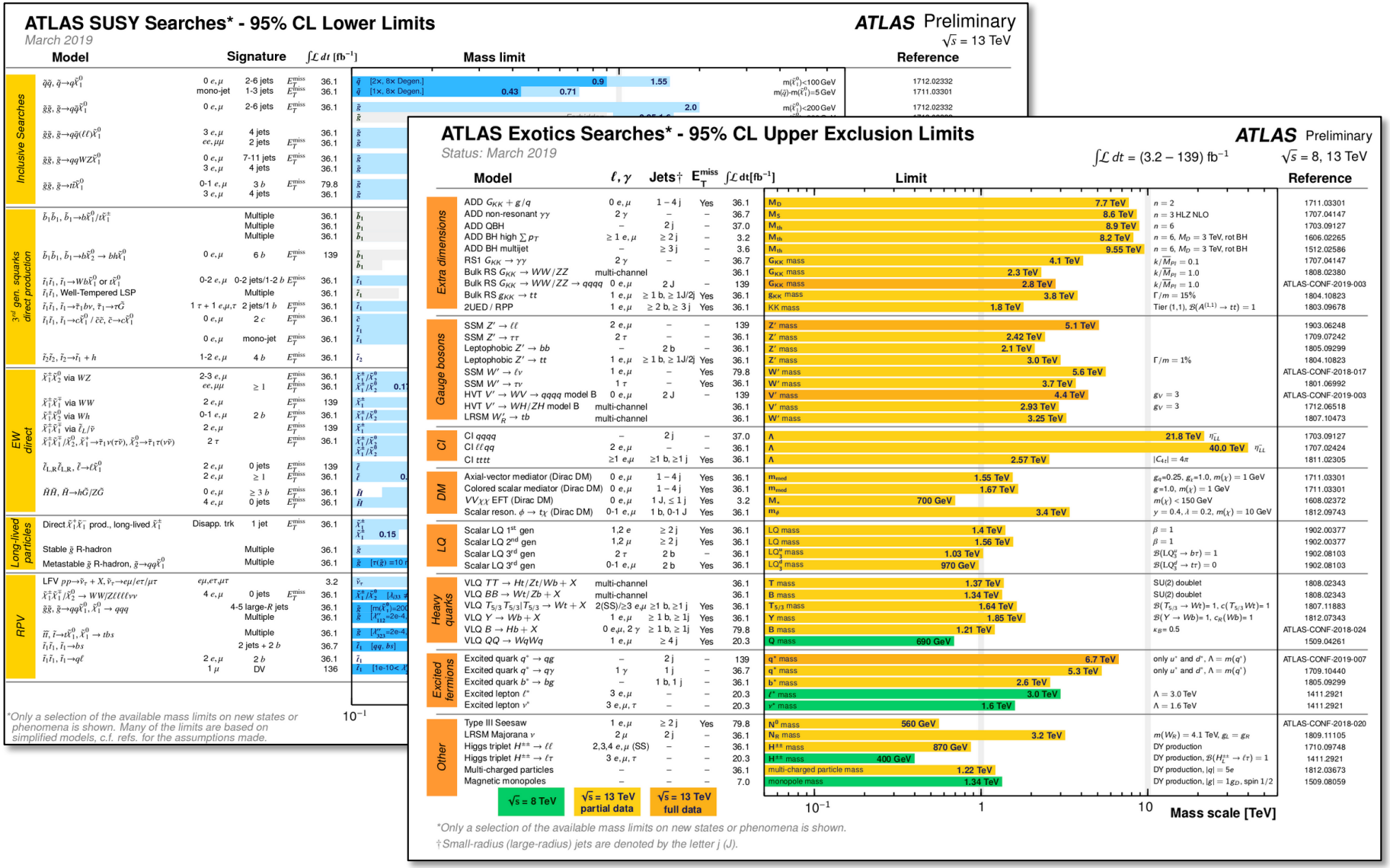
*4th NPKI Workshop: "Searching for New Physics on the Horizon"*
*Korea University, Seoul, May 12-17, 2019*

# Searches for light scalars at the LHC

Aurelio Juste
ICREA/IFAE, Barcelona

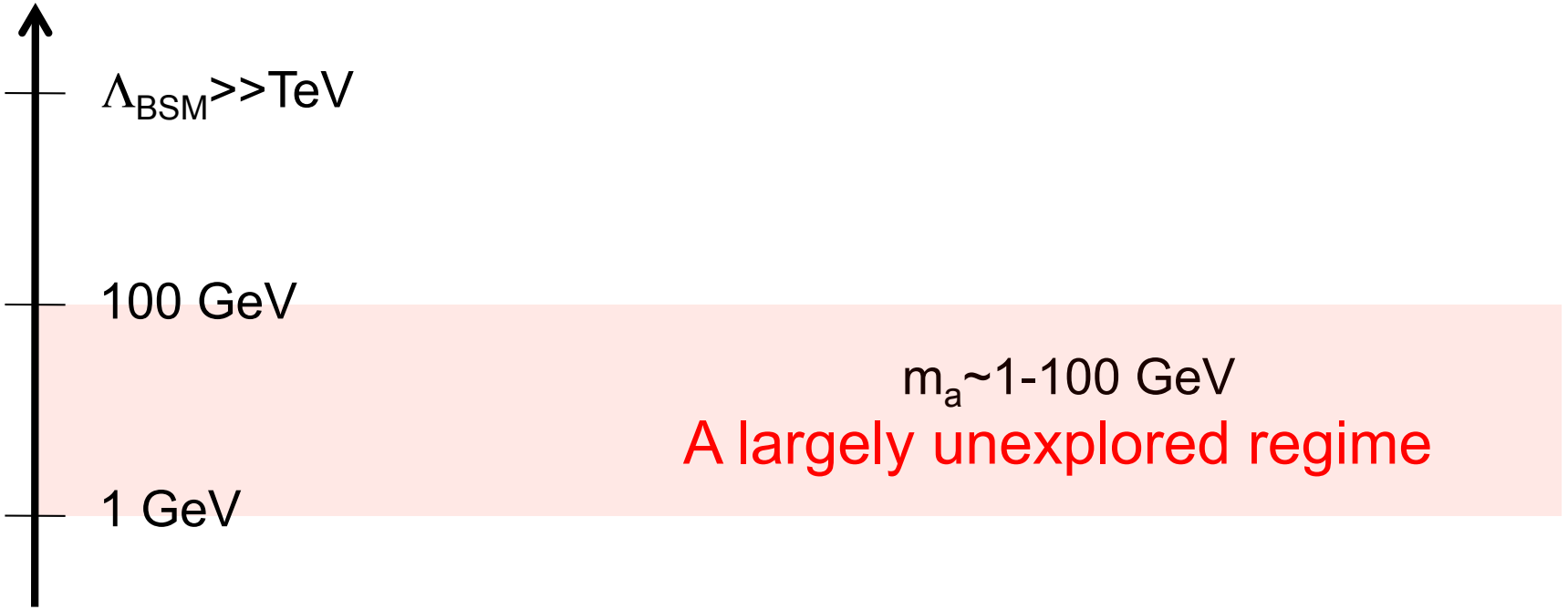
# Why light scalars?

- The LHC is pushing solutions to SM problems (hierarchy, flavor,…) to scales >>TeV.



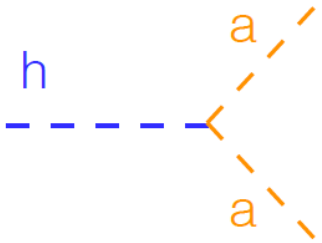
# Why light scalars?

- The LHC is pushing solutions to SM problems (hierarchy, flavor,…) to scales >>TeV.
- However, naturally light (pseudo-)scalar states could be present in the spectrum. Many BSM examples (portal DM models, ALPs, CH, SUSY, etc).



# Main search strategies at the LHC

## Exotic decays of the SM Higgs boson

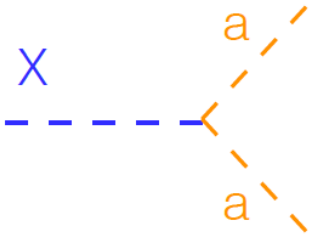



$m_h = 125$ GeV

$m_a \sim 0.5 - 60$ GeV

Both prompt and long-lived particles

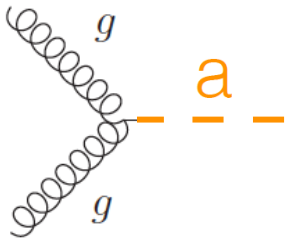
## New heavy particles decaying into lighter ones

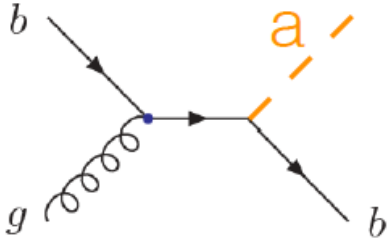


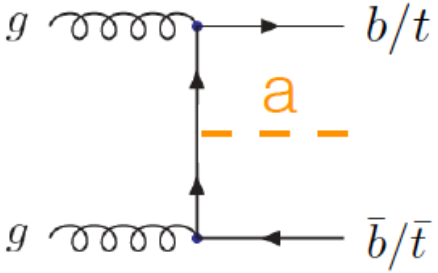

$m_X > m_h$

$m_a < m_X/2$

## Direct or associated production of light particles



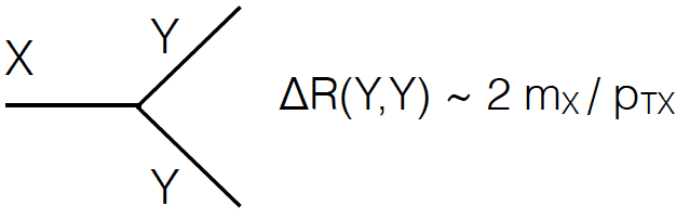
# Main search challenges at the LHC

## Trigger

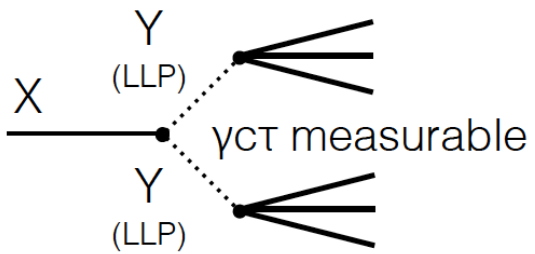
- Unless on can rely on triggering on associated object(s), often dedicated triggers are required.

## Reconstruction

- Light states often result into low $p_T$ and collimated decay products.




- In the case of long-lived particles (LLP), decay products are displaced, resulting in challenging signatures that require special techniques.




## Backgrounds

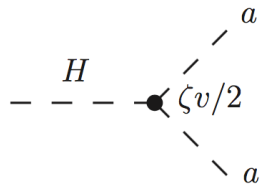
- Large backgrounds from SM processes at low $p_T$.
- Searches for LLPs also have to fight significant non-collision backgrounds (cosmics, beam halo, noise, instrumental effects, etc).

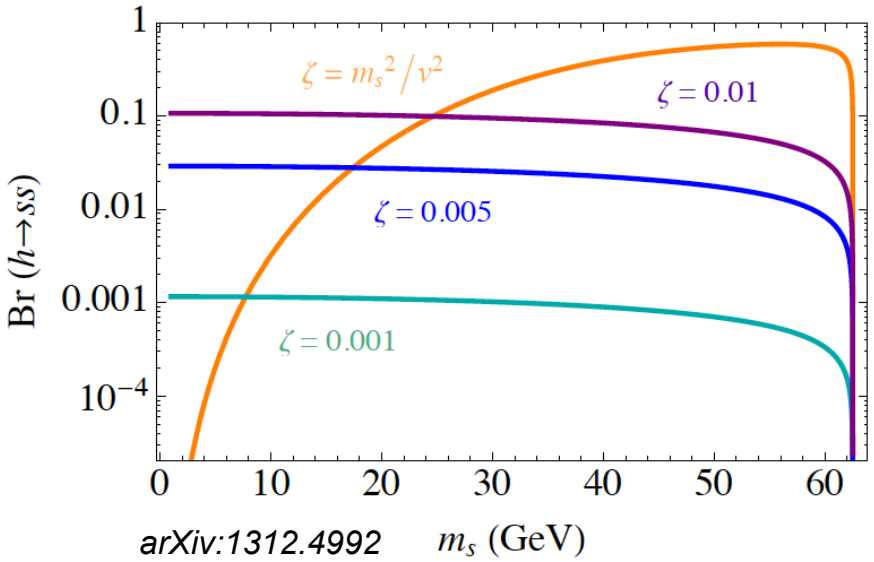
# Exotic Higgs decays

# Exotic Higgs boson decays

- Higgs decays in the SM are suppressed by small Yukawa couplings, loops, or multi-body phase space ➔ very small width: $\Gamma_{hSM}$ = 4.1 MeV.
- Even a small coupling to another light state can lead to significant branching ratio into a new decay mode. Some examples:
  - Higgs Portal models of dark matter
  - Neutral Naturalness
  - Extended Higgs sector (e.g. 2HDM+S)

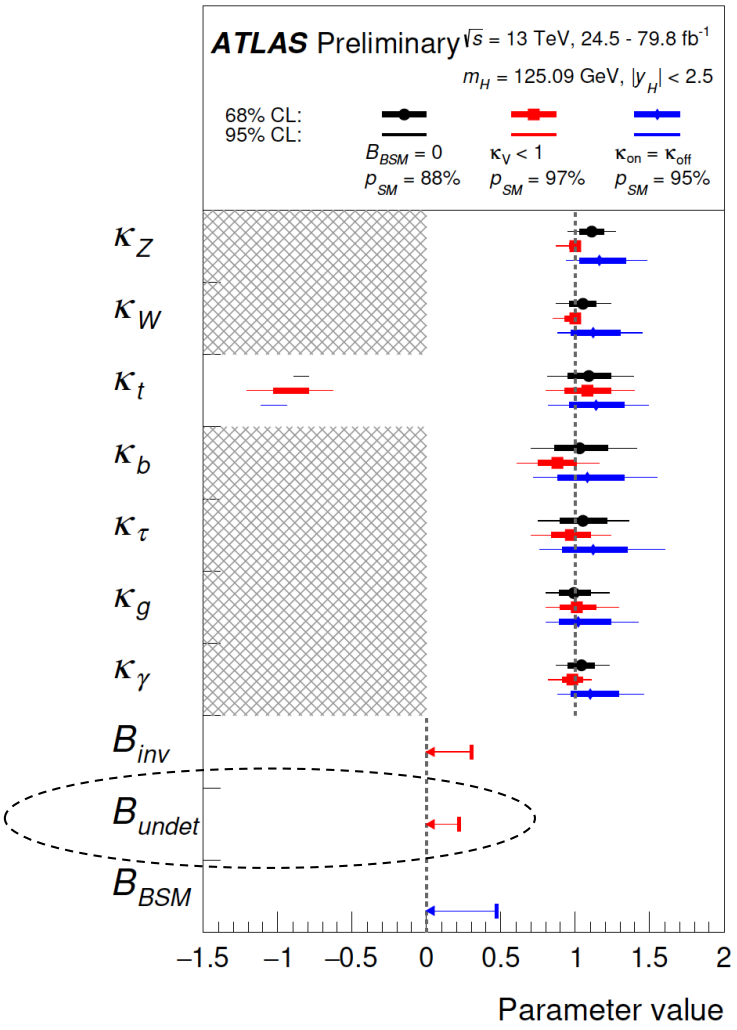
2HDM+S:




*arXiv:1312.4992*

*ATLAS-CONF-2019-005*

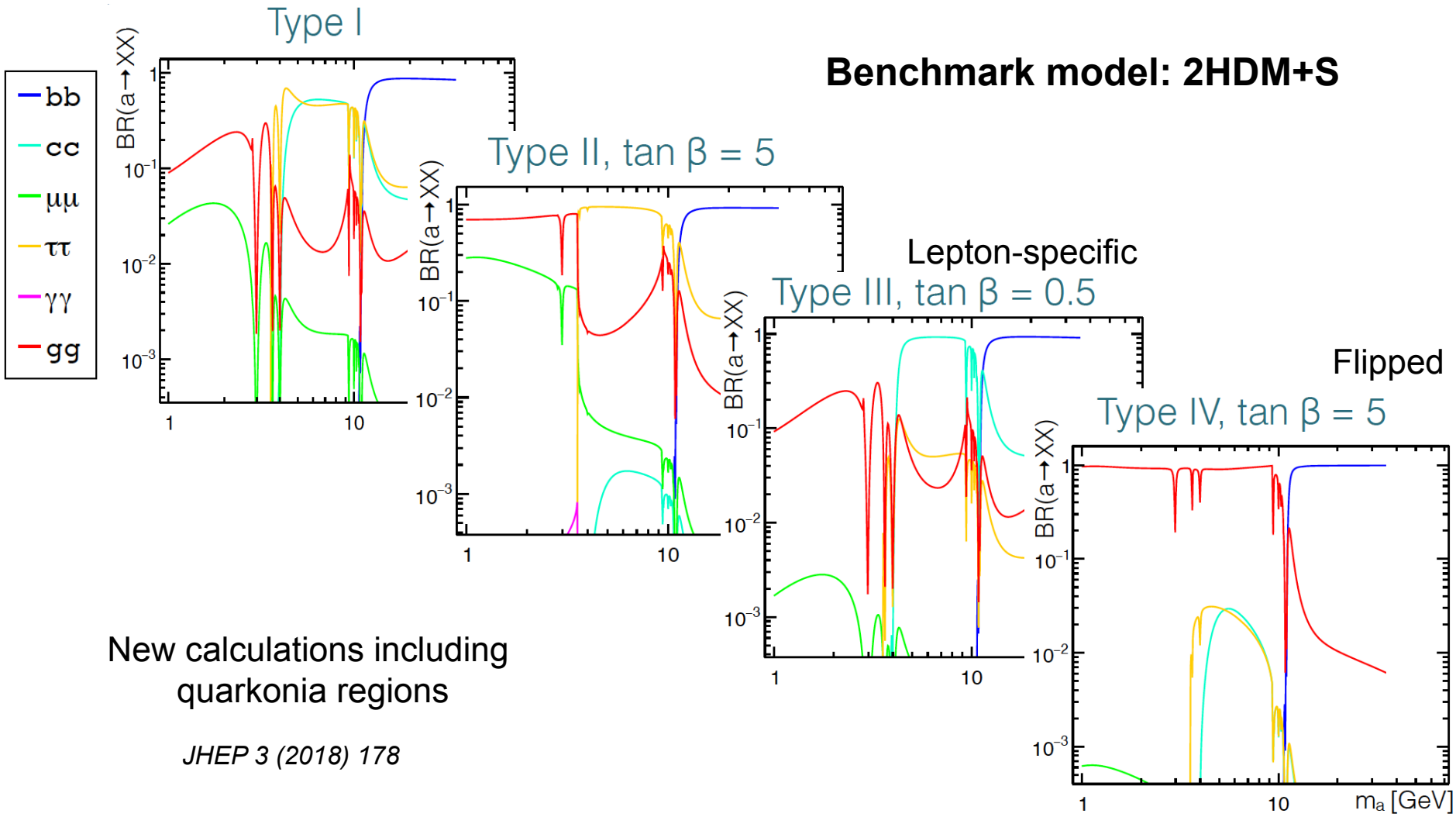



By combining Higgs σxBR measurements and invisible Higgs searches:

$BR_{undet}$ < 22% @ 95% CL

# Higgs decays to light (pseudo-)scalars

- A scalar particle mixing with the SM Higgs boson would inherit its Yukawa coupling.
- Branching ratios model dependent. Comprehensive review: arXiv:1312.4992.

