September 25 2018
Seminar at BNL

Searches for decays of a Higgs boson into pairs of light (pseudo)scalars with the ATLAS detector

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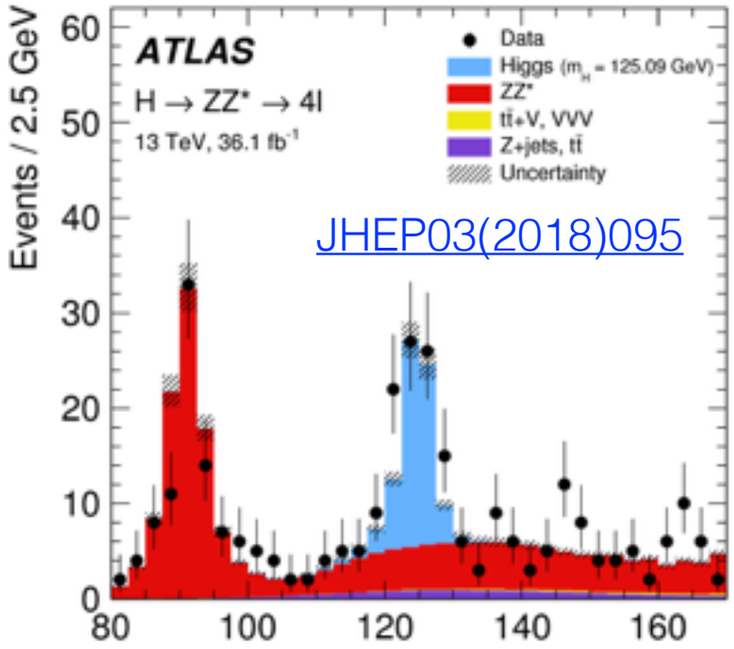
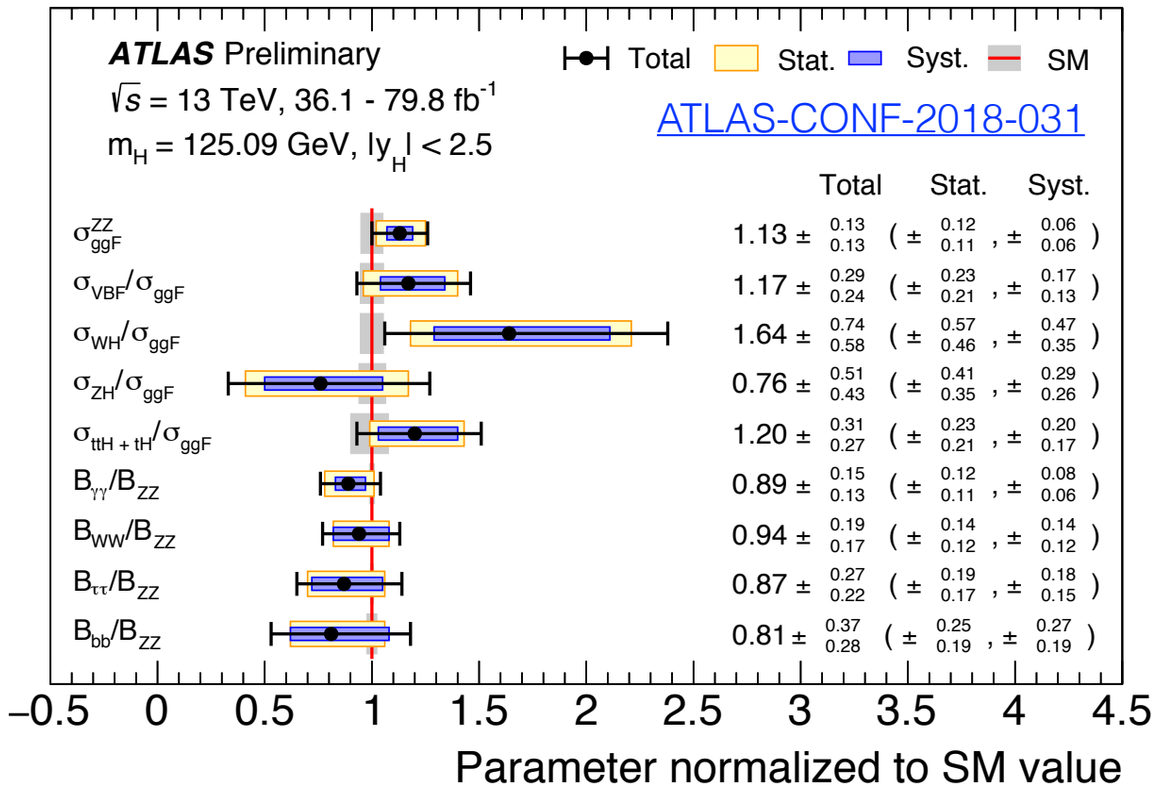
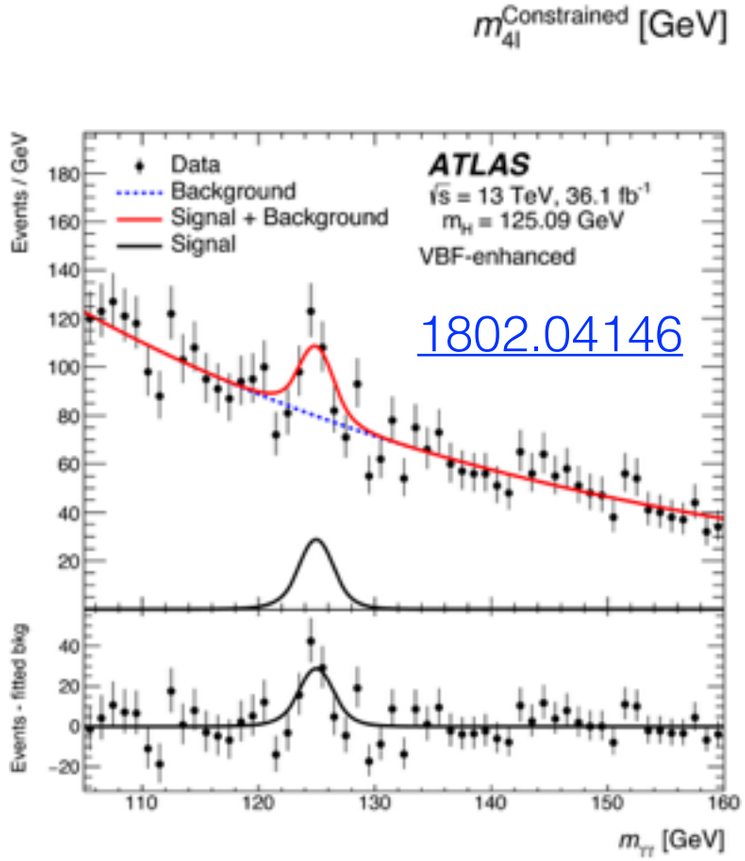
Higgs boson

- Higgs boson discovered at m_H = 124.98 ± 0.28 GeV
- All the measured properties (couplings, branching ratios…) so far consistent with that of the Standard Model (SM) Higgs boson

➡ However, there is still space for new physics in the Higgs sector!

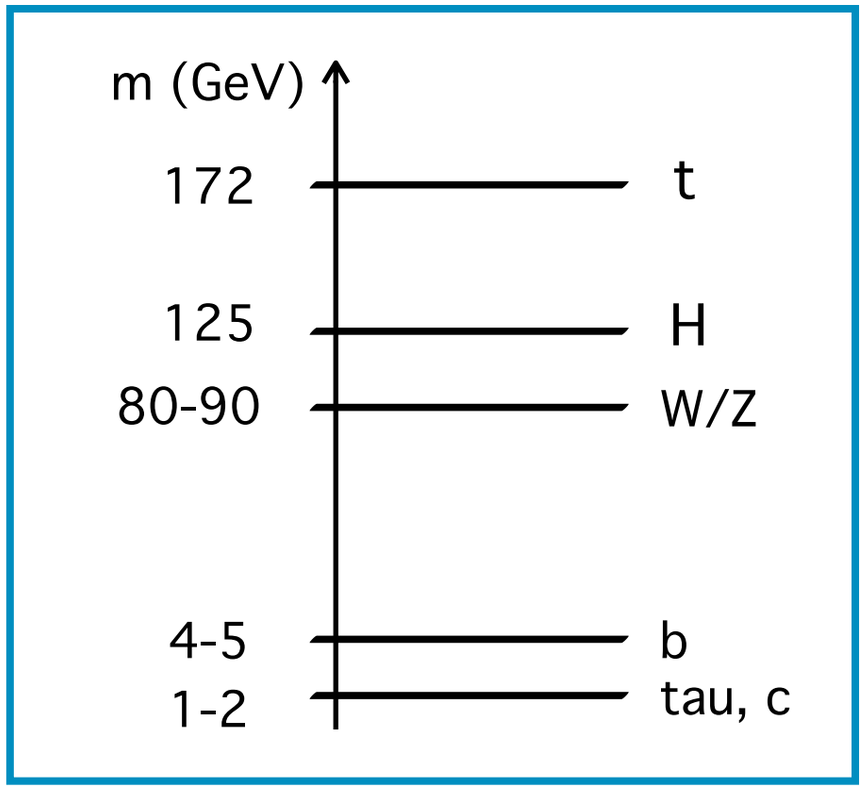






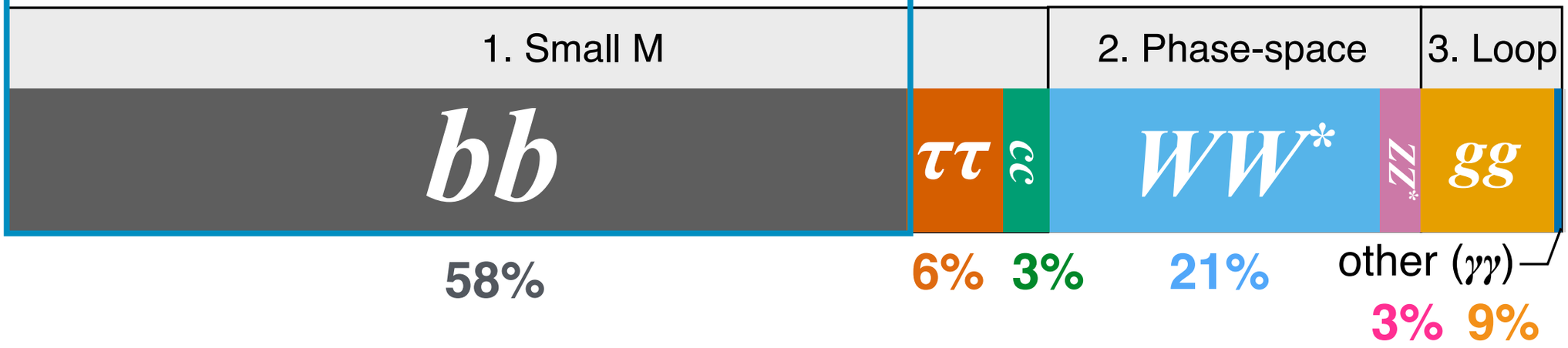
H decays

- **Yukawa couplings** - Higgs couples to particles with strength proportional to its mass
- However, decays to SM suppressed either due to small m_{SM}, phase-space or loop decays



The largest partial width is to bb

- But due to small m_b the coupling is only $y_b \sim 10^{-2}$



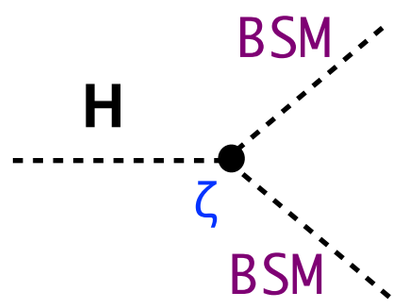
H decays

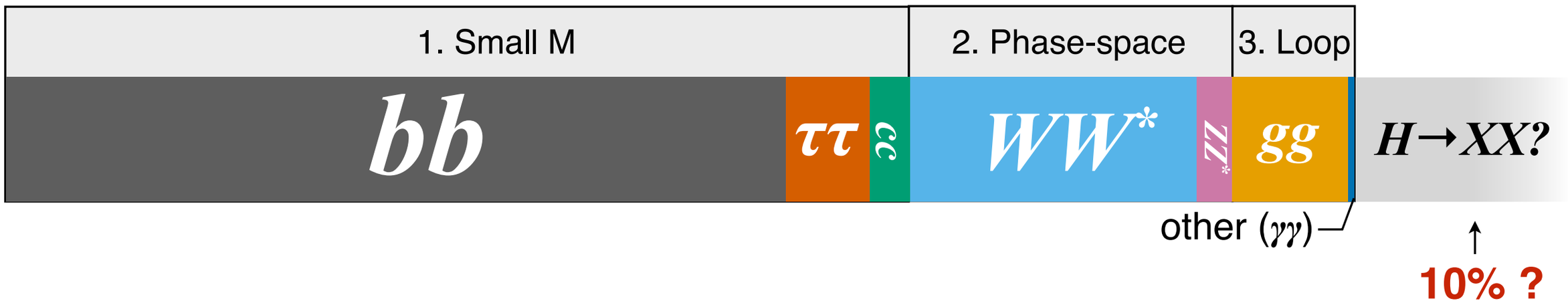
- SM Higgs has a narrow width (~4.1 MeV)
- Even coupling as small as 10^{-2} can yield Br(H→BSM) ~ 10%

$\Gamma^{SM}_{H,Total} = 4$ MeV → $\zeta = 10^{-2}$ → Br(H→BSM) ~ O(10) = exotic Higgs decays

➡ 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!**



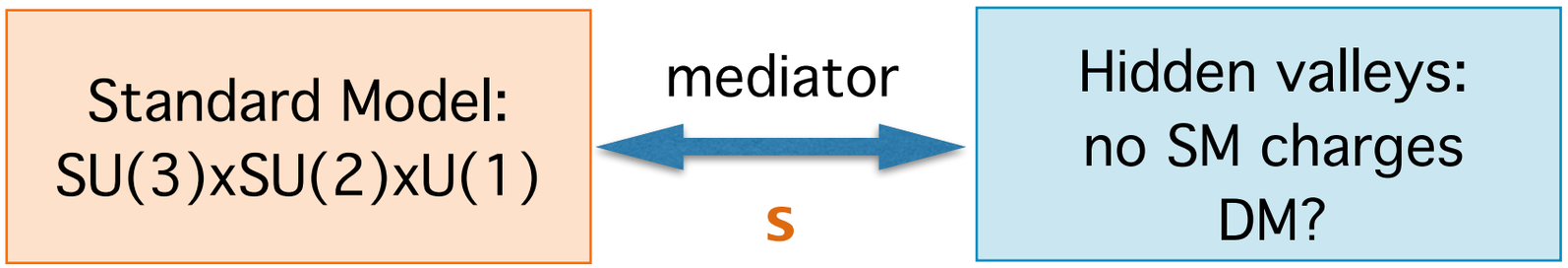


Why are exotic Higgs decays interesting?

Hidden sectors

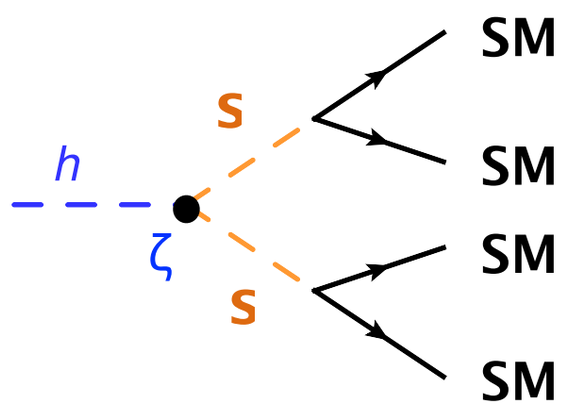
- New physics could couple to the SM only through Yukawa couplings

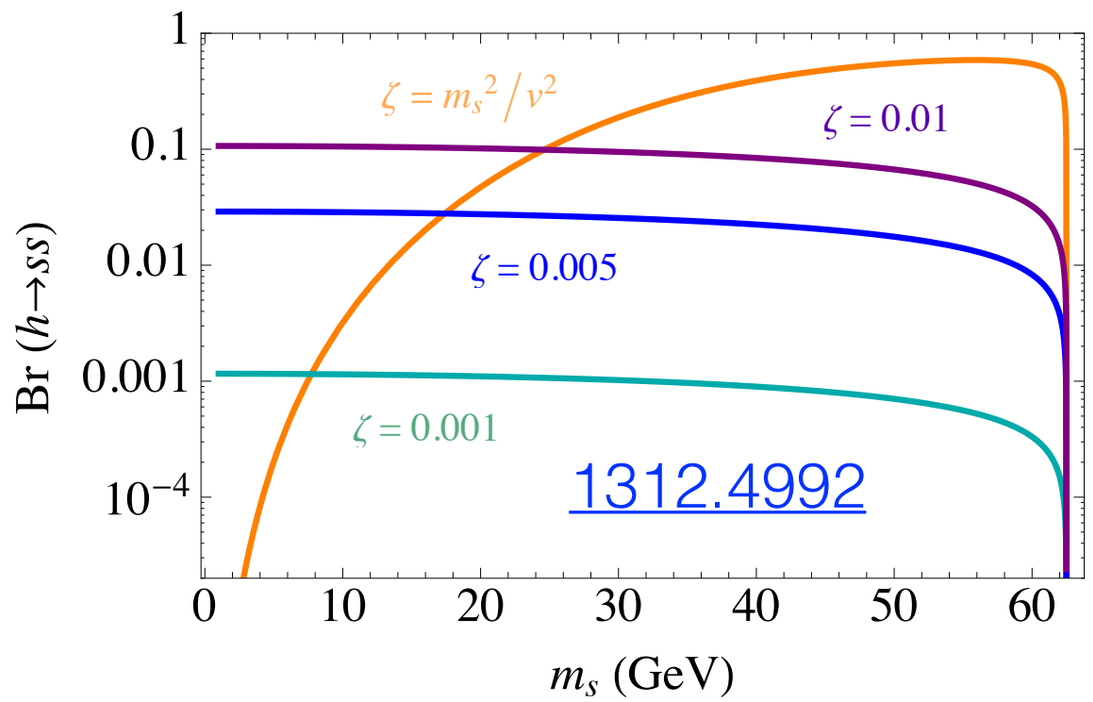
  ➡ **E.g. hidden sectors: Higgs could provide a unique access to particles that are singlets under SM interactions**



singlet mixes with H and inherits Yukawa-like couplings => can decay to the SM particles

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

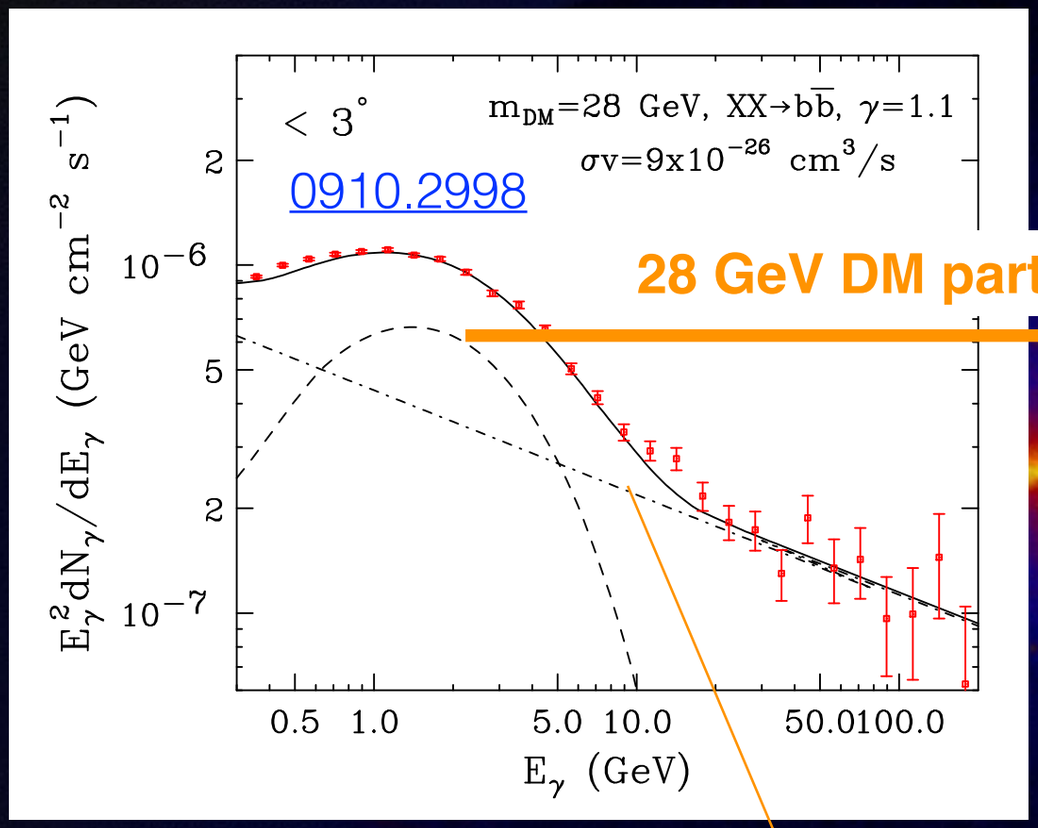




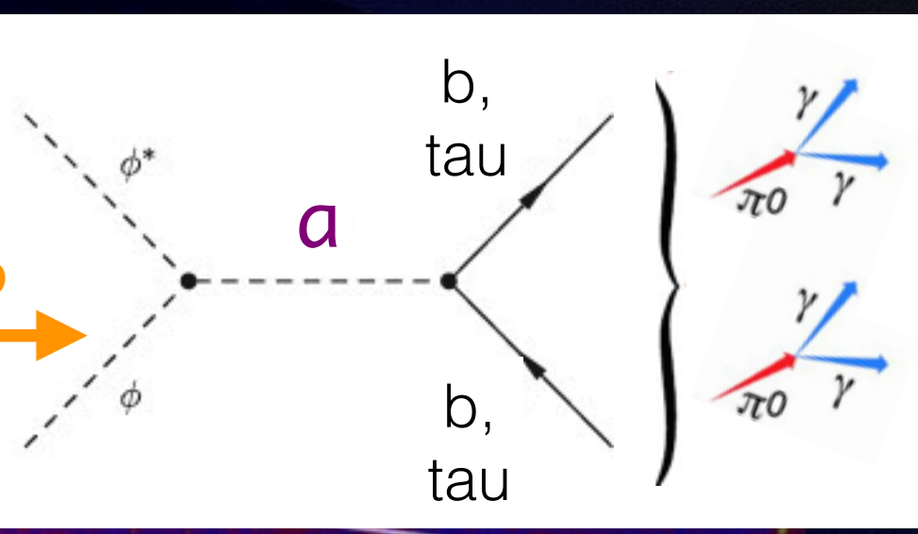
Dark matter

- The Fermi-LAT telescope observed excess of gamma-rays at the energy of 1-3 GeV coming from the centre of the galaxy

  ➡ **Could be a result of DM annihilations through a (pseudo)scalar mediator**

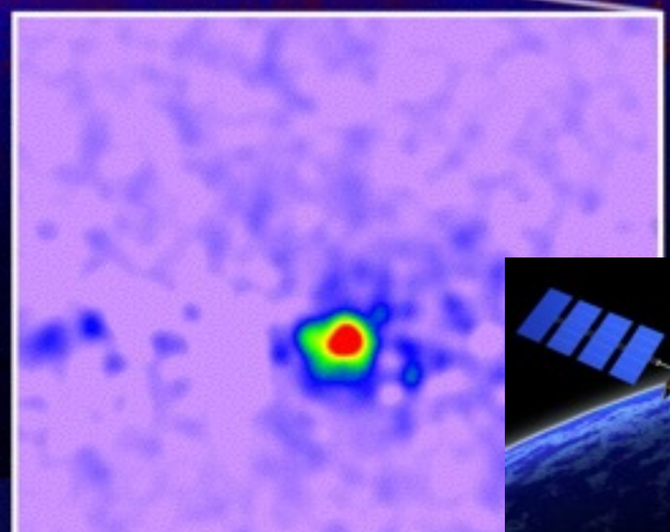


28 GeV DM particles annihilating to bb



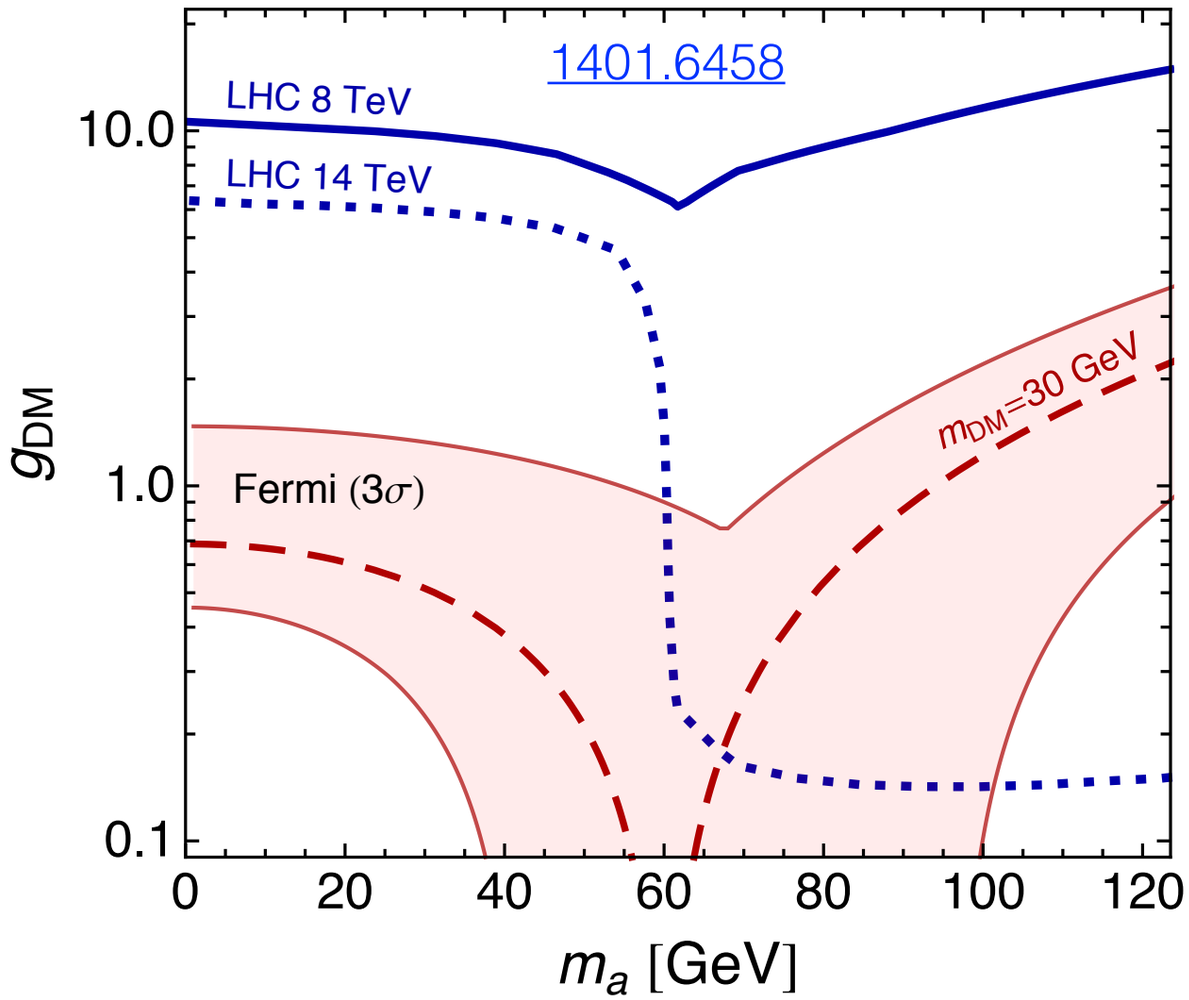
background modelling

m_{DM} ~ 20-50 GeV preferred

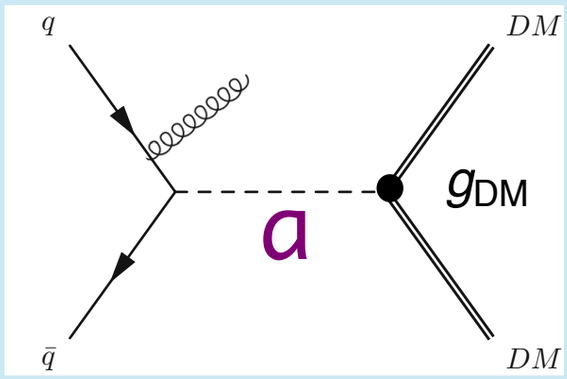


DM @ LHC

- Typical searches for DM at the LHC:
  - Produce the mediator which then decays to DM particles => invisible in the detector
  - Need an ISR object “X” which to trigger on and be able to “see” the event (j,y)
    - ➡ Mono-X signatures typically cover $M_{med}>2M_{DM}$ case



Covered by mono-jet (or multi-jet) searches at the LHC



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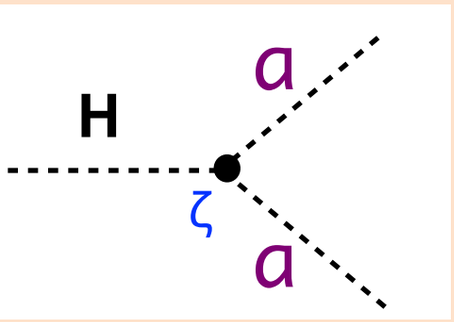
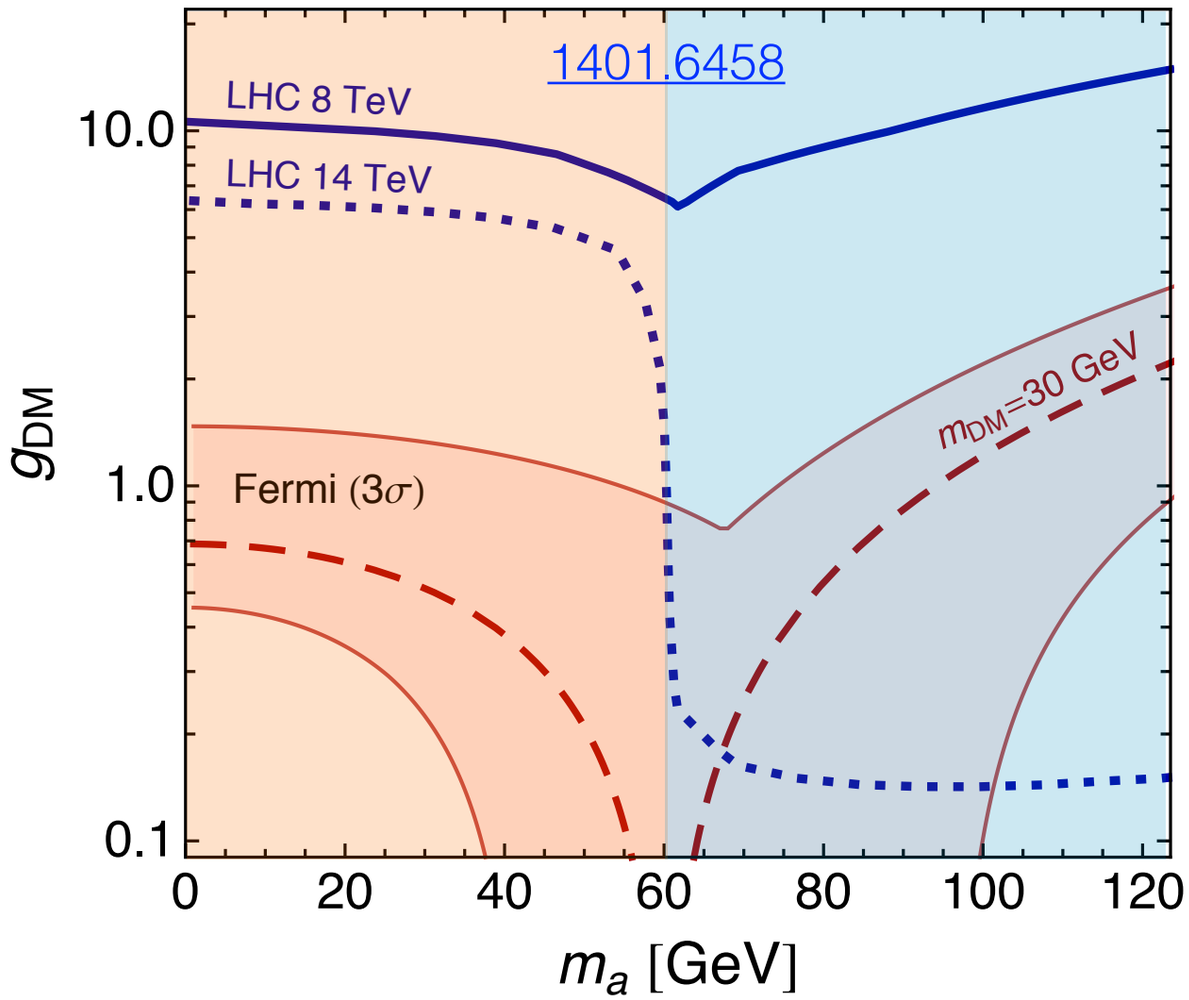
✓ **H→aa search is sensitive to mediators lighter than DM particles**

H→aa can access $M_{med}<2M_{DM}$





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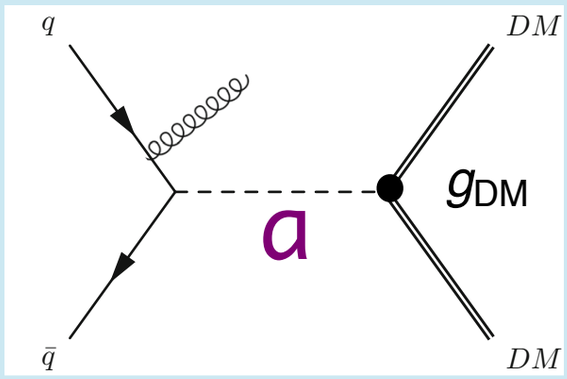


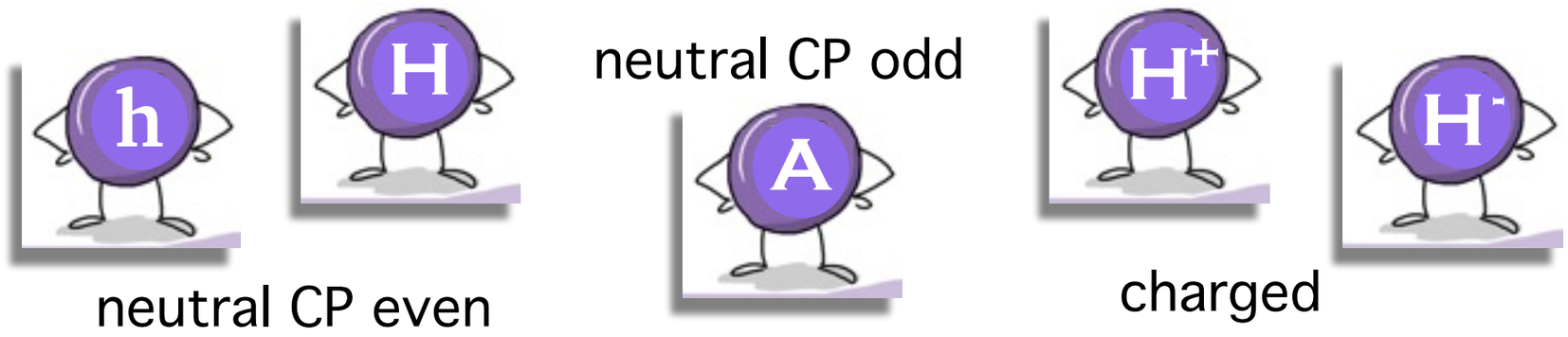
What kind of theories contain this new light (pseudo)scalar?