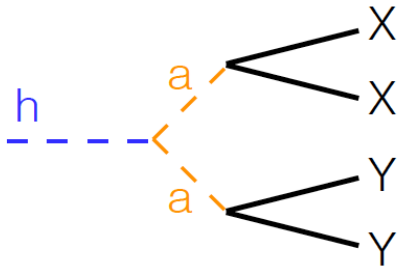



**Benchmark model: 2HDM+S**

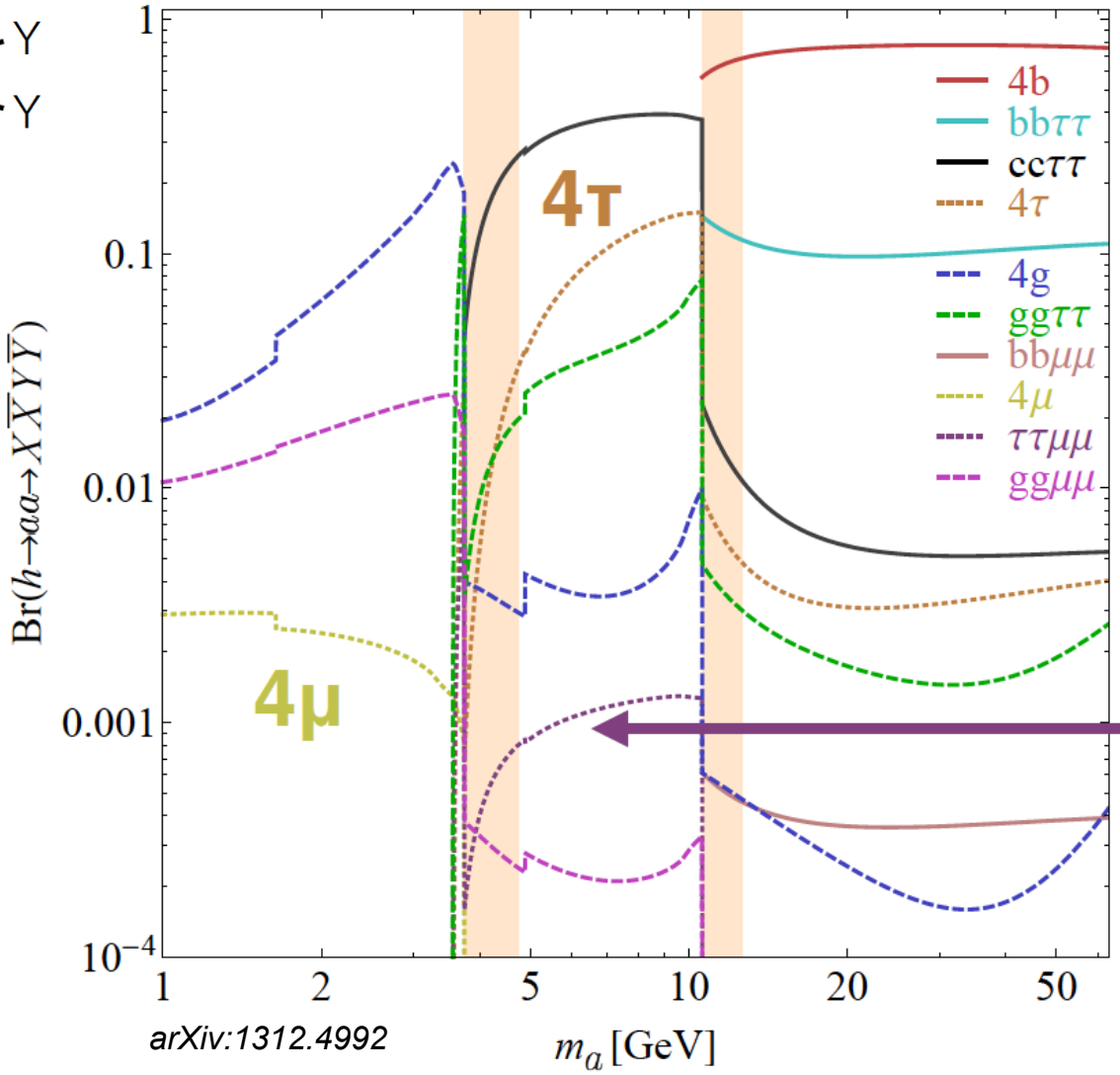
New calculations including quarkonia regions

*JHEP 3 (2018) 178*

# h→aa decays: Experimental signatures




**Benchmark model: SM+S**




4b

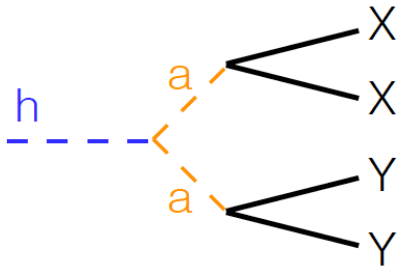
2τ2b

2τ2μ

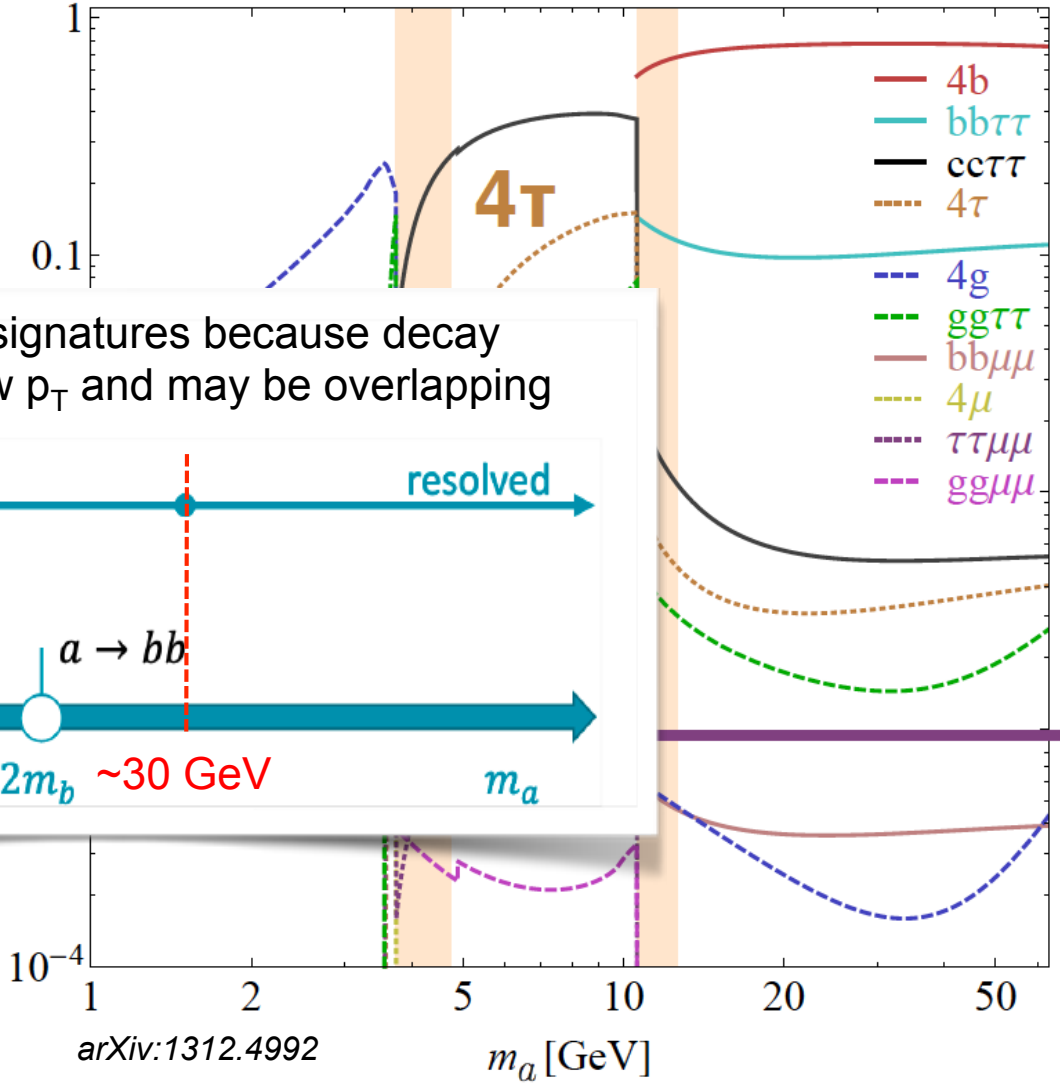
2b2μ

*arXiv:1312.4992*

# h→aa decays: Experimental signatures




**Benchmark model: SM+S**




4b

2τ2b

2τ2μ

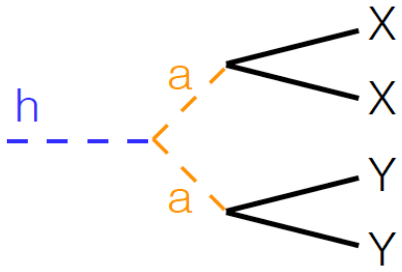
2b2μ

Challenging signatures because decay products are low $p_T$ and may be overlapping

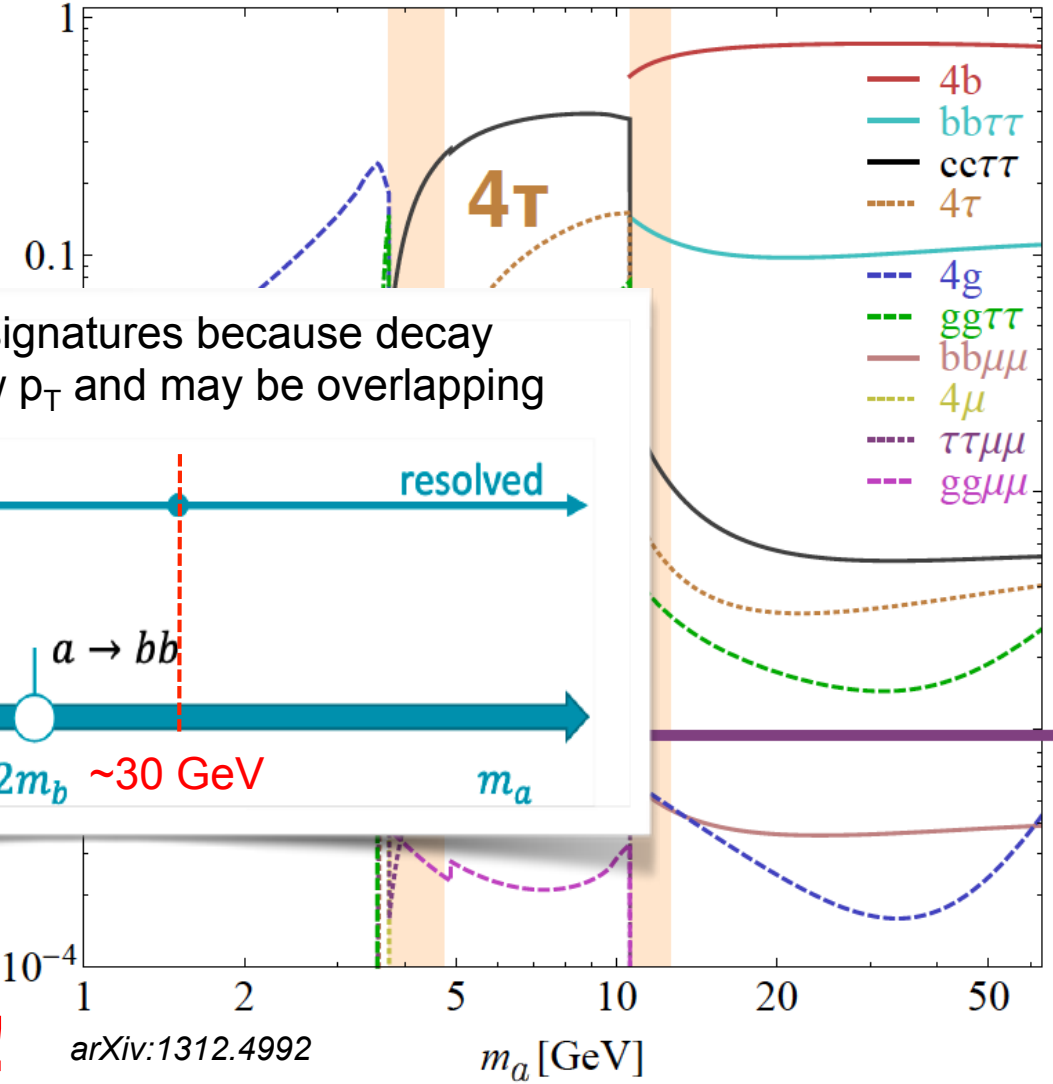



*arXiv:1312.4992*

# h→aa decays: Experimental signatures




**Benchmark model: SM+S**




4b

2τ2b

2τ2μ

2b2μ

Challenging signatures because decay products are low $p_T$ and may be overlapping




Also **4γ & 2γ2j!**

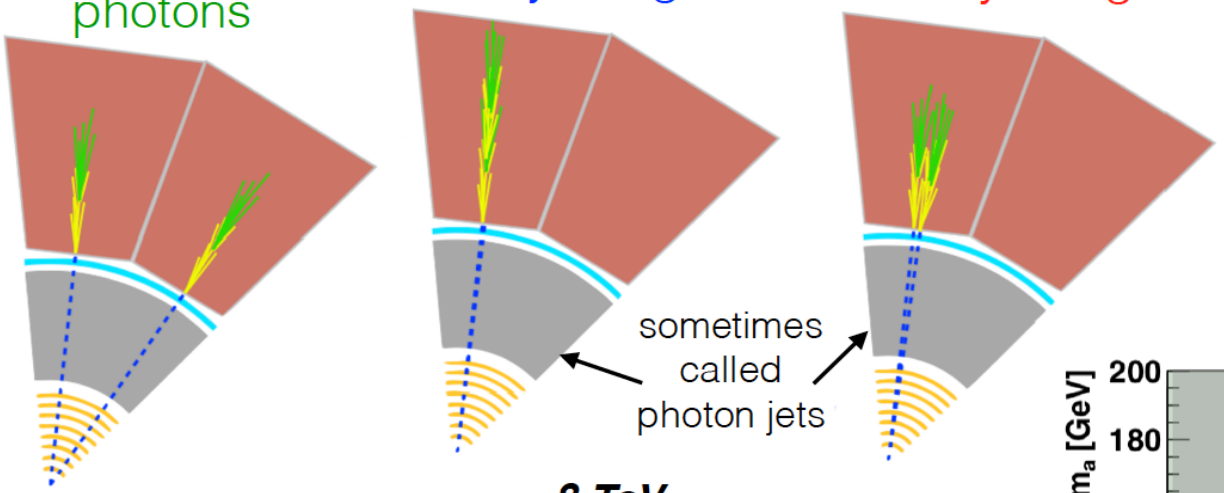
*arXiv:1312.4992*

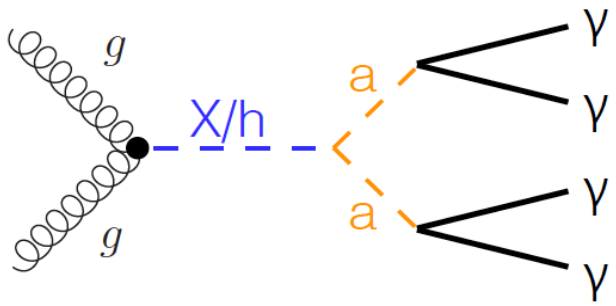
# h→aa→4γ

Isolated photons

Fully merged

Nearly-merged



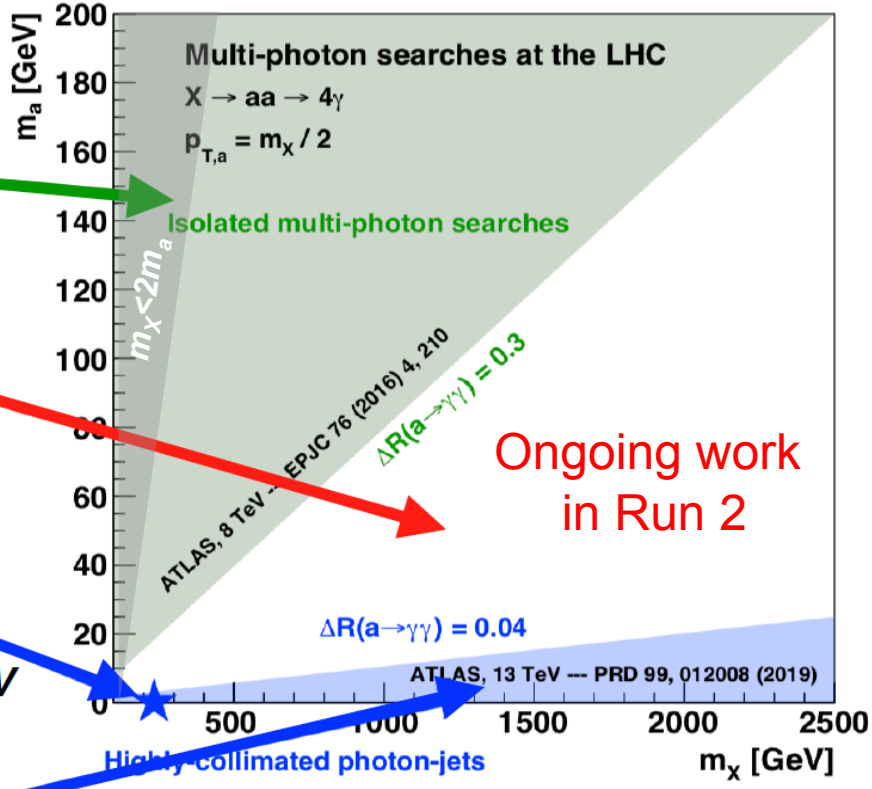




***8 TeV***
arXiv: 1509.05051
EPJC 76 (2016) 4, 210

$10 \leq m_a \leq 60$ GeV, for $m_X = 125$ GeV

Several searches targeting different regimes made possible due to trigger improvements

Not covered




Ongoing work in Run 2

$m_a \leq 400$ MeV

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

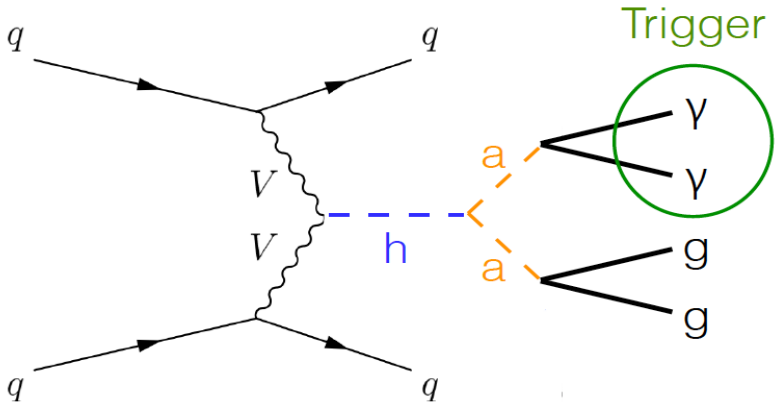
***13 TeV, for $m_X$ > 200 GeV***
arXiv: 1808.10515
PRD 99, 012008 (2019)

From J. Beacham

# h→aa→2γ2j

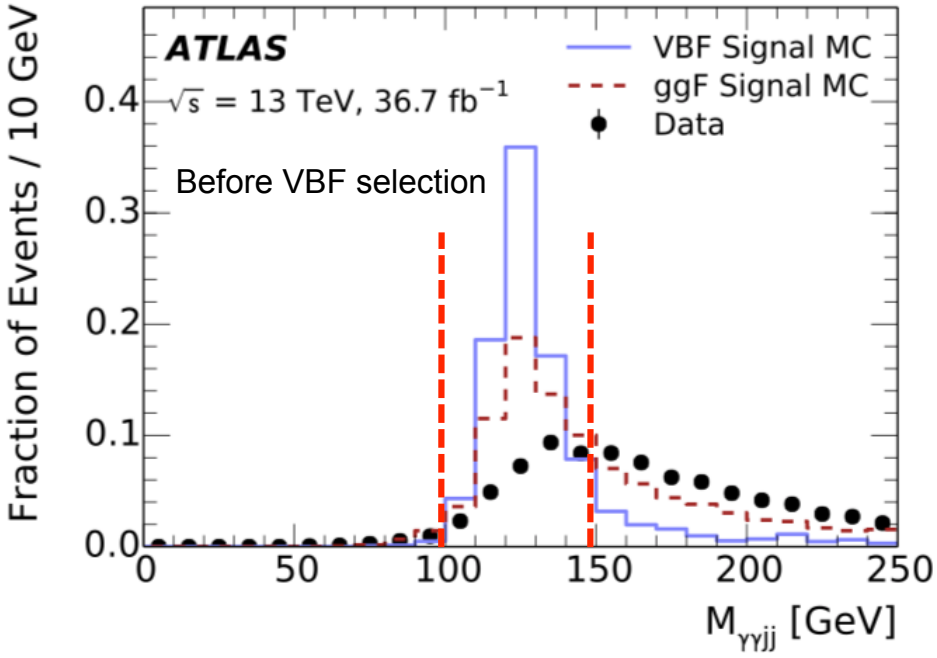
Strategy:

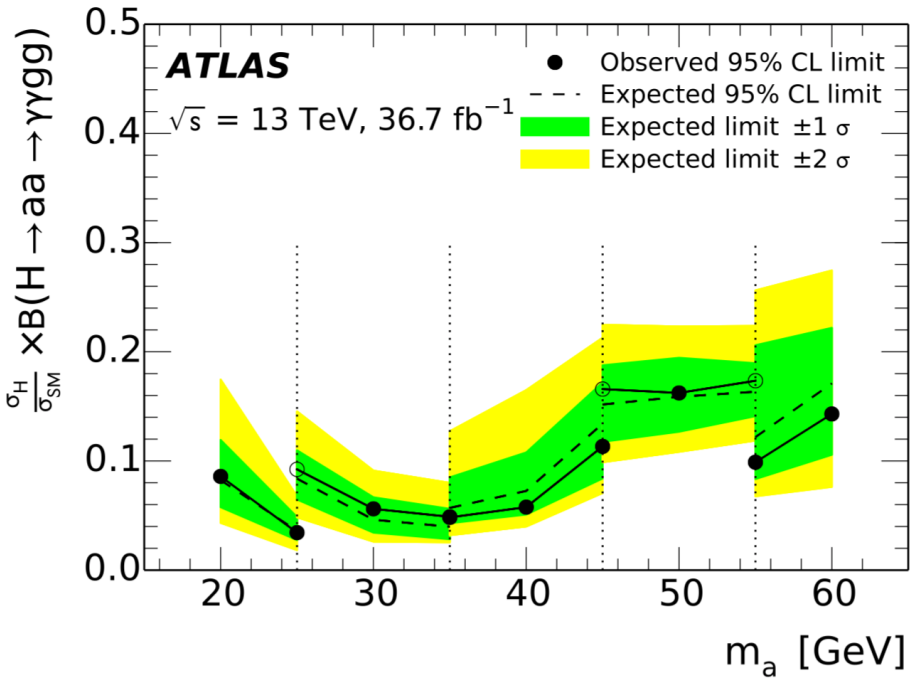
- Select events with 2 photons and ≥4 jets.
- VBF-like selection on highest dijet mass pair ($p_{Tj1}$>60 GeV, $m_{jj}$>500 GeV).
- Compatibility with h→aa→2γ2j hypothesis: $m_{\gamma\gamma}$~$m_{jj}$ and $m_{\gamma\gamma jj}$~$m_h$.
- Background estimation via ABCD method.




**Target**: $2m_b \lesssim m_a \lesssim m_h/2$

*arXiv:1803.11145*

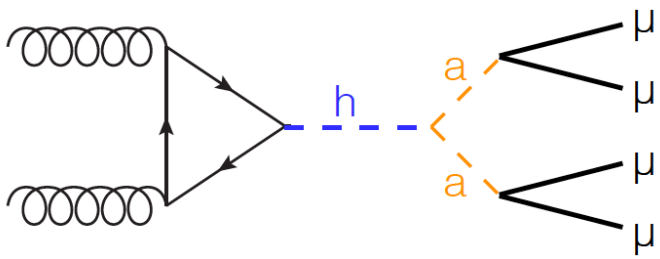


# h→aa→4μ

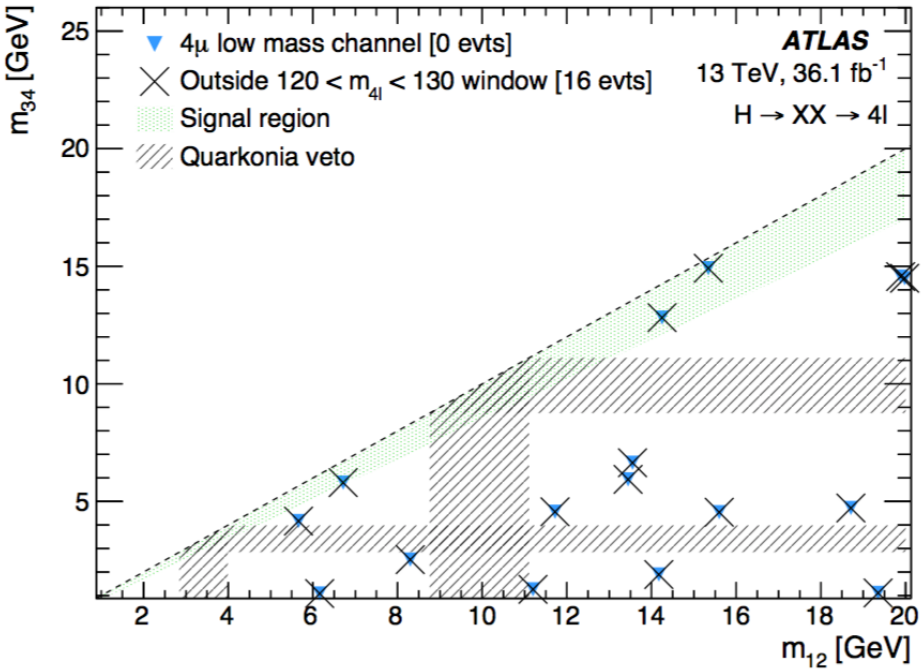
Strategy:

- Select events with 4 muons.
- Search for excess in dimuon pairs of similar mass, $m_{12}$~$m_{34}$, with $m_{4\mu}$~$m_h$.
- Main backgrounds $b\bar{b}$ and J/Ψ events, and electroweak processes (ZZ, h→ZZ*, etc).

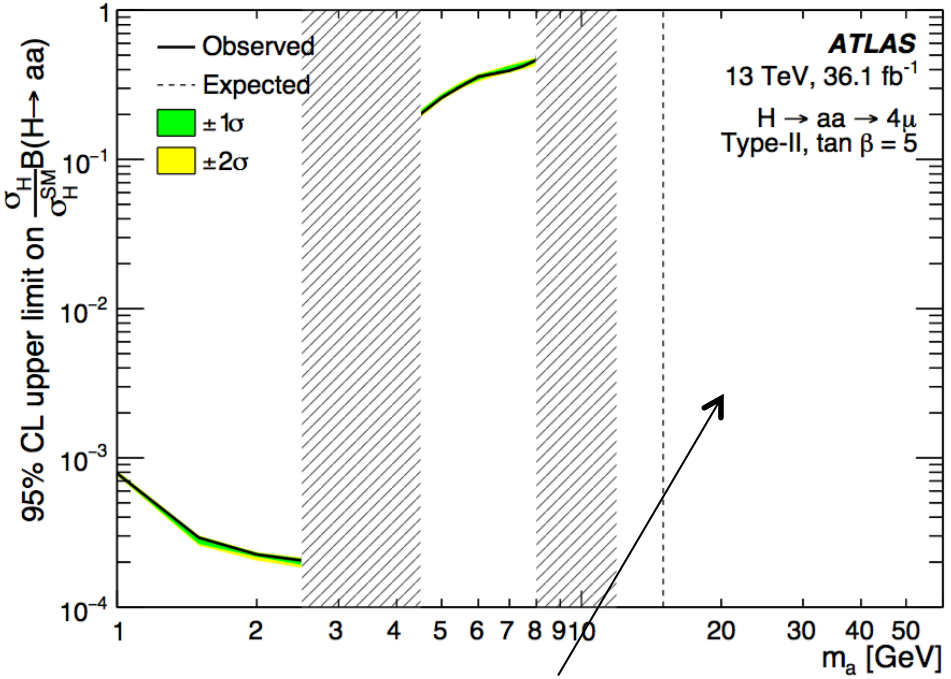



**Target**: $2m_\mu \lesssim m_a \lesssim m_h/2$

*arXiv:1802.03388*




No events observed in the signal region

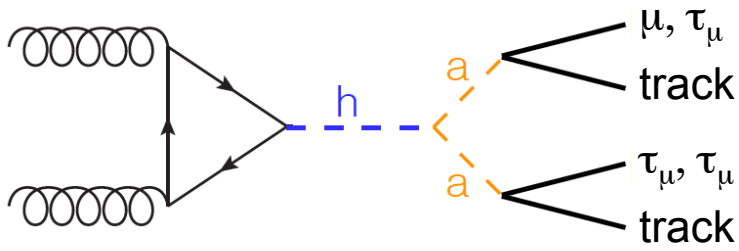



Upper limit >1 for $m_a$>15 GeV

# h→aa→2μ2τ or 4τ

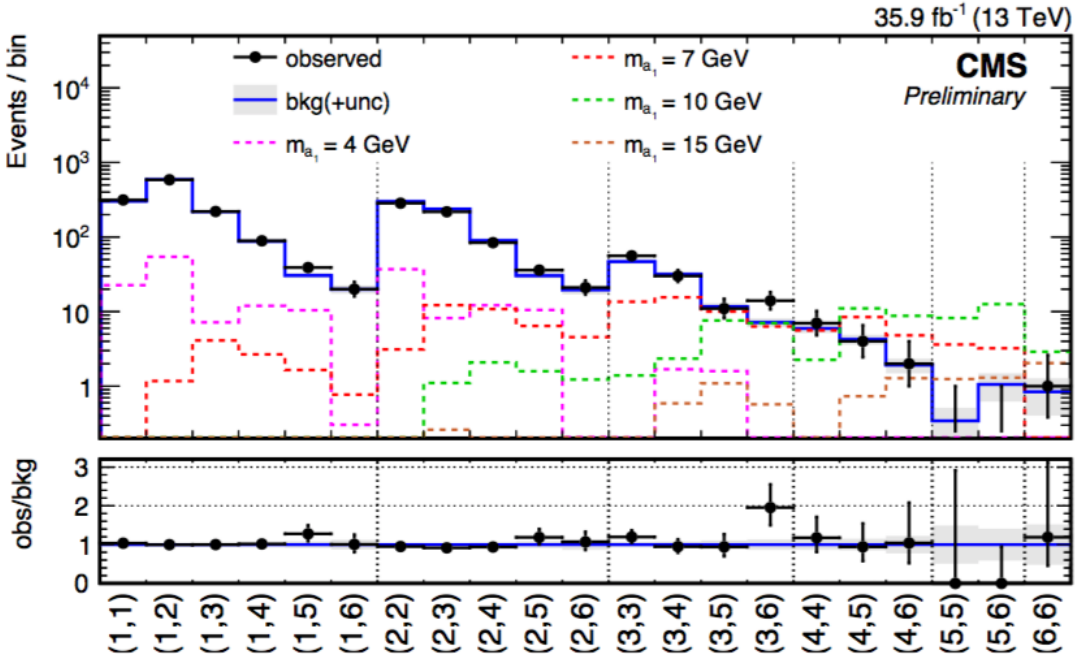
Strategy:

- Select events with 2 same-charge muons and 2 tracks.
- 2D search in $m_1$(μ,trk) vs $m_2$(μ,trk) plane.
- Main backgrounds QCD multijets with b-jets estimated using data-driven techniques.

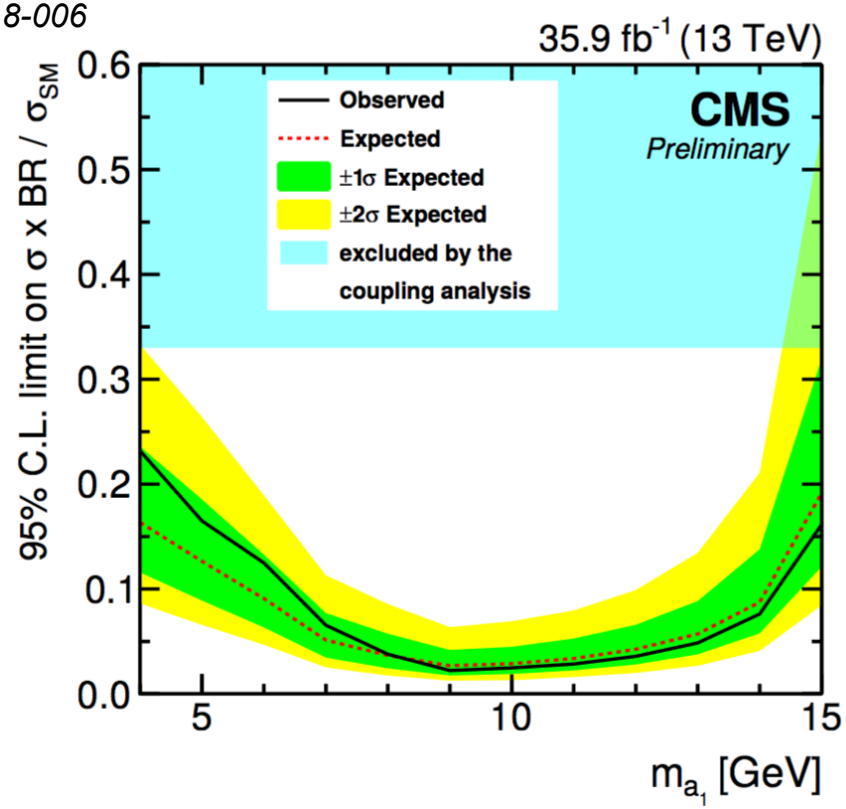



**Target**: $2m_\tau \lesssim m_a \lesssim 15$ GeV

*CMS-PAS-HIG-18-006*



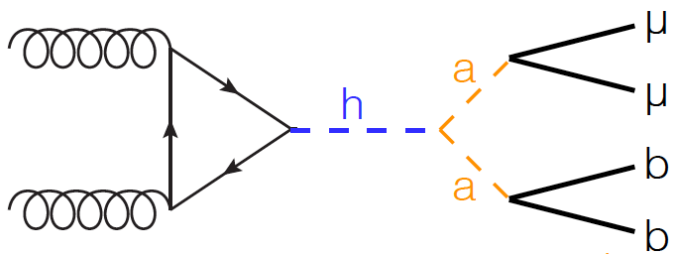

Signal template assumes BR(h→aa→4τ)=20%



# h→aa→2μ2b

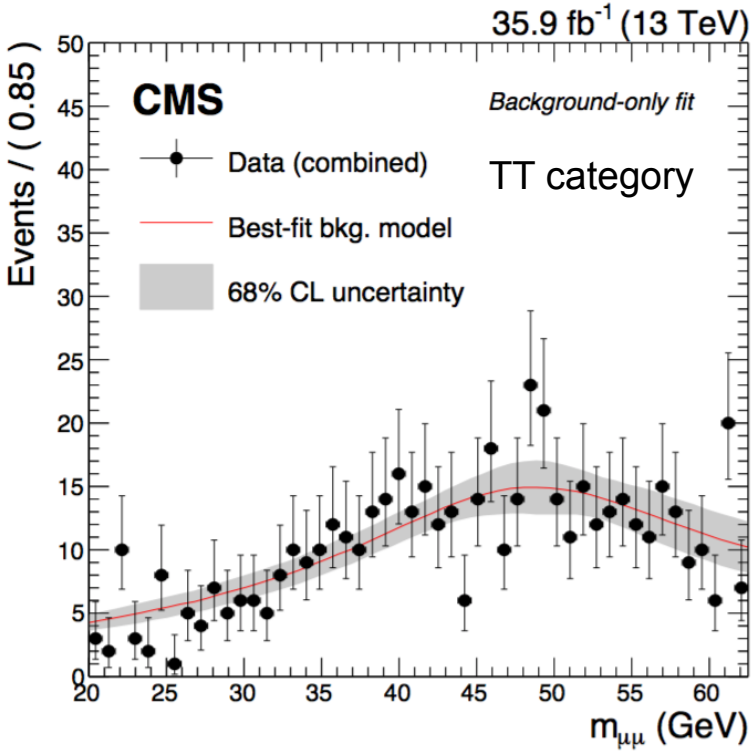
Strategy:

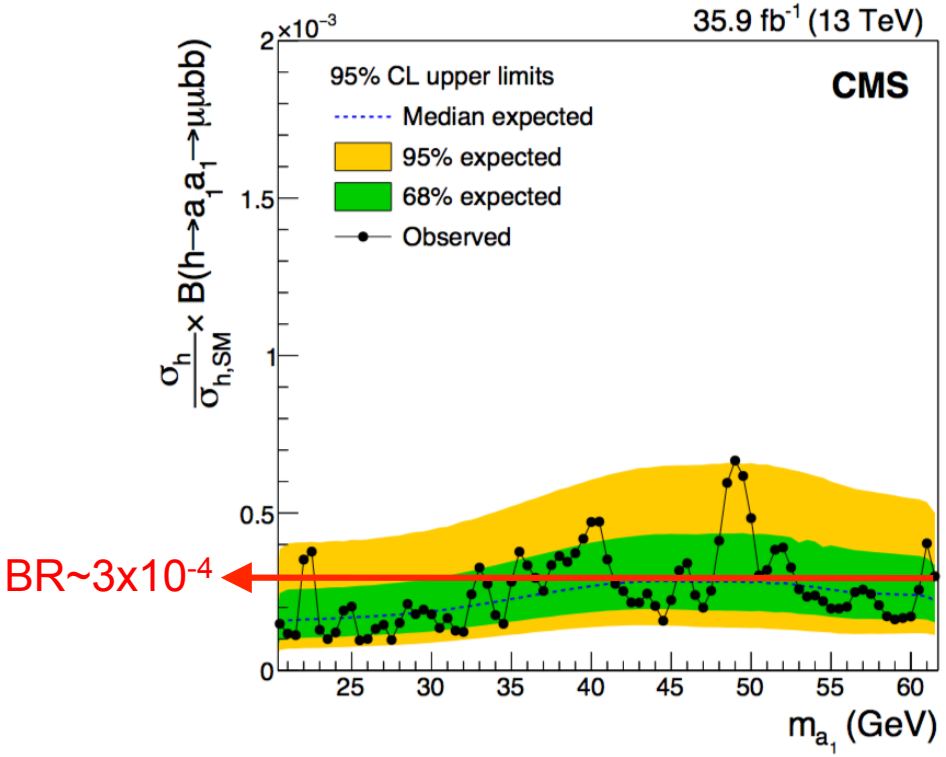
- Select events with 2 muons and 2 b-jets.
- Apply cut on chi2 requiring $m_{\mu\mu}$~$m_{bb}$ and $m_{\mu\mu bb}$~$m_h$ within resolution.
- Search for excesses in $m_{\mu\mu}$ spectrum, separately in three b-tagging categories.
- Main backgrounds Z/γ*+jets and $t\bar{t}$, parameterized from data.