Extended Higgs sectors

2HDM = 2 Higgs Doublets Model

- add another SU(2) Higgs doublet to the SM

- 5 physical states:
  (CP conserving case)



- simplified theoretical model with phenomenology common to a large class of well-motivated BSM theories

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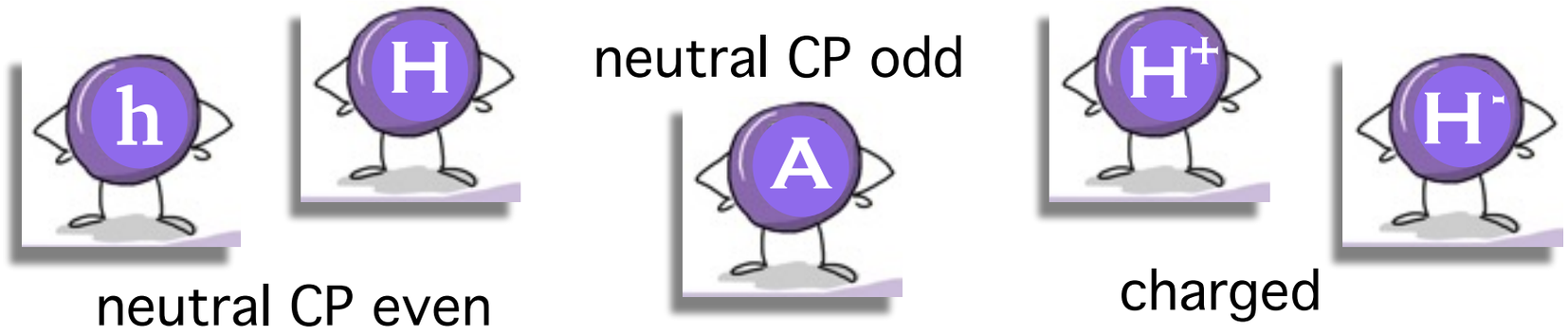
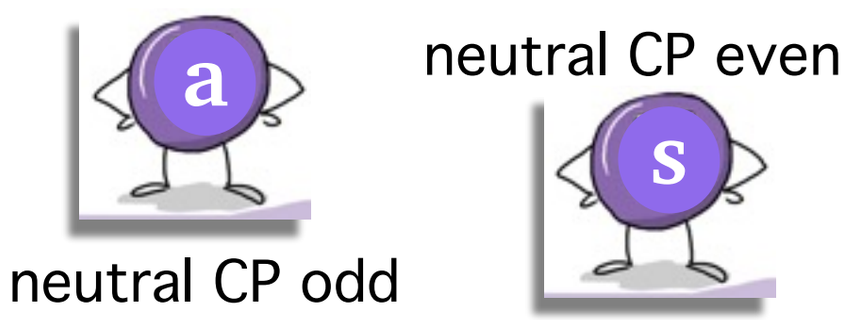


- simplified theoretical model with phenomenology common to a large class of well-motivated BSM theories

2HDM + singlet



- 2 additional physical states:
  - ➡ Possibly light ($m < m_h$)
  - ➡ **Used for the interpretation of exotic Higgs decays searches**

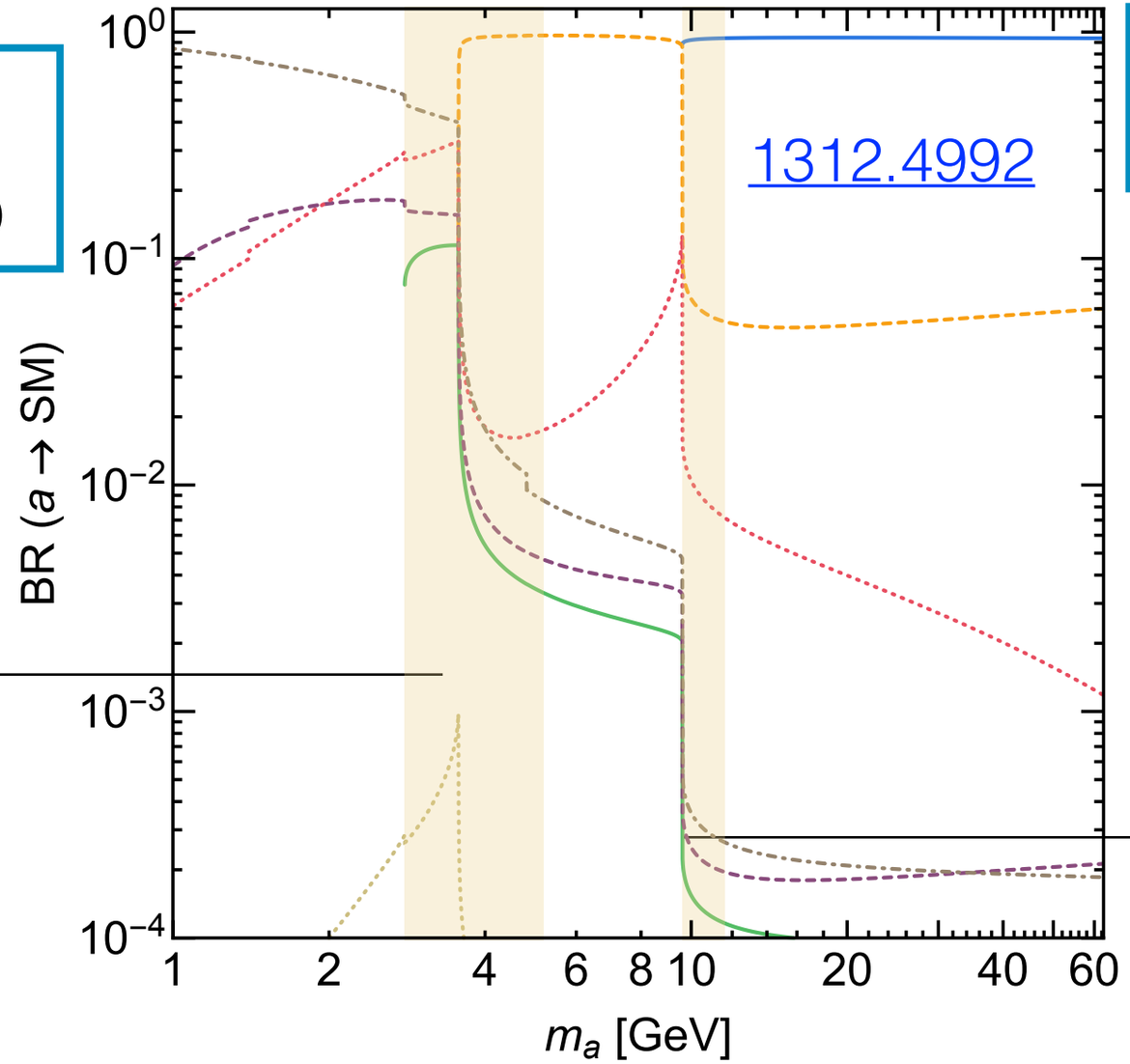
2HDM+S

- A particular 2HDM+S model means a particular choice of parameters resulting in particular set of a→SM branching fractions
  - Type II realised in e.g. NMSSM

Type II, tan β = 5

specifies how fermions couple to H fields (to avoid FCNC)

ratio of vacuum expectation values of the 2 H-doublets



2tau mass threshold

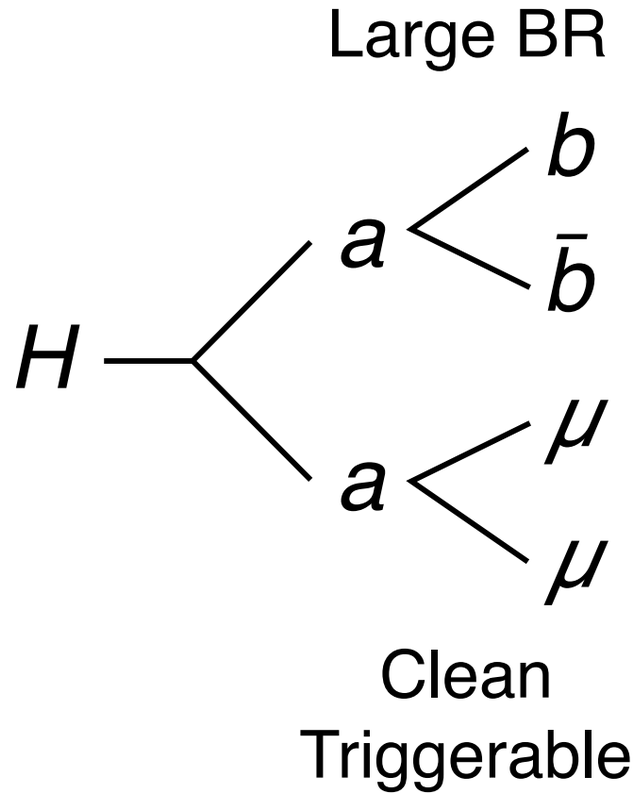
2b mass threshold

In this talk

- **Looking for 125 GeV Higgs decaying to new (pseudo)scalars "a"**
  - ➡ **bbμμ** final state

    - ✓ **bb side gives high Br(a→bb)**
    - ✓ ***μμ* side provides clean signature + triggering**

    - ‣ Search in $20<M_{\mu\mu}<60$ GeV range

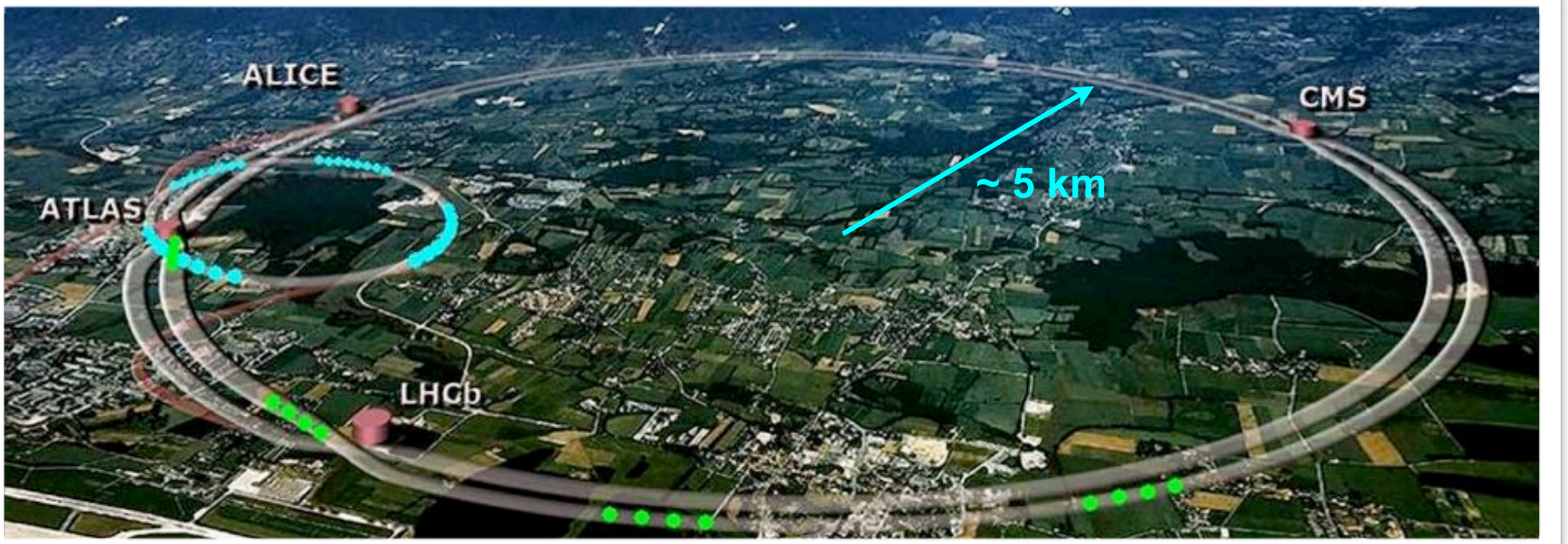


- Will mention also searches in other channels: 4b, 4μ, 2j2y

How do we look for this signal in ATLAS?

Large Hadron Collider

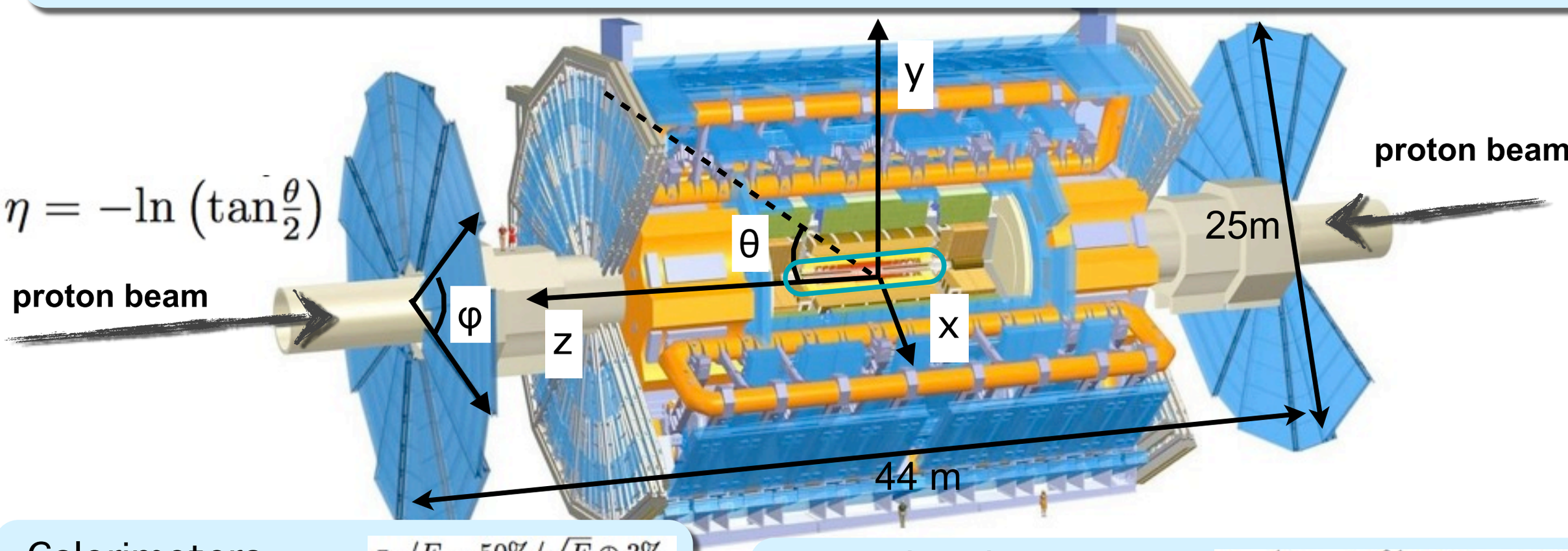
- LHC is colliding protons at the centre-of-mass energy of 13 TeV
- The analysis is based on 36 fb^{-1} of data collected in 2015+2016 by the ATLAS detector



ATLAS

Inner detector

- Si pixels & strips + transition radiation tracker
- Reco. charged particles' tracks & vertices $\sigma_{p_T}/p_T = 0.05\% \cdot p_T \oplus 1\%$
- Momentum measurement by curvature in a solenoid magnetic field (2T)



Calorimeters

$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$

- **Energy measurement** by creation and total absorption of showers
- **Electrons, photons** (liquid Argon); **jets** (tiles of scintillating plastic)

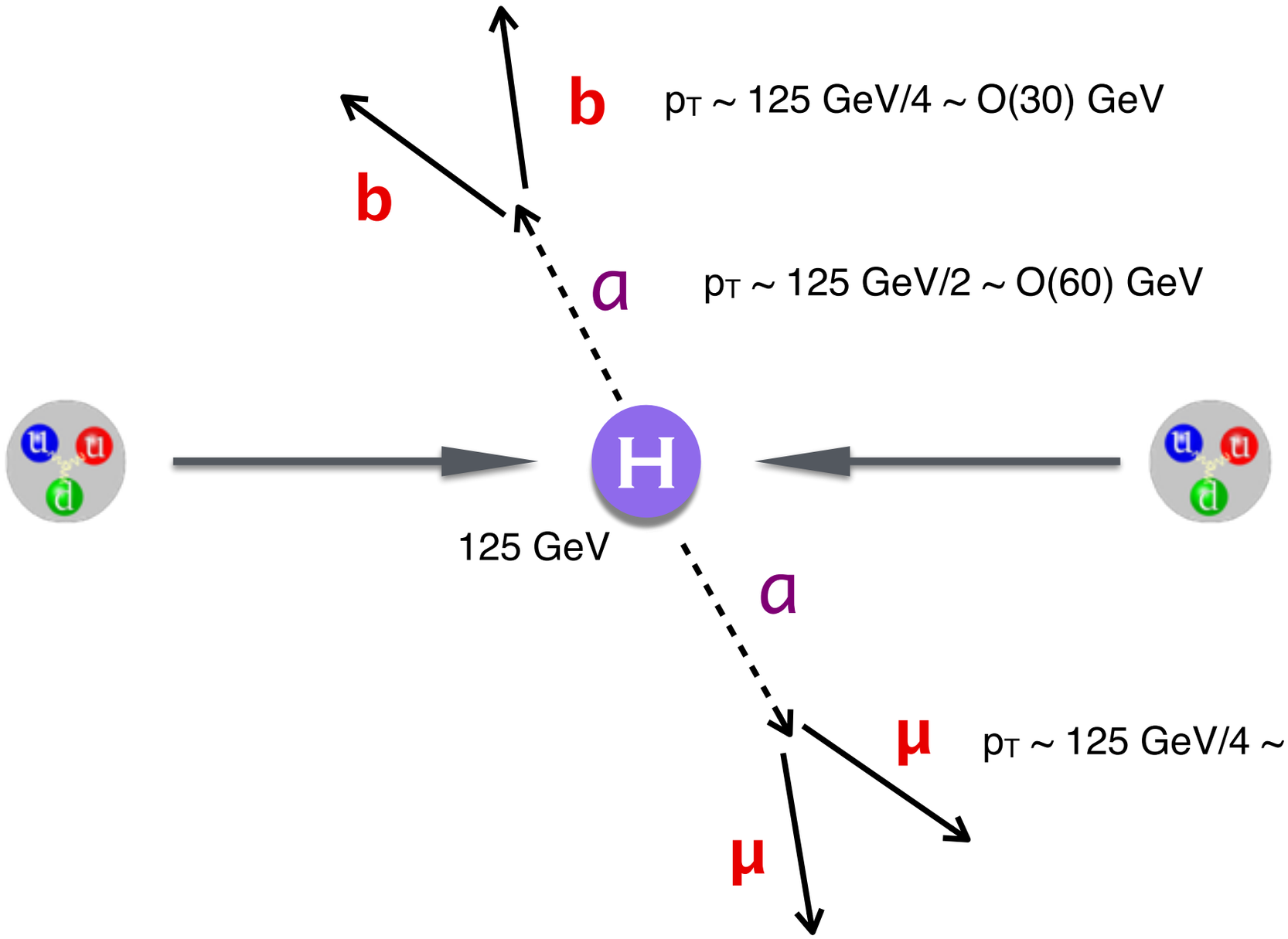
Muon chambers

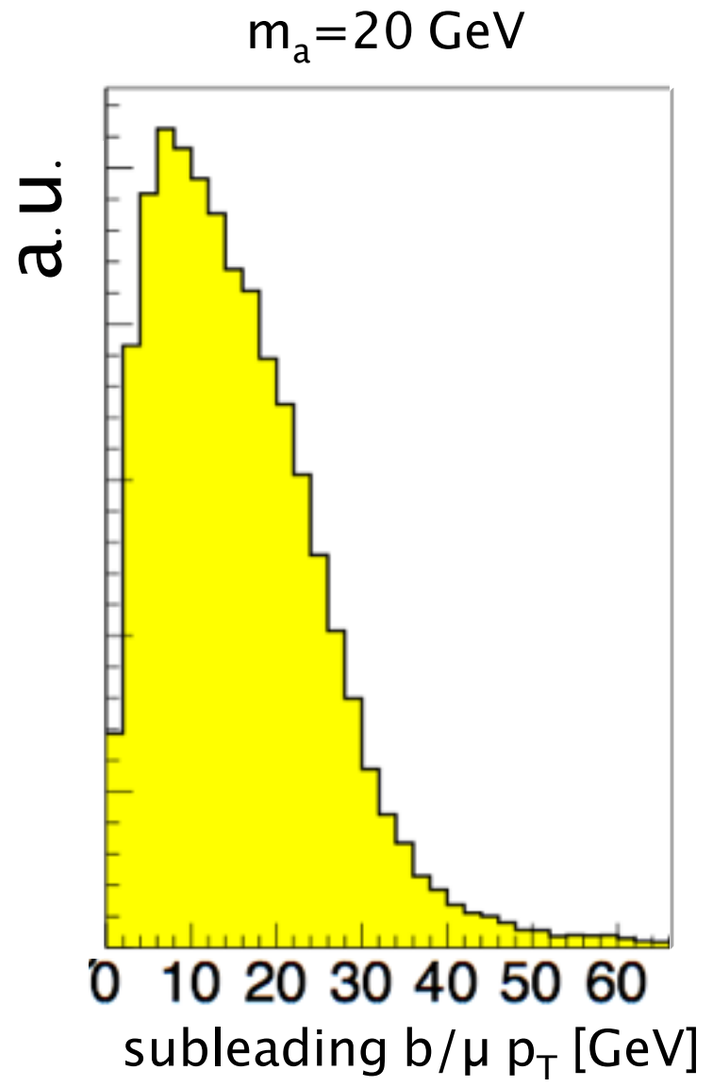
$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV

- Wire chambers for precision tracking
- Toroid magnets (4T) bend muons in η plane
- Reco. μ by **combining tracks measured in Inner detector & muon chambers**

Signal characteristics

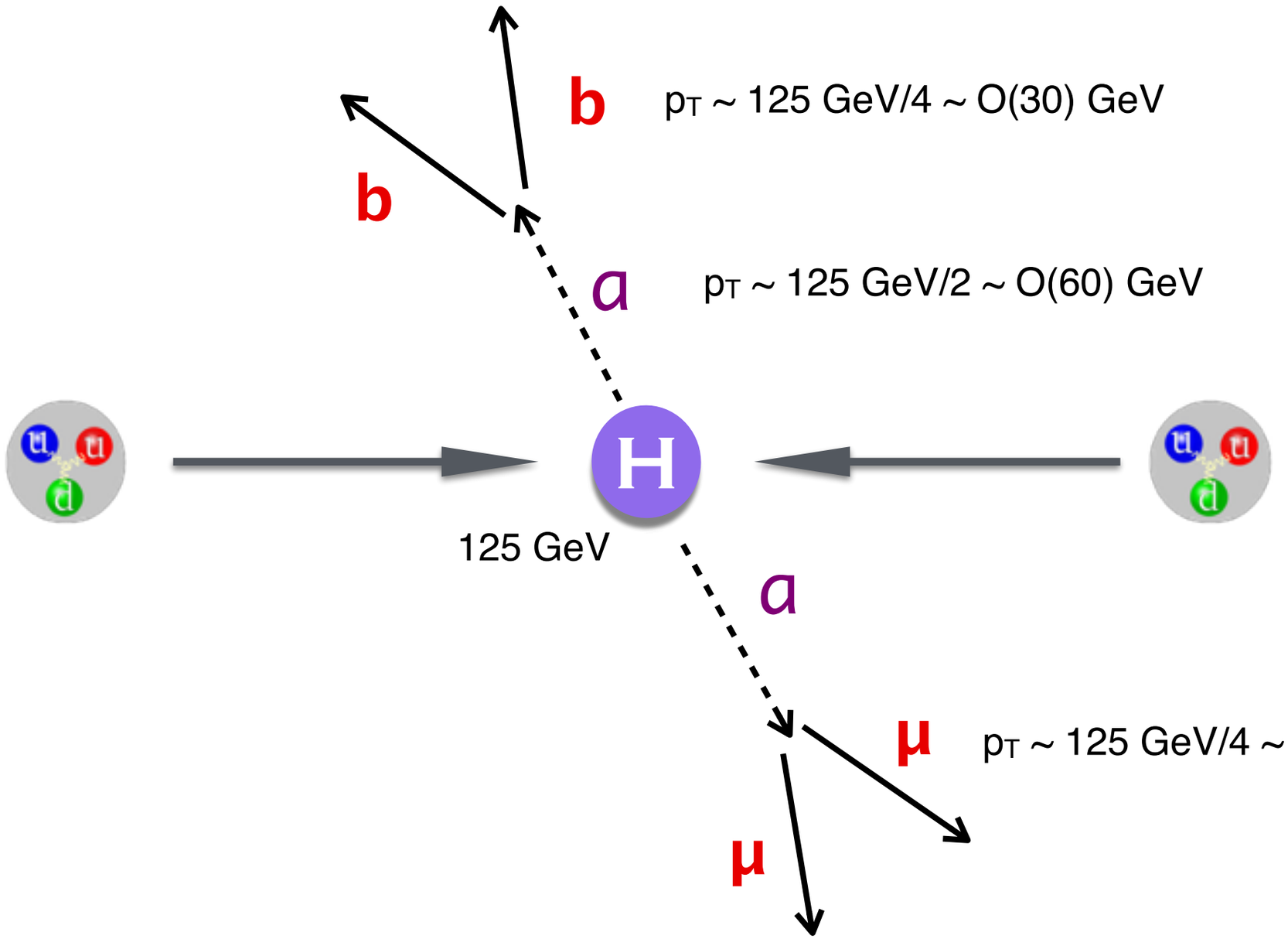
- Soft (low pT) objects in the final state

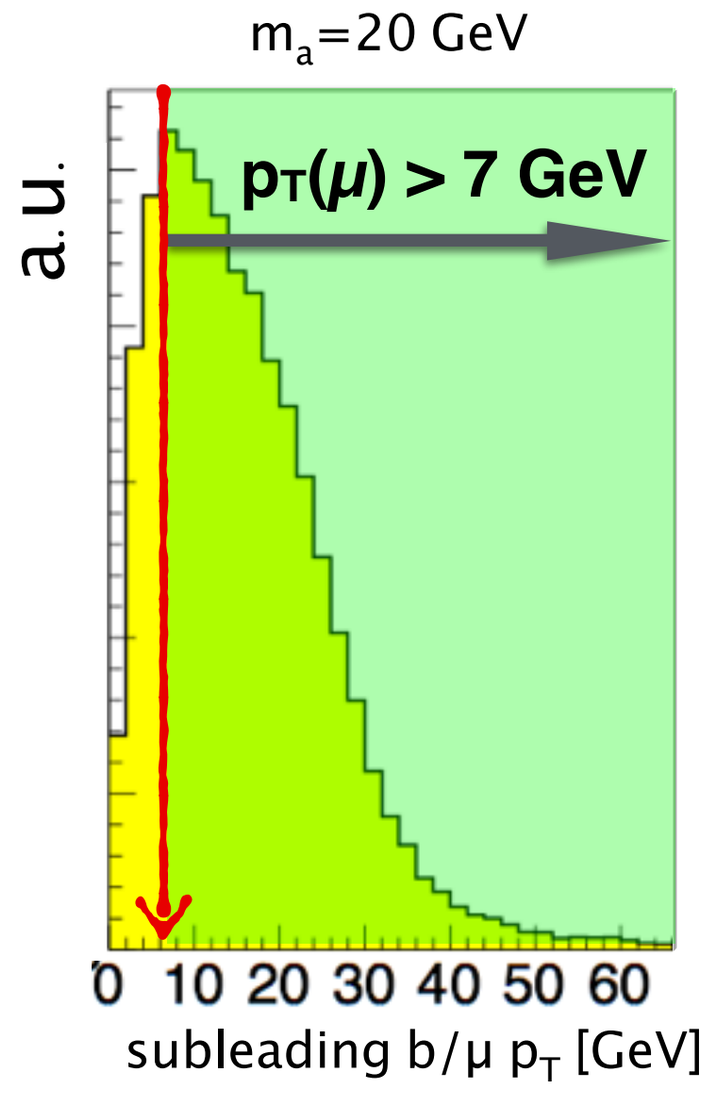




b/μ selection

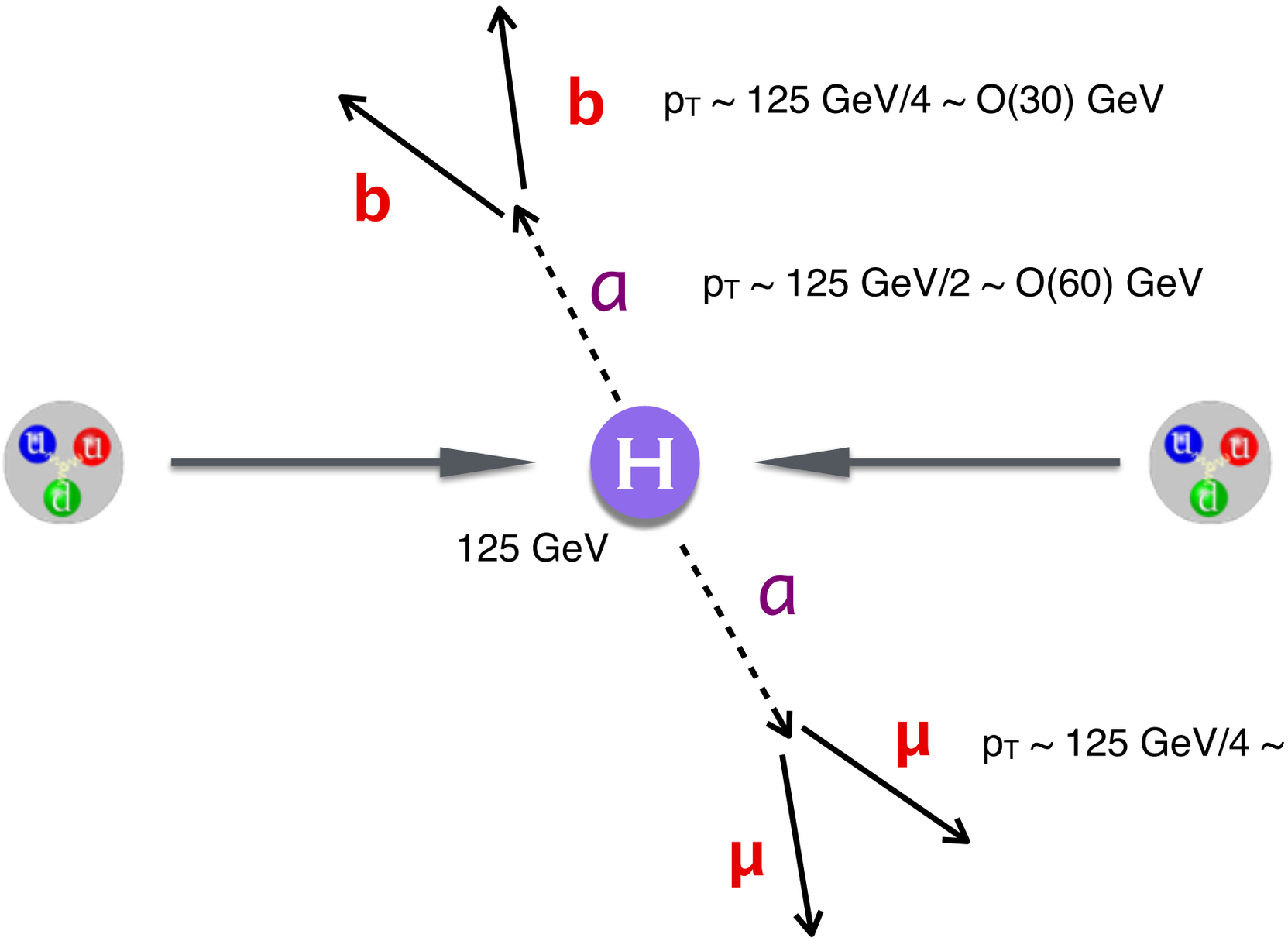
- **$p_T(\mu)$>{27,7} GeV**
  - Higher pT requirement on the leading muon due to trigger thresholds

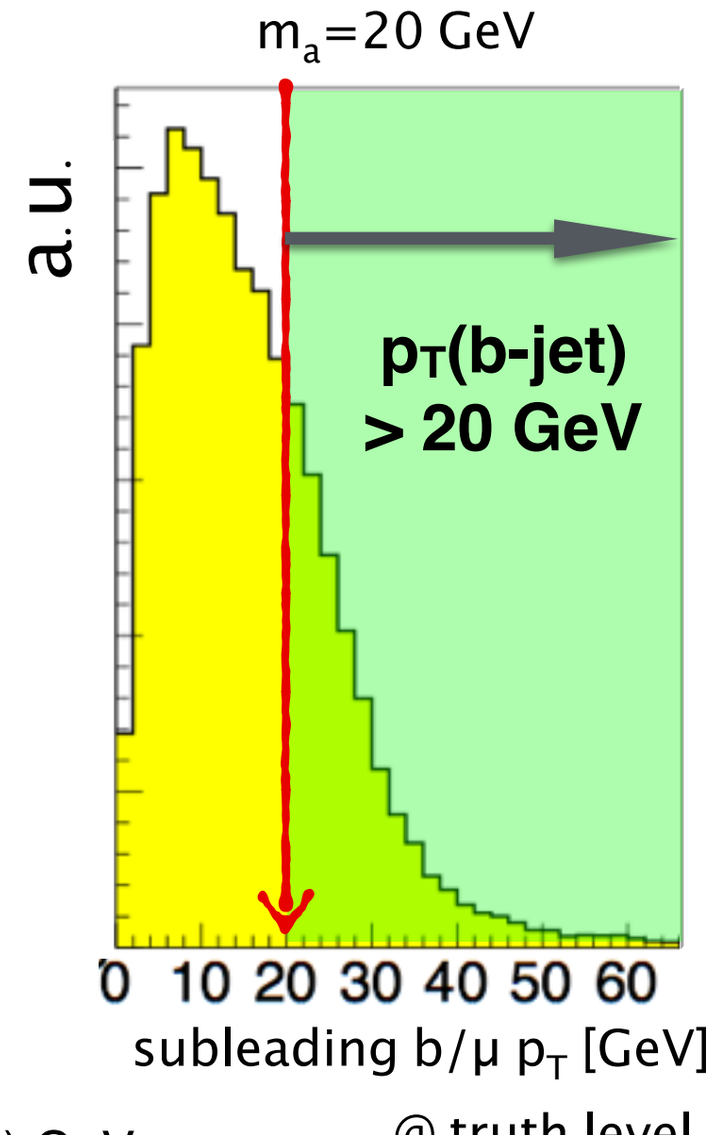




b/μ selection

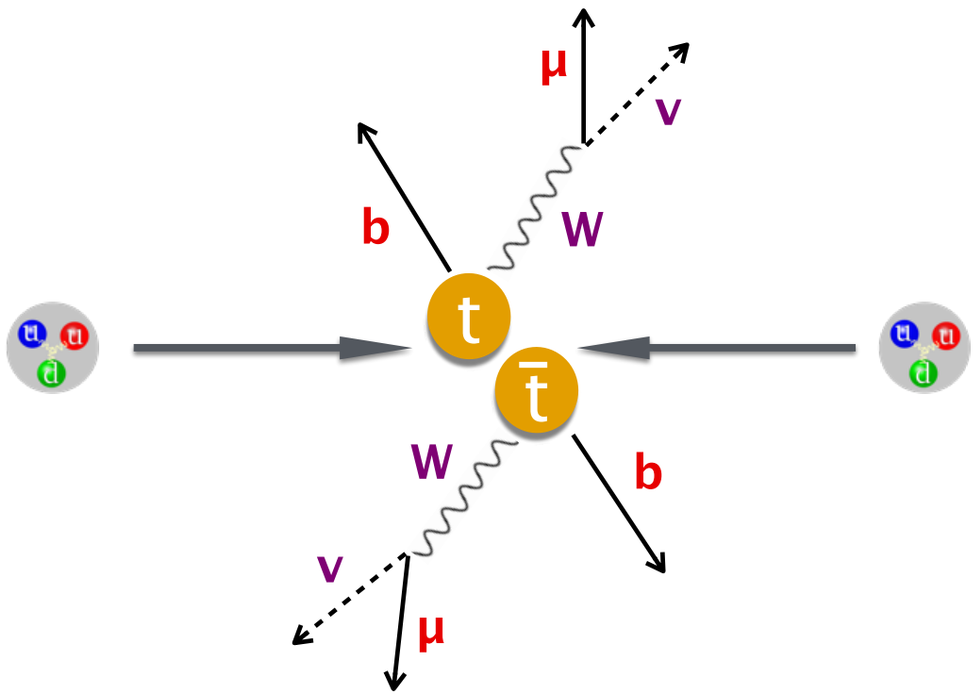
- **$p_T(\mu)$>{27,7} GeV**
- **p_T(b-jets)>{20,20} GeV**