**Target**: $2m_b \lesssim m_a \lesssim m_h/2$

*arXiv:1812.06359*

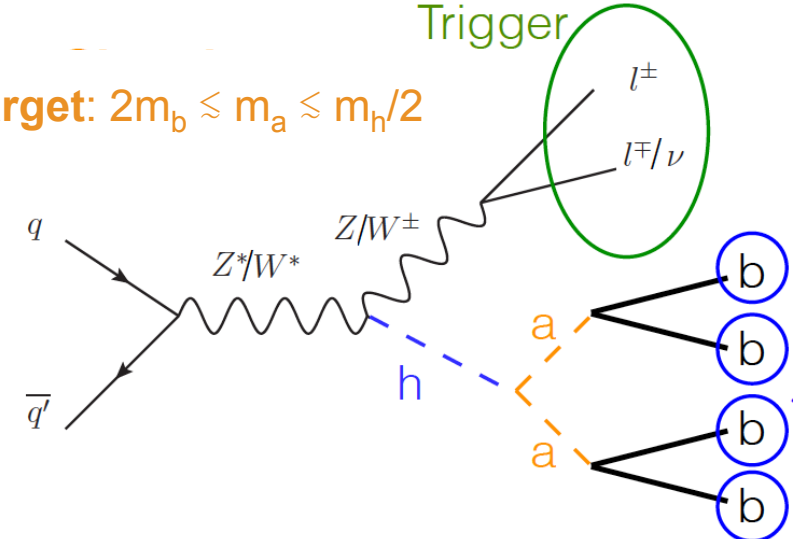


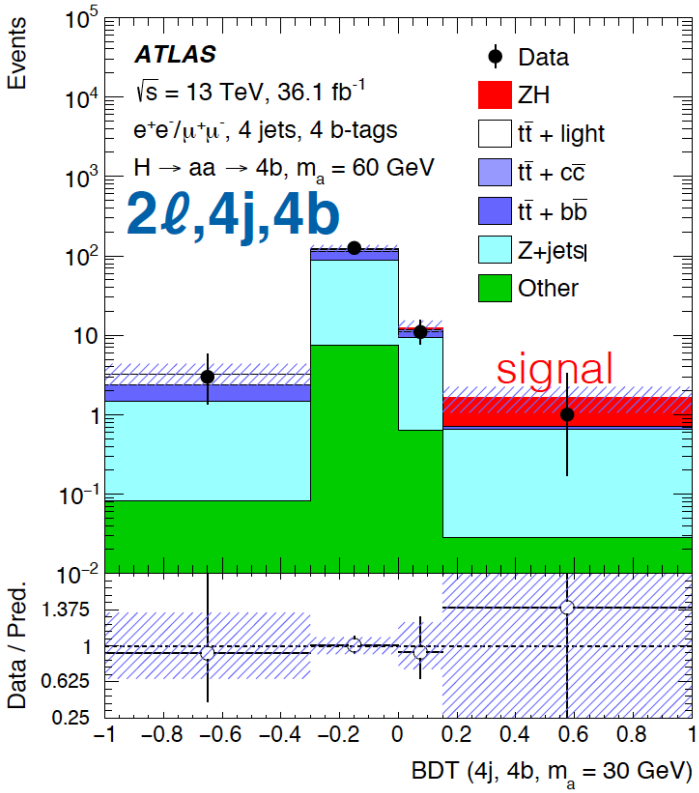



# h→aa→4b

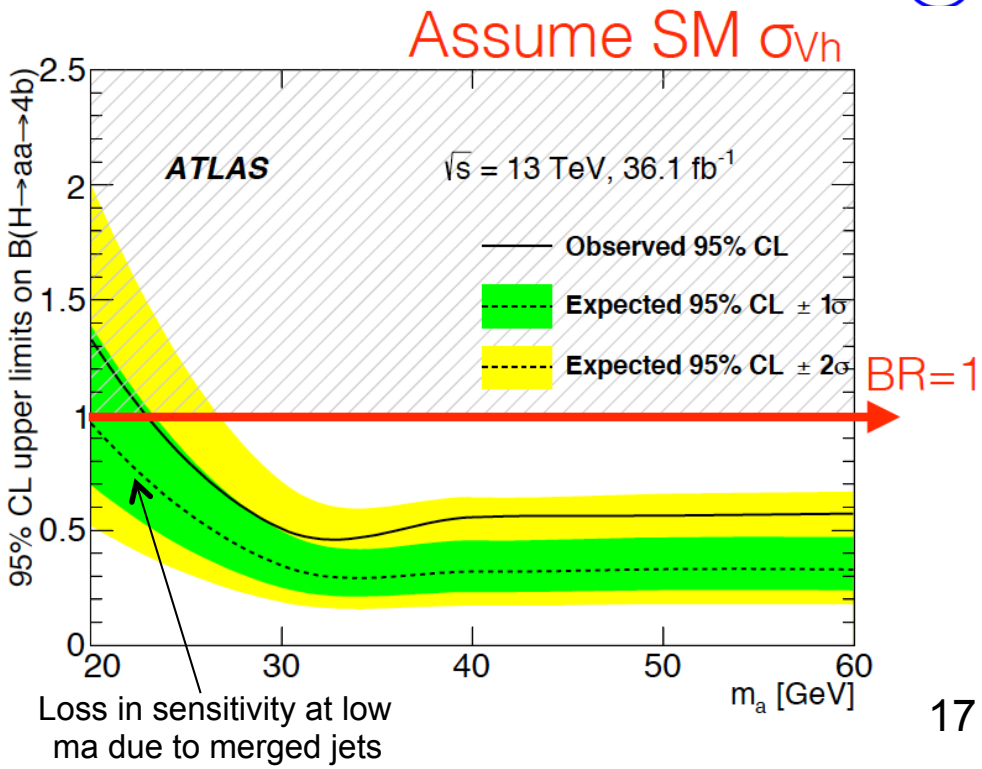
Strategy:

- Focus on Wh/Zh production modes.
- Select events with 1/2 leptons and 3/4 b-jets.
- Use MVA technique and complex background modeling.
- Main backgrounds Z+heavy-flavor and $t\bar{t}$+heavy-flavor.

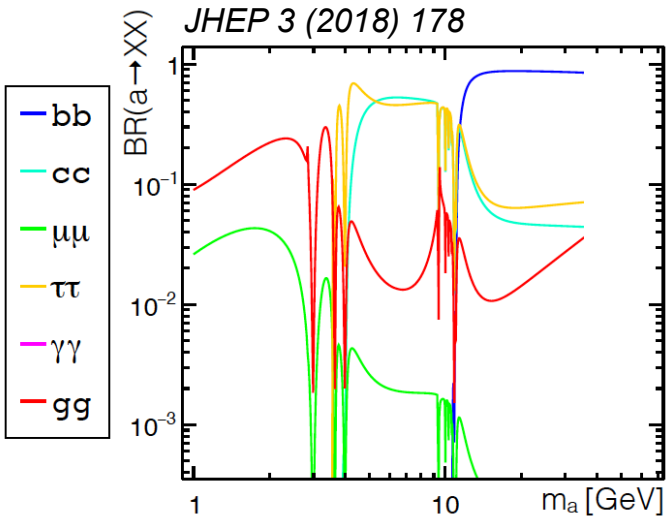



*arXiv:1806.07355*

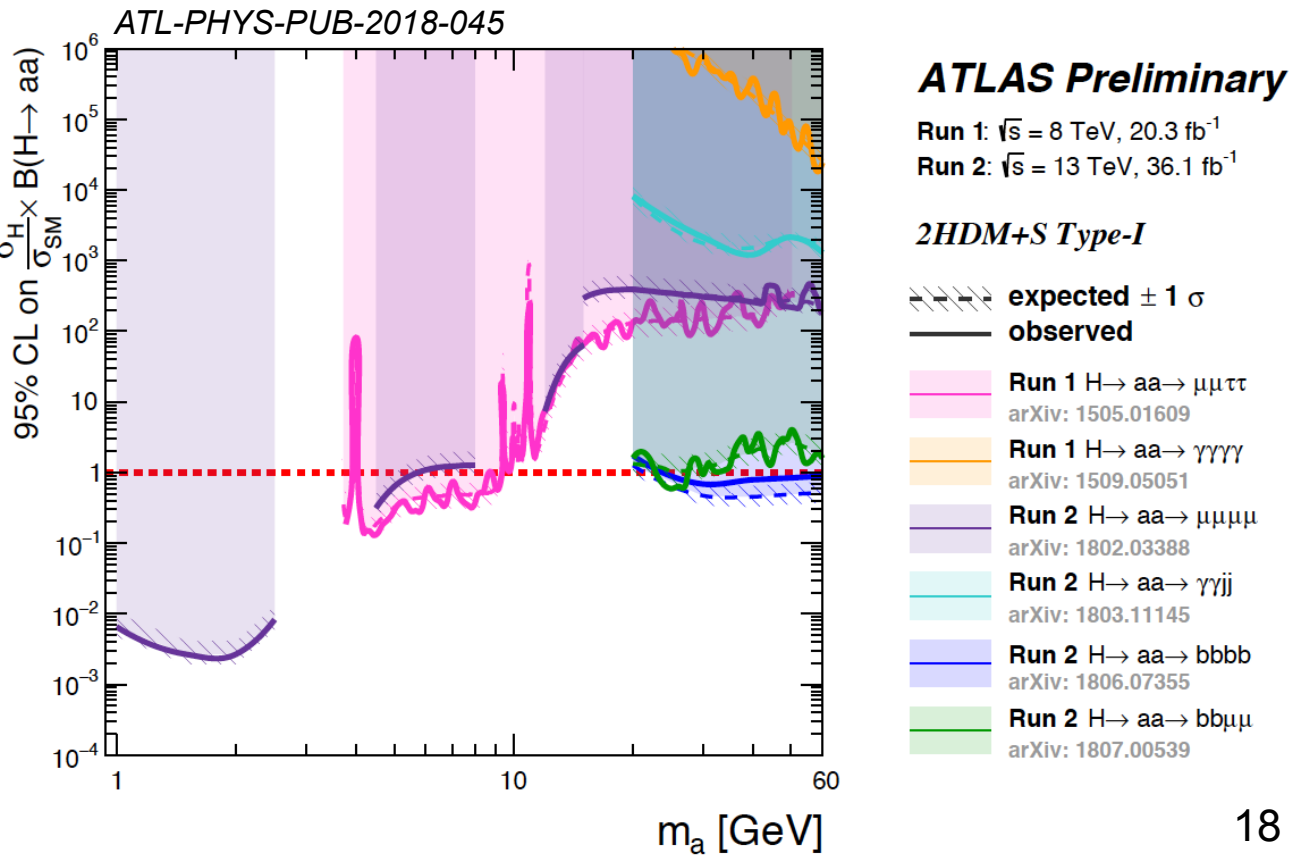


# Interpretation: 2HDM+S Type-I




Interpretation is model dependent:

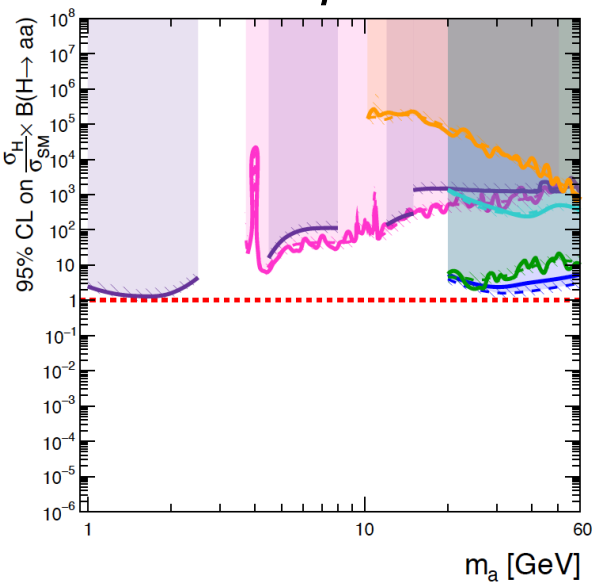
➔ need to assume a given BR(a→XX)

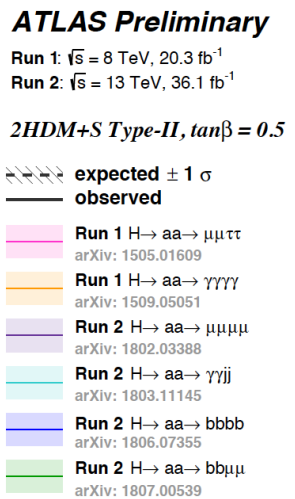


# Interpretation: 2HDM+S Type-II

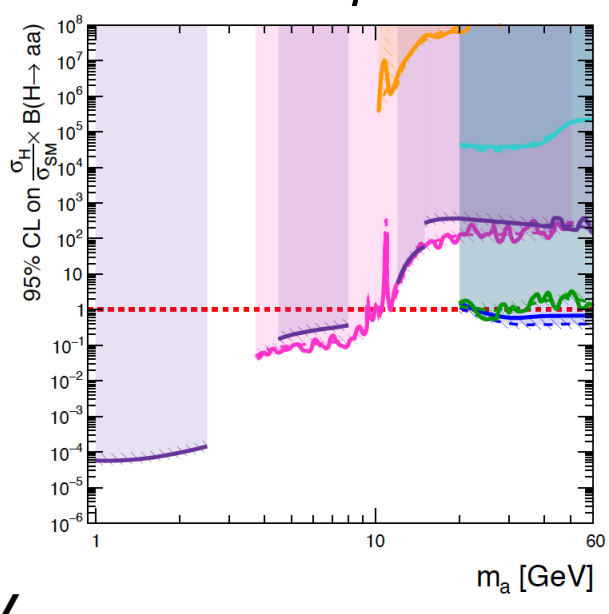
ATL-PHYS-PUB-2018-045

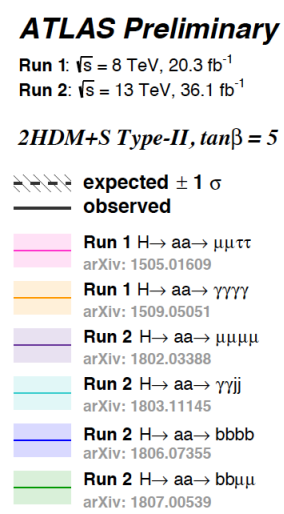
## $\tan\beta$=0.5



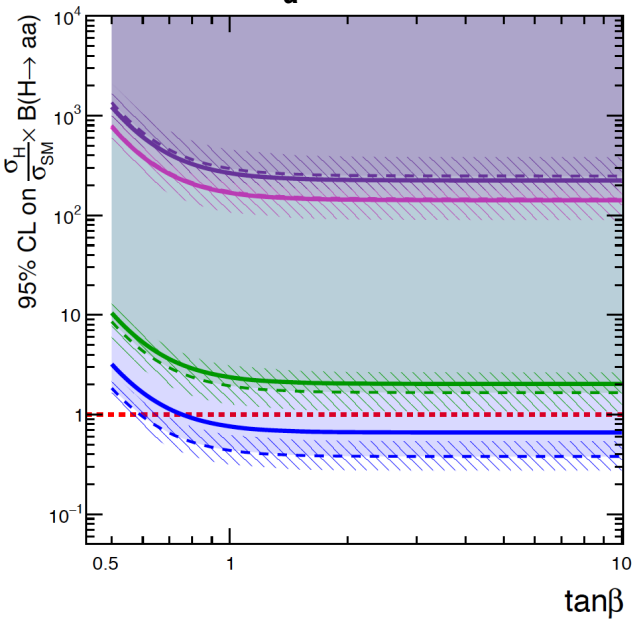



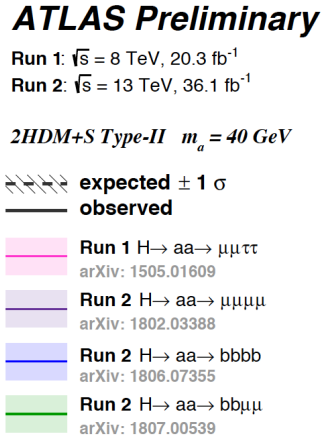

## $\tan\beta$=5




## $m_a$= 40 GeV

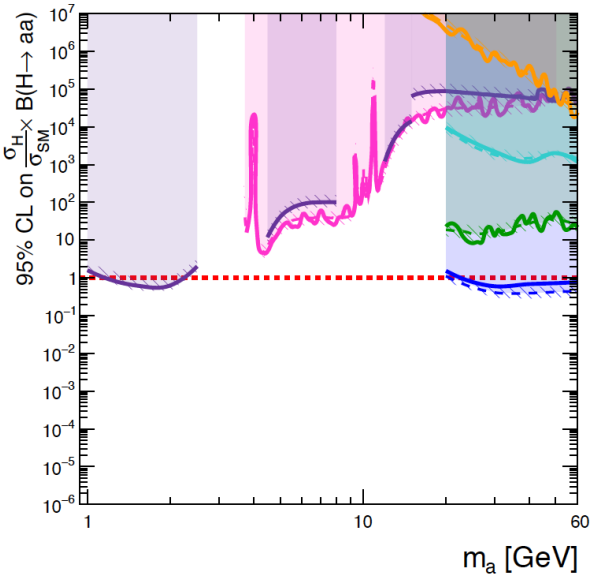


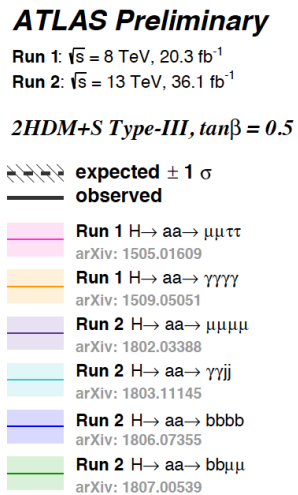



# Interpretation: 2HDM+S Type-III

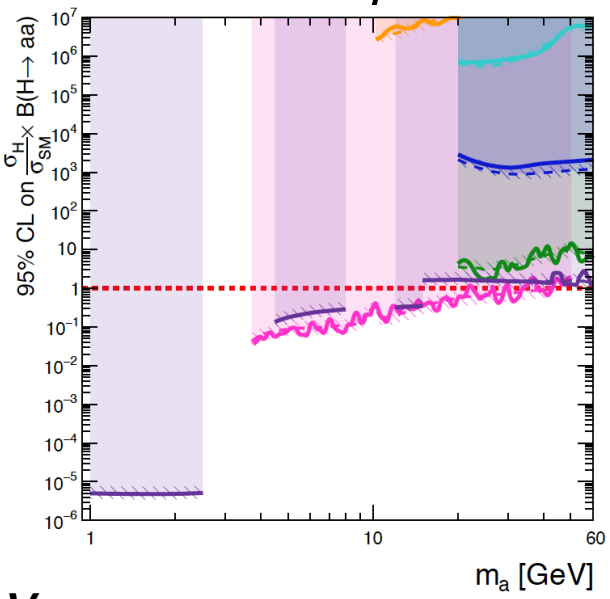
ATL-PHYS-PUB-2018-045

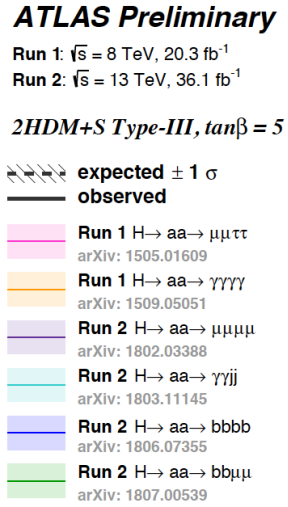
## tanβ=0.5



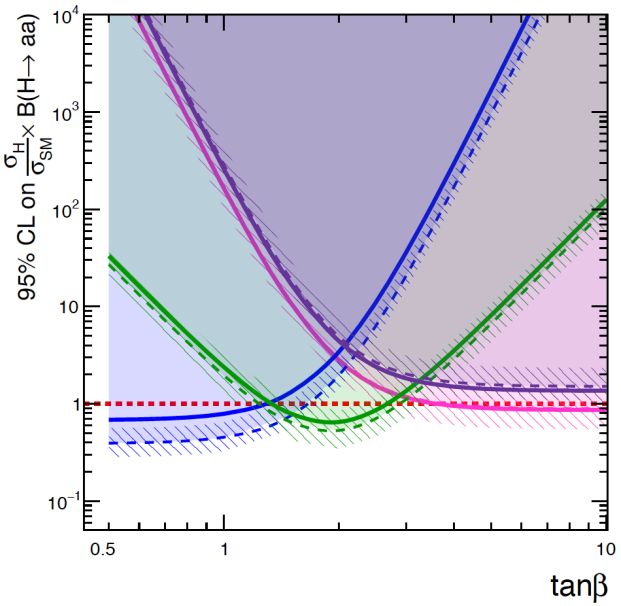



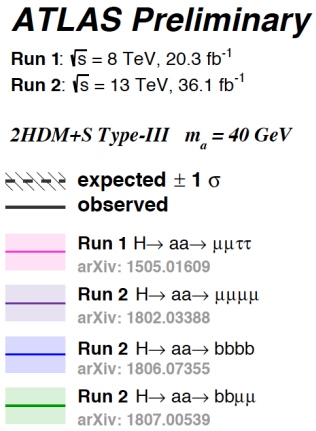

## tanβ=5




## $m_a$= 40 GeV

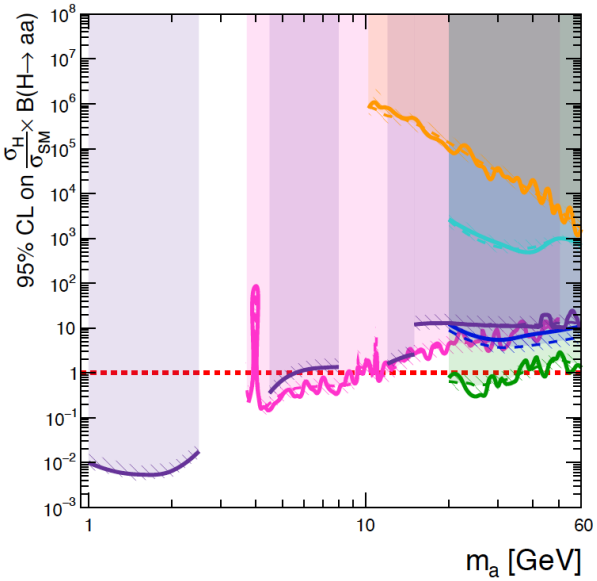


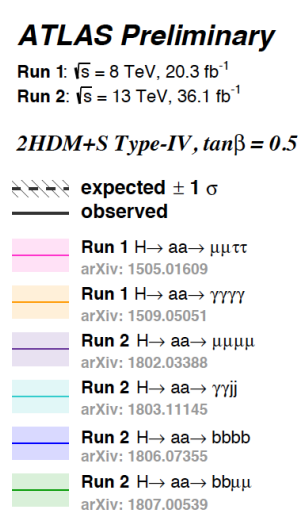



# Interpretation: 2HDM+S Type-IV

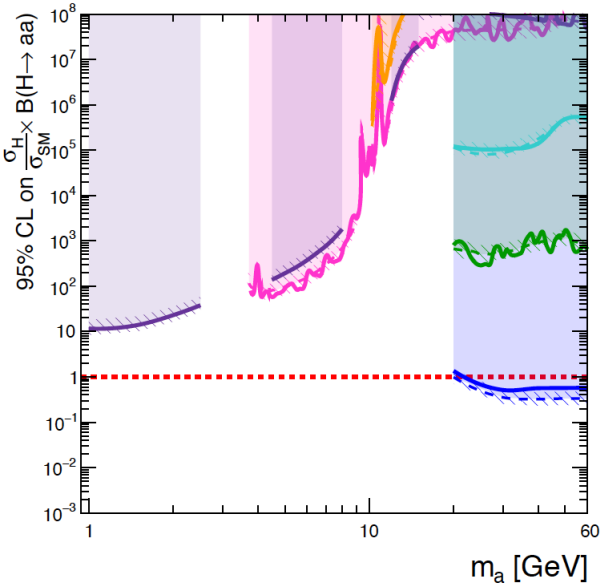
ATL-PHYS-PUB-2018-045

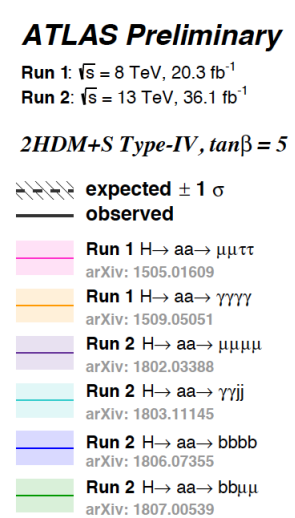
## $\tan\beta$=0.5



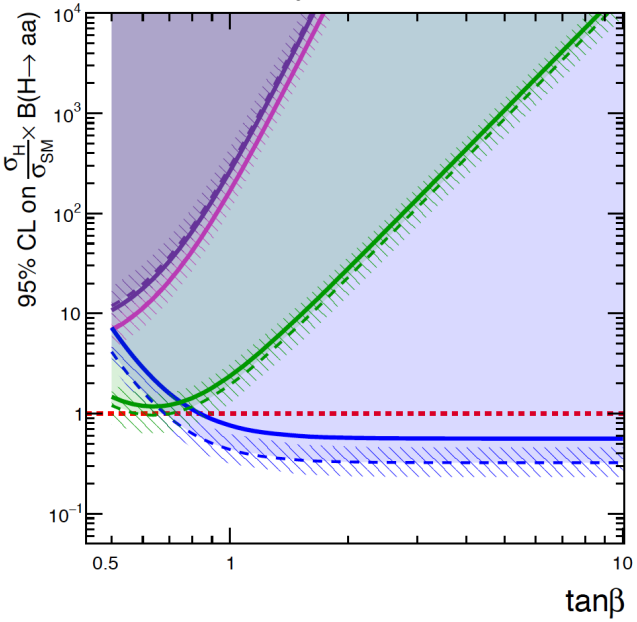



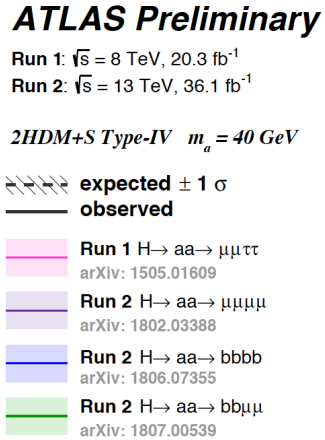

## $\tan\beta$=5




## $m_a$= 40 Gev

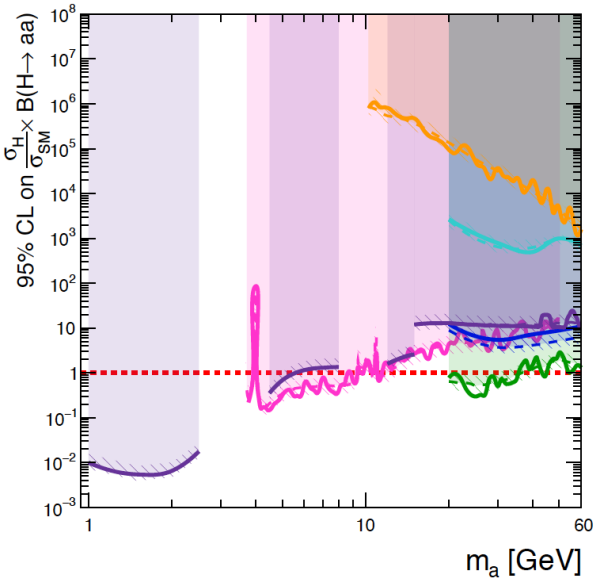


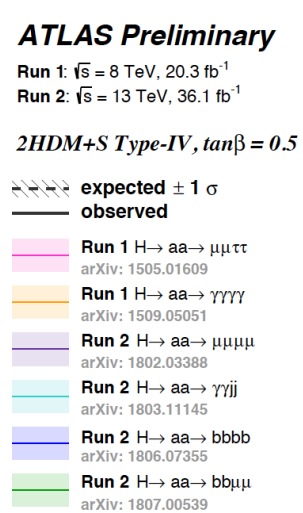



# Interpretation: 2HDM+S Type-IV

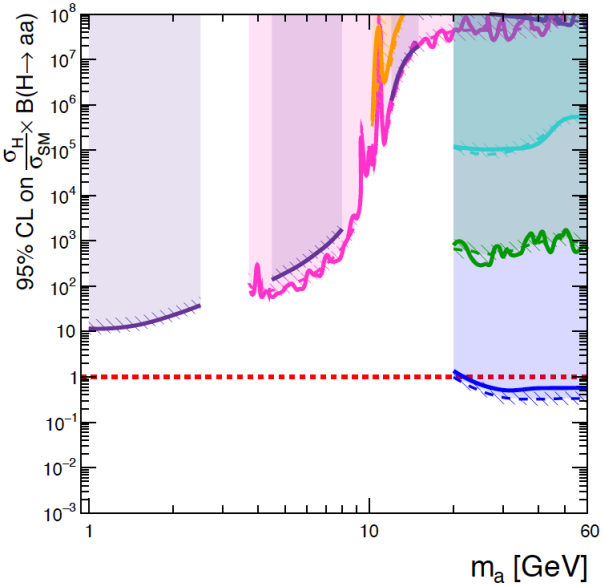
ATL-PHYS-PUB-2018-045

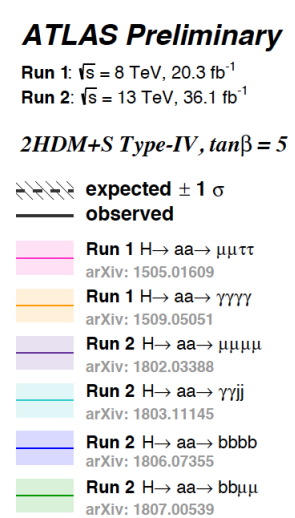
**tanβ=0.5**



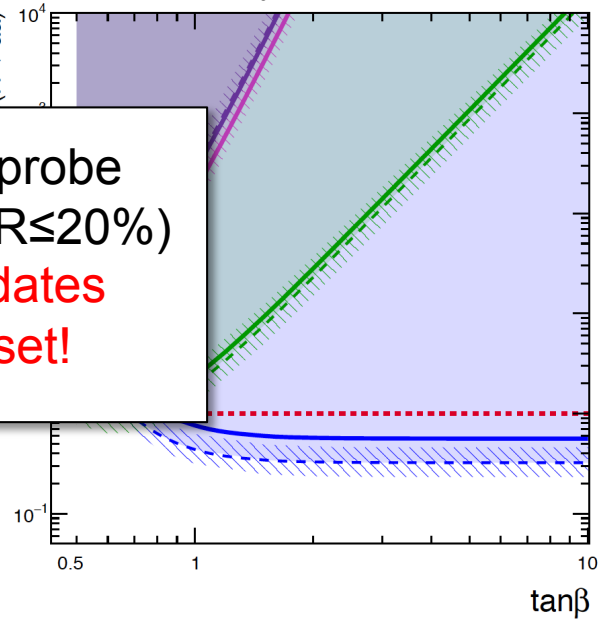



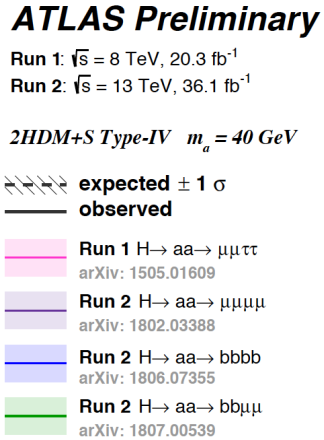

**tanβ=5**




**$m_a$= 40 Gev**



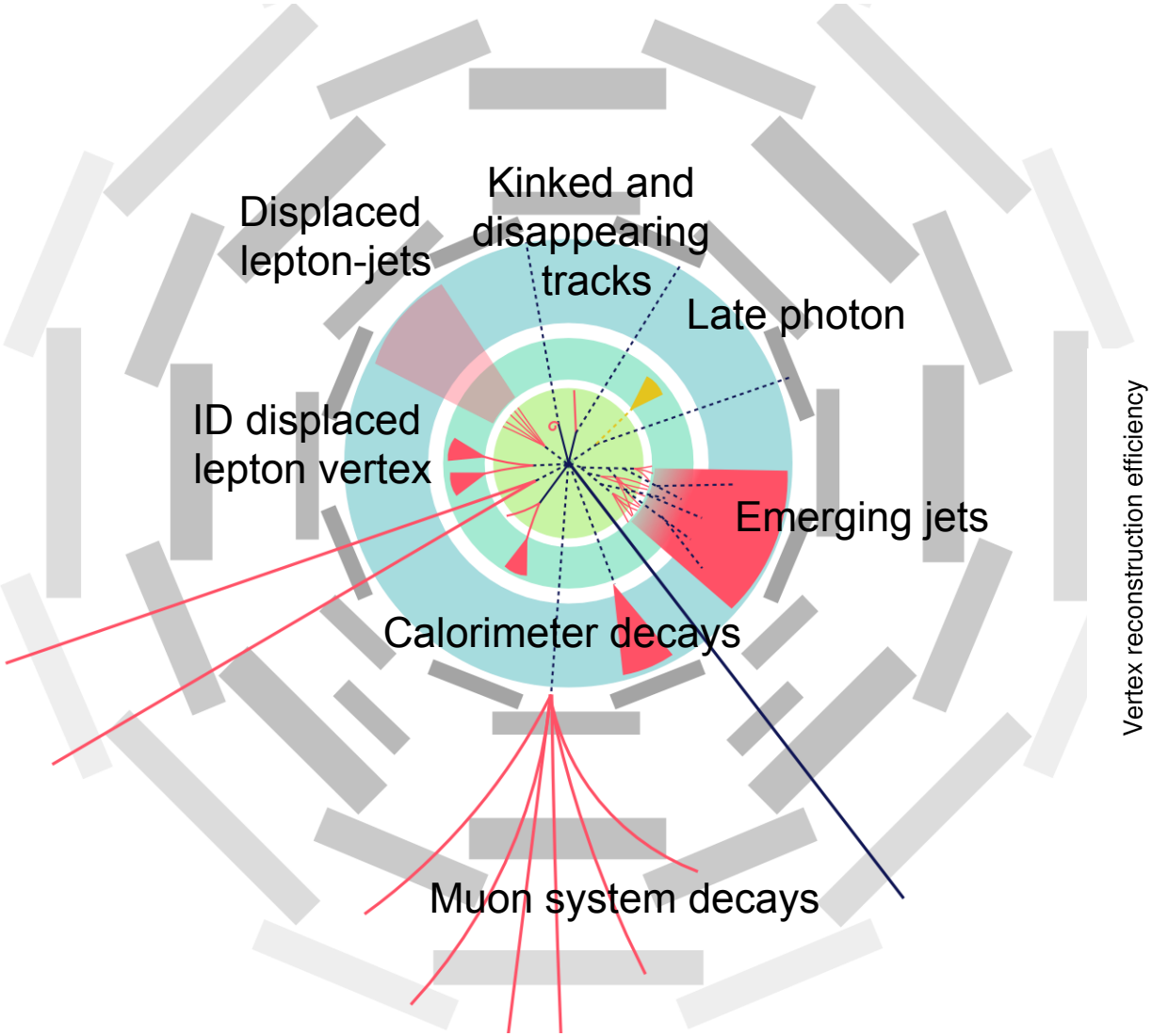




Analyses starting to probe interesting region (BR≤20%)
➔ stay tuned for updates with full 13 TeV dataset!

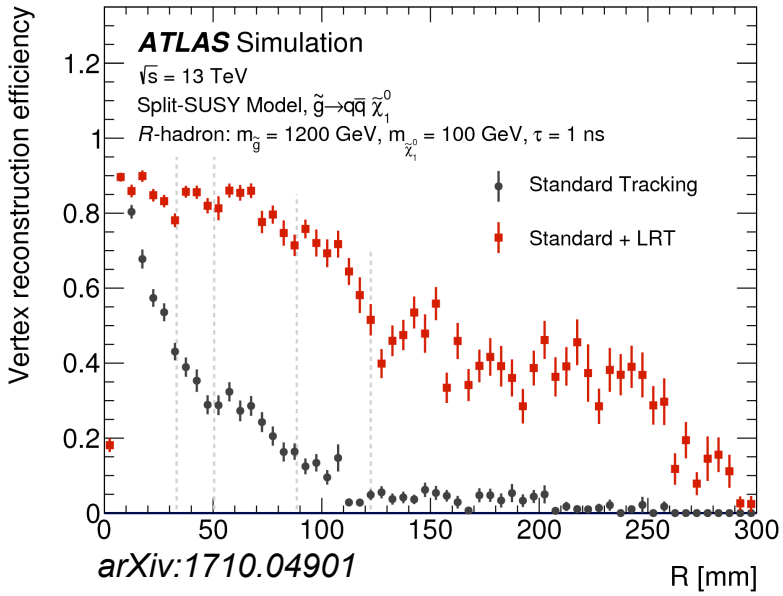
# h→LLP LLP

Many models motivating Higgs decay to long-lived particles (LLP).

➔ Multitude of signatures, most requiring dedicated reconstruction strategies and observables.



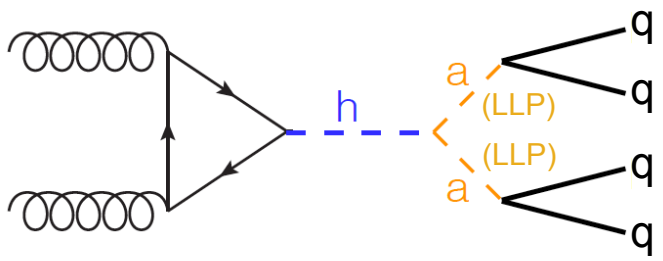

- Large-radius tracking
- Inner-detector tracklets
- Time-of-flight
- Dedicated processing and data formats
- …



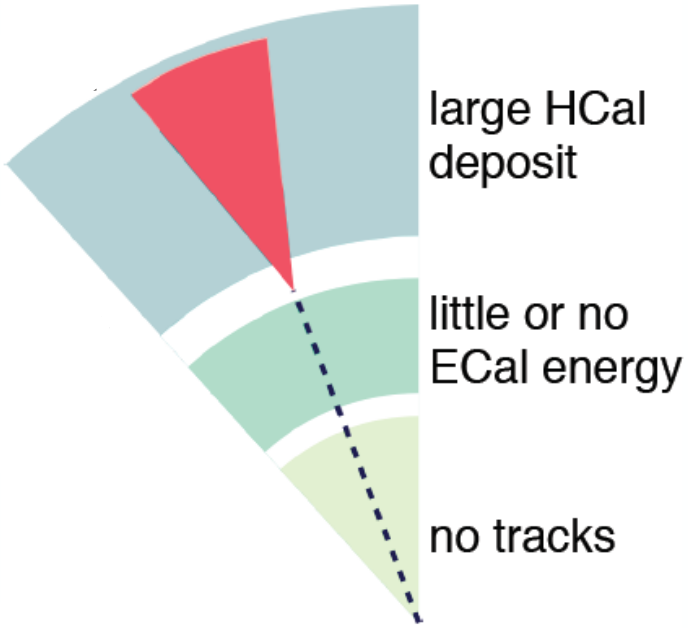
# h→displaced jets

Strategy:

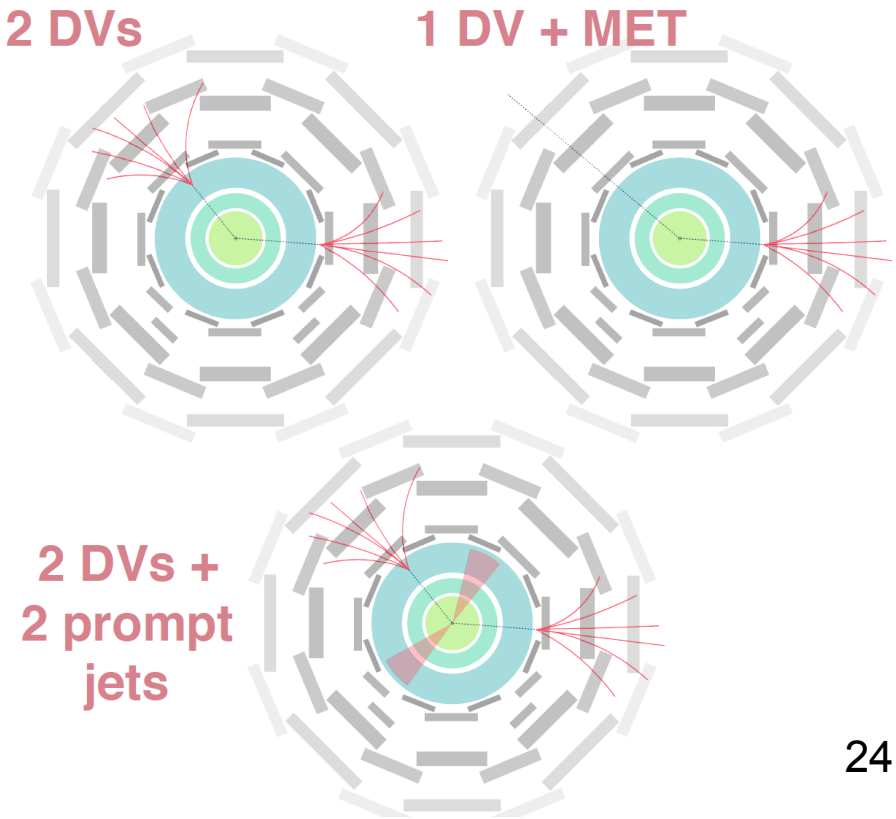
- Search for narrow jets with low ECal energy and no associated tracks.
- Search for multitrack DV in the muon system. No tracks in the inner detector nor calorimeter signals.