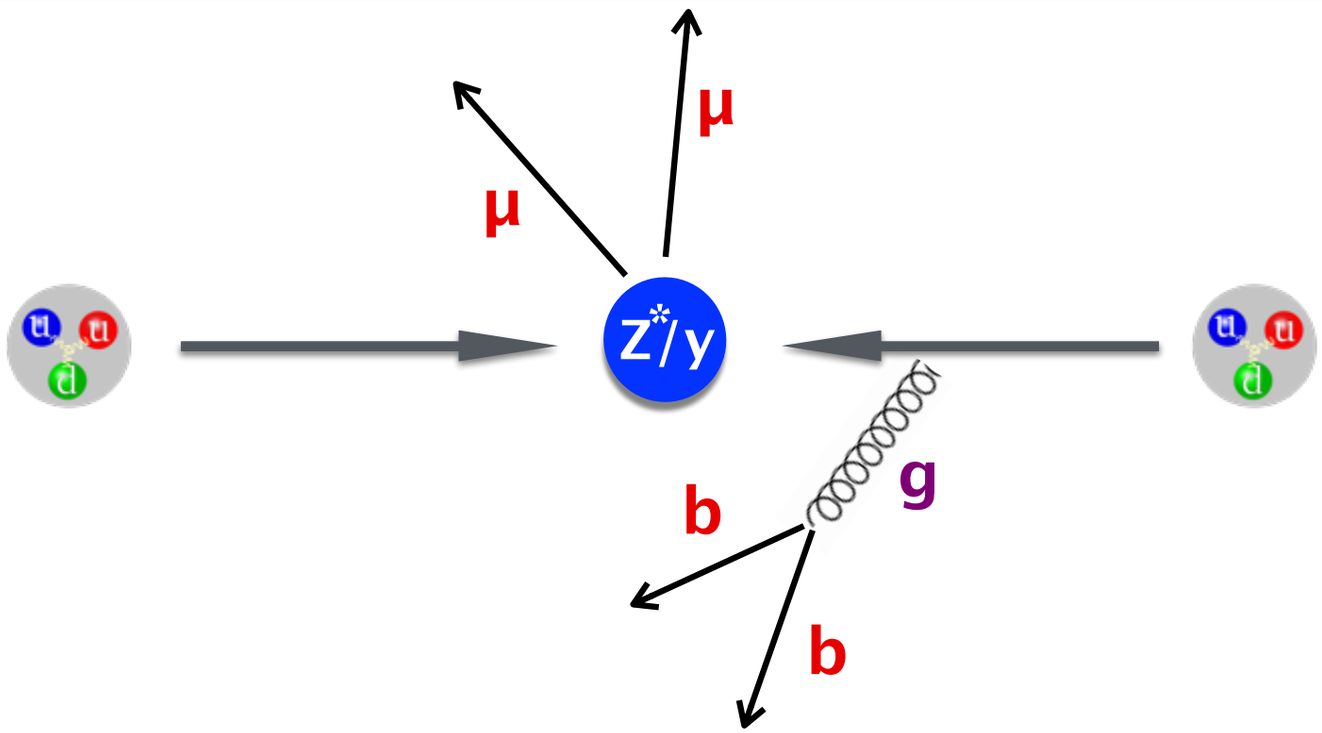
@ truth level

Backgrounds



top-quark pair production

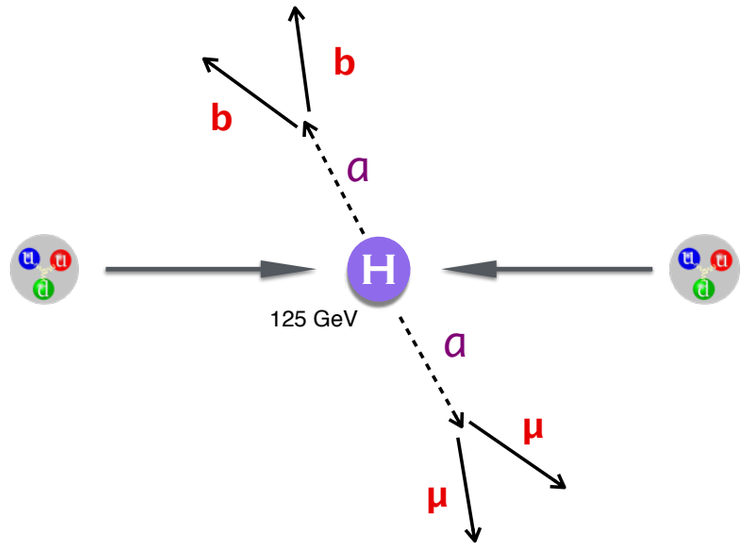
Drell-Yan + jets production



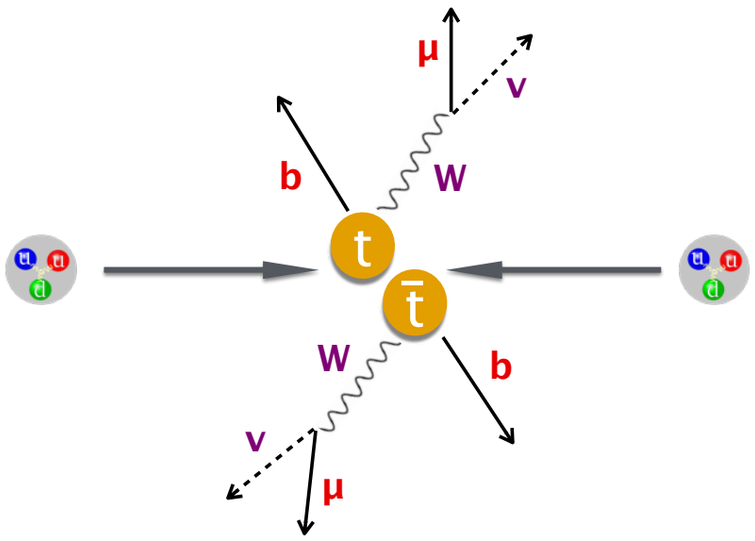
Signal vs background

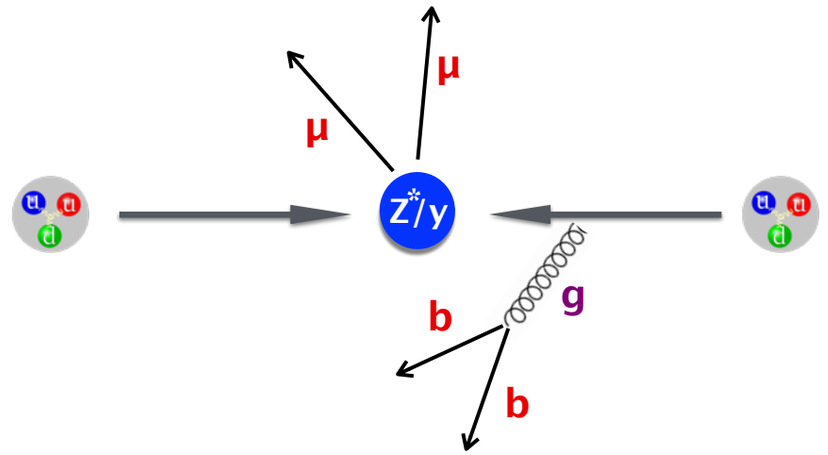
Two resonances of the same mass:

$m_{\mu\mu} \sim m_{bb}$



Non resonant production of bb / μμ

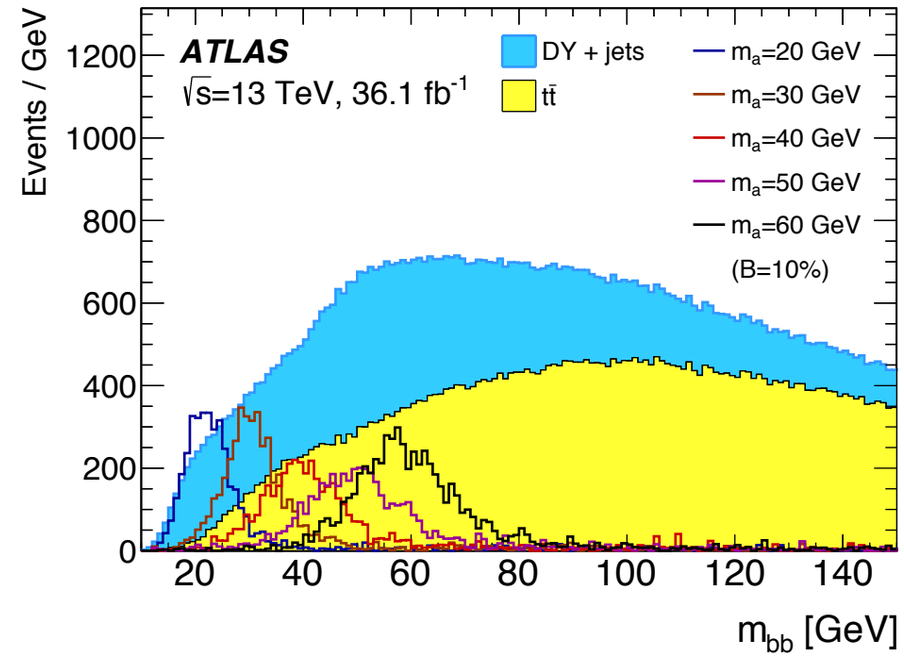


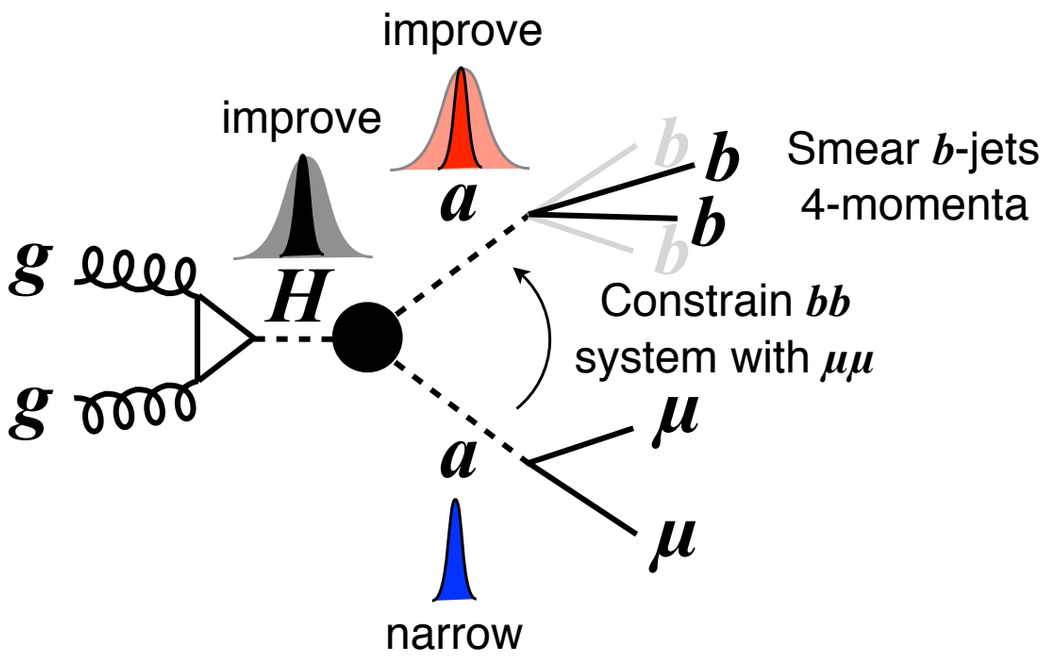


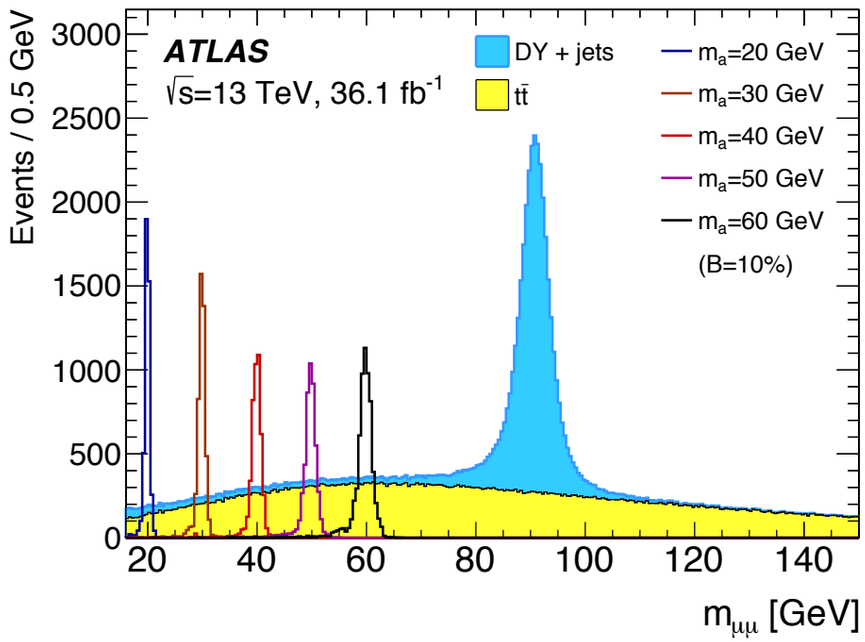
Kinematic constraints

- $m_{\mu\mu}$ resolution factor ~10 better than m_{bb} resolution

➡ **Constrain m_{bb} with well measured $m_{\mu\mu}$ in a kinematic-likelihood (KL) fit**







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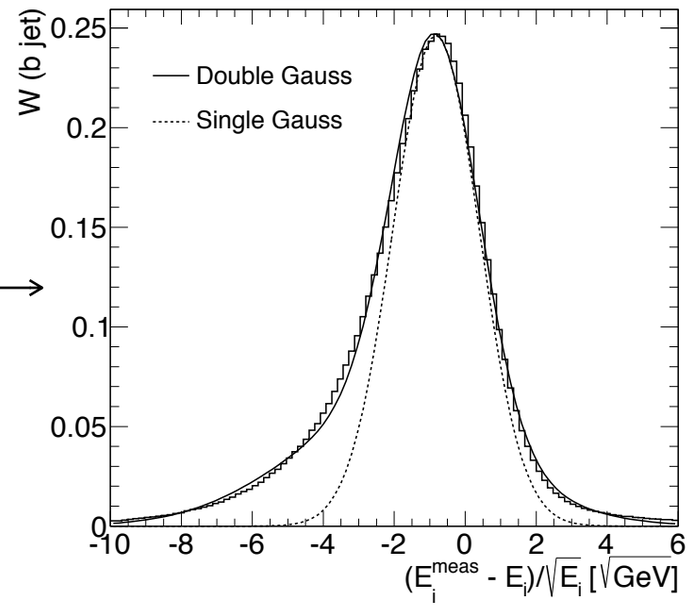
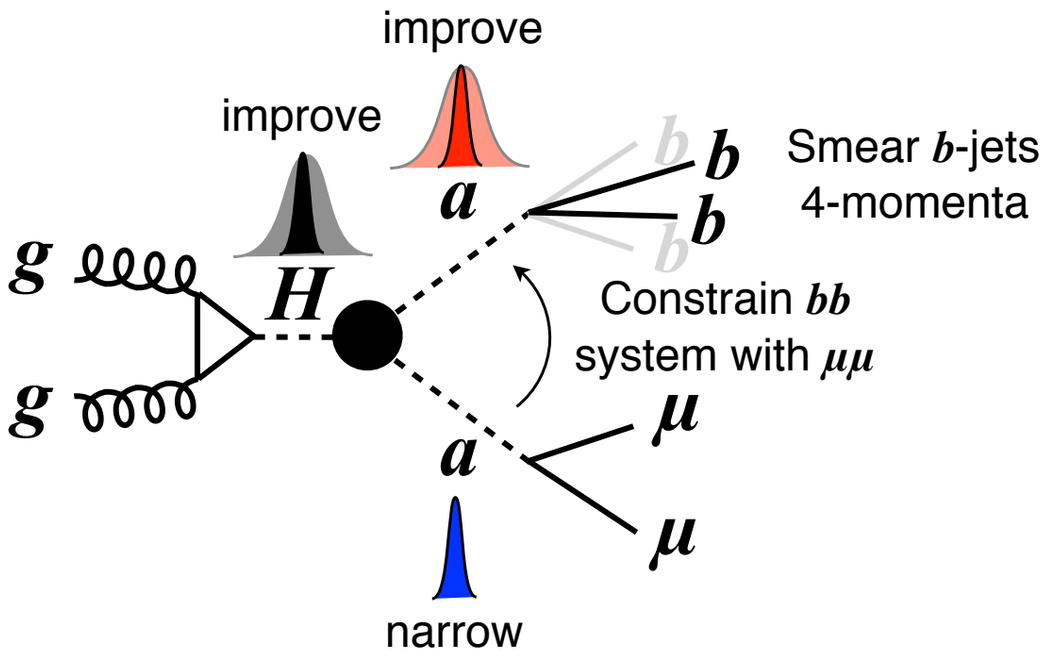
$$L = W(\hat{E}_{b_1}, E_{b_1}) \cdot W(\hat{E}_{b_2}, E_{b_2}) \cdot \frac{k}{(m_{bb}^2 - m_{\mu\mu}^2)^2 + m_{\mu\mu}^2\Gamma^2}$$

Breit-Wigner constraint

resolution constraints on b-jets (transfer functions)

1312.5595





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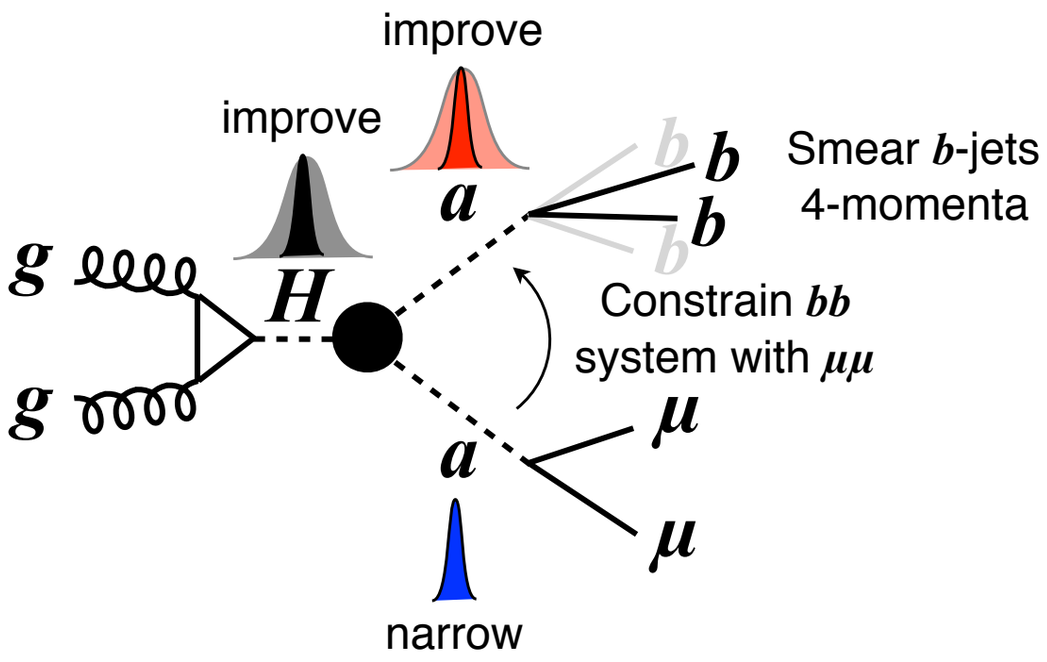
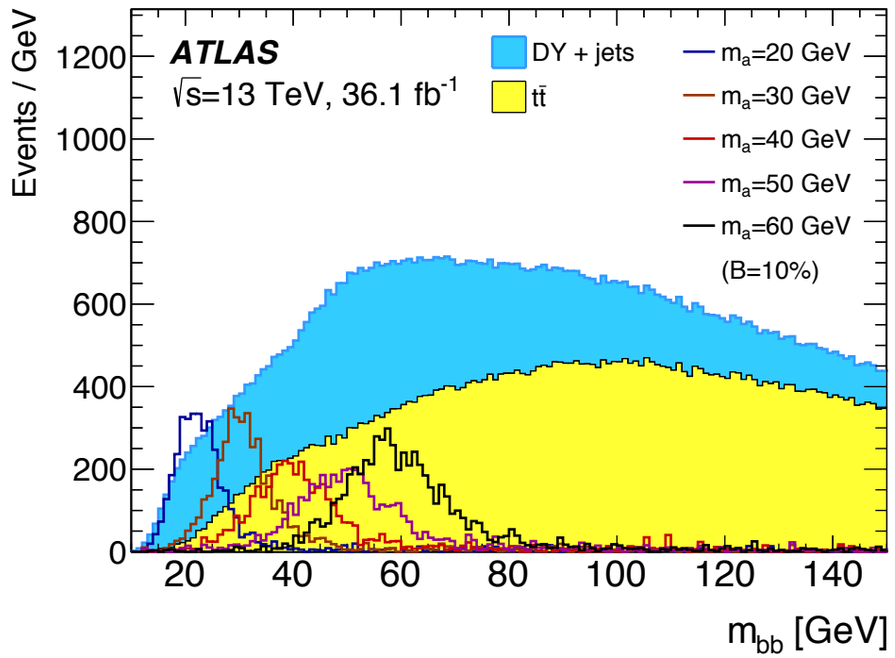
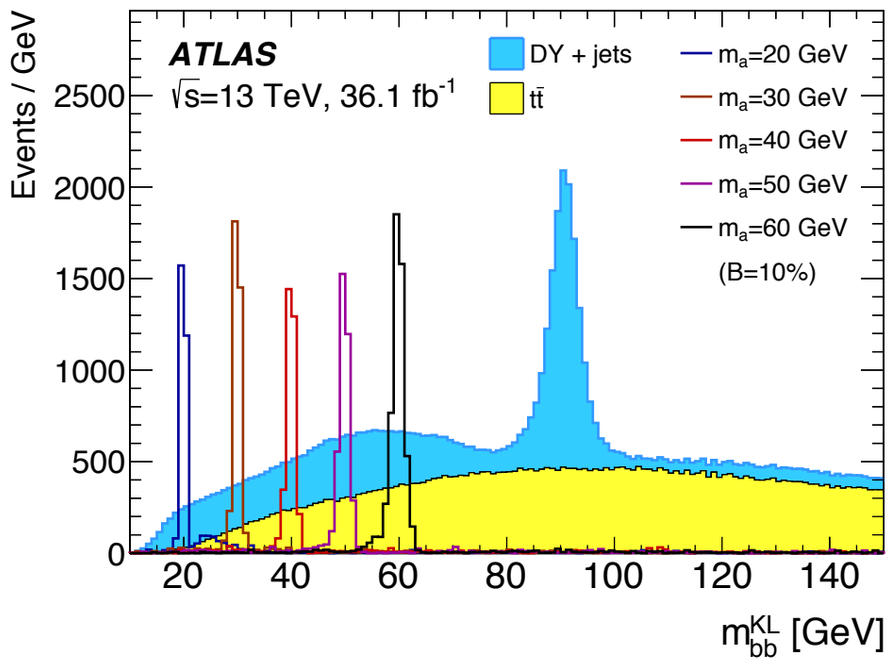
- Maximize the likelihood to find the best-fit value: m_{bb}^{KL}







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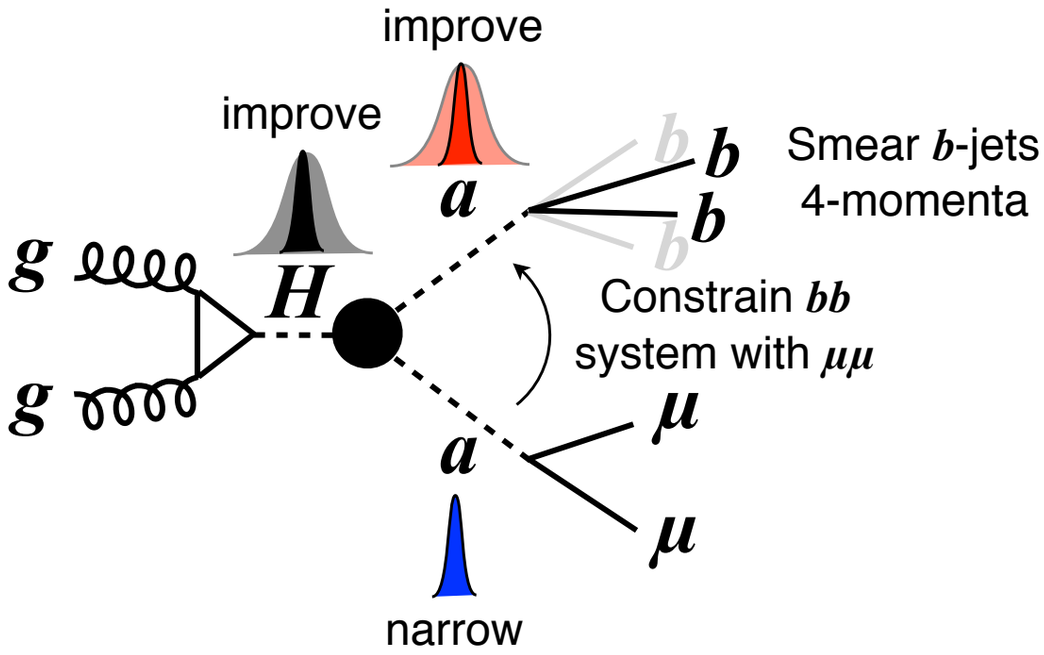
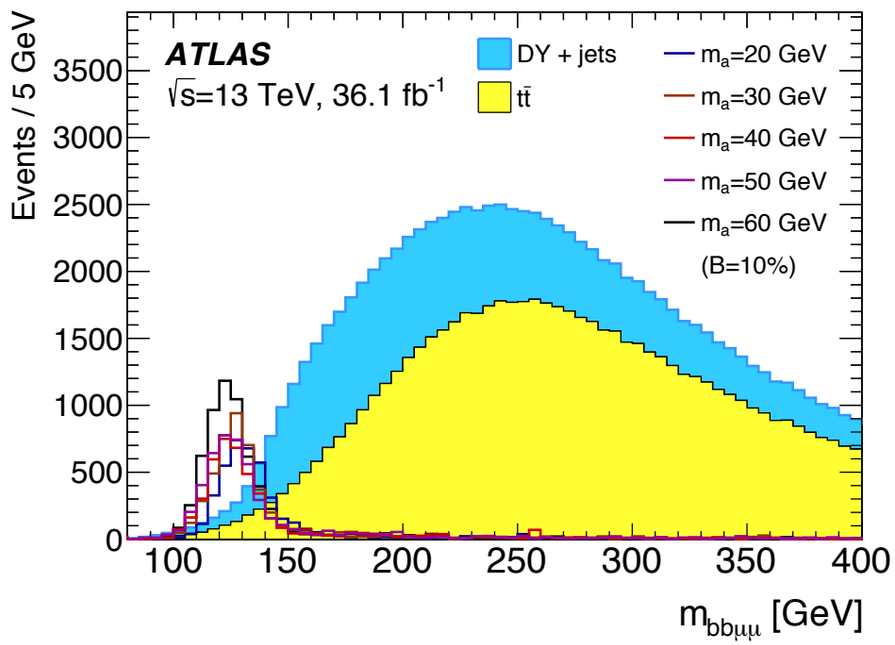
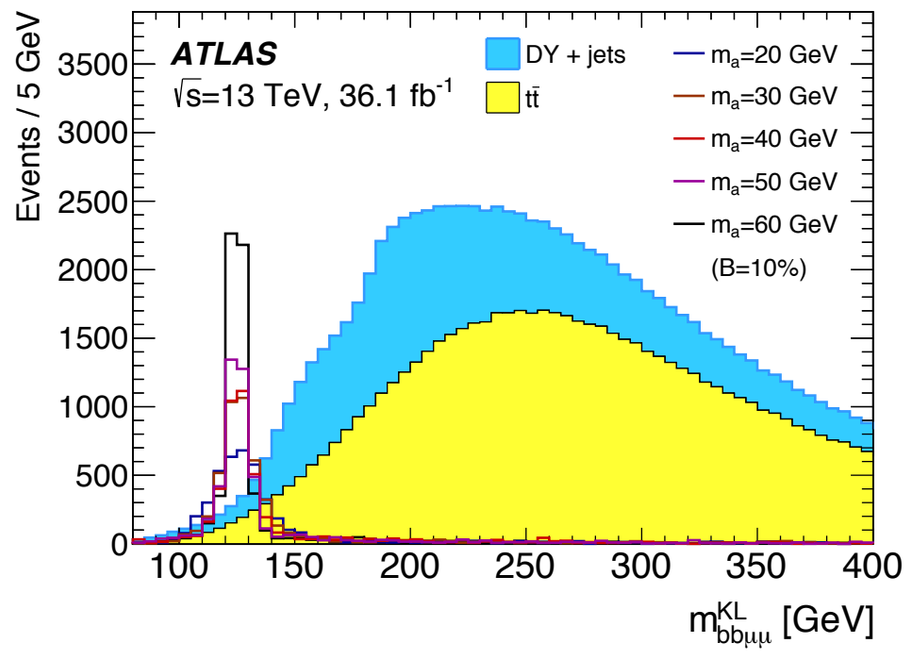
- Maximize the likelihood to find the best-fit value: m_{bb}^{KL}

✓ **$m_{bb\mu\mu}$ resolution improved by factor ~2**







Kinematic constraints

- $m_{\mu\mu}$ resolution factor ~10 better than m_{bb} resolution

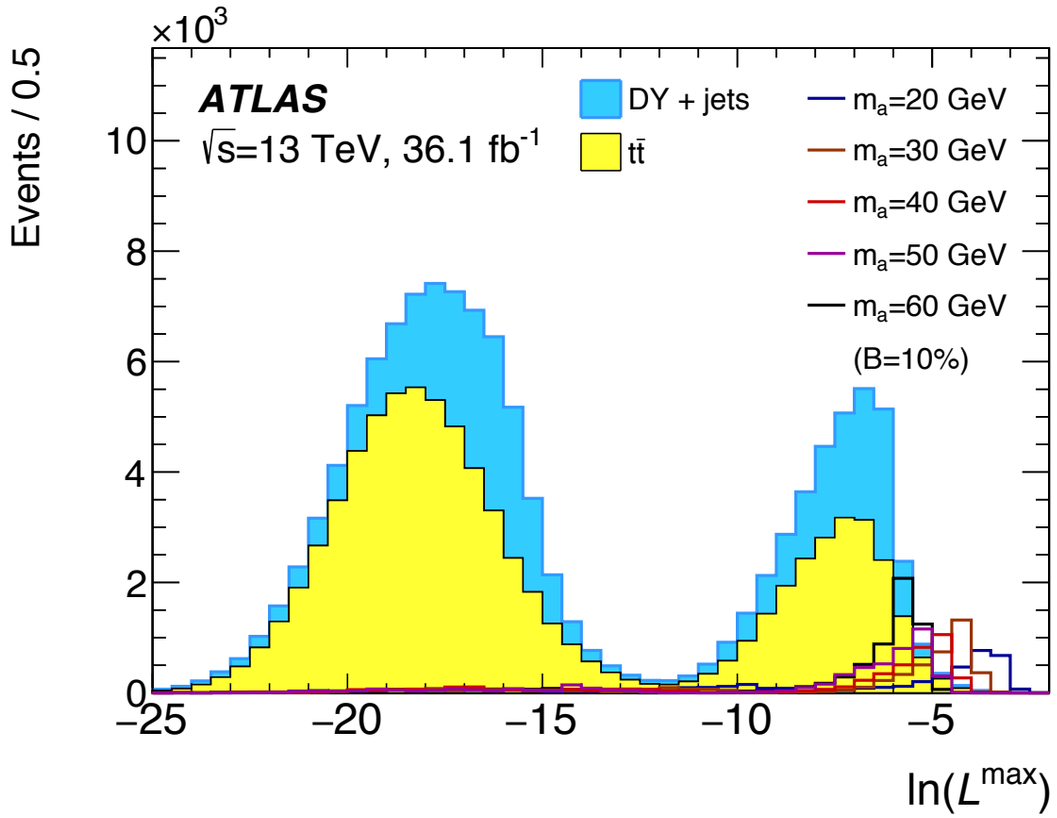
➡ **Constrain m_{bb} with well measured $m_{\mu\mu}$ in a kinematic-likelihood (KL) fit**

$$L = W(\hat{E}_{b_1}, E_{b_1}) \cdot W(\hat{E}_{b_2}, E_{b_2}) \cdot \frac{k}{(m_{bb}^2 - m_{\mu\mu}^2)^2 + m_{\mu\mu}^2\Gamma^2}$$