*arXiv:1902.03094*



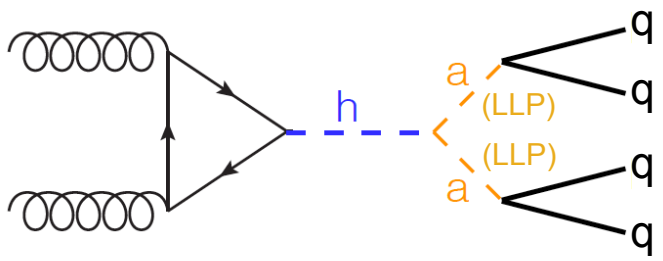

*arXiv:1811.07370*



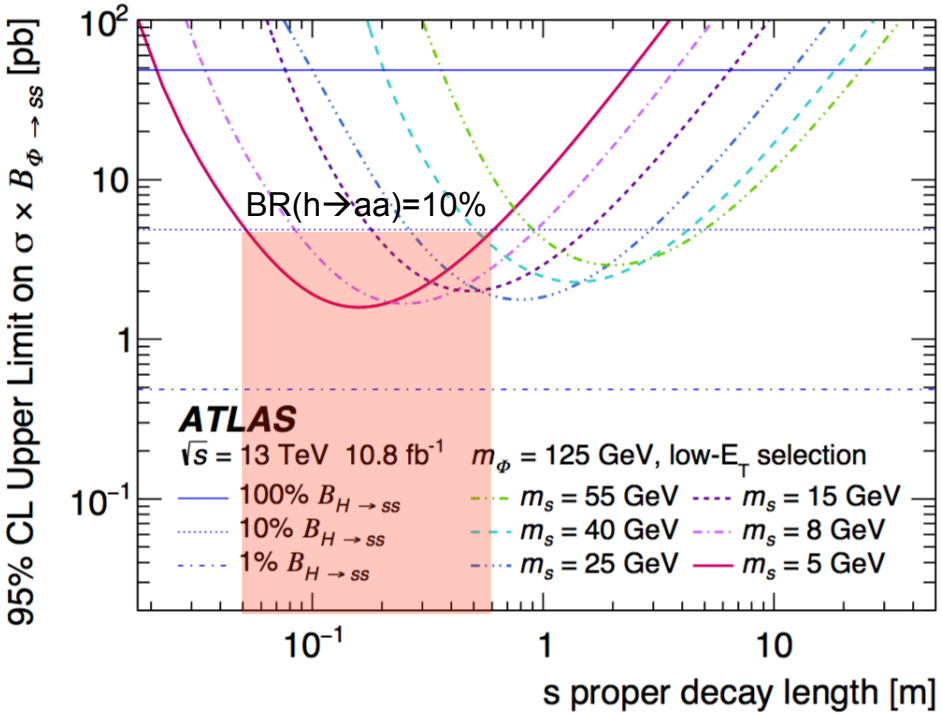
# h→displaced jets

Strategy:

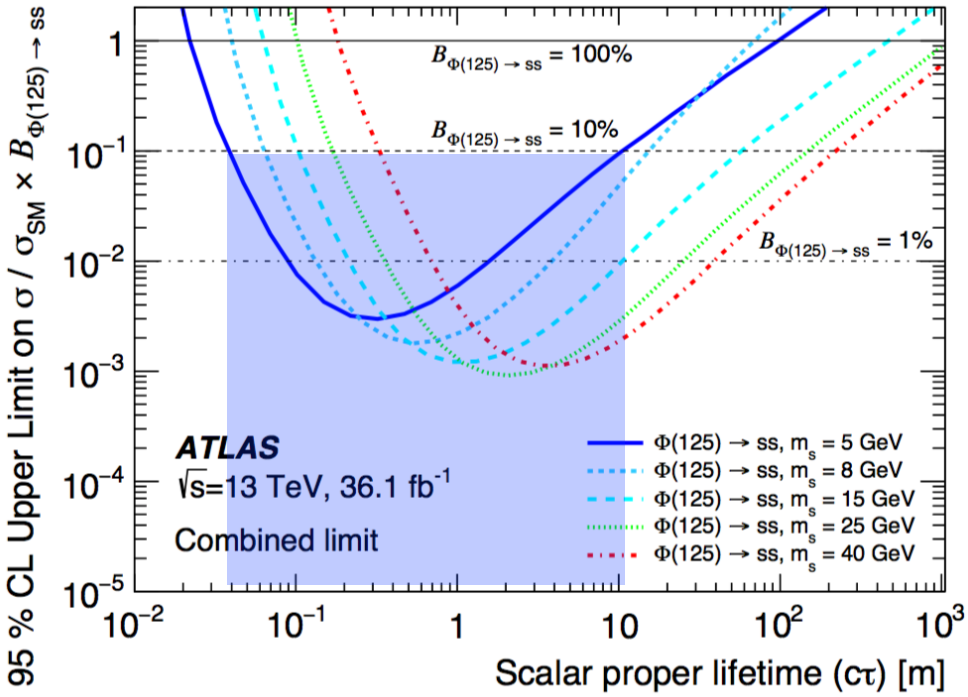
- Search for narrow jets with low ECal energy and no associated tracks.
- Search for multitrack DV in the muon system. No tracks in the inner detector nor calorimeter signals.



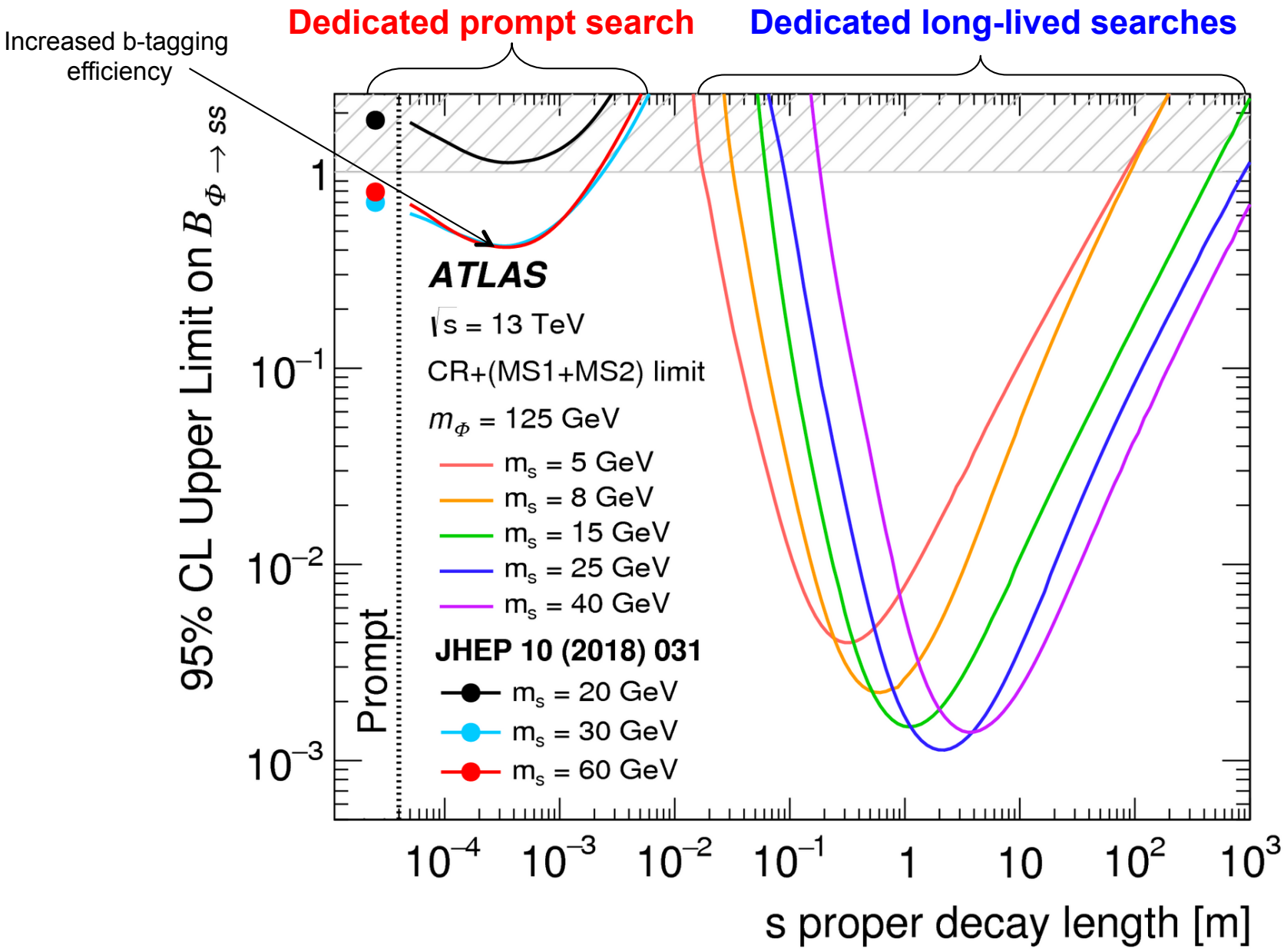

*arXiv:1902.03094*



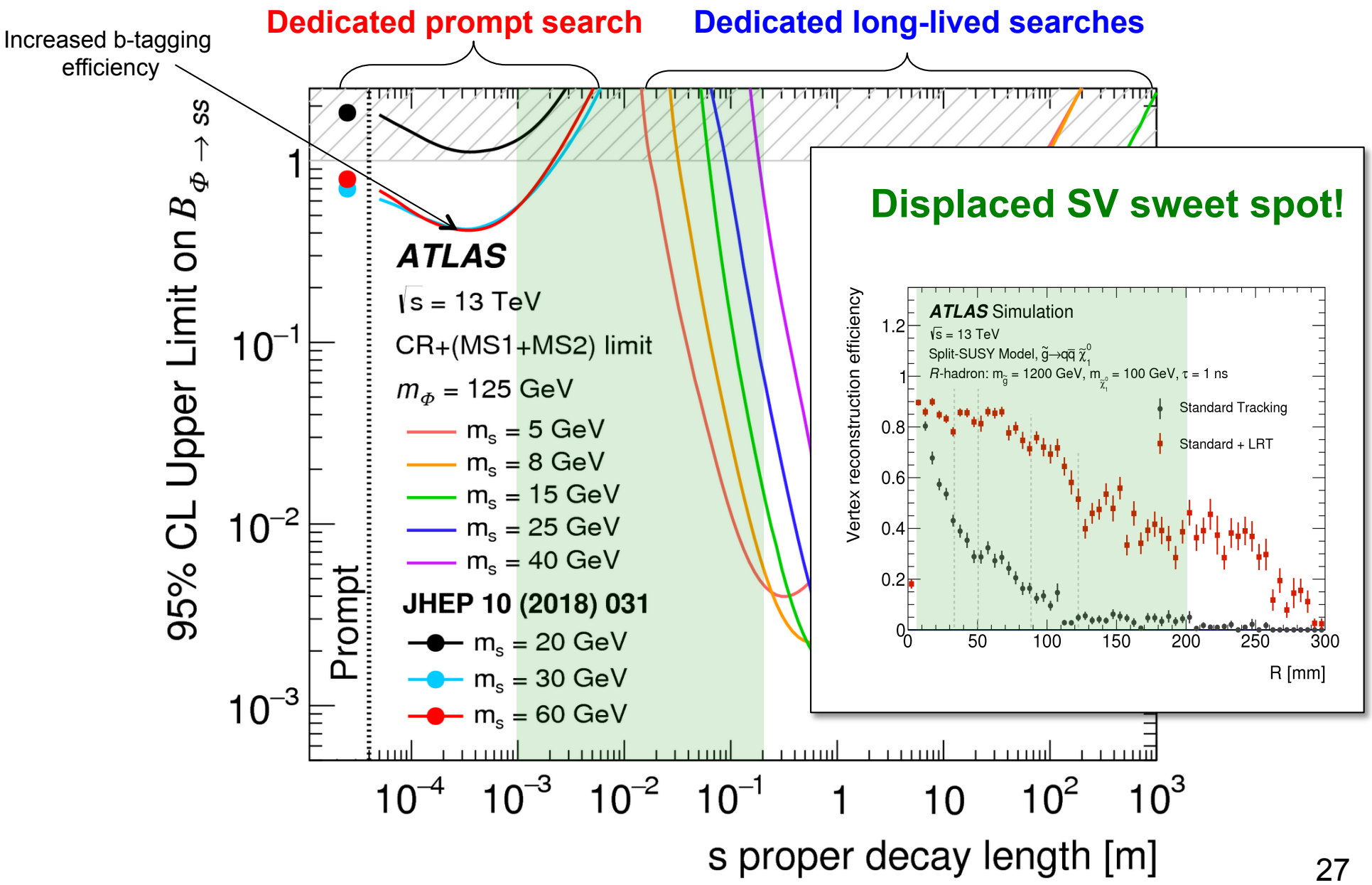

*arXiv:1811.07370*



# h→aa→4b: long-lived interpretation



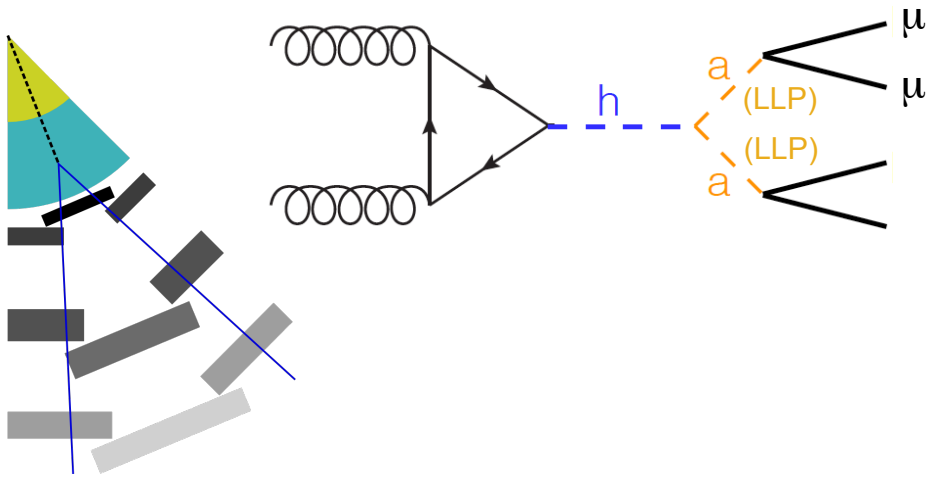
# h→aa→4b: long-lived interpretation



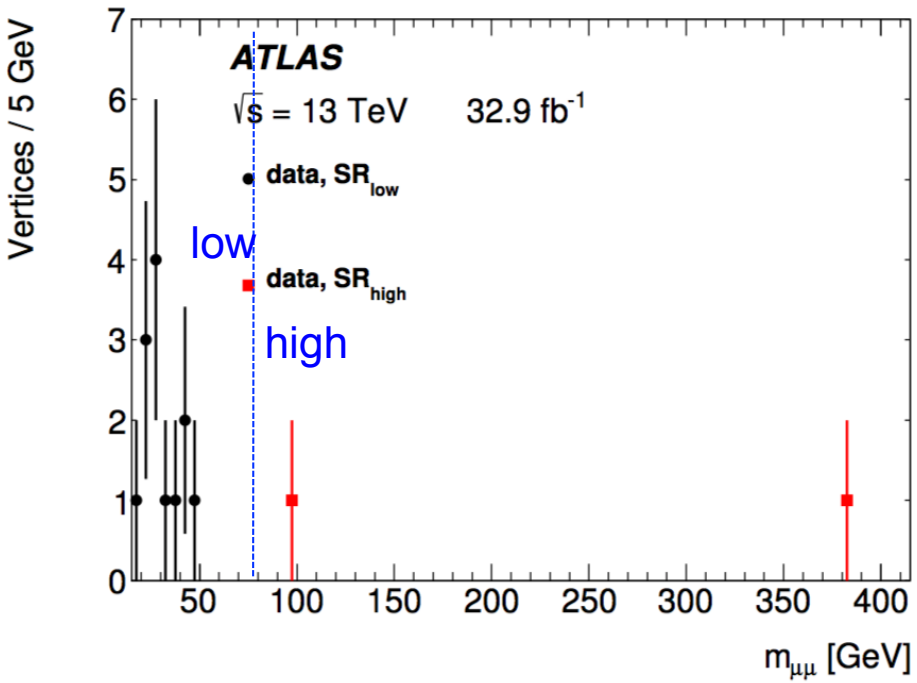
# h→displaced μμ + X

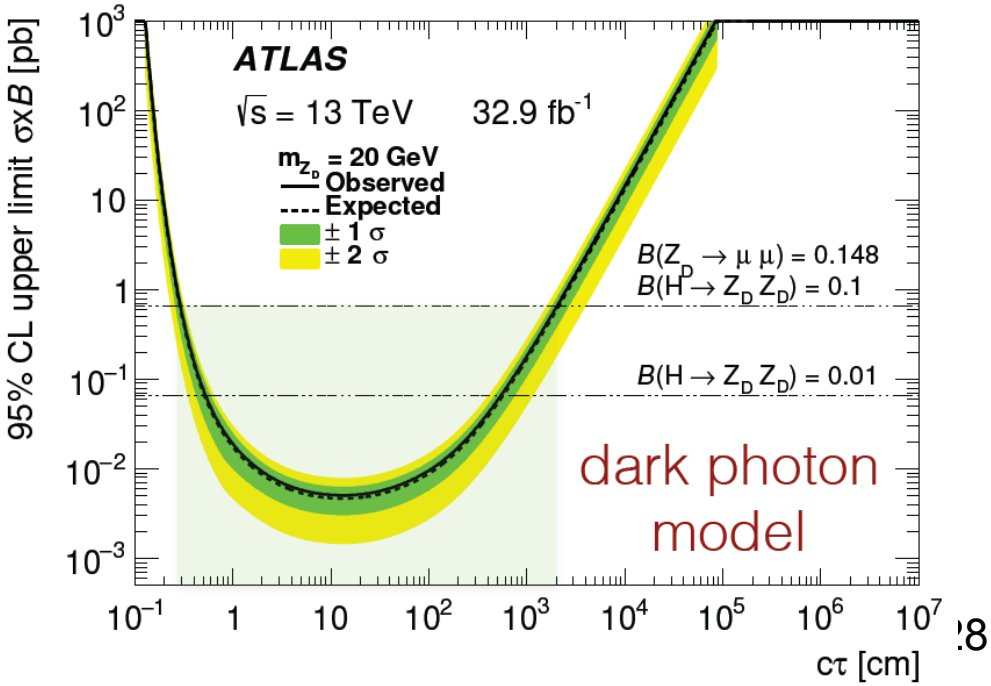
Strategy:

- Search events with muon-system-only muon candidates compatible with originating from a common displaced vertex (DV).
- In ATLAS can detect OS dimuon DVs in large decay volume ($|r_{vtx}|$<400 cm and $|z_{vtx}|$< 600 cm).
- Low backgrounds.




*arXiv:1808.03057*



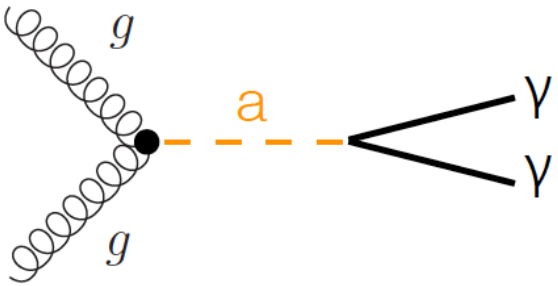



# Direct or associated production

# Direct production: a→γγ

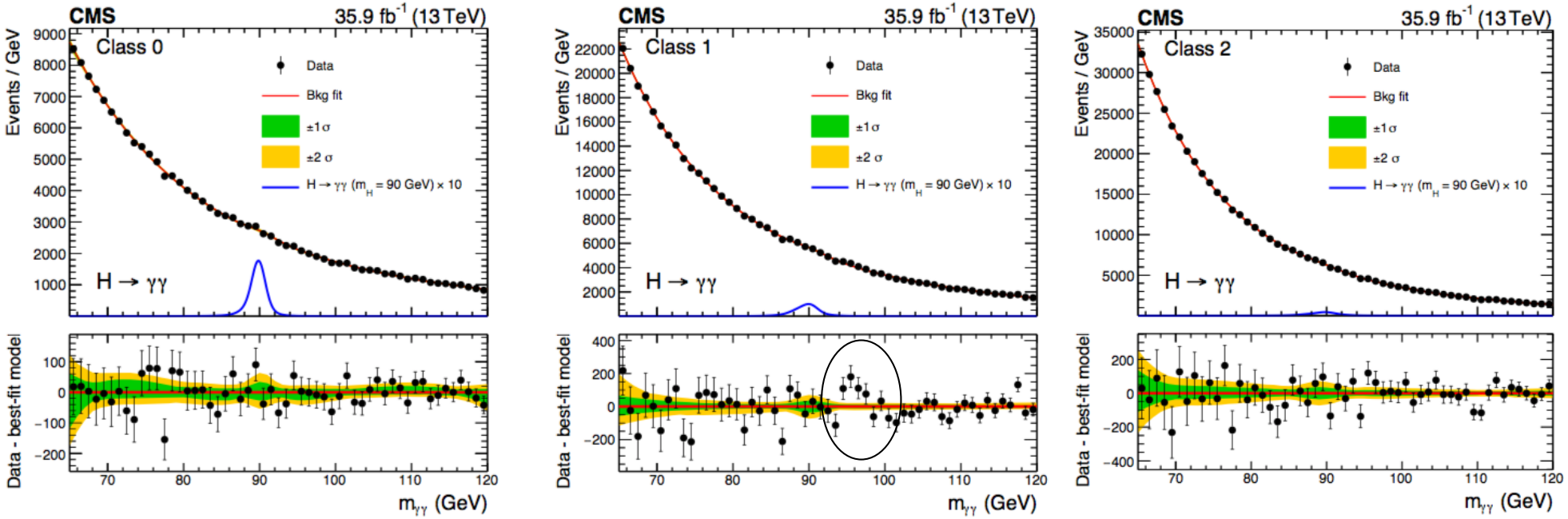
Strategy:

- Search for a→γγ resonance in $m_{\gamma\gamma}$ spectrum.
- Low-mass reach limited by diphoton trigger.
- Define event categories according to expected sensitivity (ATLAS: conversions, CMS: γγ kinematics, mass resolution, γID BDT output).




**Target**: ~70 ≲ $m_a$ ≲ 110 GeV

*arXiv:1811.08459*



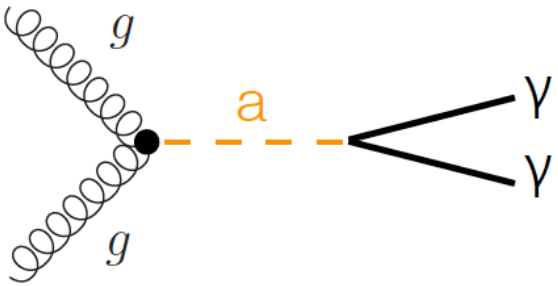

Expected sensitivity

Similar picture in Run 1

# Direct production: a→γγ

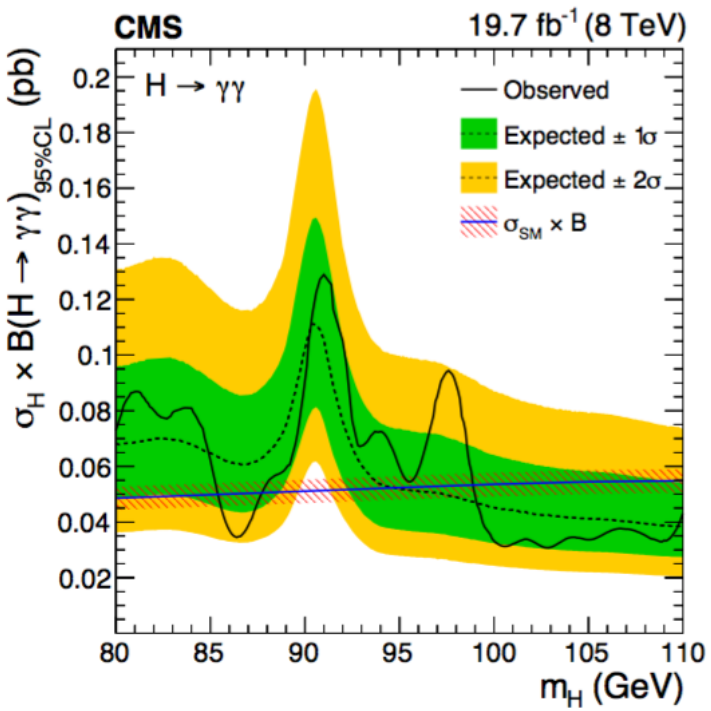
Strategy:

- Search for a→γγ resonance in $m_{\gamma\gamma}$ spectrum.
- Low-mass reach limited by diphoton trigger.
- Define event categories according to expected sensitivity (ATLAS: conversions, CMS: γγ kinematics, mass resolution, γID BDT output).



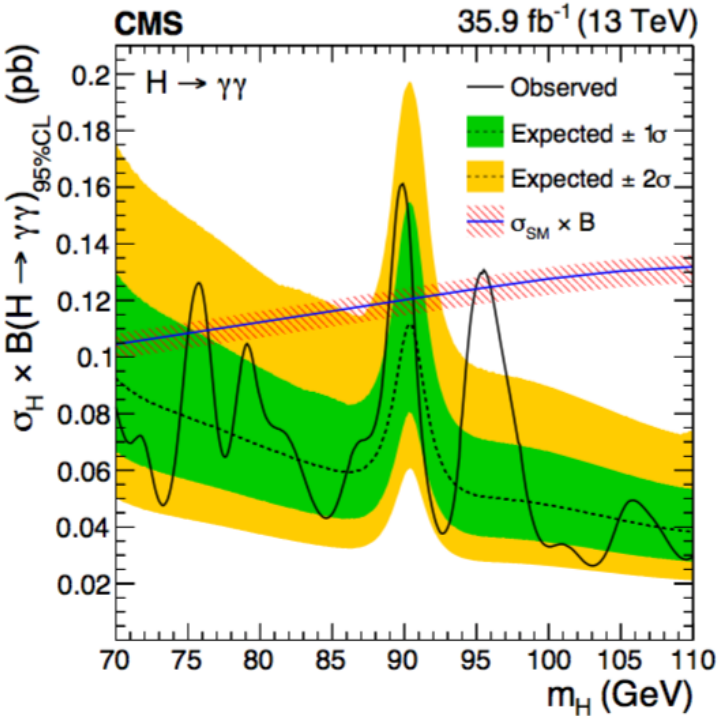

**Target**: ~70 ≲ $m_a$ ≲ 110 GeV

*arXiv:1811.08459*




Local significance @ 97.7 GeV: 2.0σ

*arXiv:1811.08459*

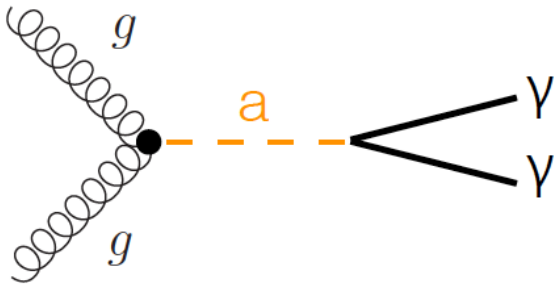



Local (global) significance @ 95.3 GeV : 2.90σ (1.47σ)

# Direct production: a→γγ

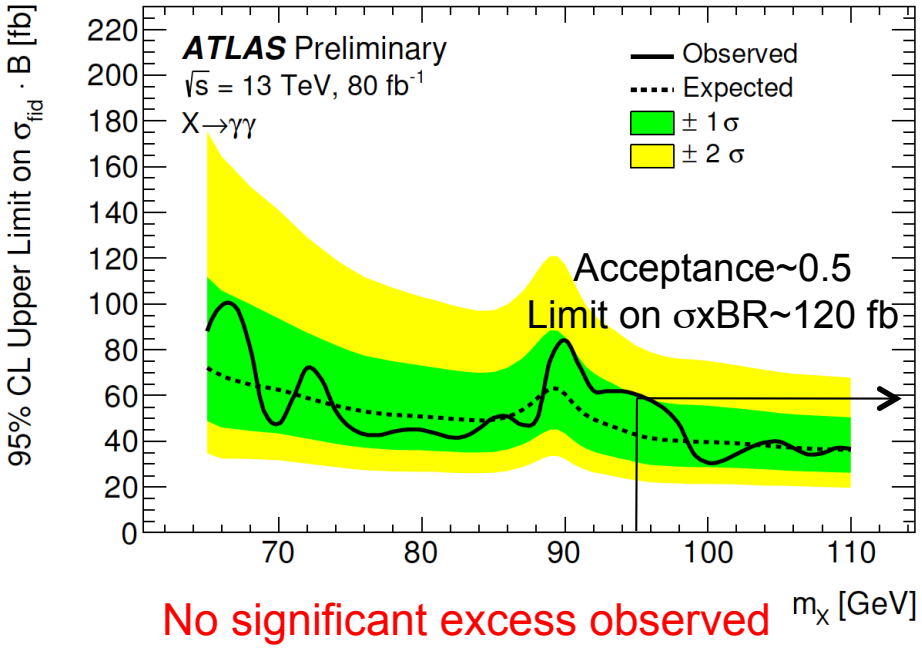
Strategy:

- Search for a→γγ resonance in $m_{\gamma\gamma}$ spectrum.
- Define event categories according to expected sensitivity (ATLAS: conversions, CMS: γγ kinematics, mass resolution, γID BDT output).
- Low-mass reach limited by diphoton trigger.



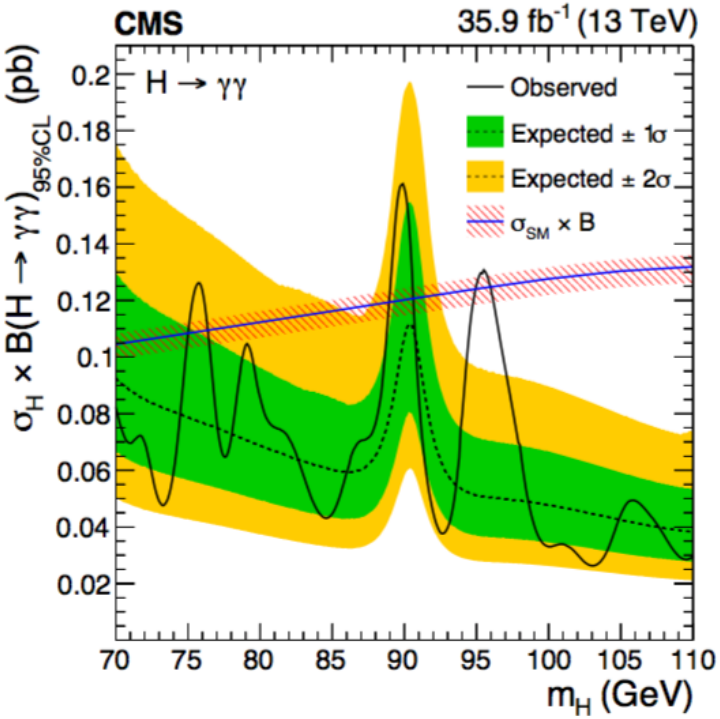

**Target**: ~70 ≲ $m_a$ ≲ 110 GeV

*ATLAS-CONF-2018-025*




No significant excess observed
**but inconclusive…**

*arXiv:1811.08459*

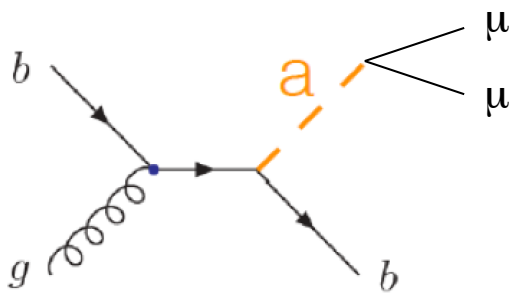



Local (global) significance @ 95.3 GeV : 2.90σ (1.47σ)

# Associated production: a(→μμ)+jets

Strategy:

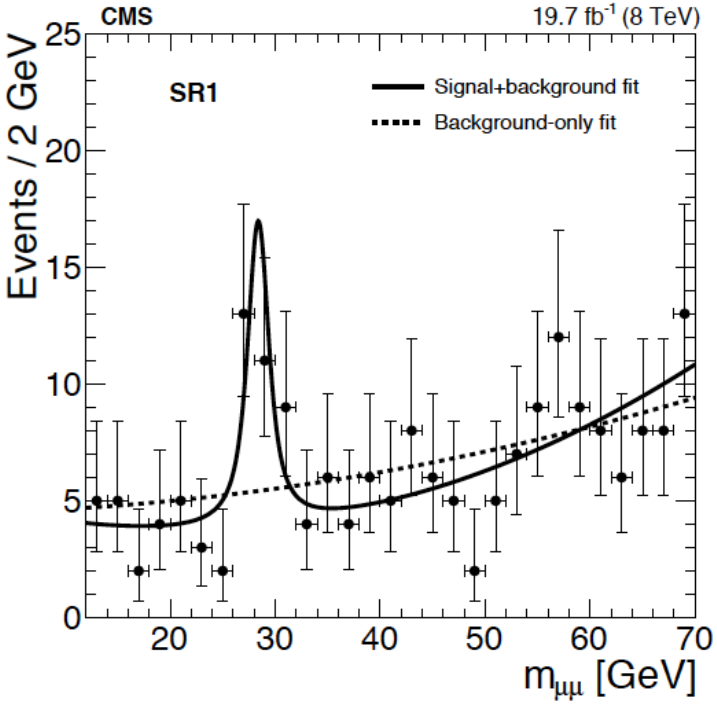
- Search for a→μμ in association with a b-jet and an additional jet.
- Two signal regions based on additional jet: SR1: forward (|η|>2.4); SR2: central (|η|<2.4).
- Main backgrounds from low-mass Drell-Yan and $t\bar{t}$.



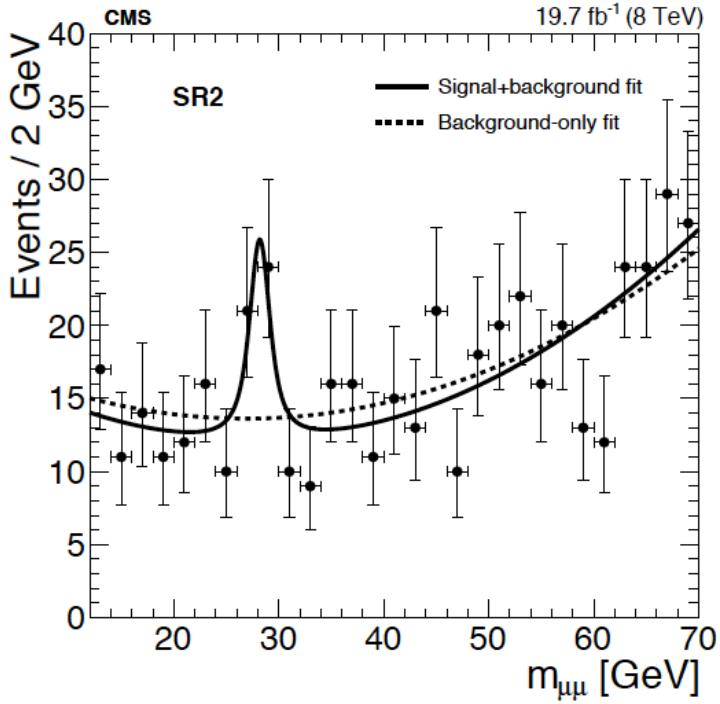

**Target**: ~12 ≲ $m_a$ ≲ 70 GeV

Excess at a mass of ~28 GeV observed in Run 1…

*arXiv:1808.01890*




Local significance: 4.2σ

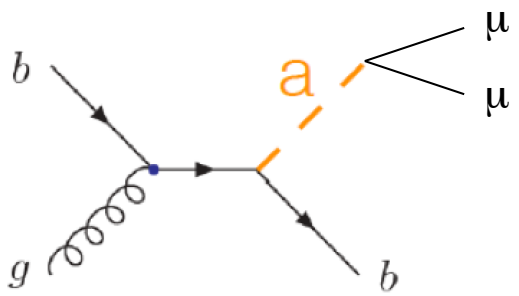



Local significance: 2.9σ

# Associated production: a(→μμ)+jets

Strategy:

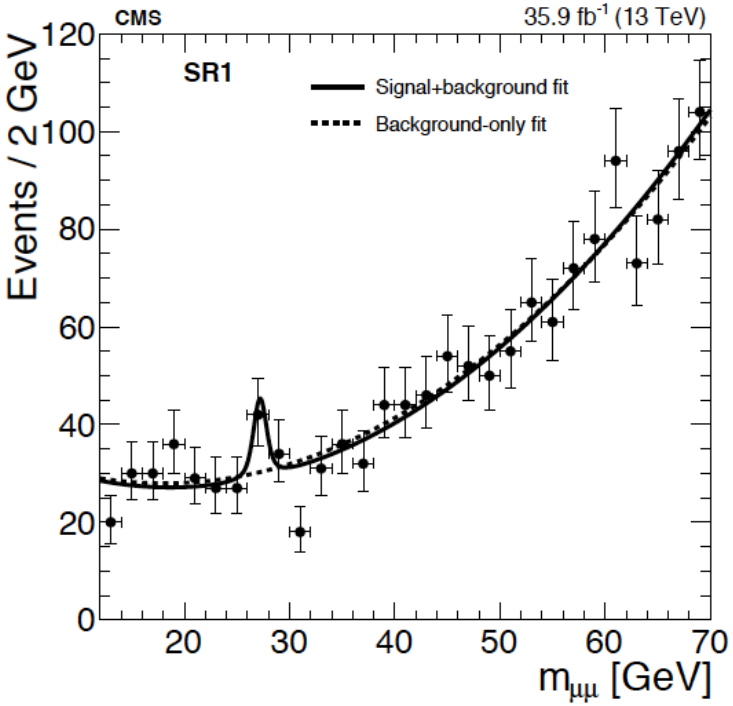
- Search for a→μμ in association with a b-jet and an additional jet.
- Two signal regions based on additional jet:
  SR1: forward (|η|>2.4); SR2: central (|η|<2.4).
- Main backgrounds from low-mass Drell-Yan and $t\bar{t}$.