- Maximize the likelihood to find the best-fit value: m_{bb}^{KL}

✓ **$m_{bb\mu\mu}$ resolution improved by factor ~2**

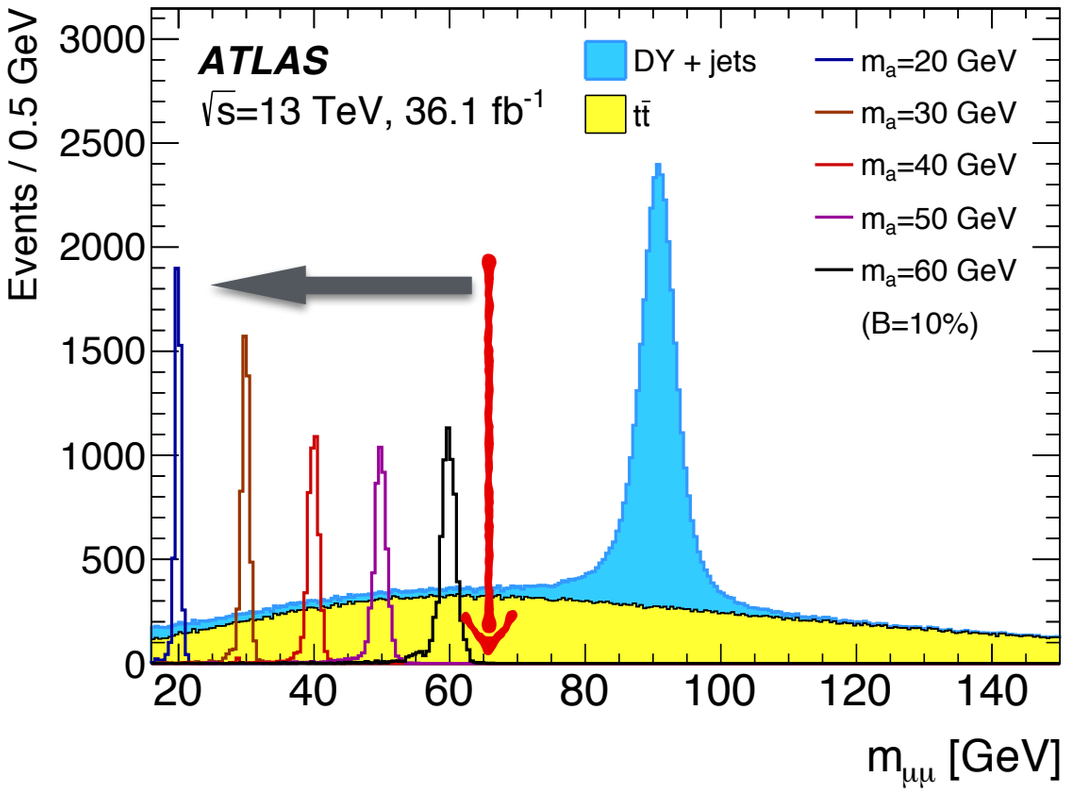
✓ **max value of ln(L) quantifies how well an event fits the m_{bb}~$m_{\mu\mu}$ constraint**

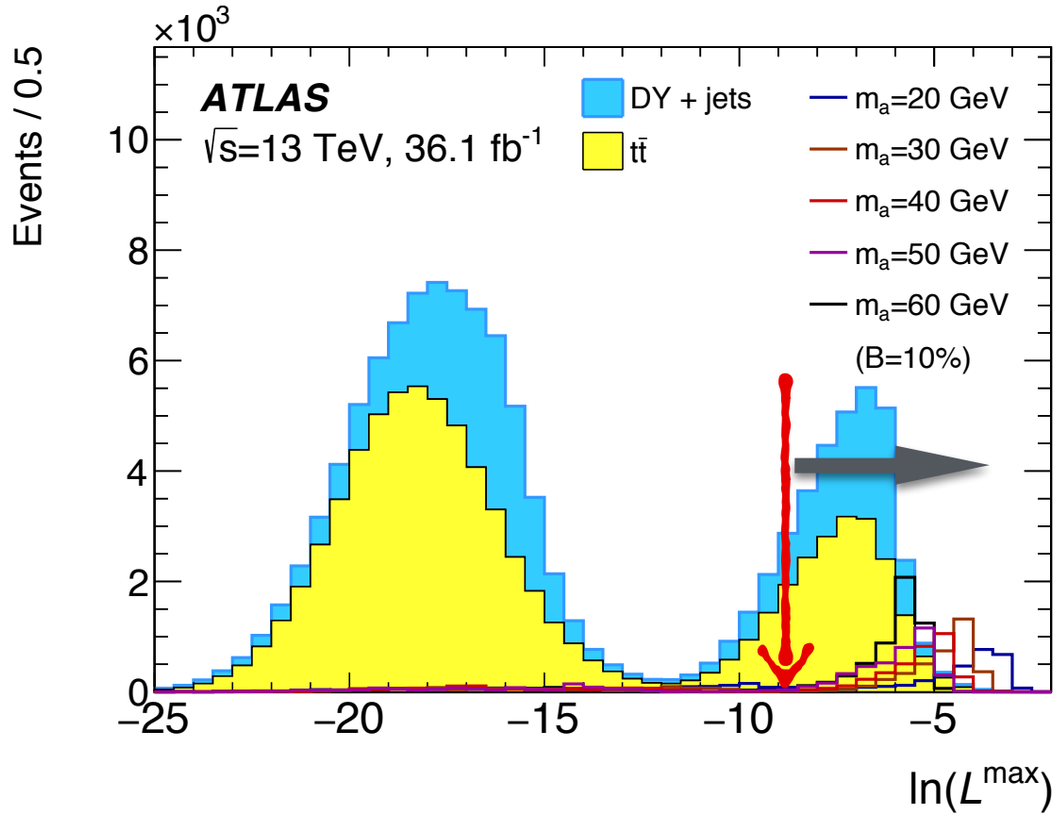


Signal selection

- Apply a set of cuts to select signal and reject backgrounds = signal region

  - $18 < m_{\mu\mu} < 64$ GeV
  - $\ln(L) > -8$



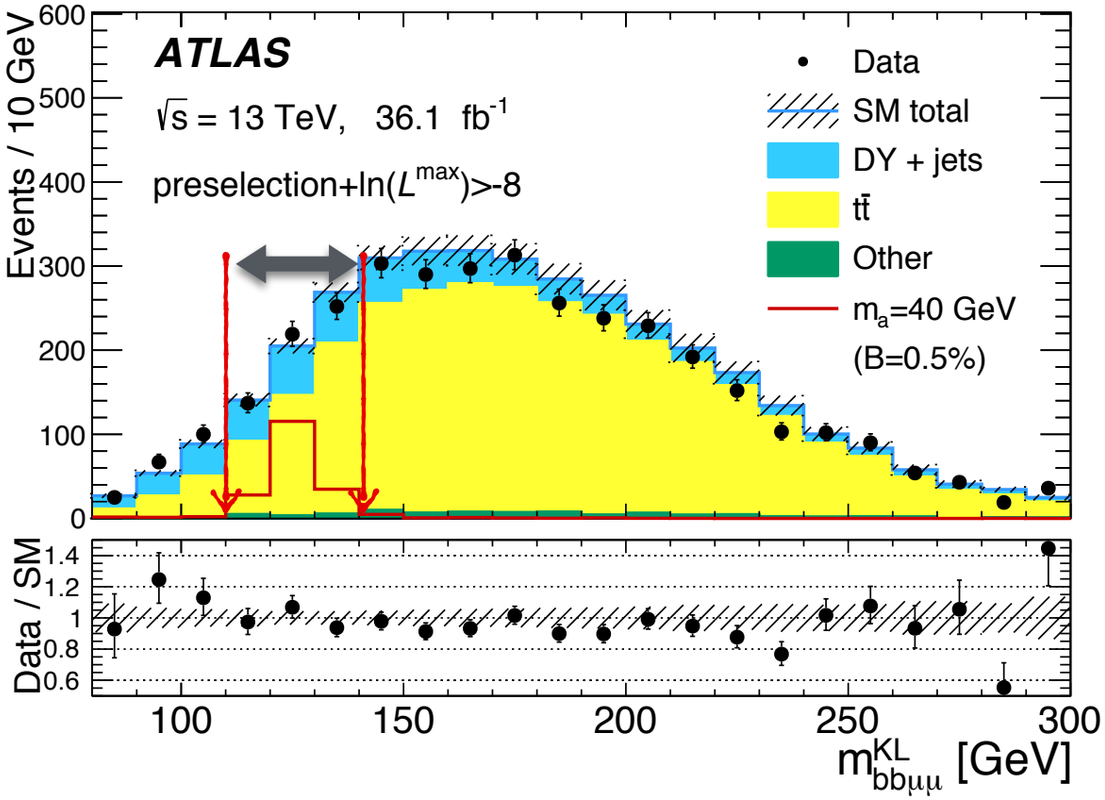


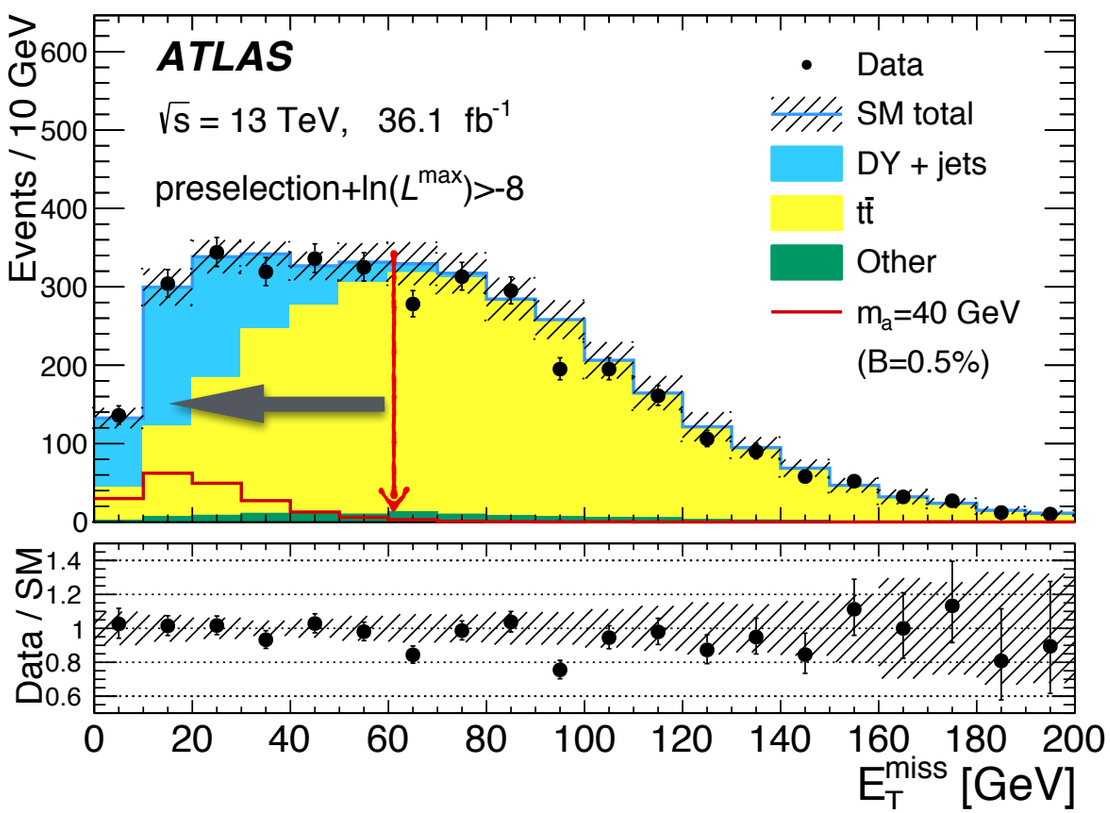
Signal selection

- Apply a set of cuts to select signal and reject backgrounds = signal region

  - $18 < m_{\mu\mu} < 64$ GeV
  - $\ln(L) > -8$
  - $|m_{bb\mu\mu} - 125\ \text{GeV}| < 15$ GeV
  - MET<60 GeV

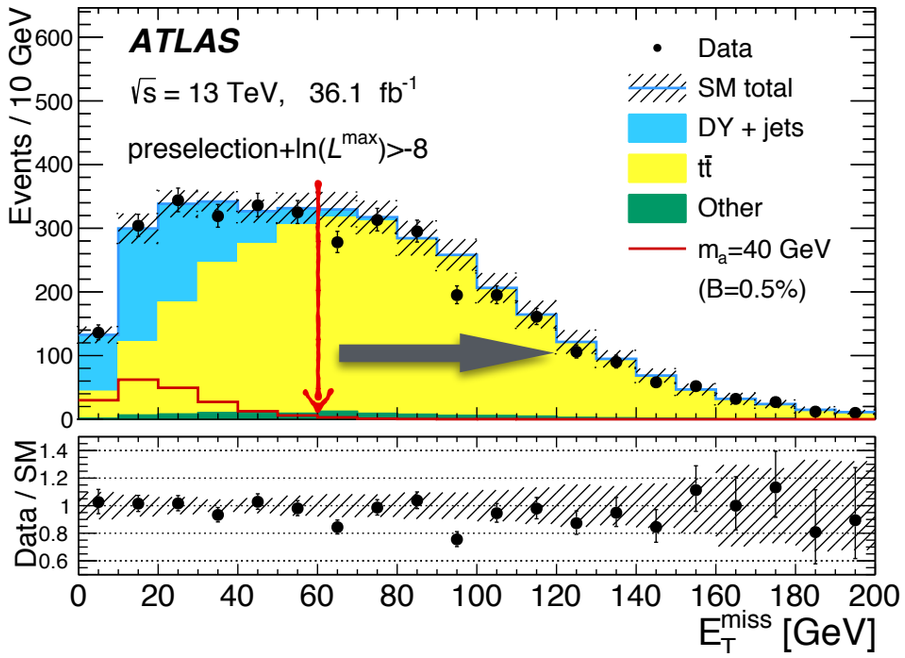
➡ **Look for a resonant-like excess above the background prediction in $m_{\mu\mu}$ spectrum**

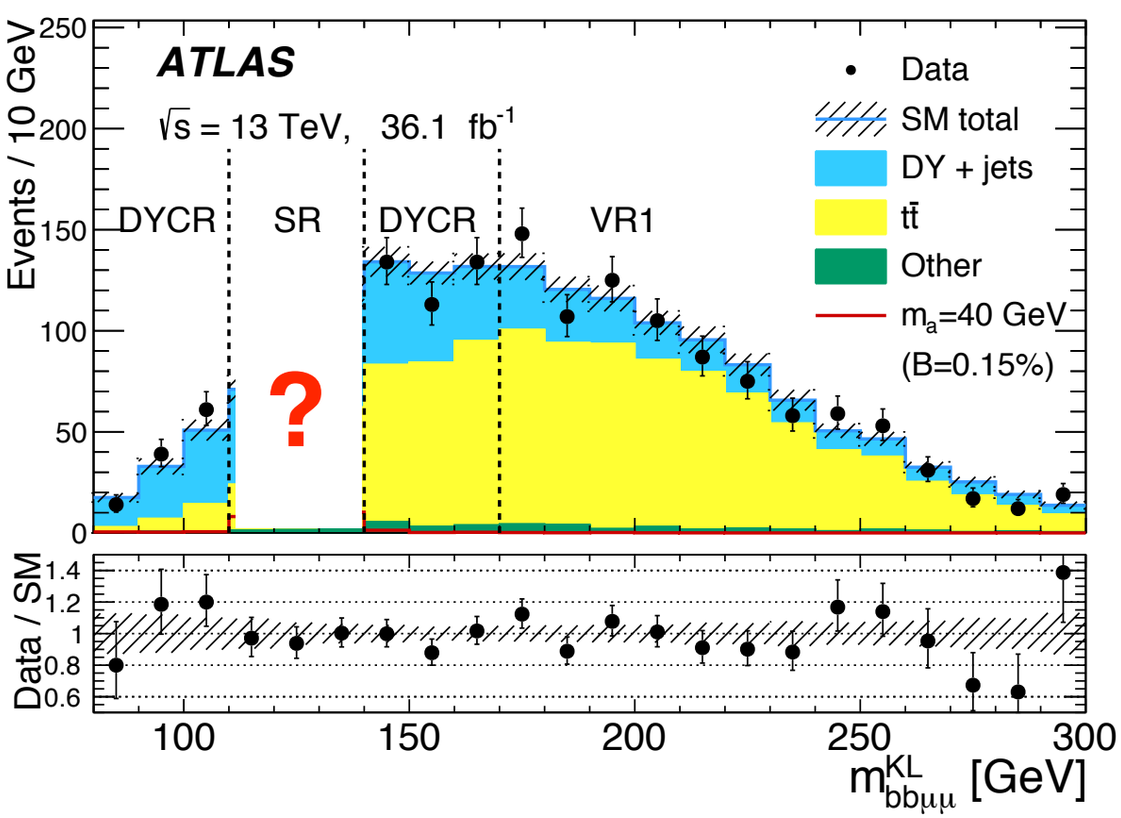


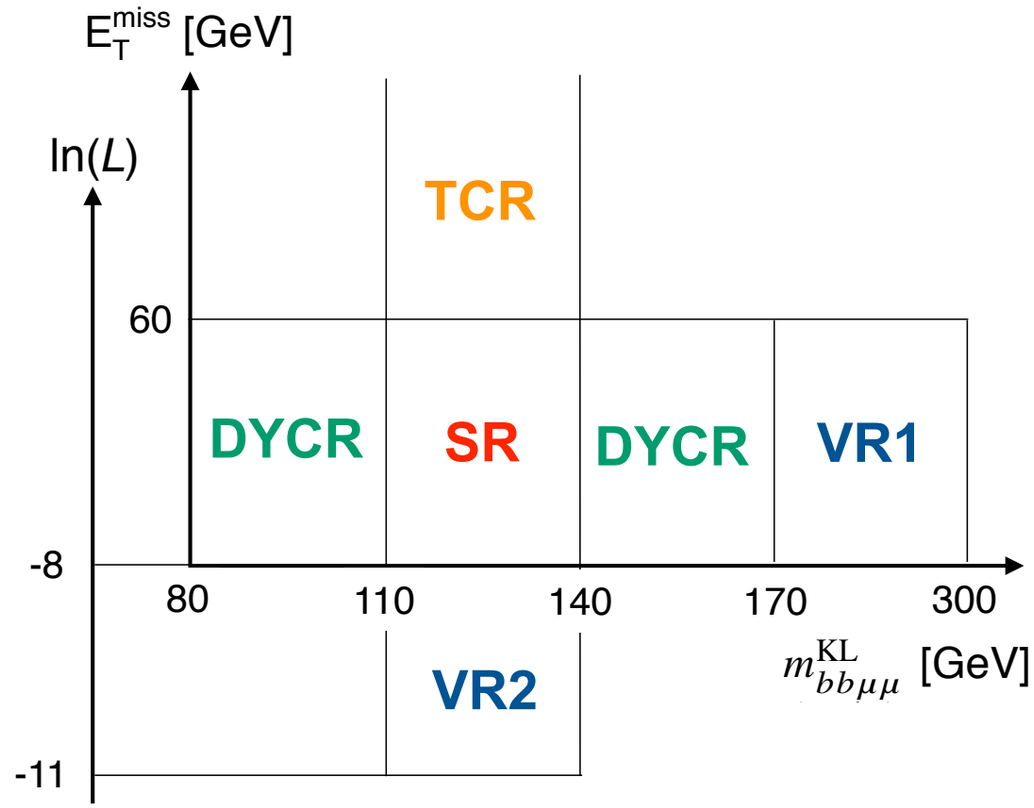


Analysis regions

- 1 signal region (SR)
- 2 control regions (CR) to constrain the normalisations of the dominant backgrounds
- 2 validation regions (VR) to validate the background modelling before looking at the SR

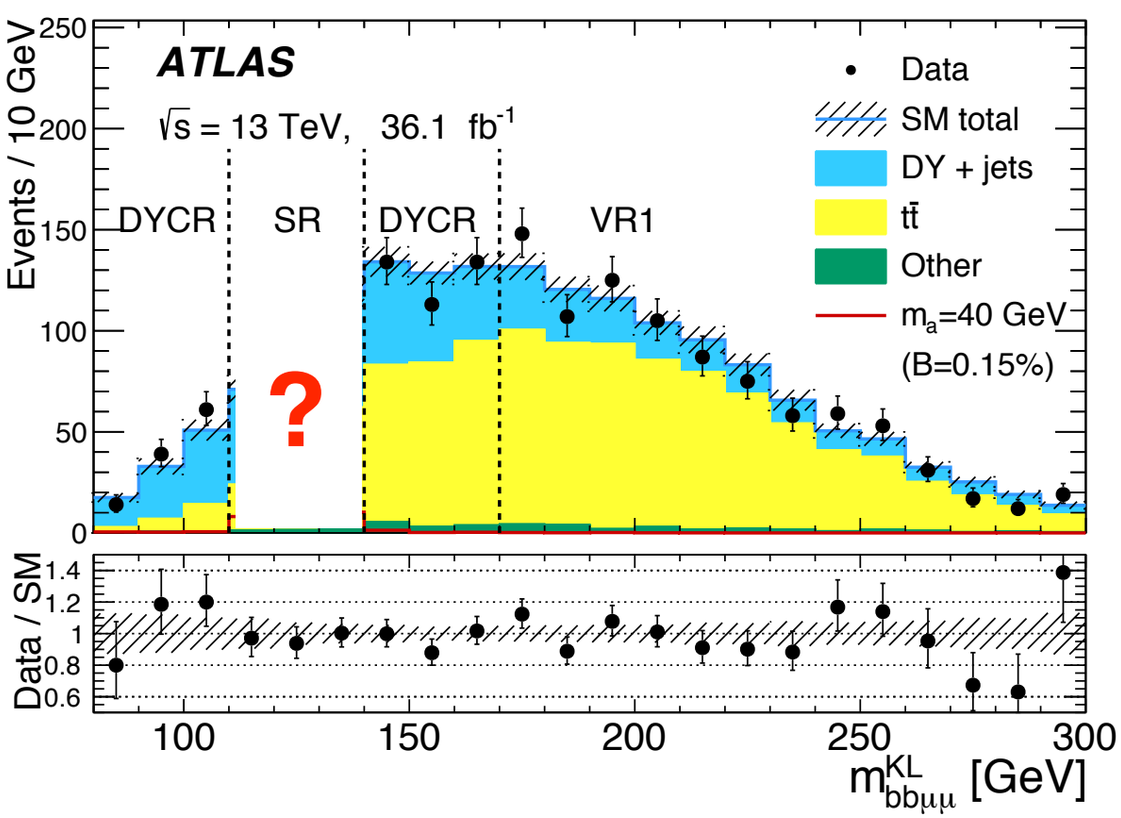


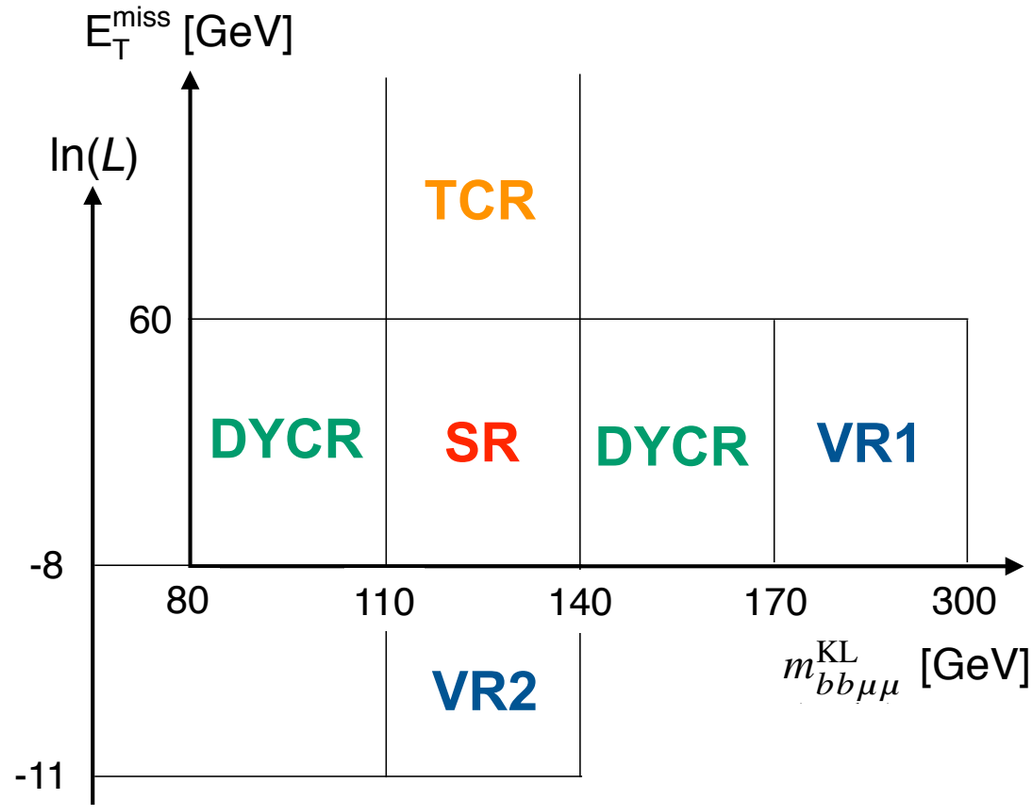




Background estimation

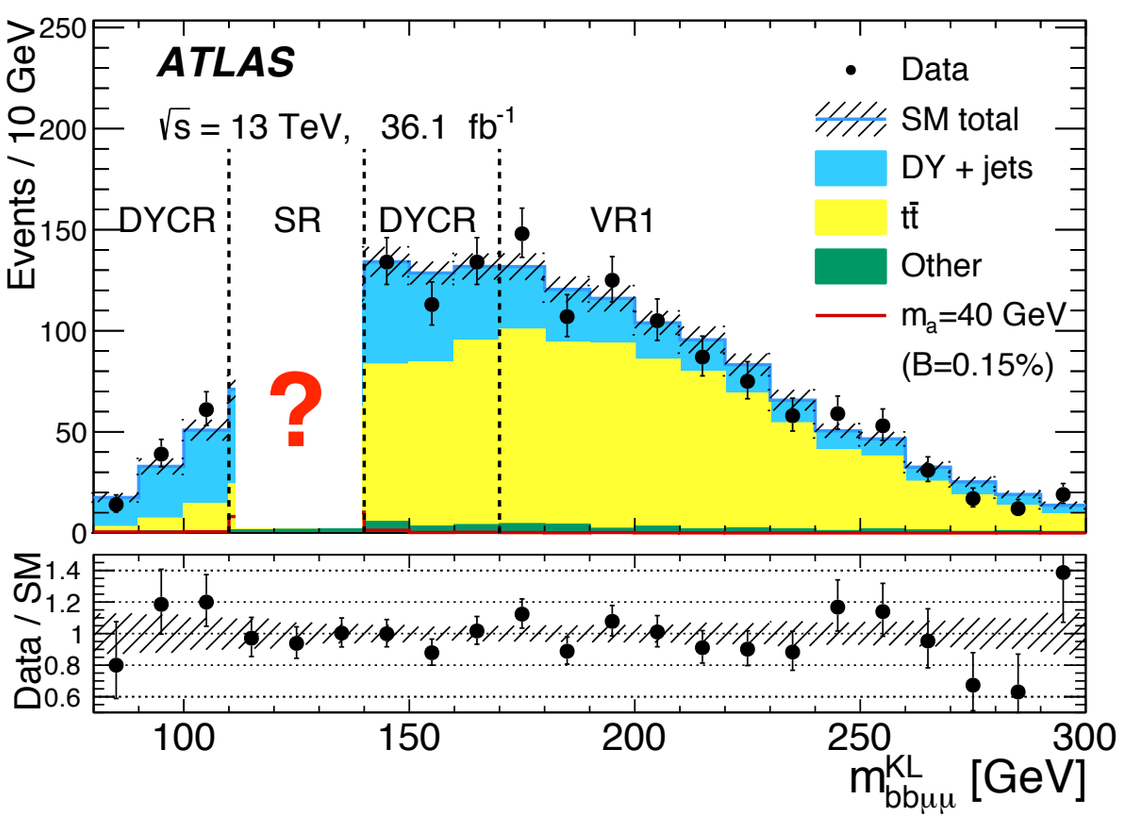
- **ttbar**: Model shapes of kinematic distributions with MC
- **DY+jets**: Model shapes of kinematic distributions with the template extracted from the data
  - **Normalize tt MC & DY template simultaneously in a fit to the data over CRs**
- **Minor backgrounds** (dibosons, single-top, ttV & W+jets) contribute ~1% in the SR
  - **Estimate using MC only**

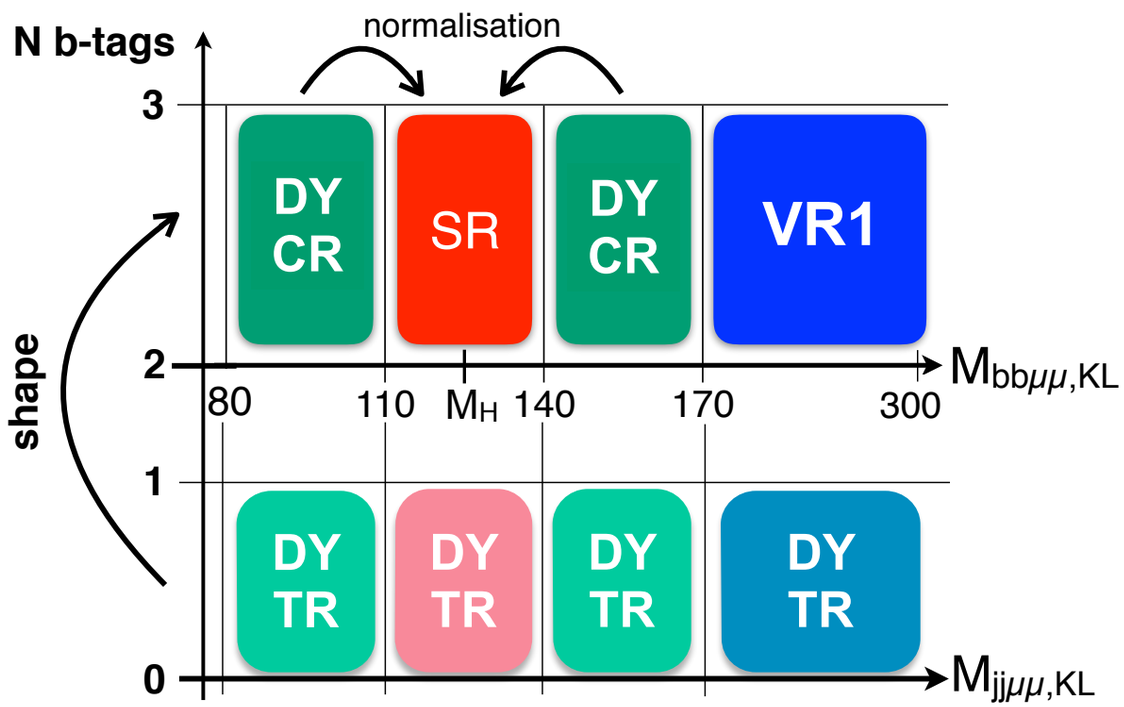




DY templates

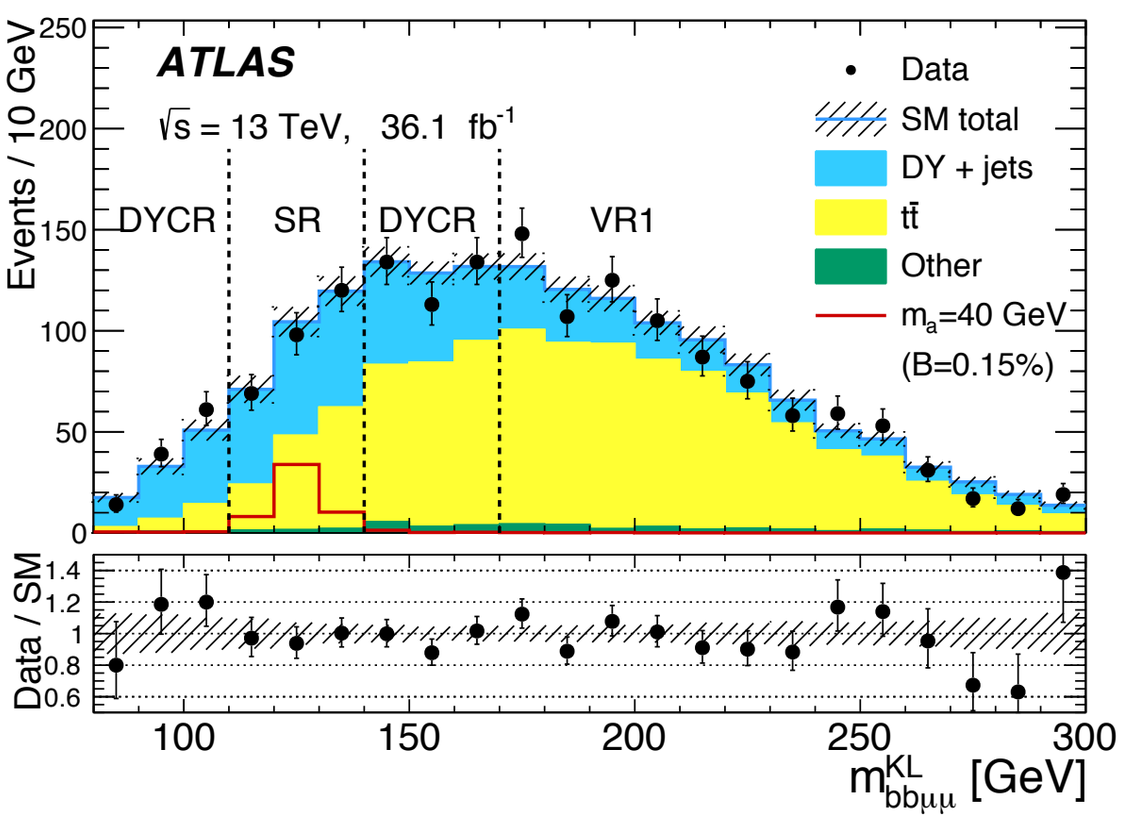
- For each analysis region define the DY template region (DYTR) by requiring 0 b-tagged jets in an event (instead of 2 b-tagged jets)
- All other selection criteria remain the same
- DYTR defined in such way are >90% pure in DY+jets events
- Use 2 leading non b-tagged jets in construction of m_{bb} & $m_{bb\mu\mu}$