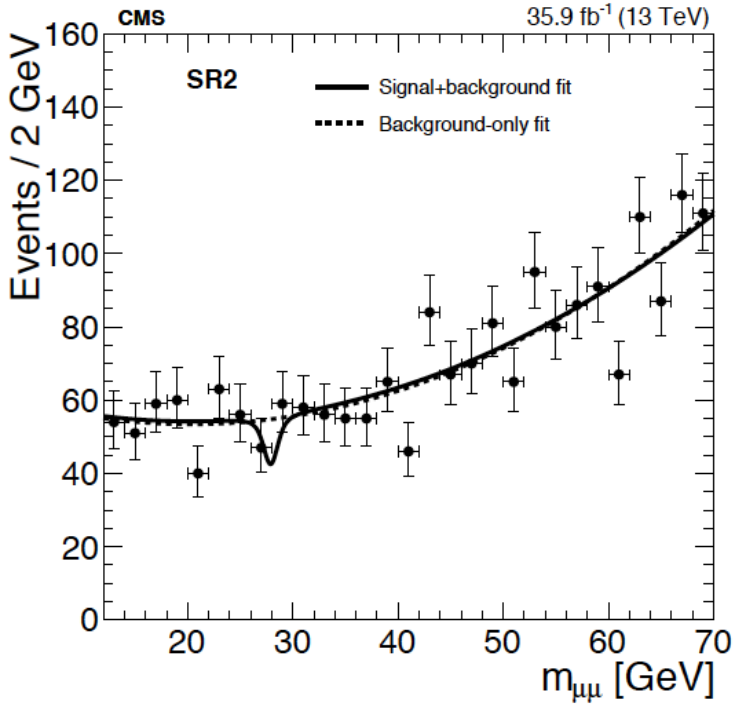

**Target**: ~12 ≲ $m_a$ ≲ 70 GeV

…but **not confirmed** in Run 2

*arXiv:1808.01890*




Local significance: 2.0σ

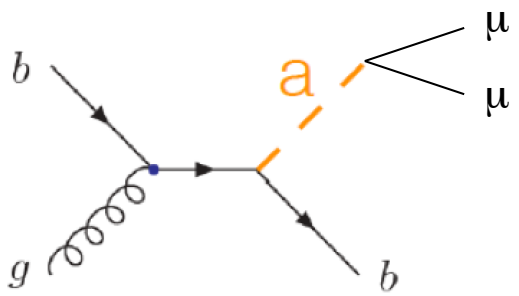



Local significance: -1.4σ

# Associated production: a(→μμ)+jets

Strategy:

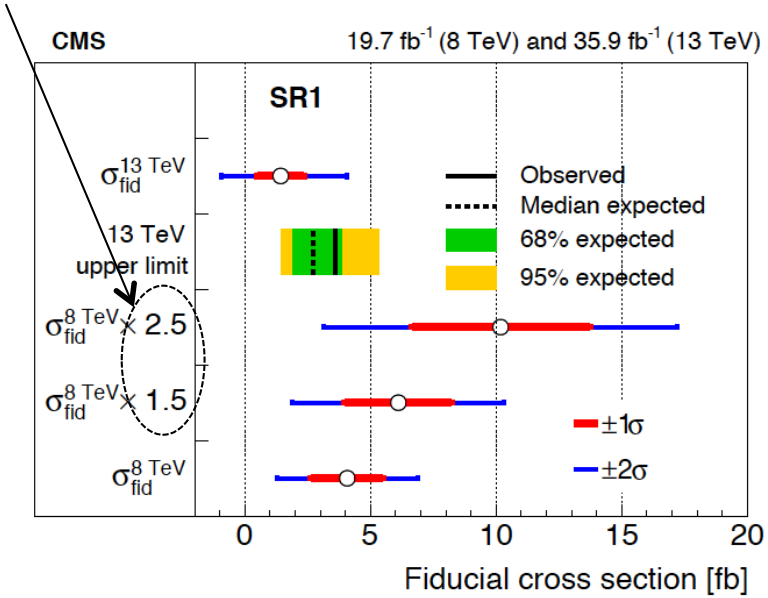
- Search for a→μμ in association with a b-jet and an additional jet.
- Two signal regions based on additional jet:
  SR1: forward (|η|>2.4); SR2: central (|η|<2.4).
- Main backgrounds from low-mass Drell-Yan and $t\bar{t}$.

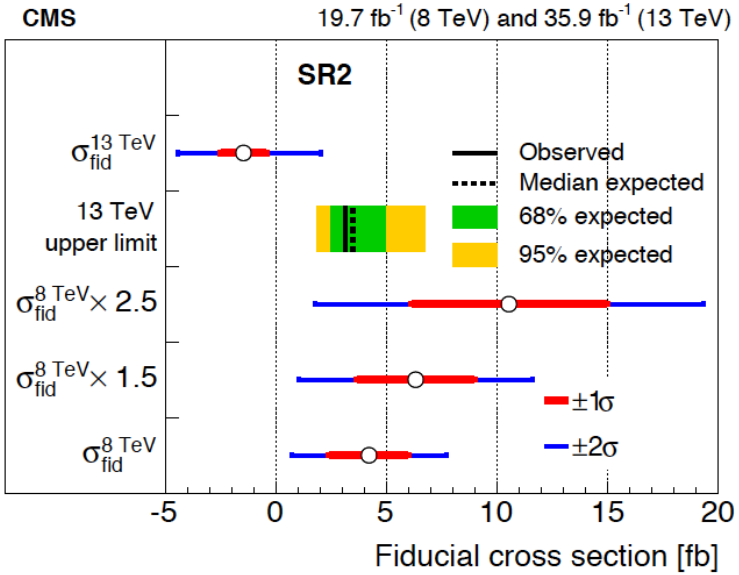



**Target**: ~12 ≲ $m_a$ ≲ 70 GeV

Expect:
$\sigma_{gg}(13\ TeV)/\sigma_{gg}(8\ TeV)\sim 2.5$
$\sigma_{qq}(13\ TeV)/\sigma_{qq}(8\ TeV)\sim 1.5$

*arXiv:1808.01890*



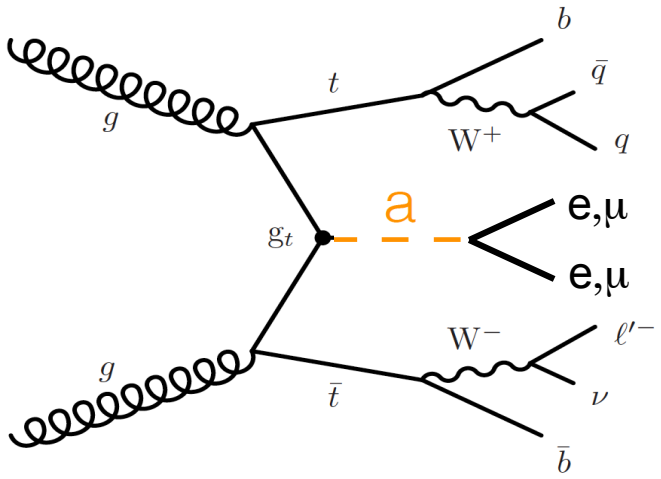




Waiting for more data and additional theoretical input

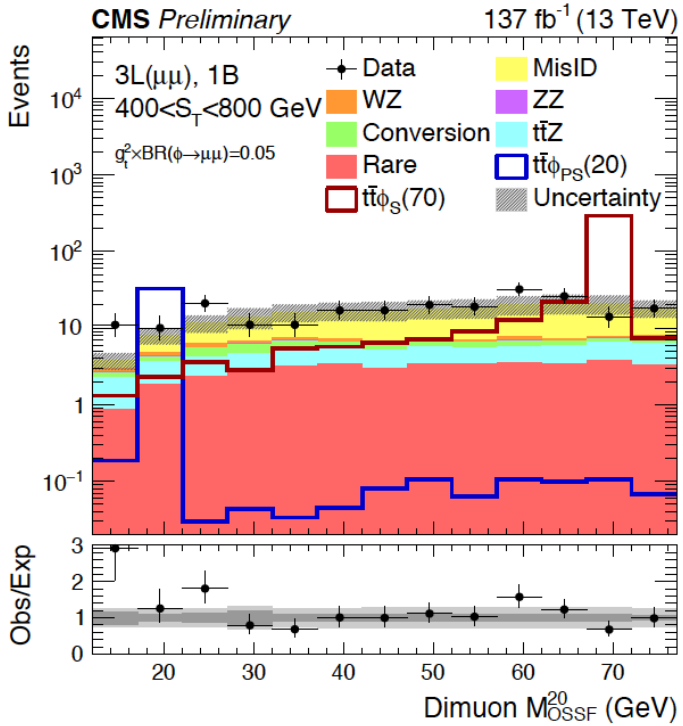
# Associated production: $t\bar{t}a(\rightarrow ee, \mu\mu)$

Strategy:

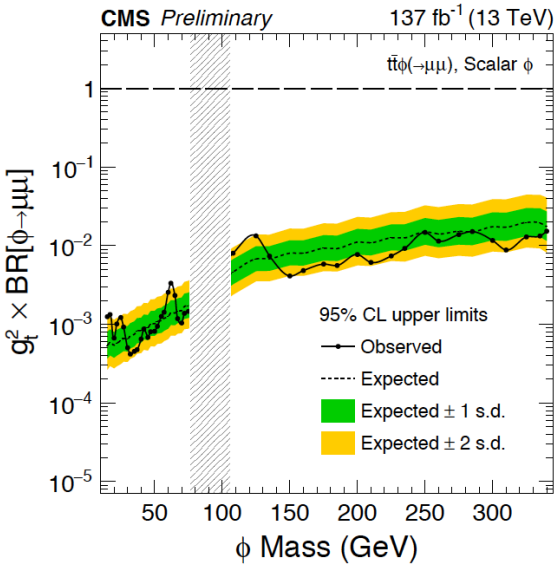
- Target both scalar and pseudo-scalar hypotheses.
- Select events with ≥3 electrons or muons.
- Categorize events depending on lepton multiplicity (3 or ≥4), b-tag multiplicity (0 or ≥1), and $S_T$ (scalar sum of $p_T$ of leptons, jets and $E_{Tmiss}$).
- Main backgrounds fake leptons, dibosons, and $t\bar{t}Z$.

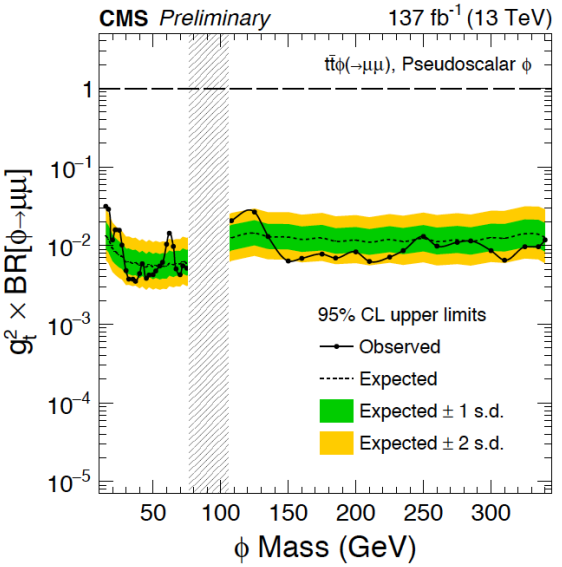



**Target**: $15 \lesssim m_a \lesssim 75$ GeV & $108 \lesssim m_a \lesssim 340$ GeV




*CMS-PAS-EXO-19-002*




Broad program of $t\bar{t}a$ searches ramping up

# Summary and outlook

- Program of searches for light scalars at the LHC is in full swing:
  - Exotic decays of the SM Higgs boson
  - Decays of new heavy particles
  - Direct or associated production

- Need to make sure no stone is left unturned!
  - Uncovered channels & regions of phase space, gaps in LLPs, etc
  - Mixed decays (e.g. h→aa→ff+$E_{Tmiss}$) → largely uncovered so far
  - Other production channels?

- Signatures explored are motivated by broad range of phenomenology
  - Benchmark models are very useful to guide analyses
  - Further theoretical input is much welcome!

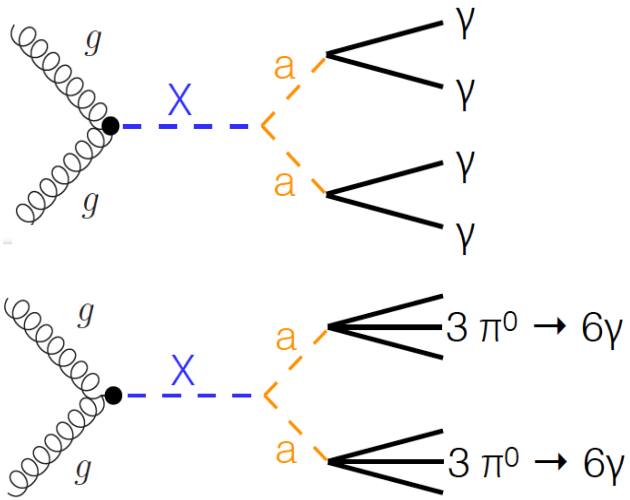
Stay tuned for full Run 2 results!

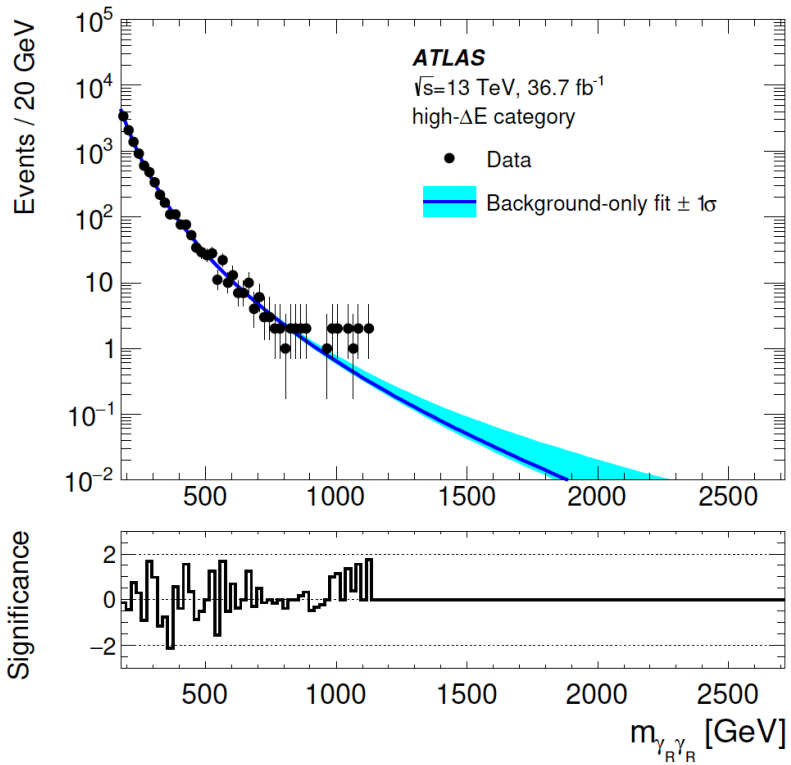
# Backup

# X→aa→4γ

Strategy:

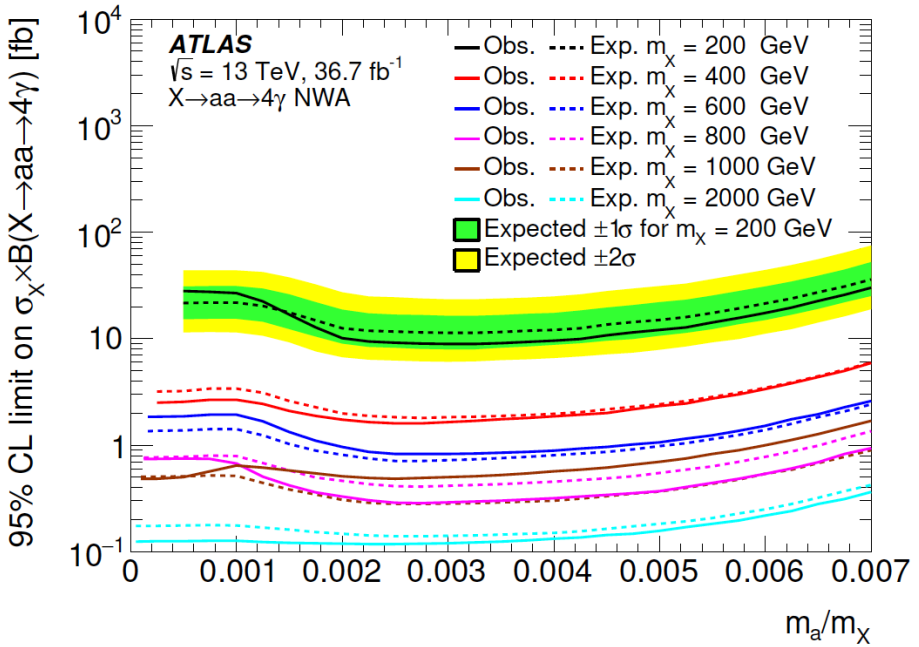
- Focus on collimated regime with multiple photons reconstructed as a single photon ($\Delta R(\gamma\gamma)<0.04$, typical size of EM cluster).
- Loosened photon selection dropping requirements related to finely segmented 1st strip layer of EM calorimeter.
- Standard resonance search in $m_{\gamma\gamma}$ spectrum.




*arXiv:1808.10515*

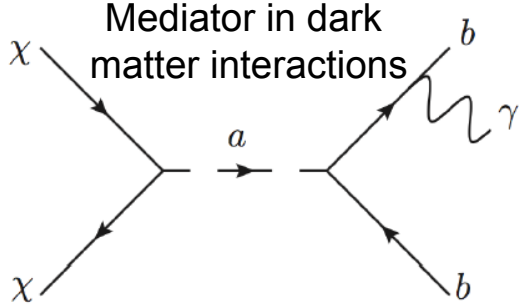
**Target**: $0.1 \lesssim m_a \lesssim 10$ GeV for $0.2 \lesssim m_X \lesssim 2$ TeV

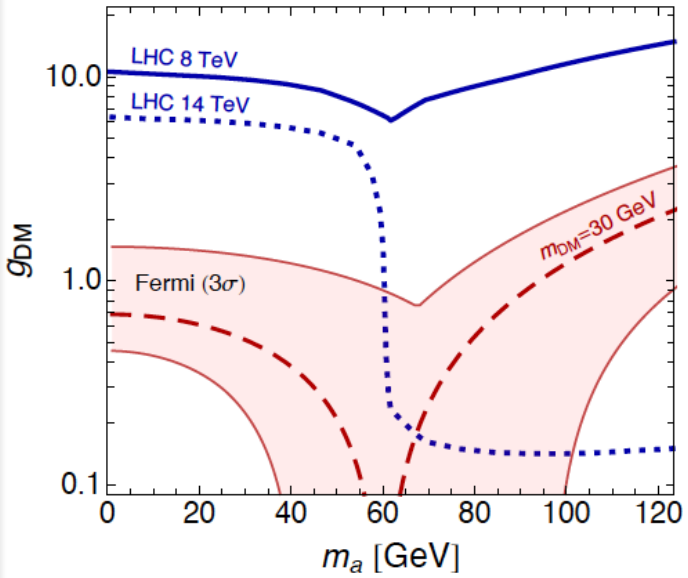


# Some BSM examples

## Dark Matter

Mediator in dark matter interactions

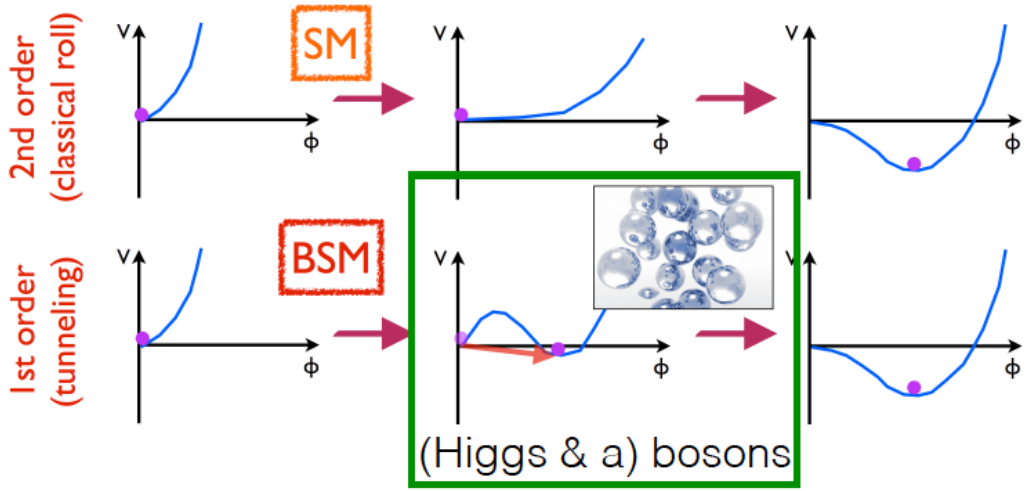



*See e.g. arXiv:1401.6458*

## EW baryogenesis

EW symmetry breaking as strong first-order phase transition




*See e.g. arXiv:0705.2425*

# Some BSM examples

## Axion-like particles (ALPS)

### FROM A NEW CONFINING SECTOR

Natural strong sector: composite Higgs models

Example: SO(6)/SO(5) has 5 PGB, the Higgs and a singlet

$$m_\eta \sim c \times m_h \times \frac{f}{v} \sim 5 - 500\ \text{GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$$

model-dependent, see e.g. Gripaios+ 0902.1483, Redi Tesi 1205.0232

### FROM SUPERSYMMETRY

Spontaneously broken $U(1)_R$
➔ R-axion a

$100\ \text{MeV} \lesssim m_a \ll M_{SUSY}$

*arXiv:1702.02152*