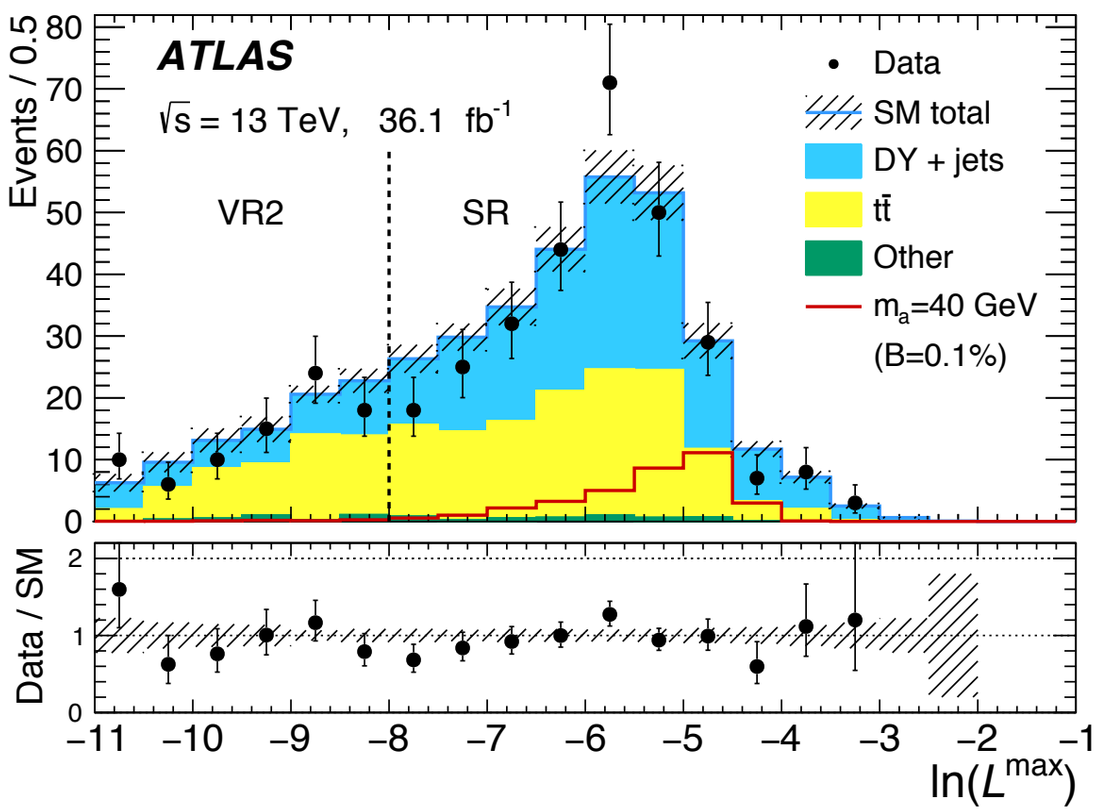




Post-fit distributions

- Good agreement between the data and the background expectation, both in shape and normalisation in all CRs & VRs
- No excess observed in the SR





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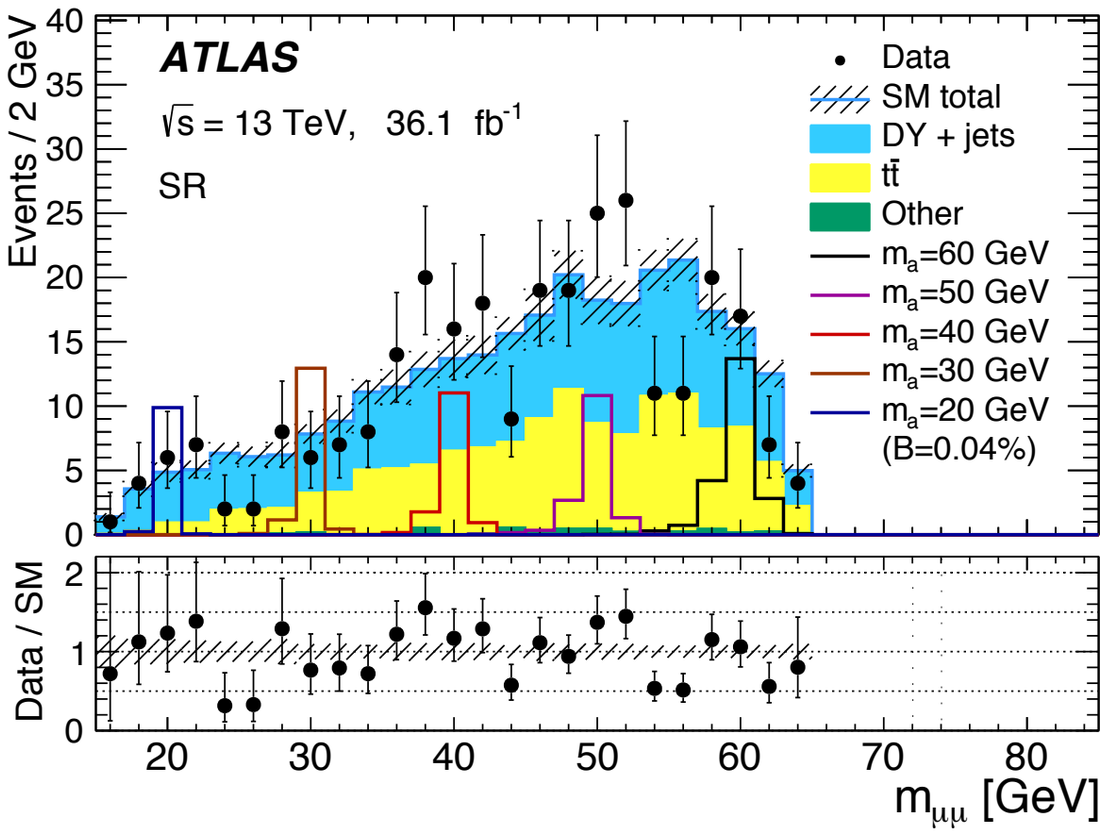
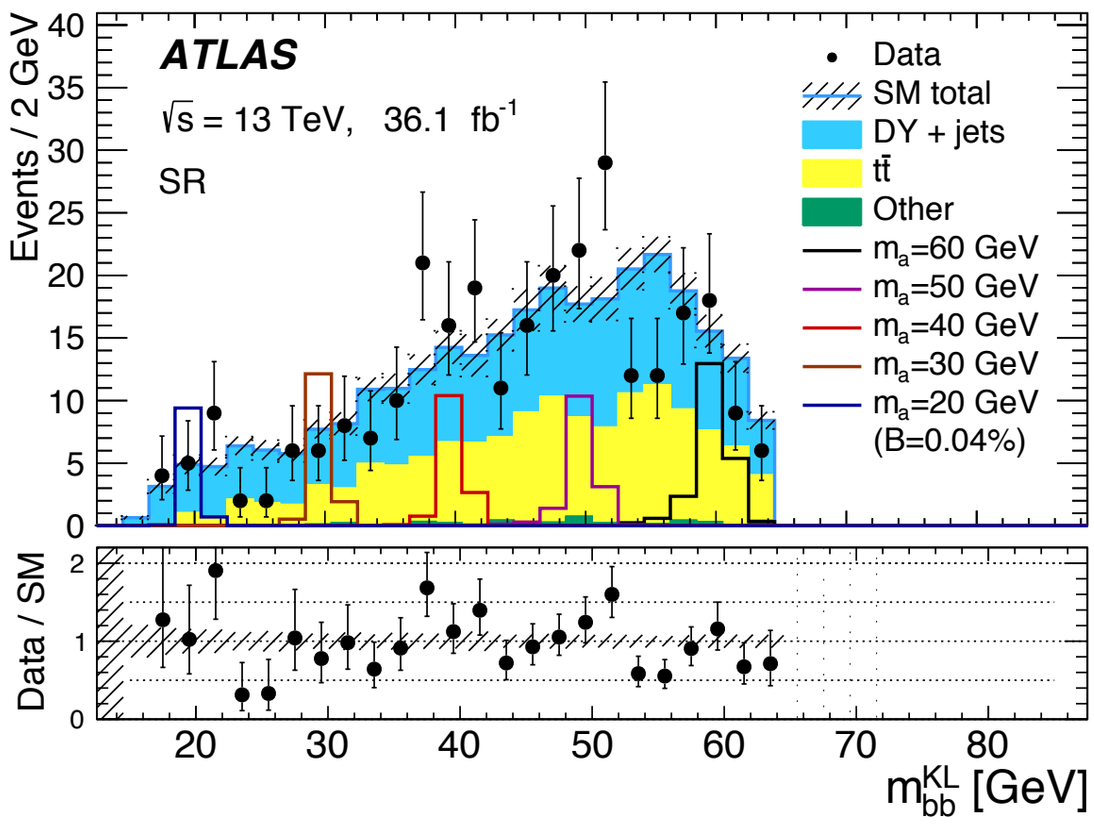
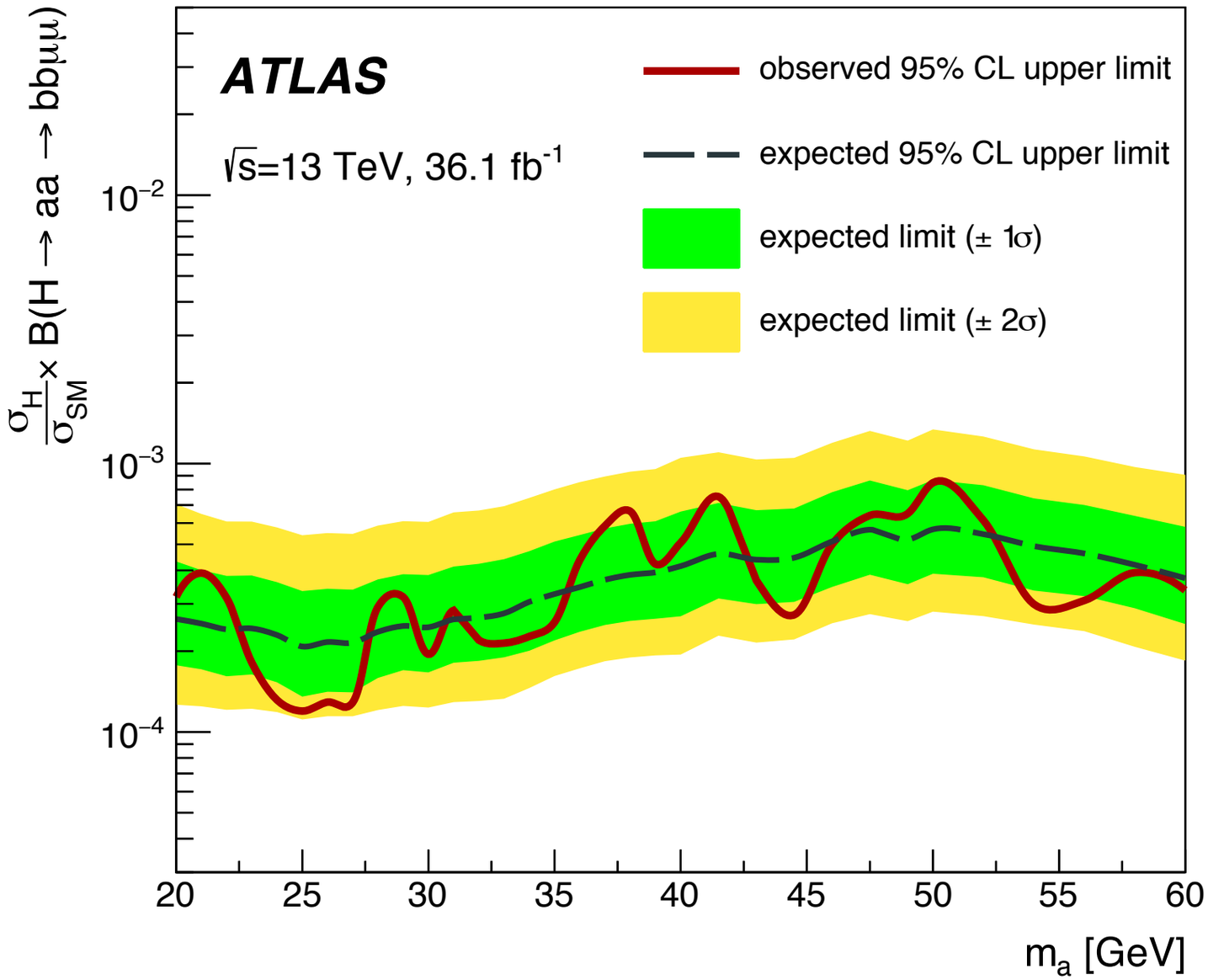




Limits

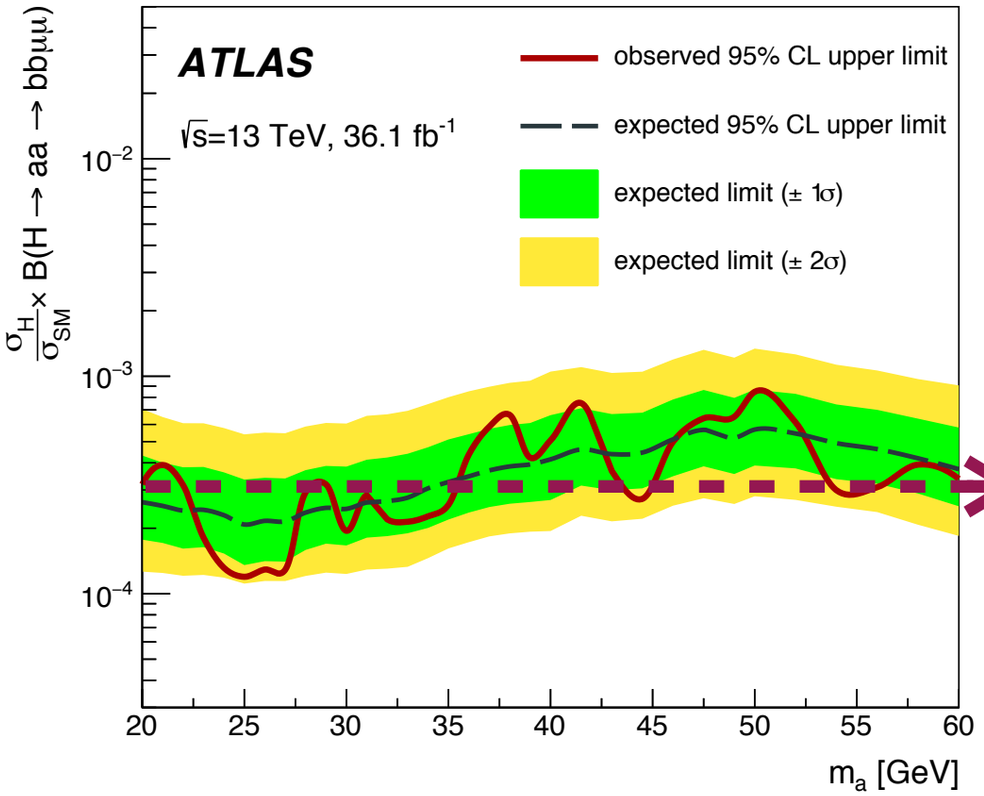
1807.00539



What does this mean?

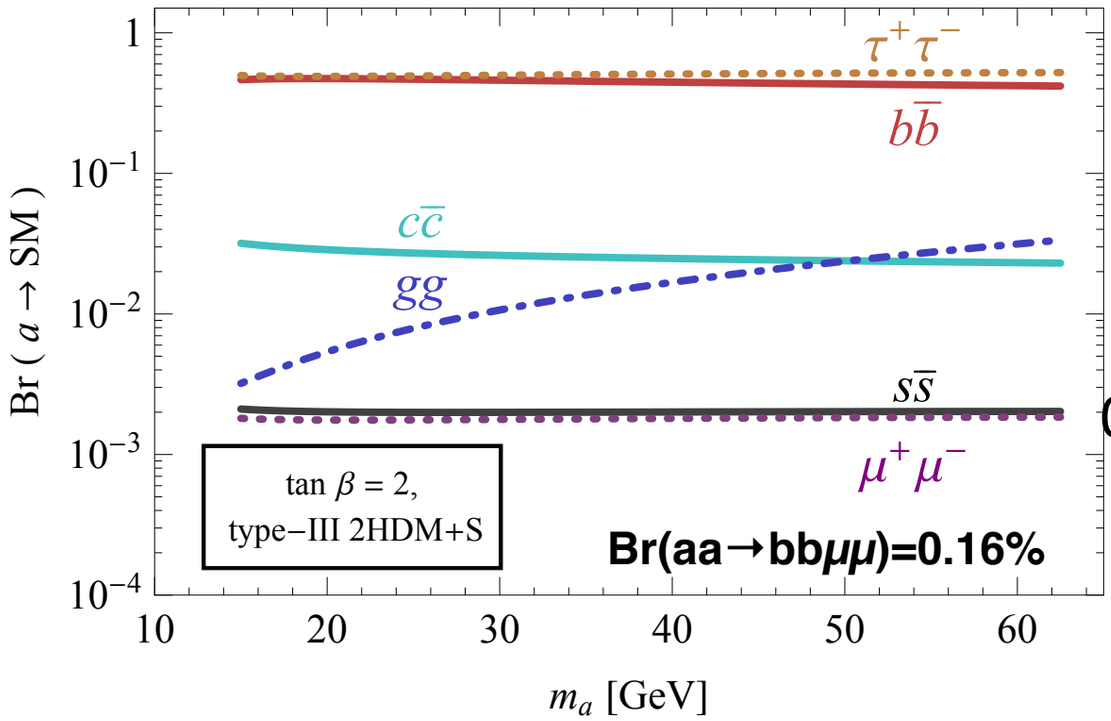
- Assuming SM H production cross section, limits are **Br(H→aa→bb$\mu\mu$)< 0.03%**
- Plug in an allowed value for **H→aa: Br(H→aa)=20%**
  - Br(aa→bb$\mu\mu$)< 0.15%
  - Under the above assumptions, the most optimistic 2HDM+S model predicting Br(aa→bb$\mu\mu$)=0.16% is excluded at 95% CL

➡ **The analysis is probing interesting parameter space**



0.0003

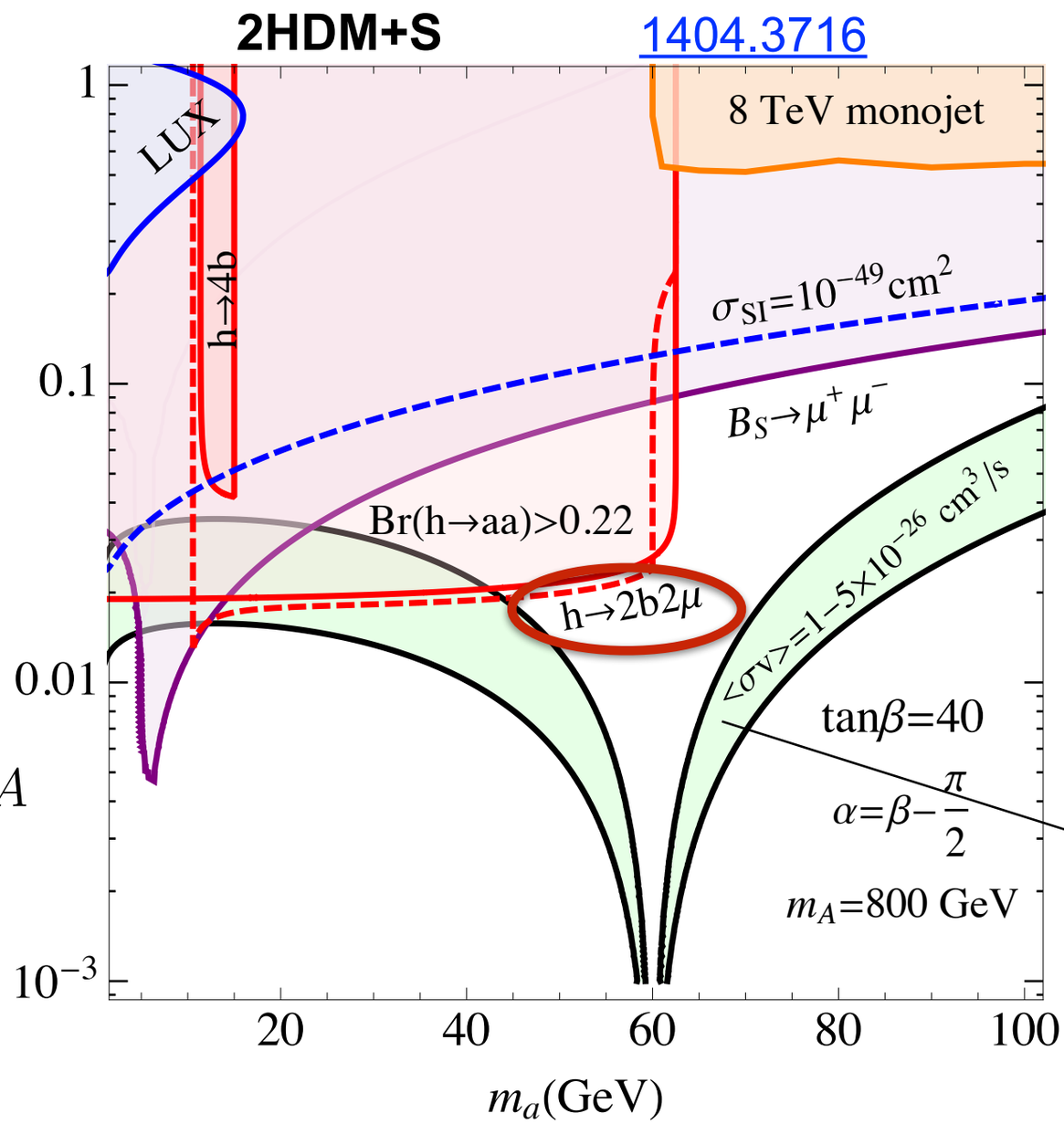
arXiv:1412.4779



…in terms of y-ray excess?

mixing angle between the singlet & H-doublet state θ

$$a = \cos\theta_a S_I + \sin\theta_a A$$

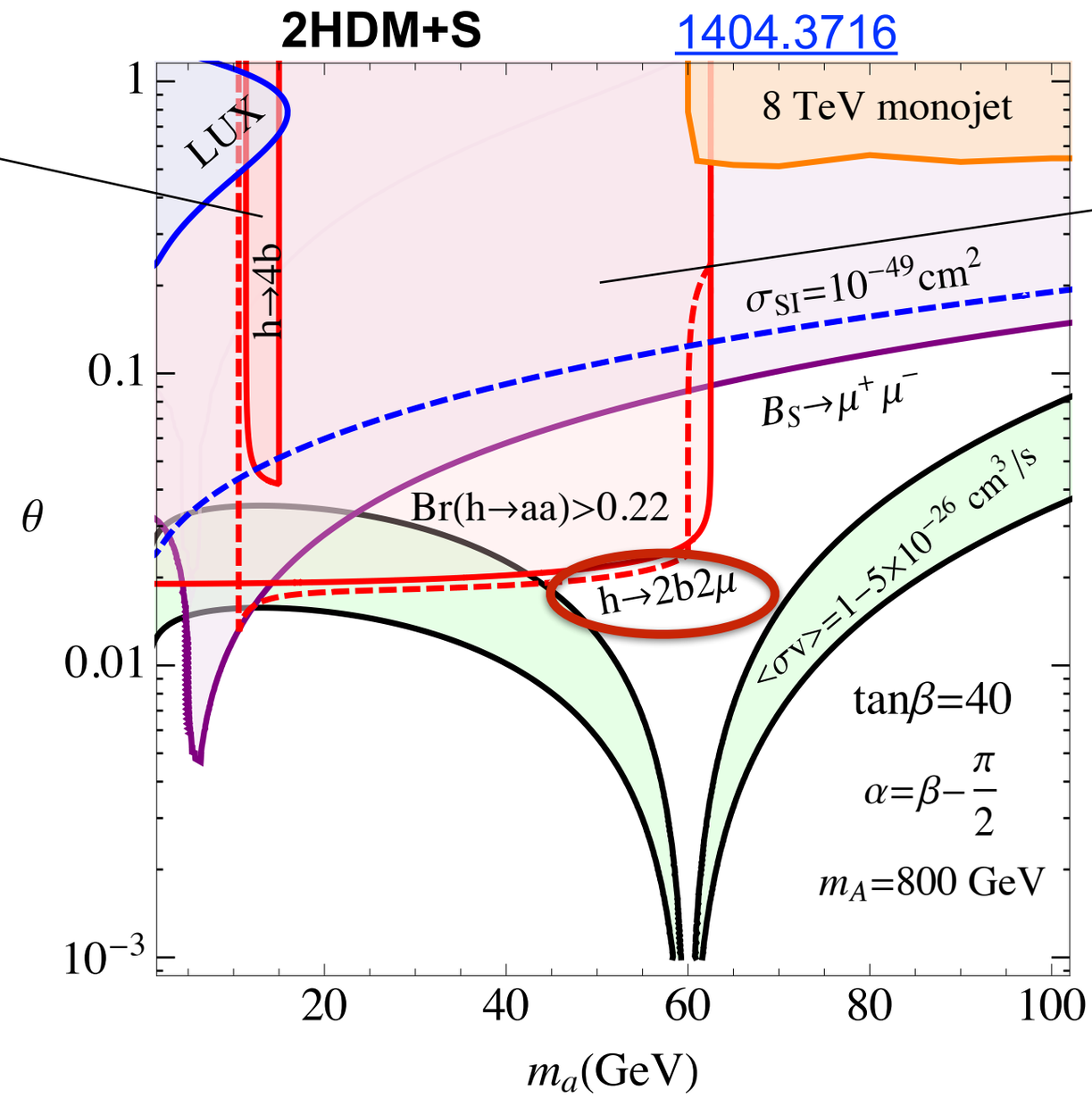


Green region consistent Fermi-LAT data

…in terms of y-ray excess?

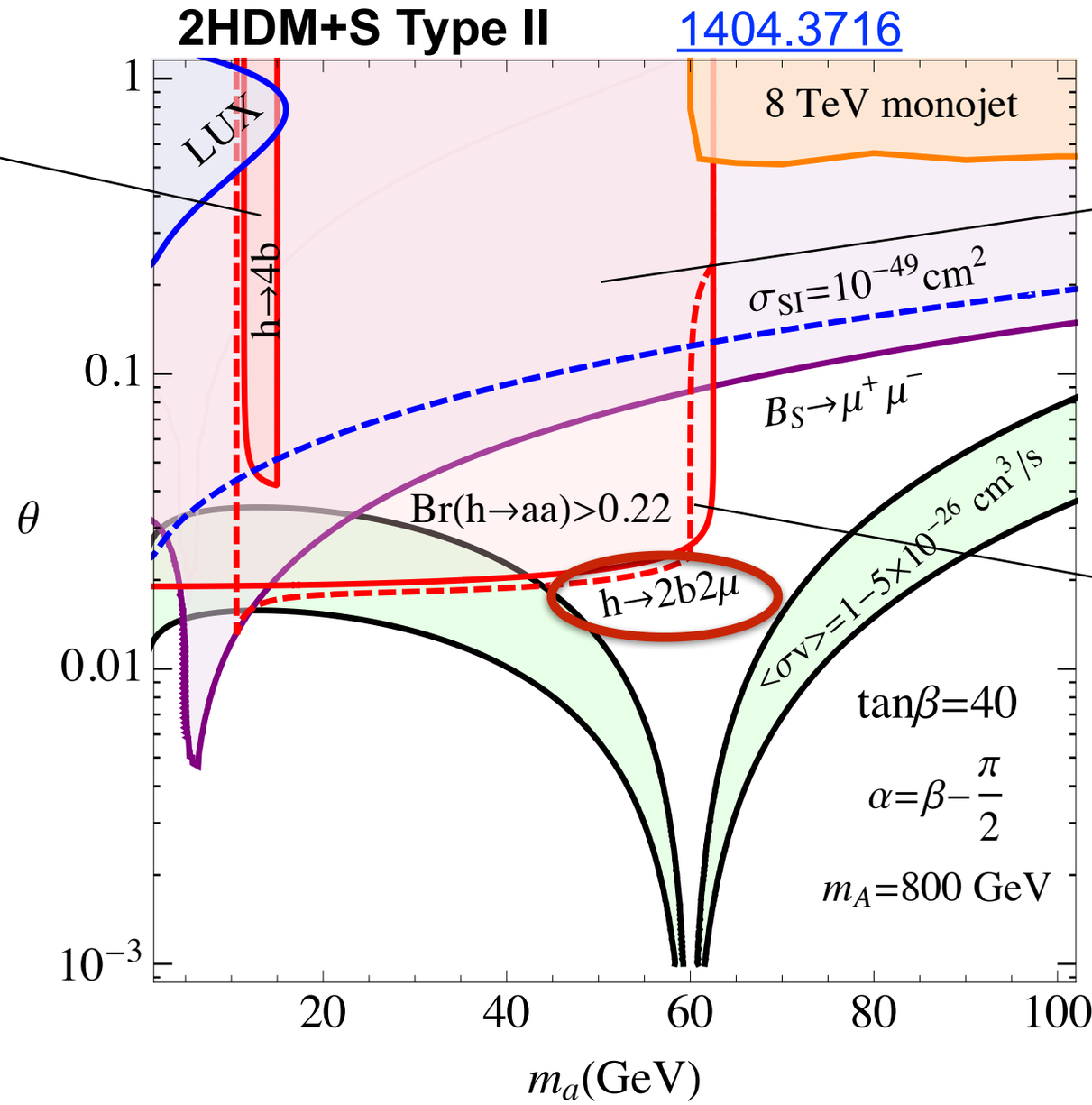
limits from Vh(→bb) CMS search

indirect limit from fits to H properties assuming SM H production



...in terms of y-ray excess?

limits from Vh(→bb) CMS search



indirect limit from fits to H properties assuming SM H production

could be probed by limiting

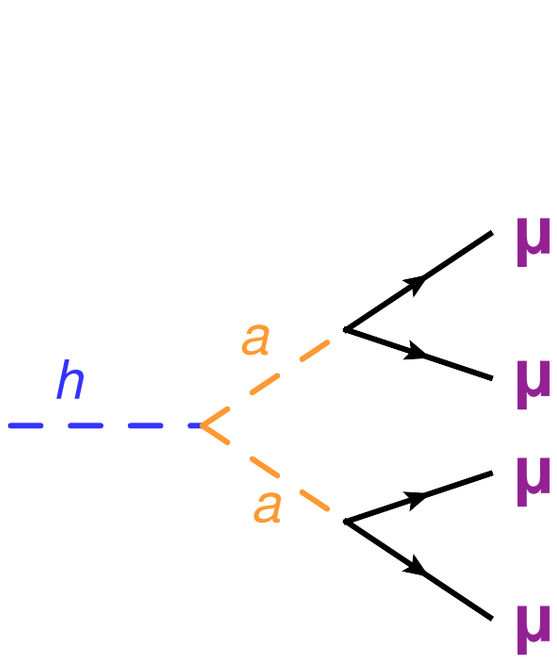
$$\mathrm{Br}\,(h \to aa \to 2b2\mu) \lesssim 10^{-4}$$

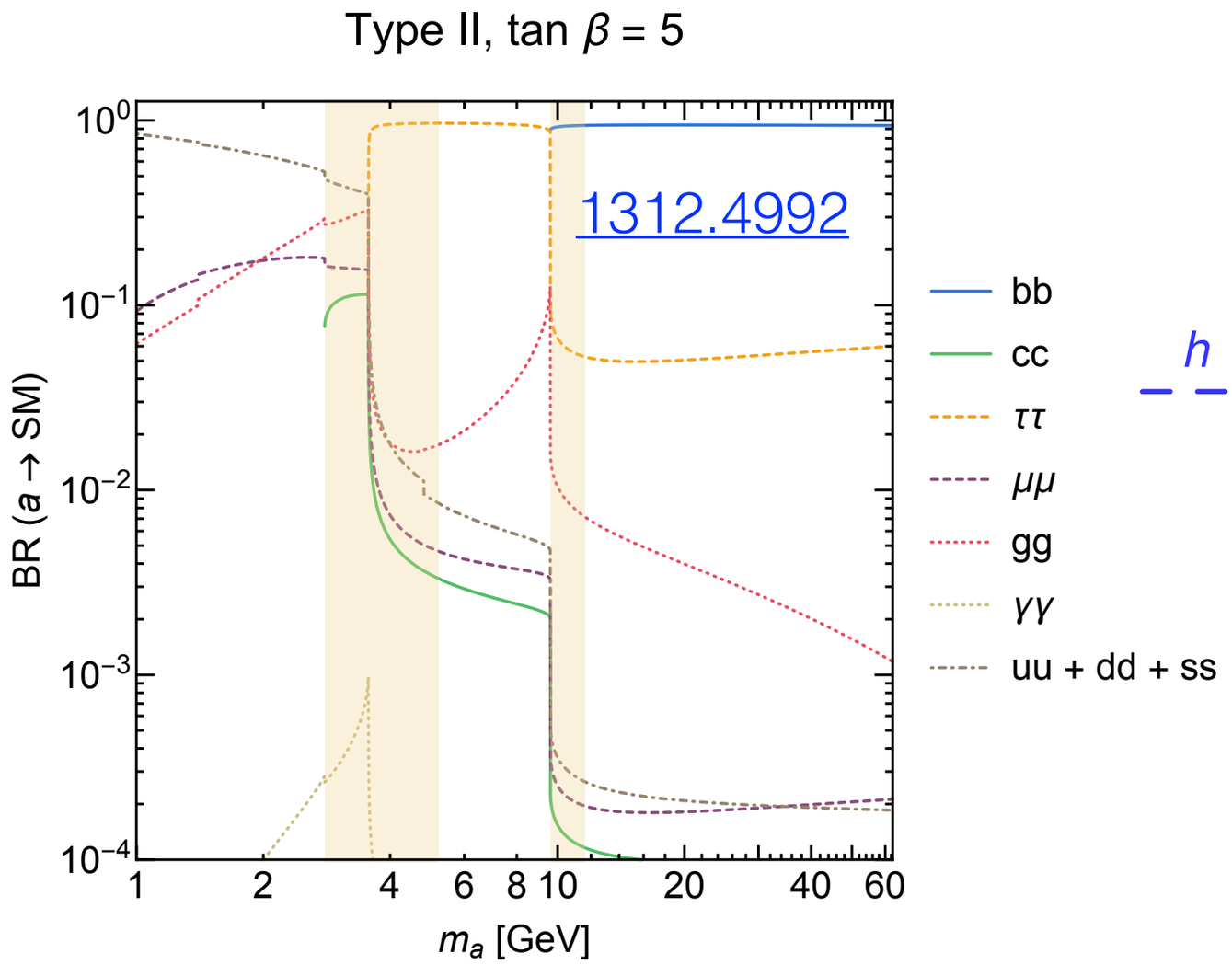
- Assuming SM H production cross section, **observed limits** are **Br(H→aa→bb$\mu\mu$)<(1-8)*10^{-4}**

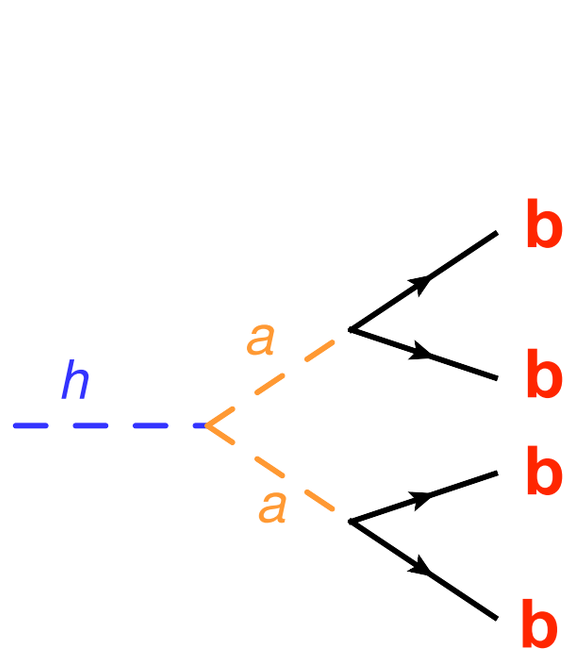
  ➡ **The analysis is probing the interesting parameter space!**

Other channels

- For $m_a > 2m_b$ Br($a \to bb$) dominates
- Below 2b threshold, 4μ analysis becomes sensitive





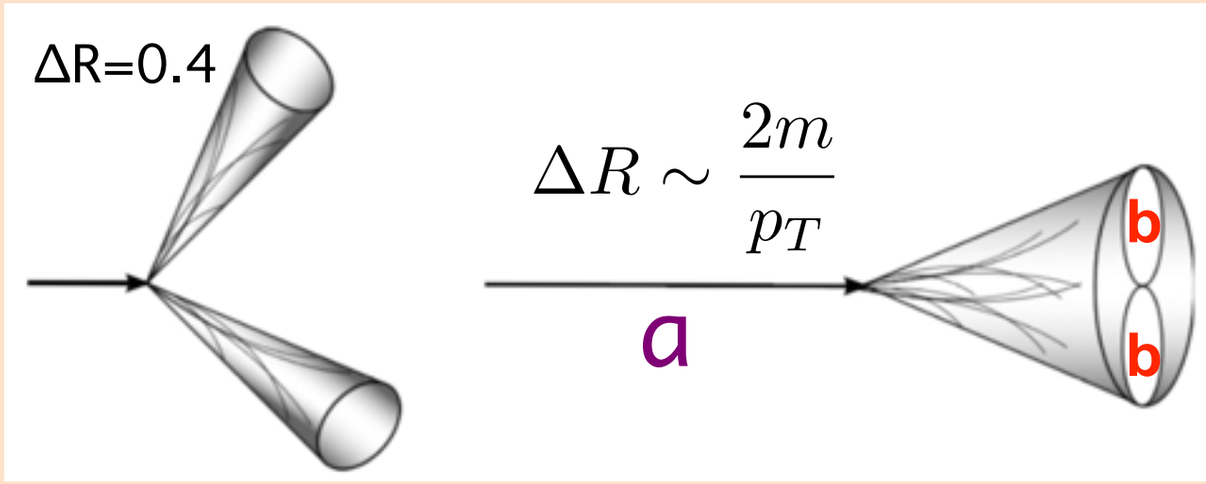


$H \rightarrow aa \rightarrow 4b$

1806.07355

- Challenges:
  - 4 soft b-jets - what to trigger on?
  - High multi-jet & tt+heavy-flavour backgrounds
  - Jet merging at low m_a => loose the signal acceptance

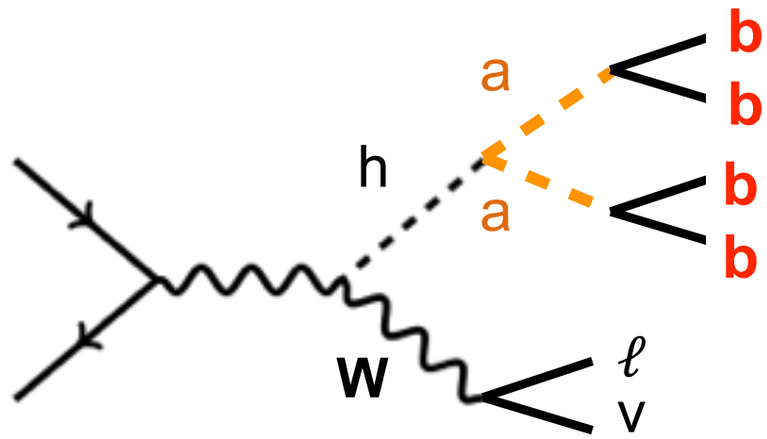
when $m_a << m_H$:
jets from a-decays become collimated

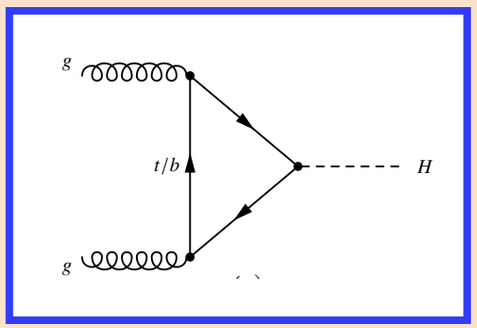


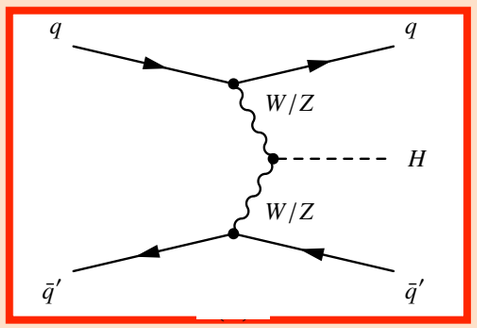
ma~20 GeV, p_T~40 GeV => ΔR~0.1

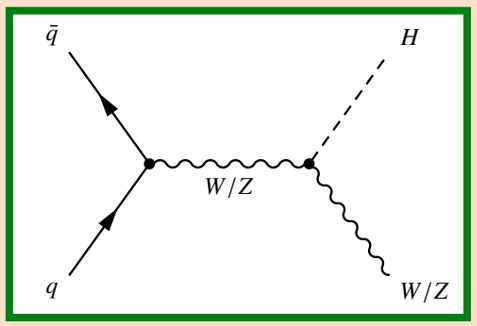
H→aa→4b

- **Look for W/Z associated production**
  - Trigger on leptons from W/Z decays
  - Suppresses multijet backgrounds
  - However, cross-section only ~2 pb
    - ~0.36 pb assuming V→lep

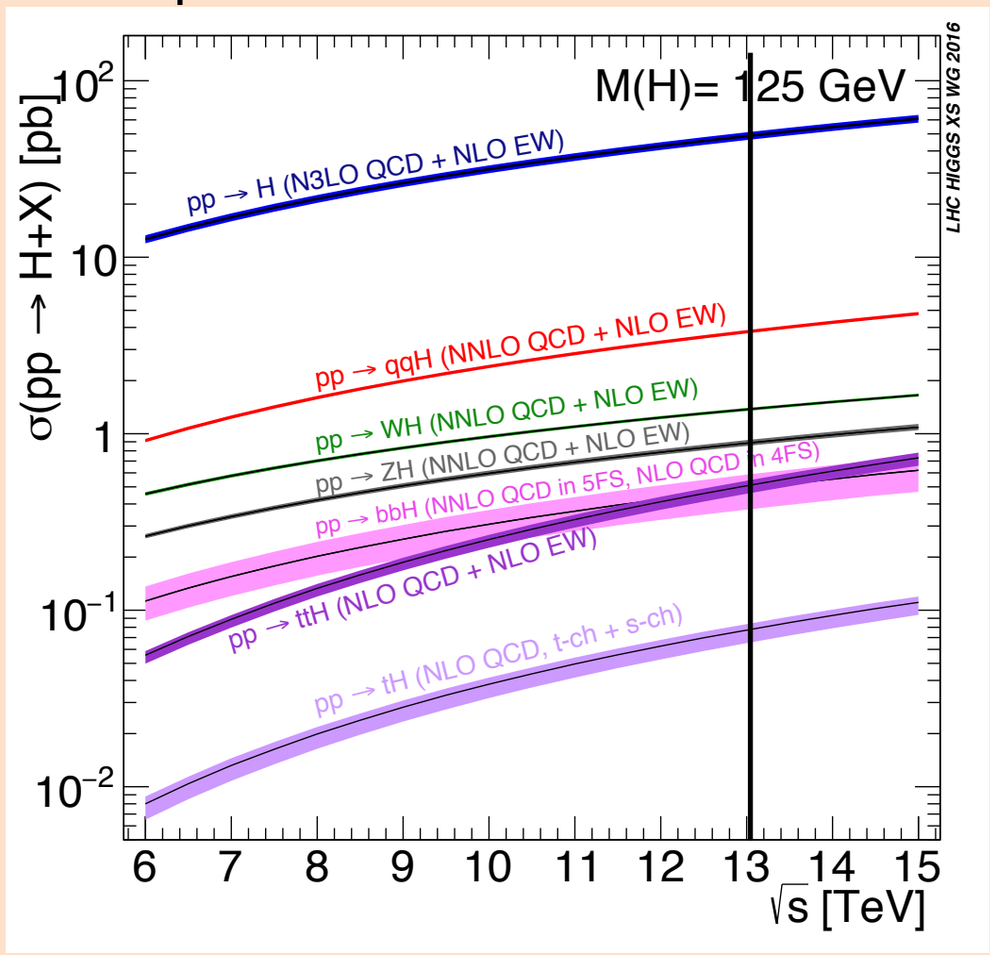








H production cross-sections



H→aa→4b

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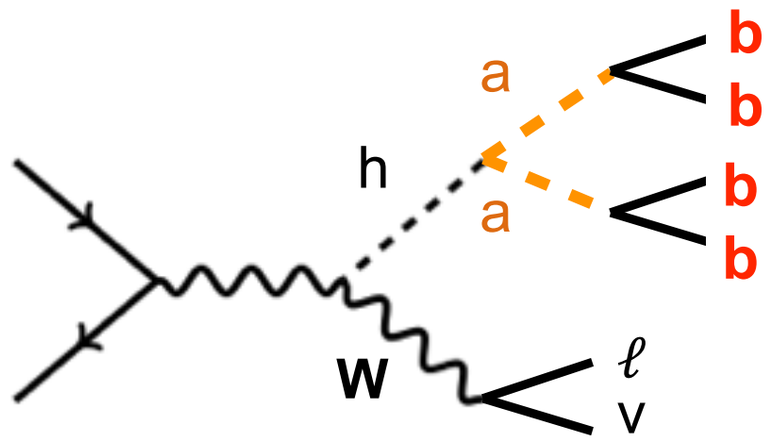
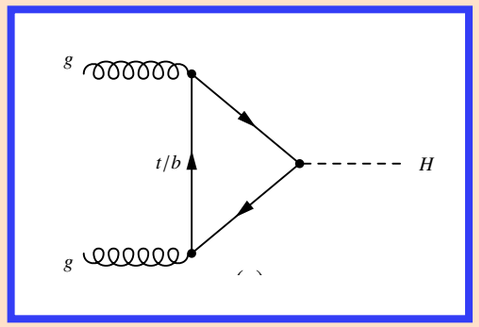
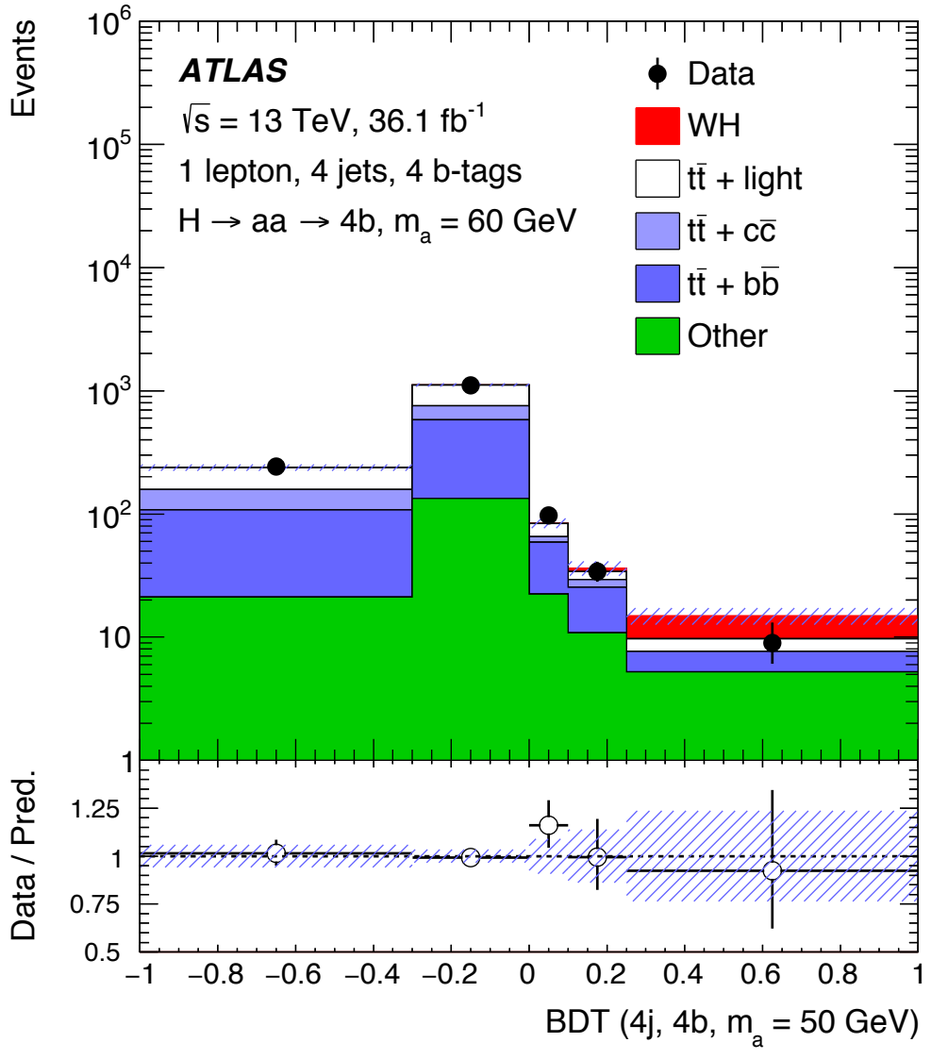


- Compare to bbμμ:
  - ggF cross section ~48 pb => **~100 higher production rate**
  - Br(a→μμ) smaller than Br(a→bb) => **~10^3-10^4 lower decay rate**
  - clean signature from a→μμ => **lower backgrounds**

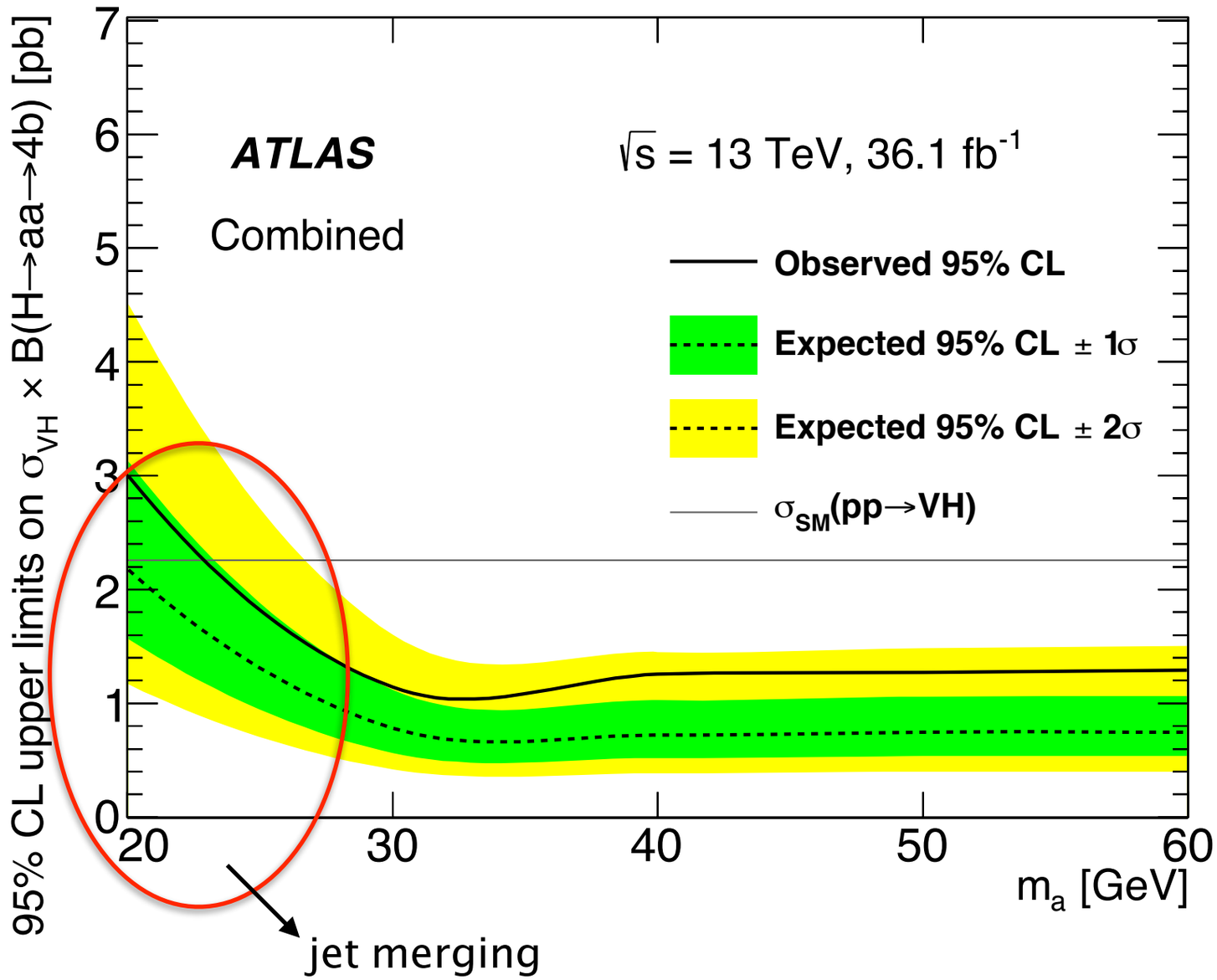


H→aa→4b

- **A multivariate discriminant (BDT) is built to discriminate the signal from the backgrounds**
  - Takes as input various kinematic variables that behave differently for the signal and backgrounds
  - Calculates a BDT “score” which quantifies how signal-like or background-like an event is

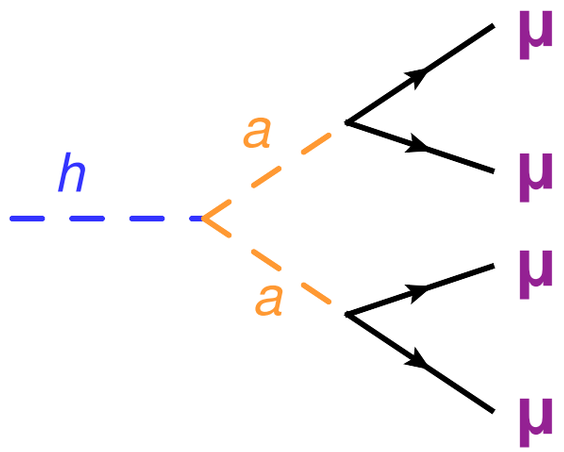


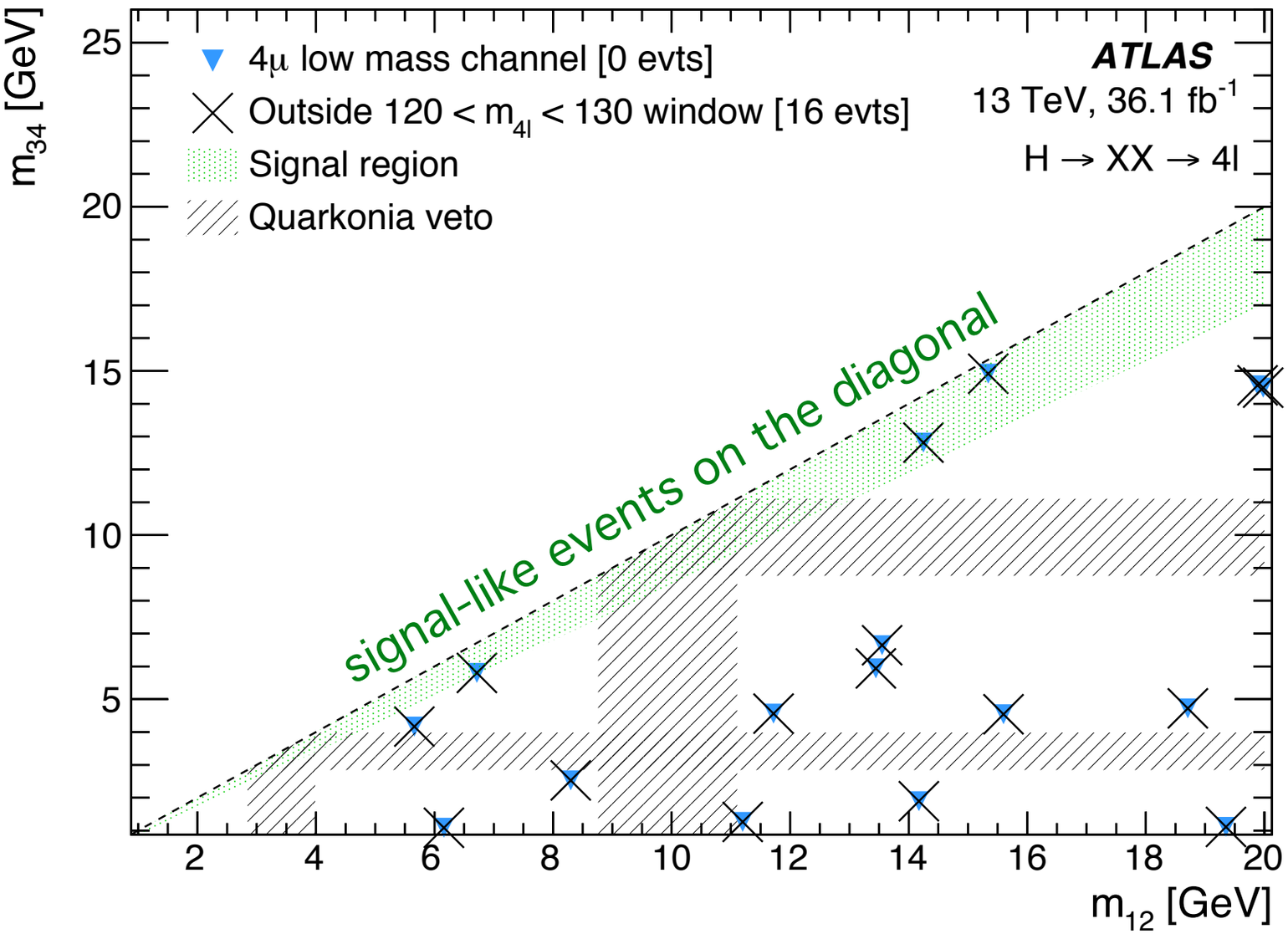
H→aa→4b

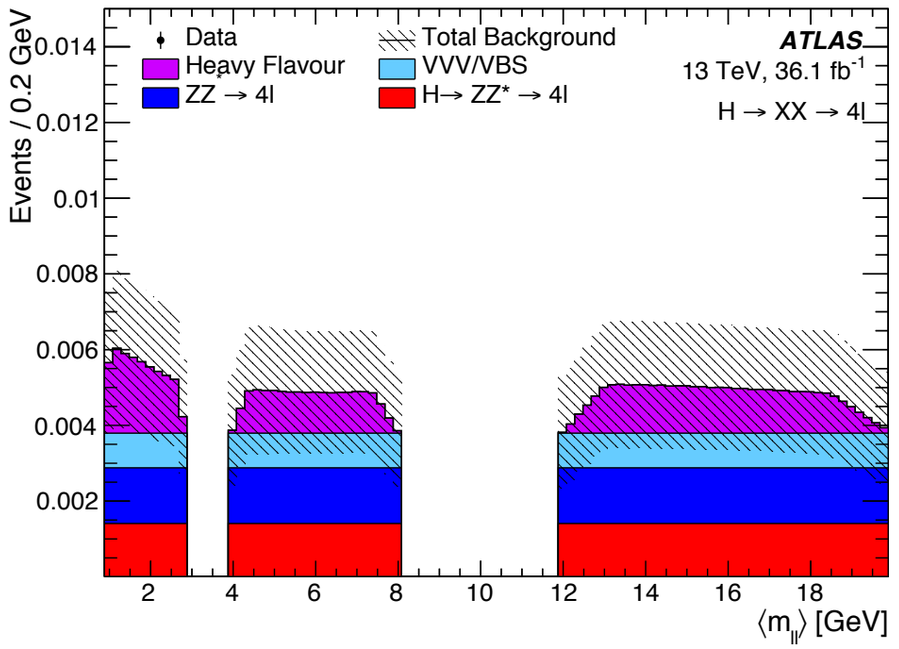

ATLAS
Combined
√s = 13 TeV, 36.1 fb-1
Observed 95% CL
Expected 95% CL ± 1σ
Expected 95% CL ± 2σ
σSM(pp→VH)
95% CL upper limits on σVH × B(H→aa→4b) [pb]
ma [GeV]
jet merging

H→aa→4μ

- Search for excess in 2D $m_{\mu\mu}$ spectrum



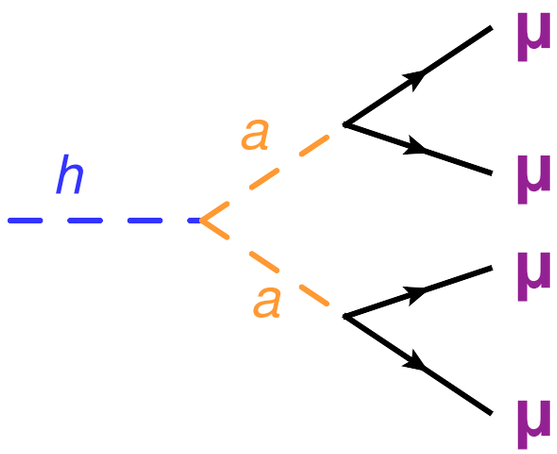


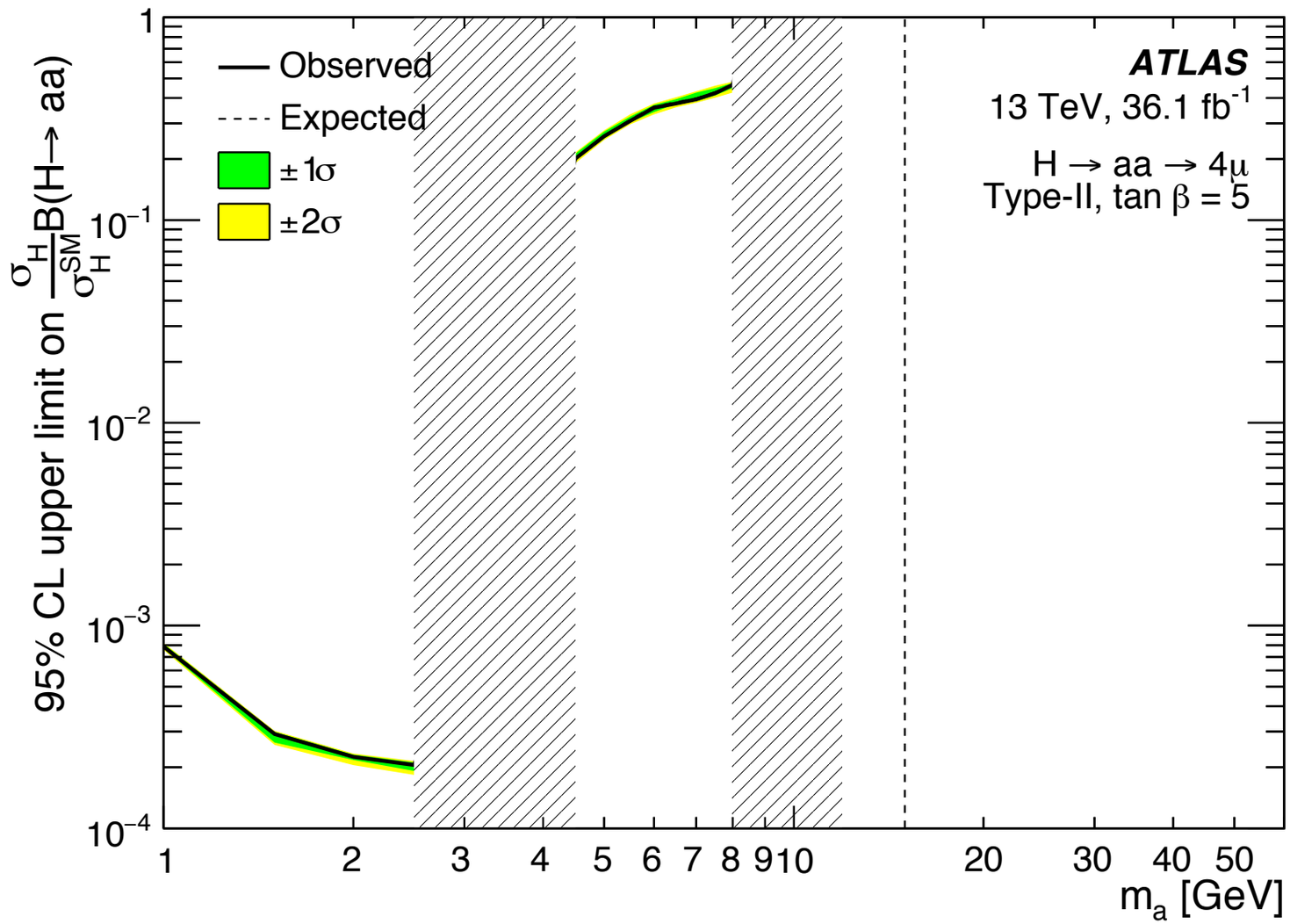


1802.03388

H→aa→4μ

- Search for excess in 2D $m_{\mu\mu}$ spectrum
- Sets limits only in the low mass range



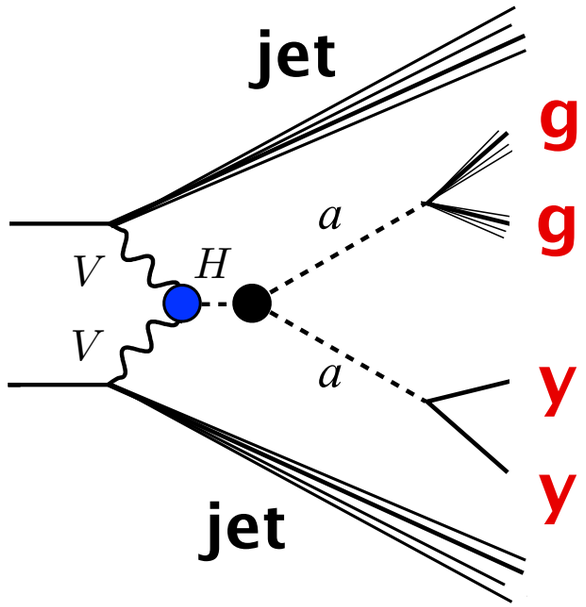


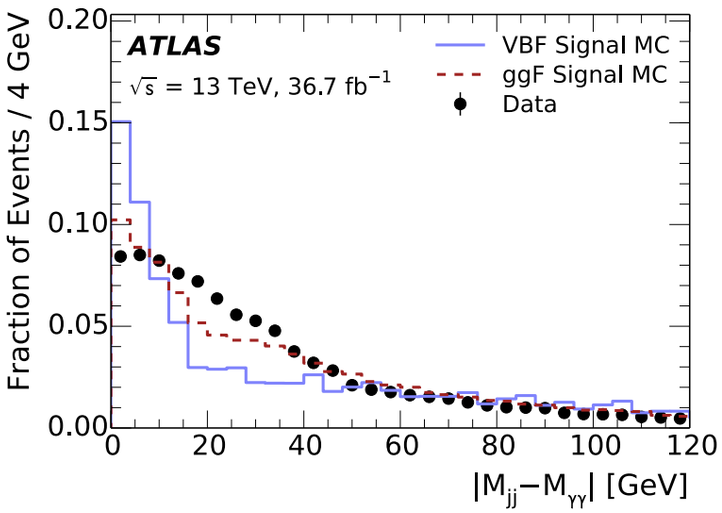
H→aa→jjyy

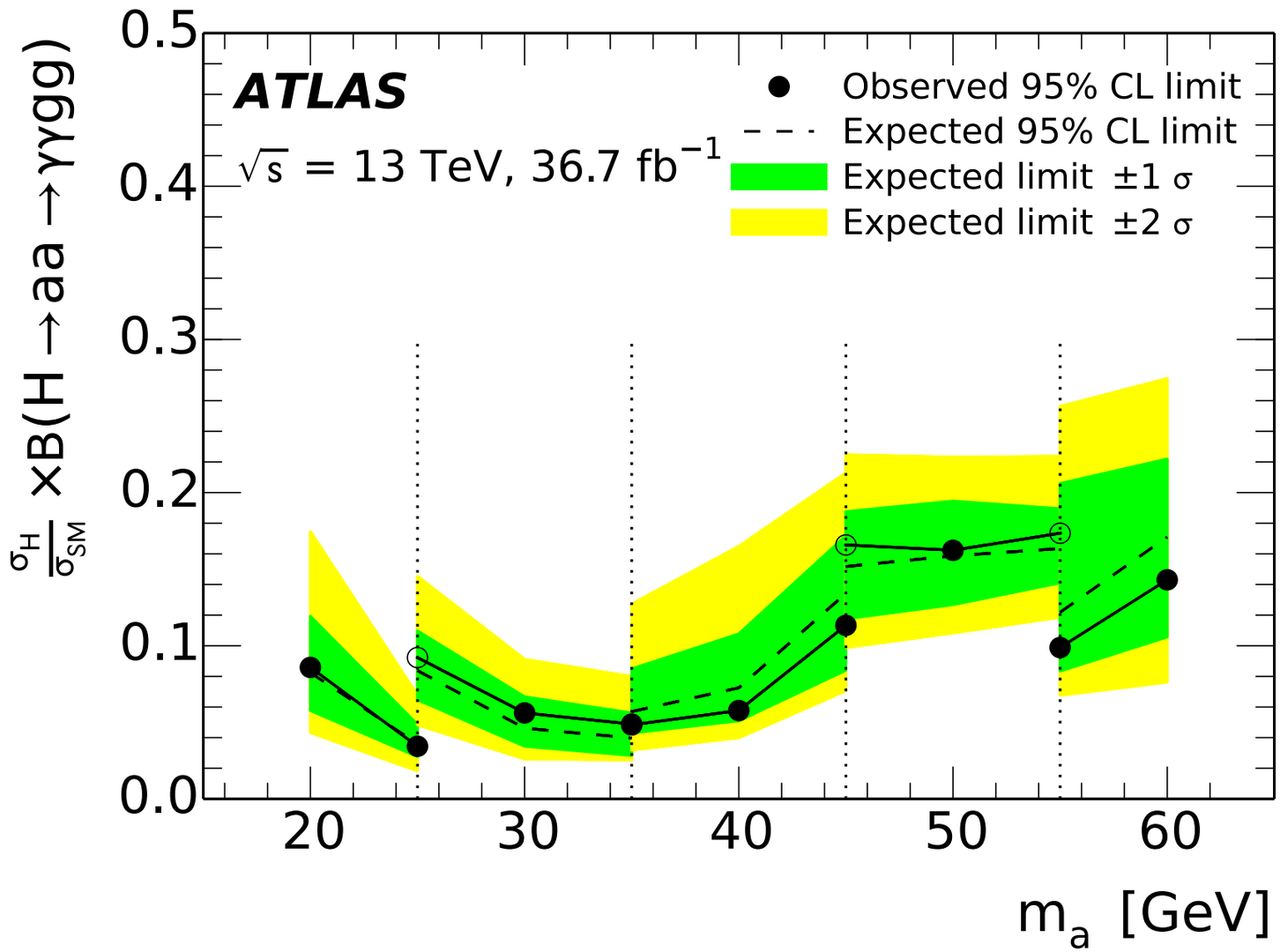
- Fermiophobic a
  - E.g scalar coupled to new charged & coloured vector-like states: $\lambda_i s\bar{\psi}_i\psi_i$

1803.11145

- Dominant yy+multijet background estimated using data-driven "ABCD" method based on inverting y ID and $|M_{jj}-M_{yy}|$ criteria

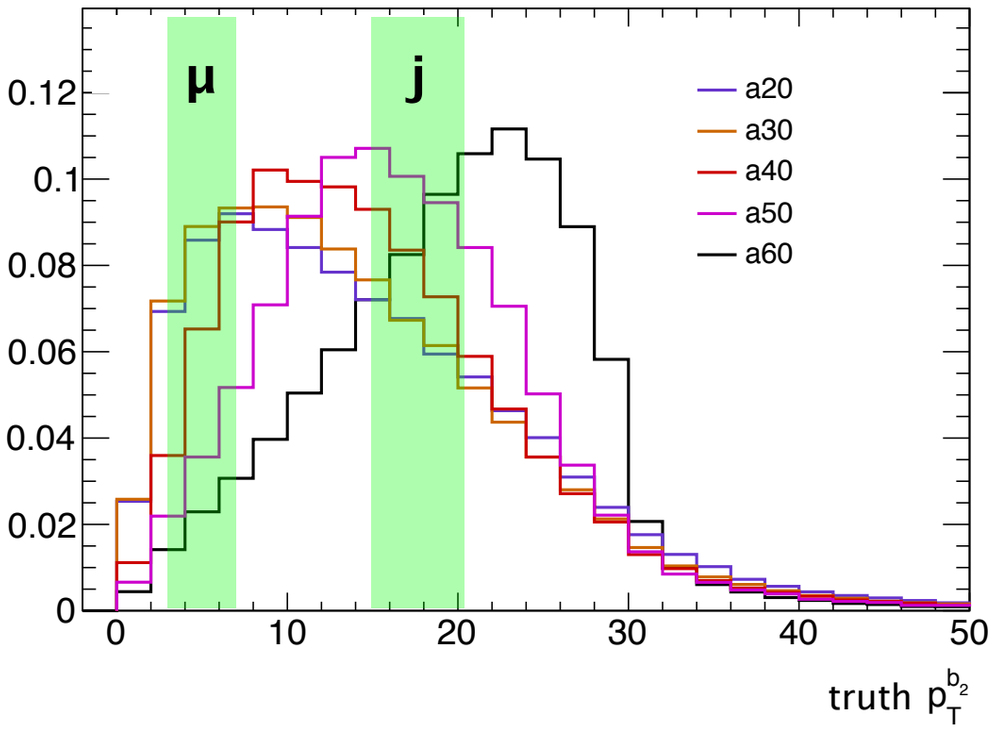


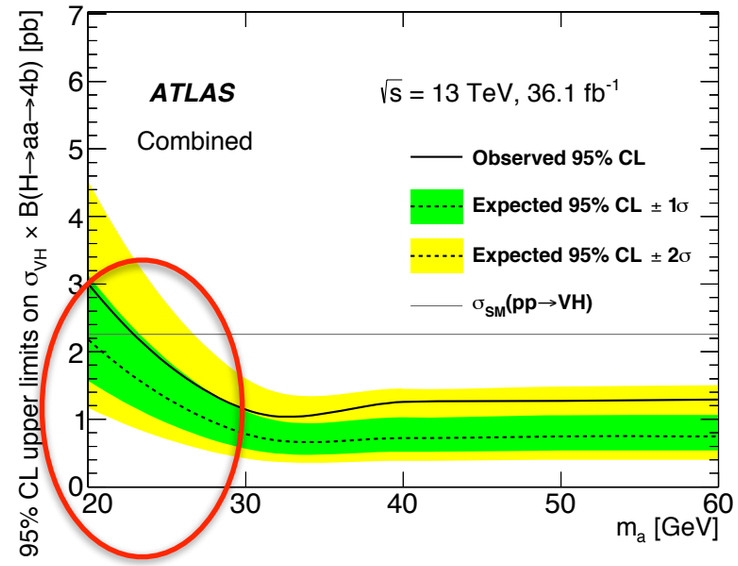




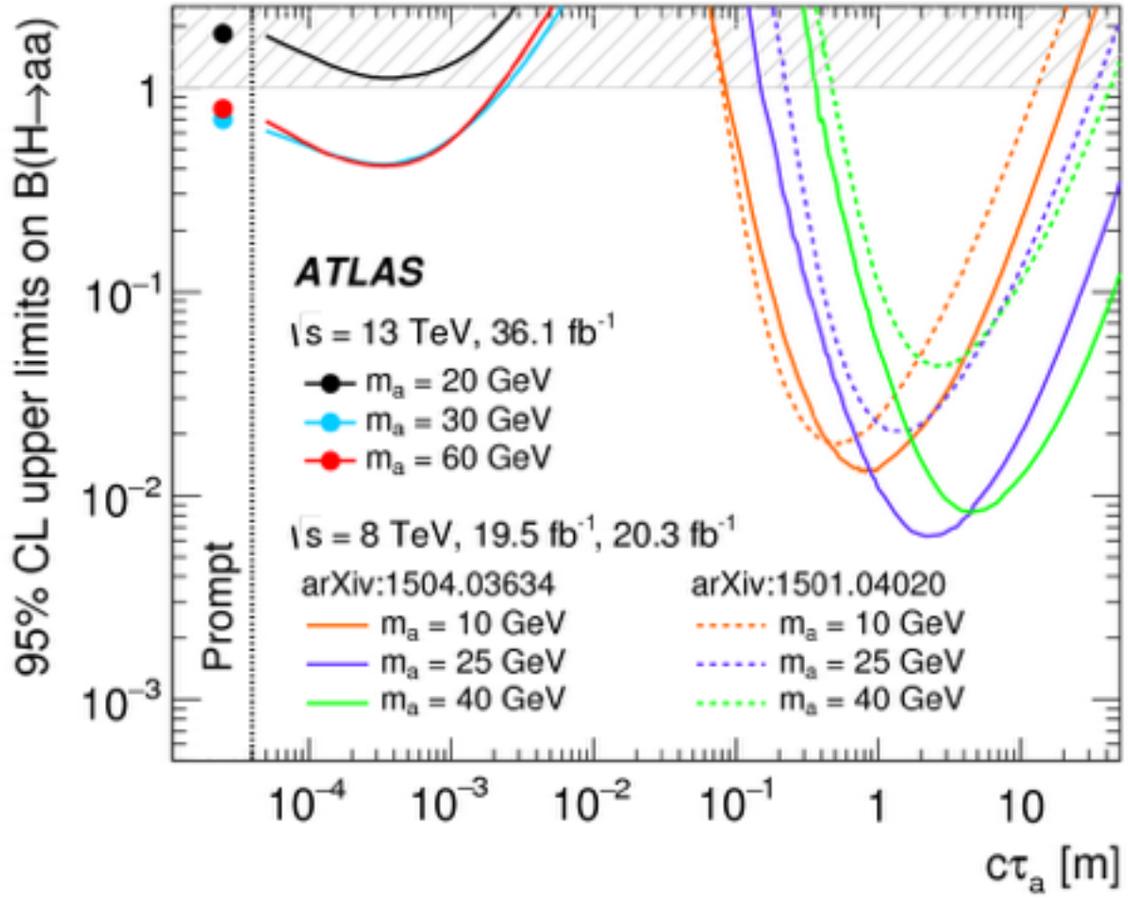
Future improvements

- Increase the acceptance for soft objects
  - **Muons down to 3 GeV**
  - **PFlow (track) jets down to 15 (7) GeV**
- Merged jets for lower masses: **a→bb tagger**
- Other final states
  - CMS 2b2tau: 1805.10191
  - CMS 4tau: 1510.06534
  - Za: ATLAS ZZ_d 1802.03388
  - Long-lived scalars





HIGG-2017-05



Summary

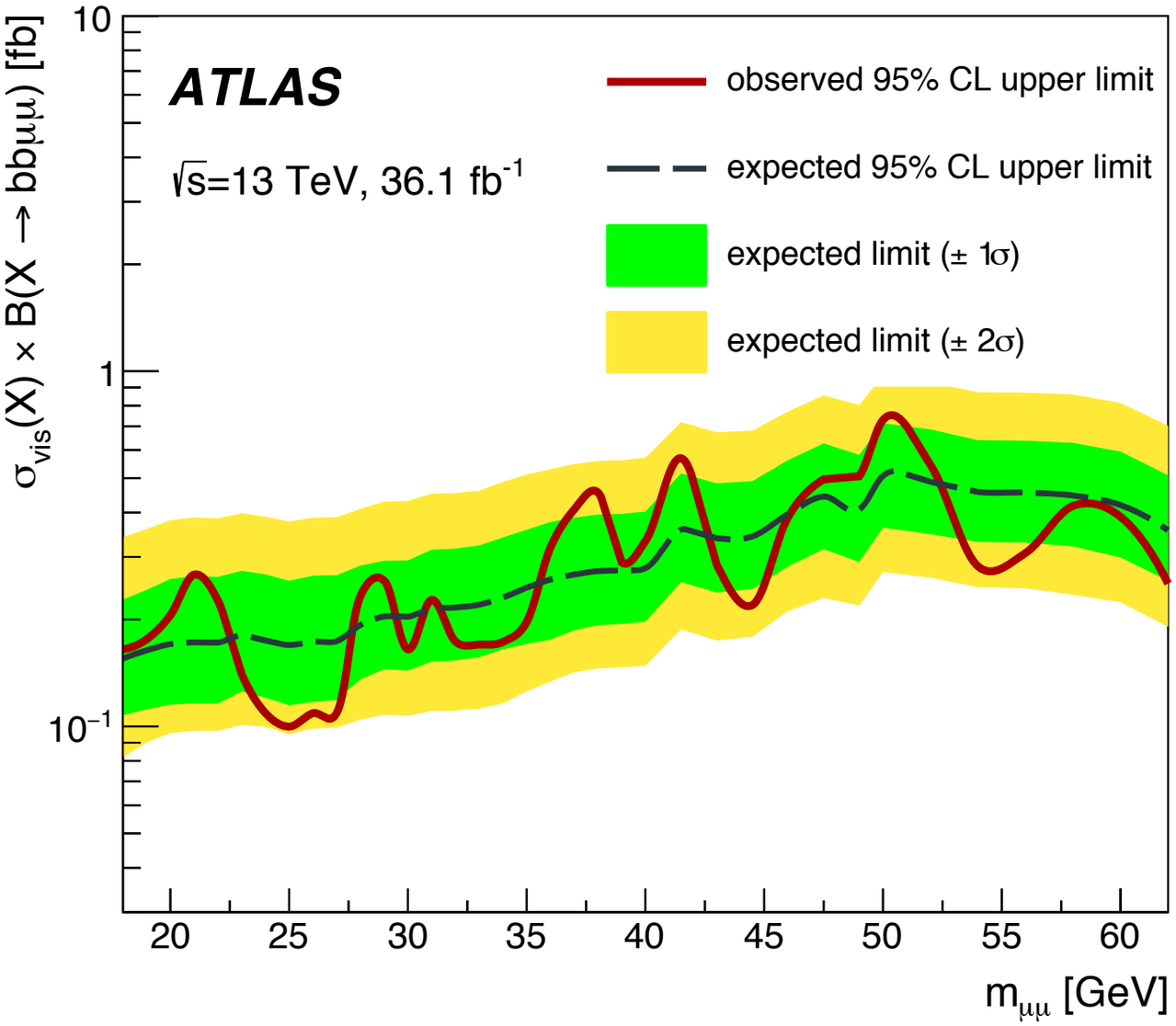
- Searches for new particles in H-boson decays are very interesting
  - Still relatively unconstrained
  - **It could be the only way that new physics couples to the SM**, i.e. only way to discover it
- Shown analyses in several channels (with newest results): 2b2μ, 4b, 4μ, 2j2γ
  - **Beginning to probe the interesting parameter space**
- Many new channels and results planned for the end of Run II
- Stay tuned!

Backup

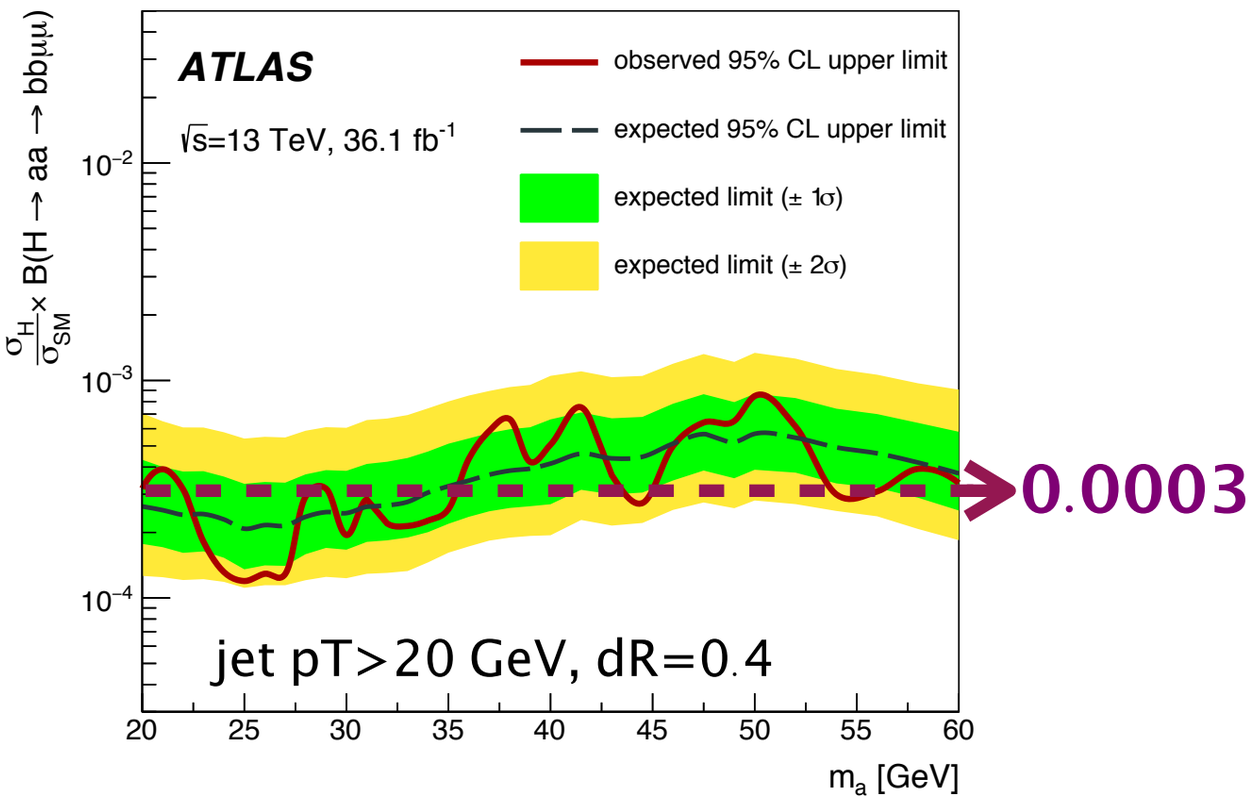
Systematic uncertainties

Source	Total background [%]	Signal [%]
DY: normalisation	9.3 - 15	–
DY: flavour composition	7 - 11	–
DY: background subtraction	0.4 - 2.4	–
$t\bar{t}$: hard-scatter generation	3.6 - 8.6	–
$t\bar{t}$: hadronisation/fragmentation	3.2 - 7.7	–
$t\bar{t}$: normalisation	2 - 5	–
$t\bar{t}$: ISR/FSR	1 - 2.4	–
MC statistics	2.4 - 4.9	2.3 - 4.6
b-tagging	0.6 - 1.5	17 - 19
Jet-energy resolution	0.3 - 2.9	5.2 - 8.4
Jet-energy scale	0.3 - 2.9	3.9 - 6.5
Muon-p_{T} resolution	0.1 - 2.2	0.3 - 1.2

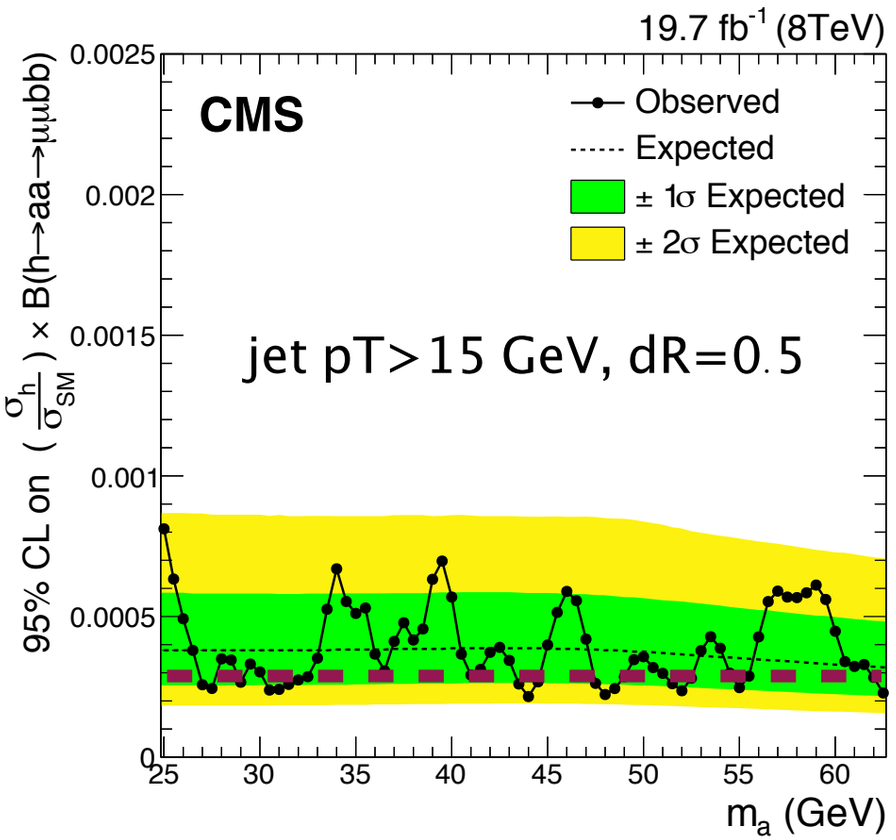
Model-independent limits



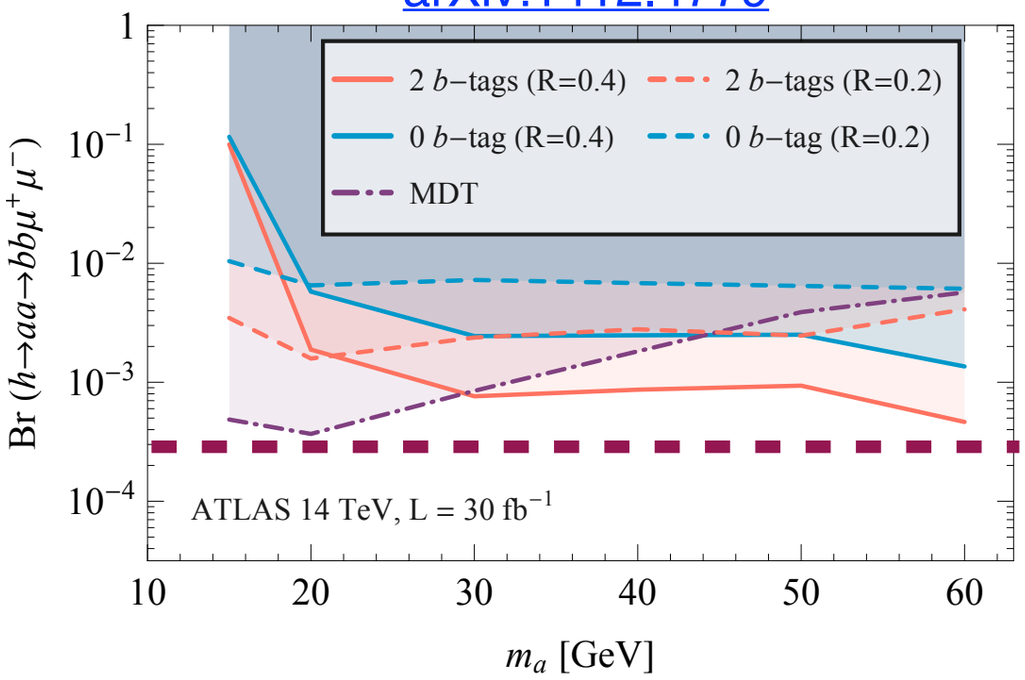
Limits comparison

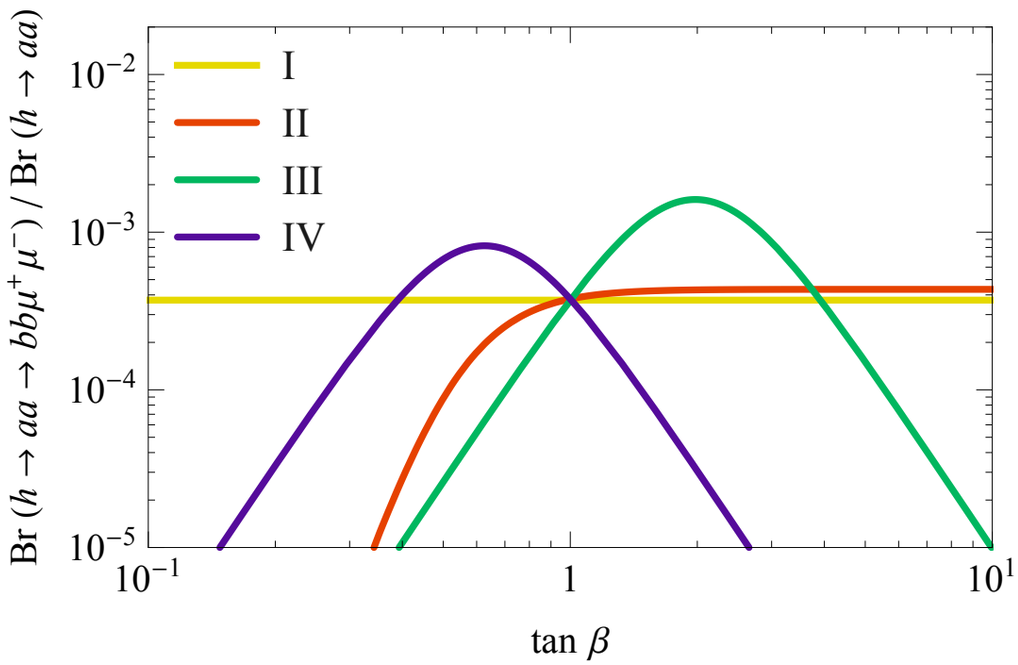


0.0003

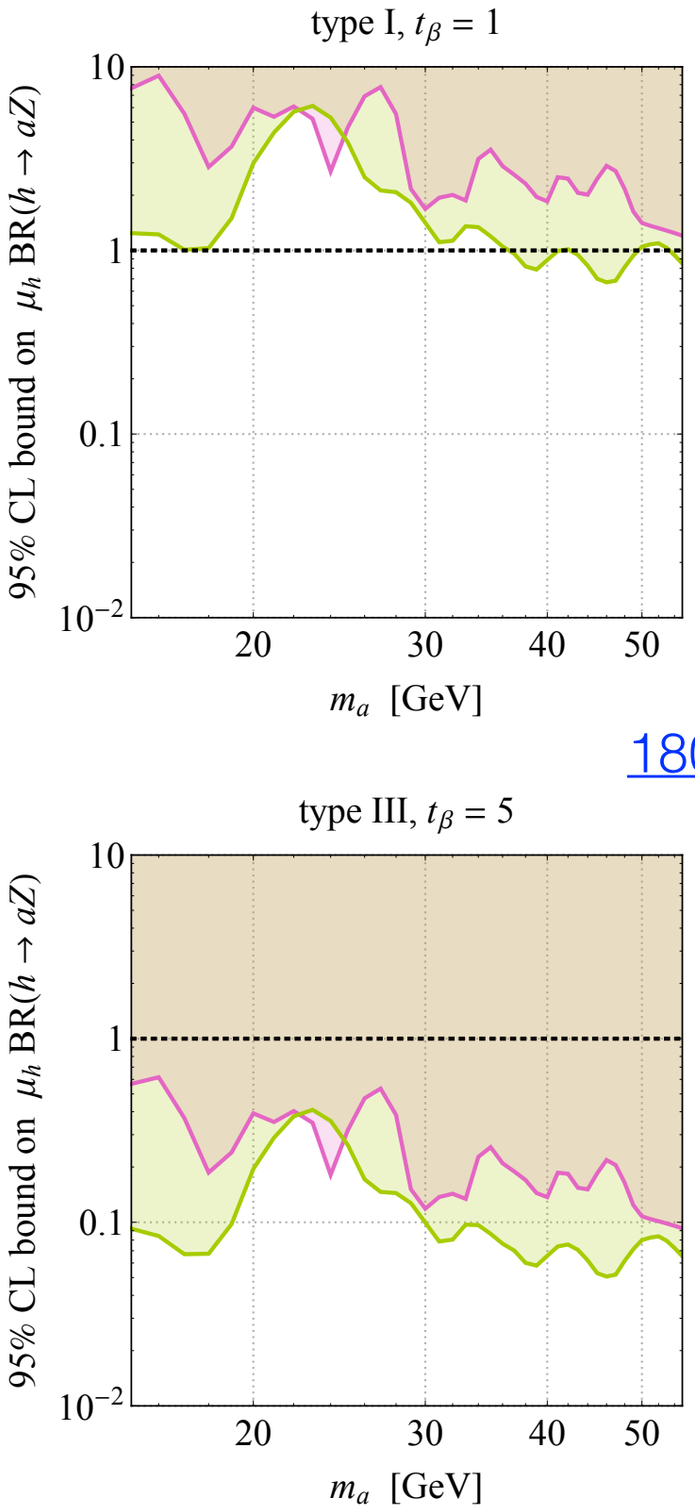


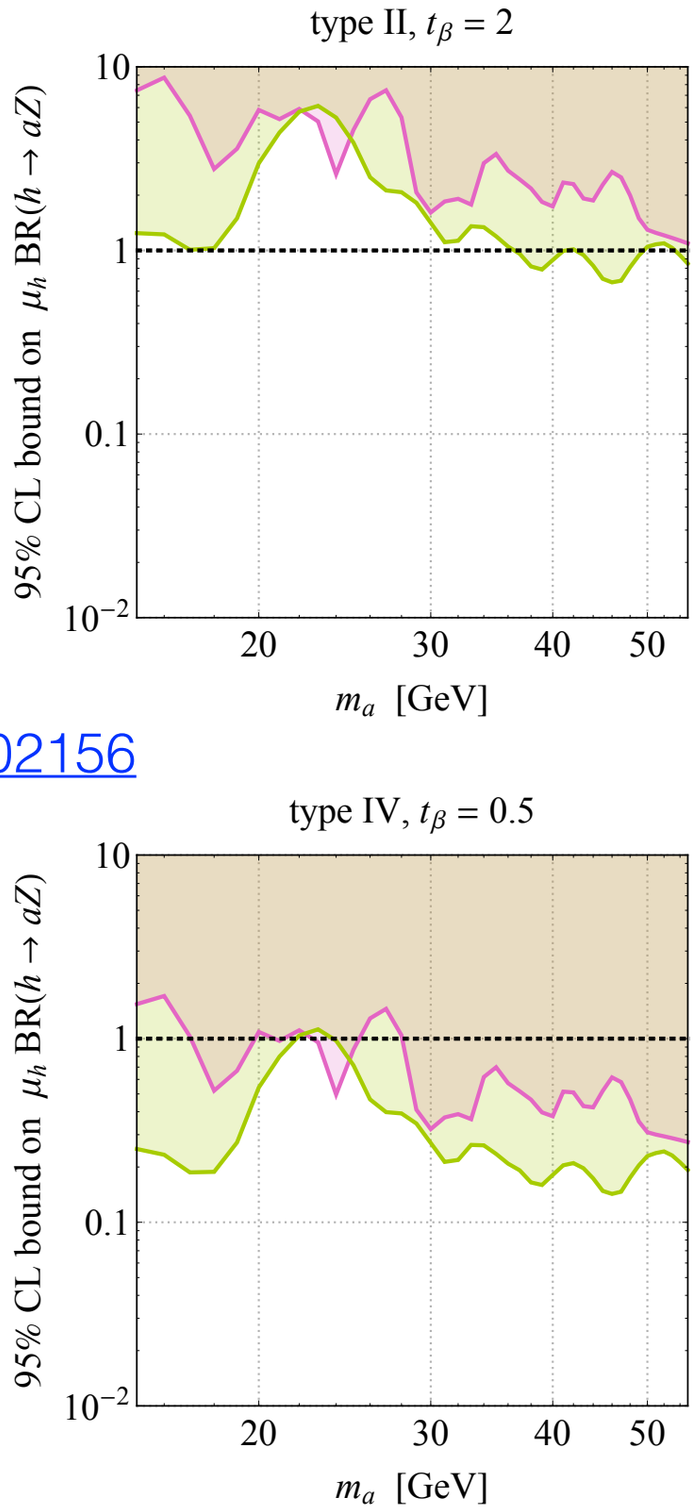
arXiv:1412.4779



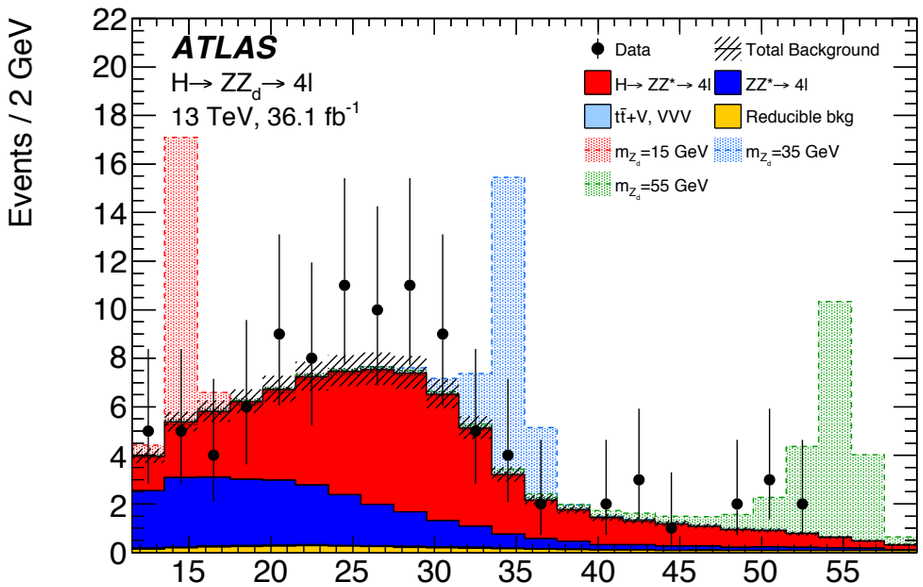


h→Za limits

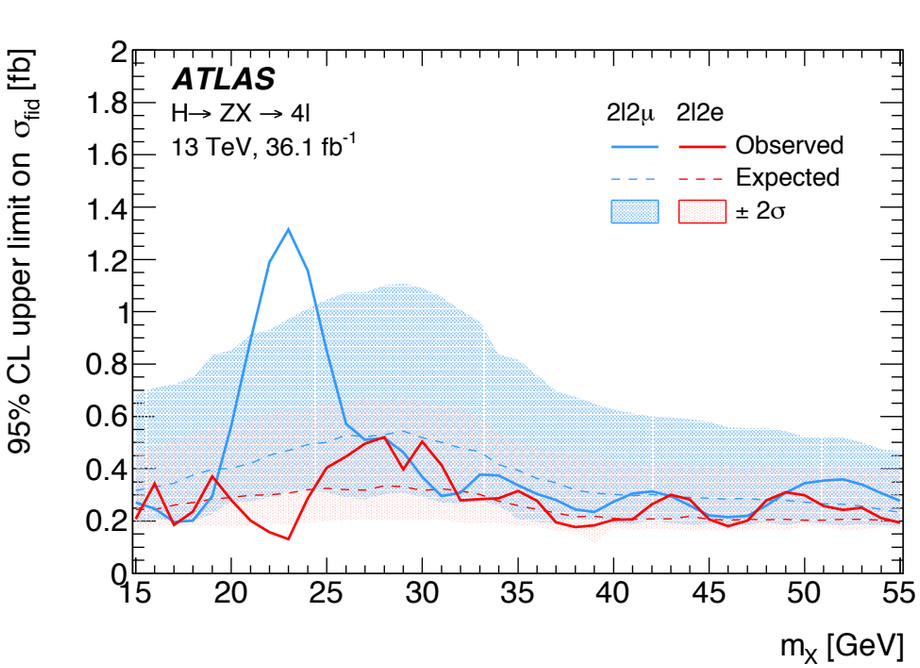




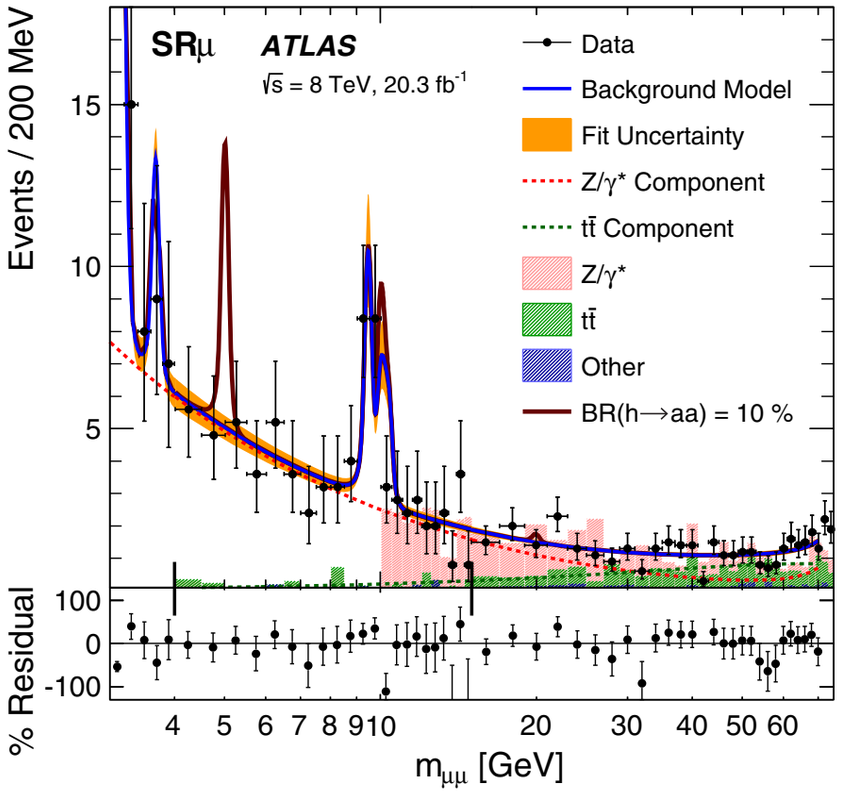
1802.02156

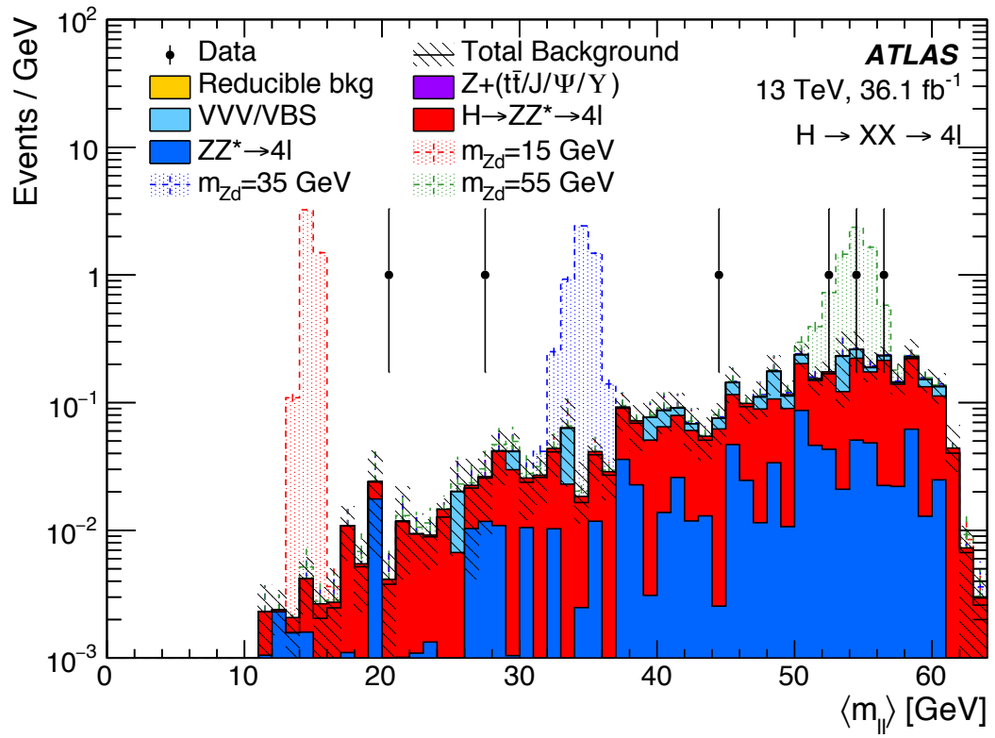


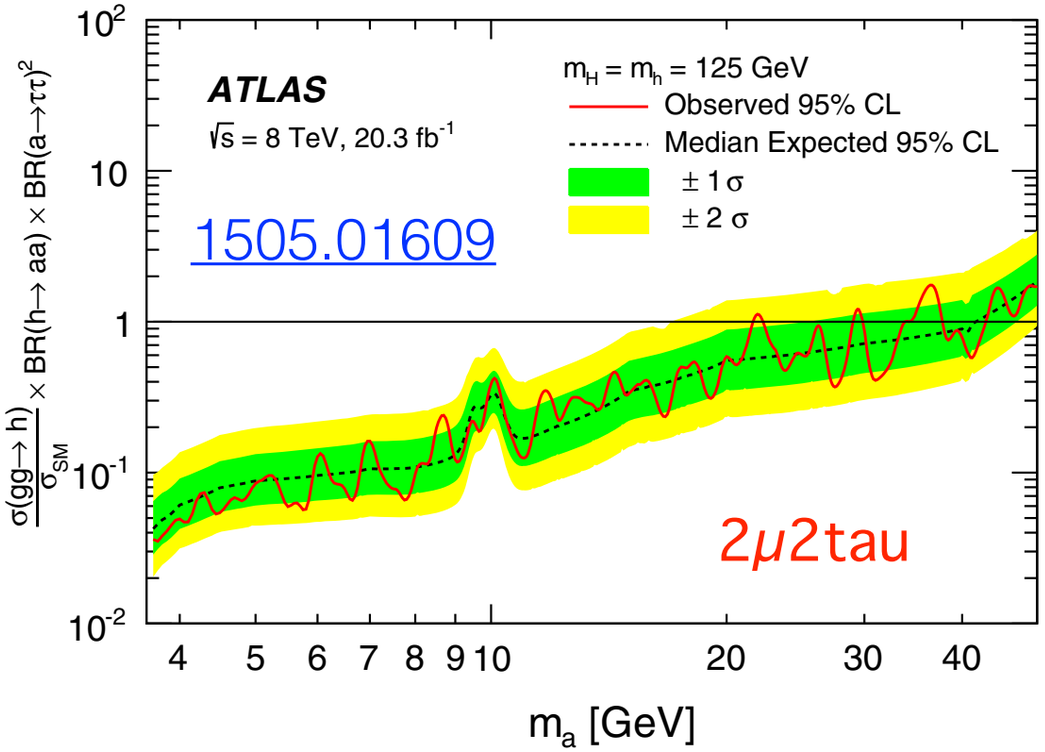
1802.03388

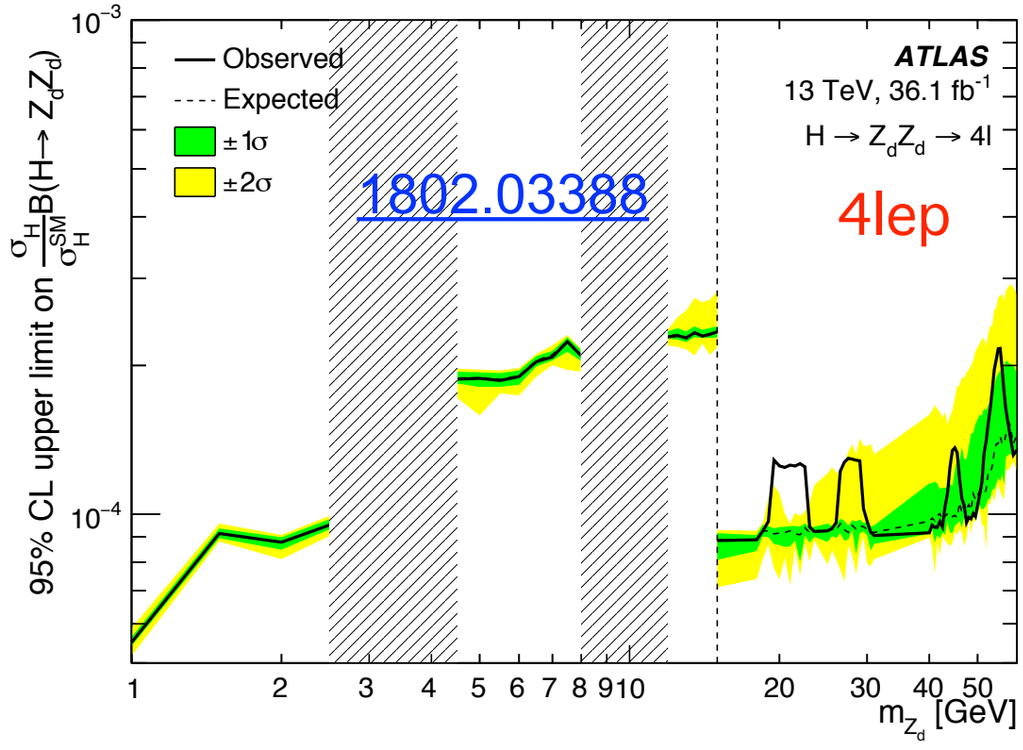


Other ATLAS analyses

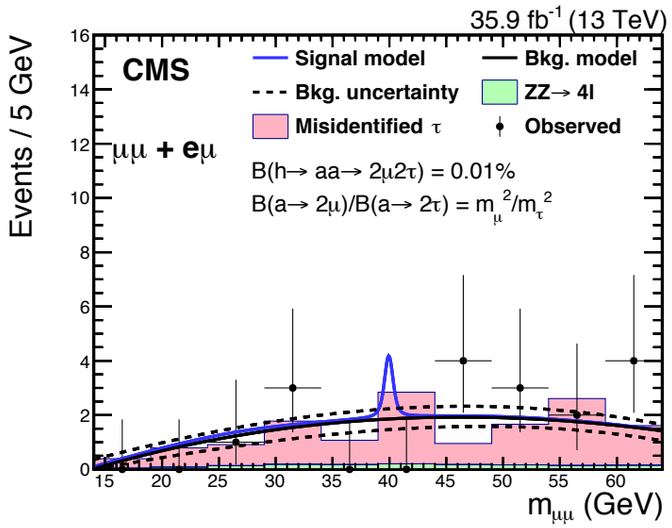


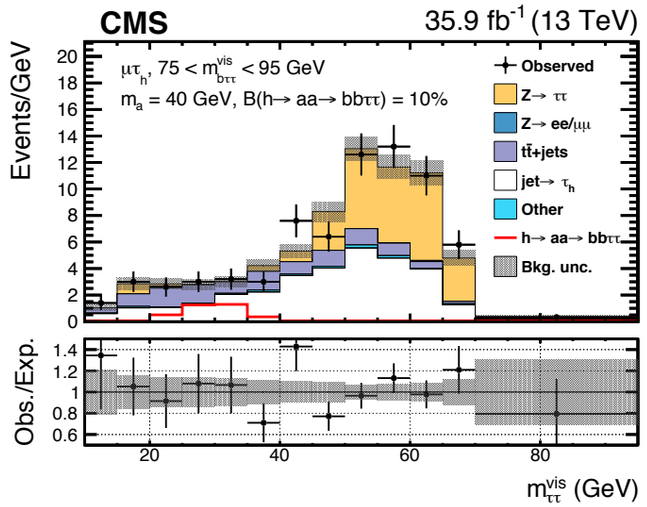


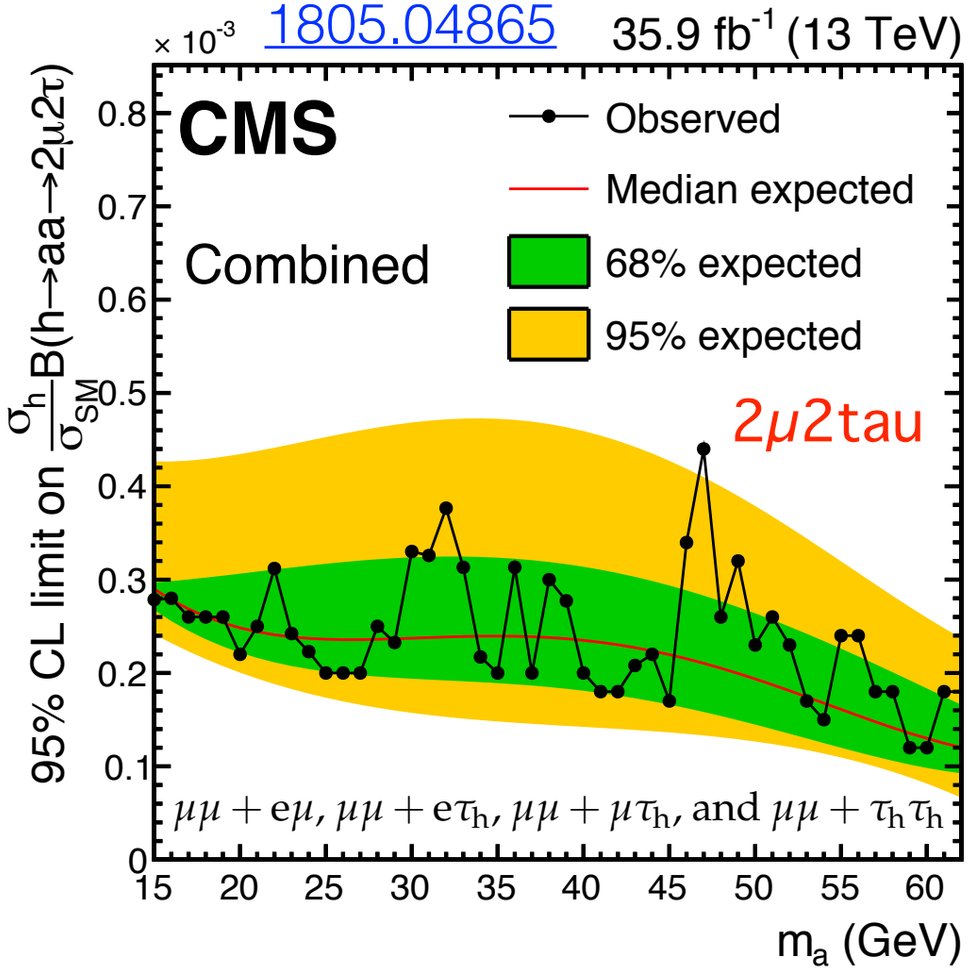


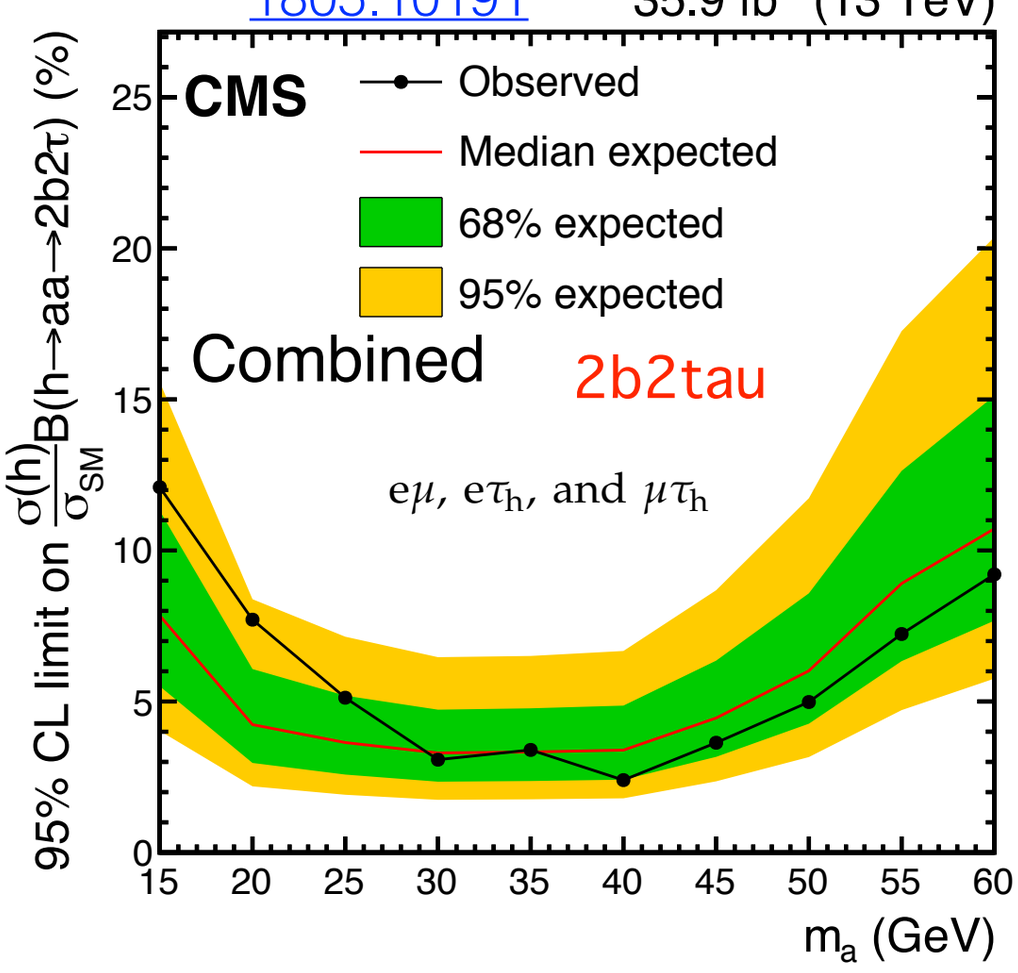


CMS analyses

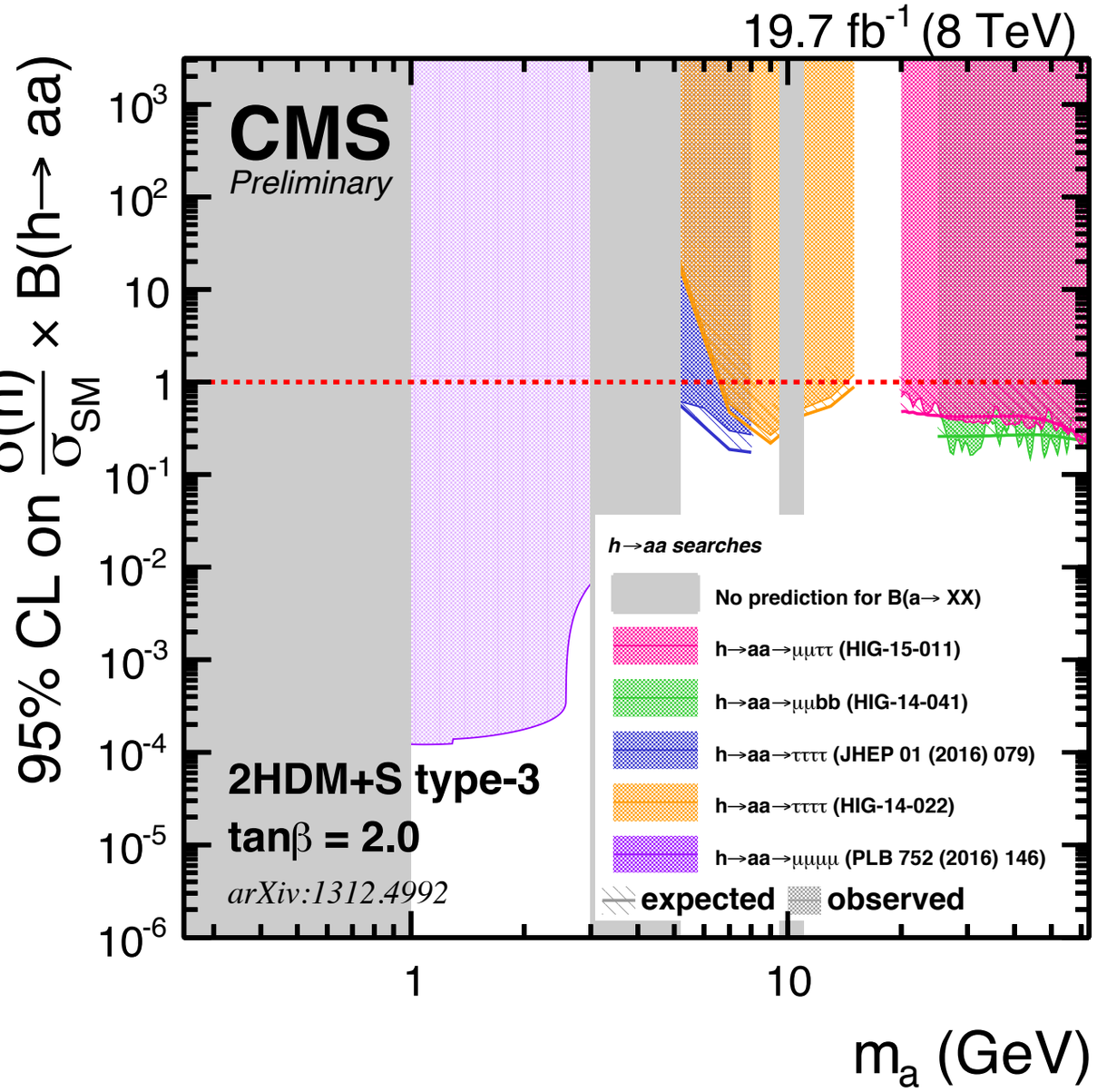


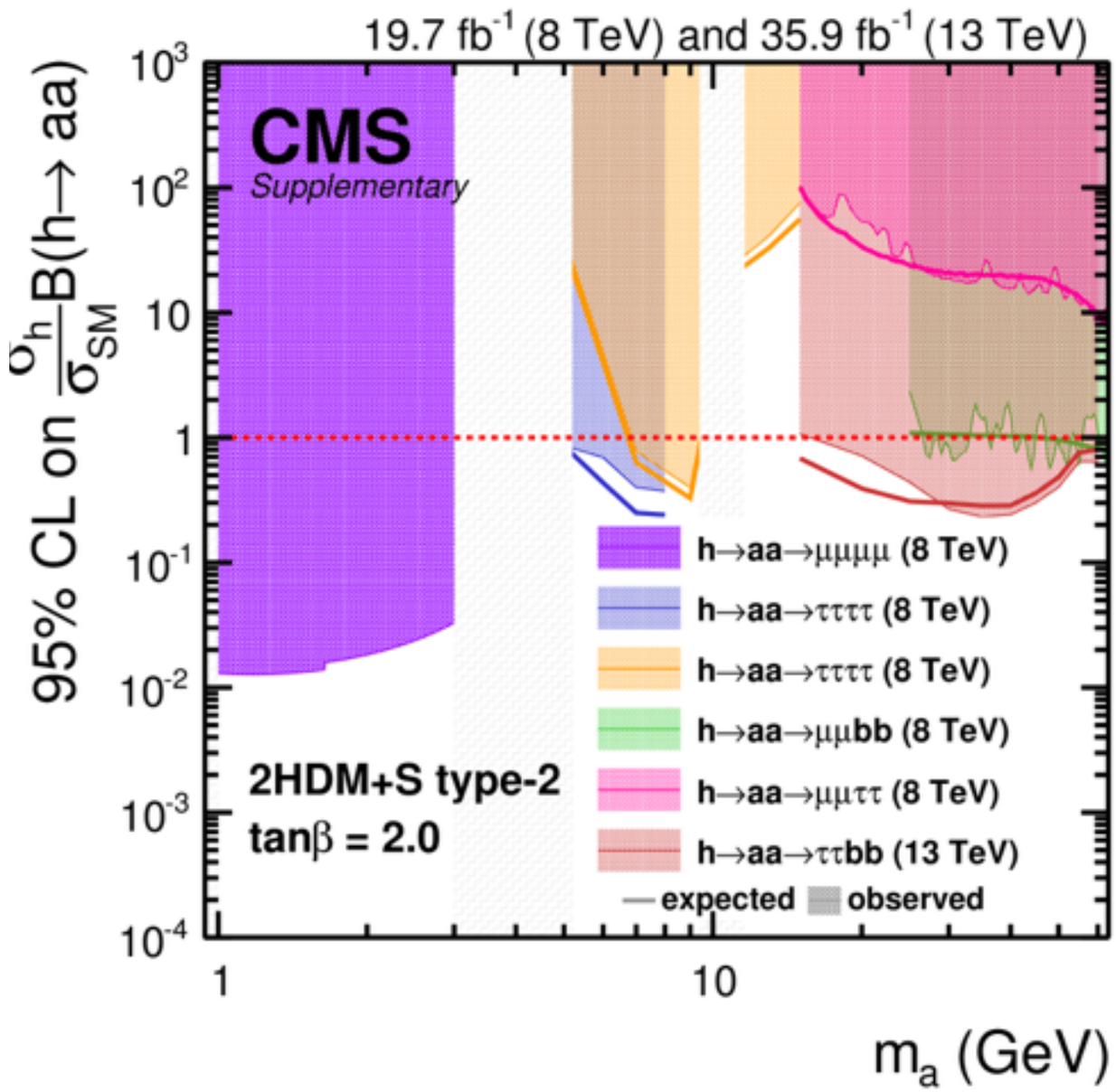




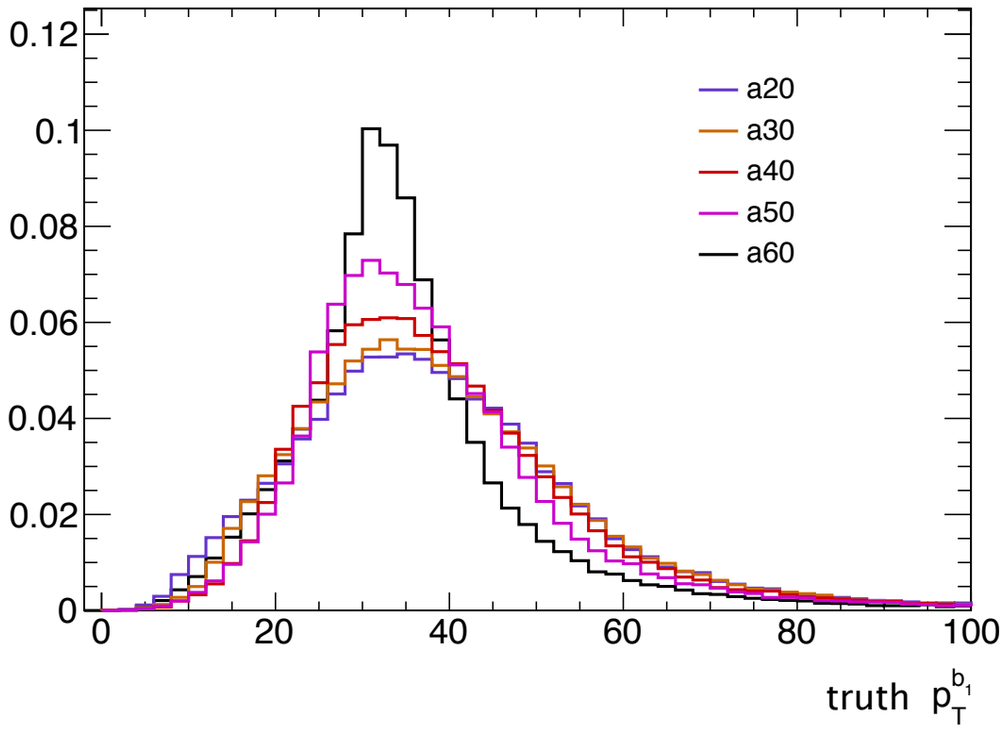


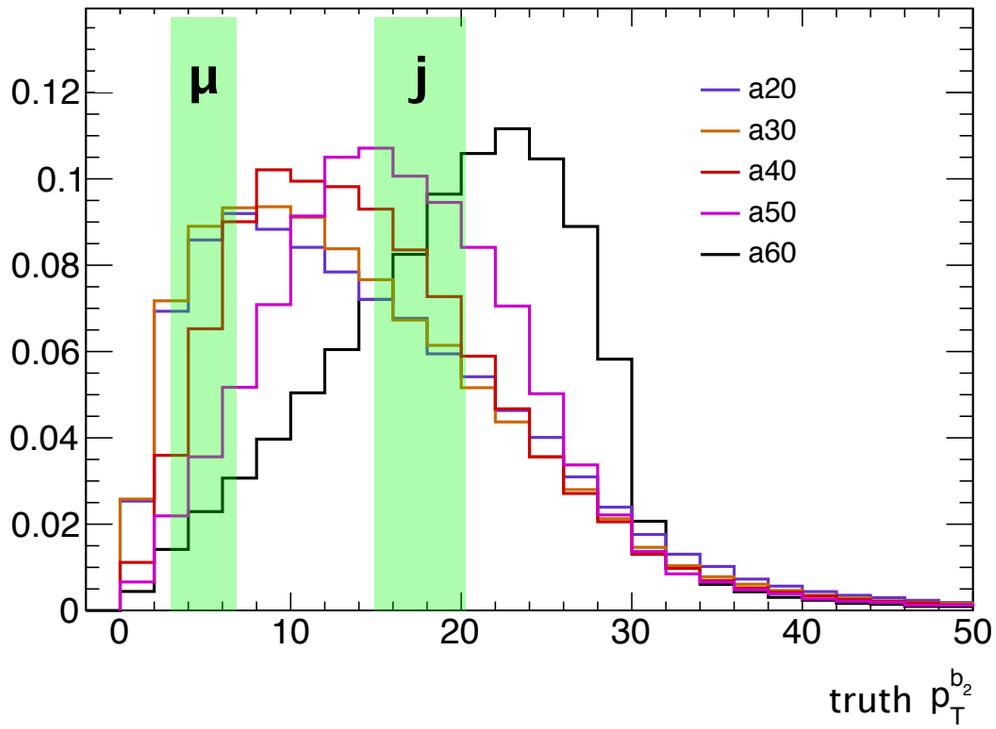
CMS analyses





a-decay products

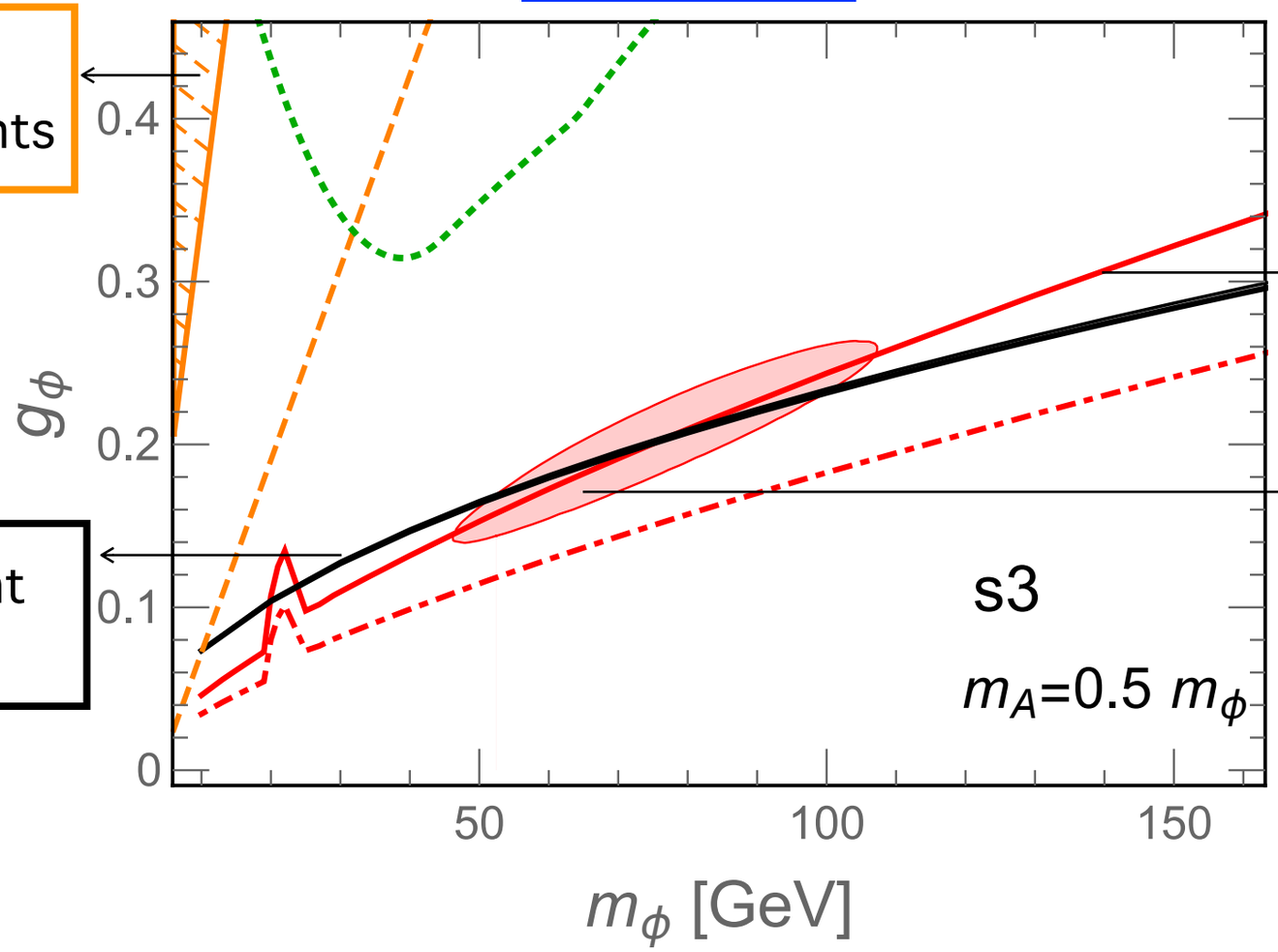




Dark matter & y-ray flux

1711.03878

Bounds form direct detection experiments



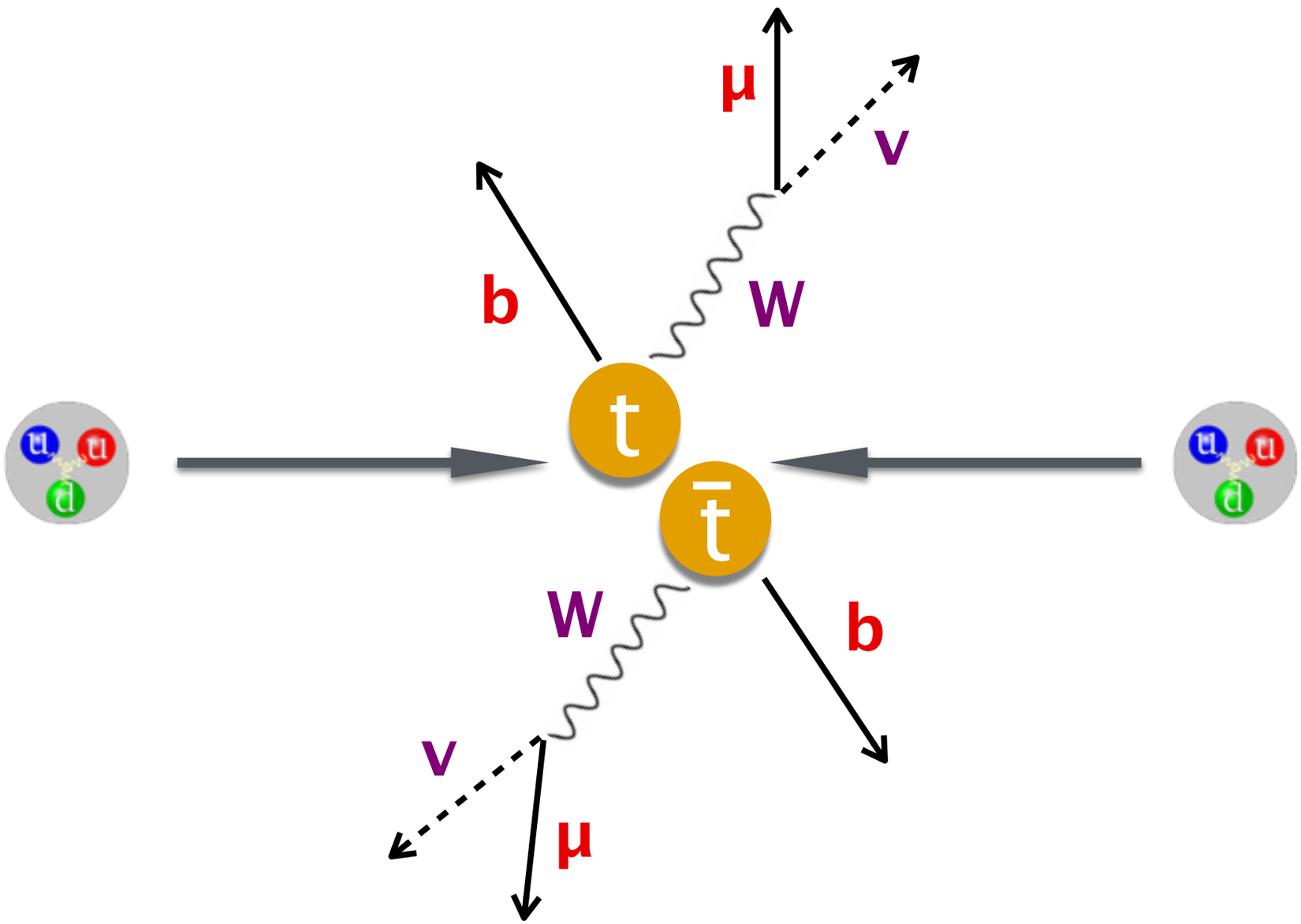
Above red line excluded by non-observation of y-ray emissions from dwarf galaxies

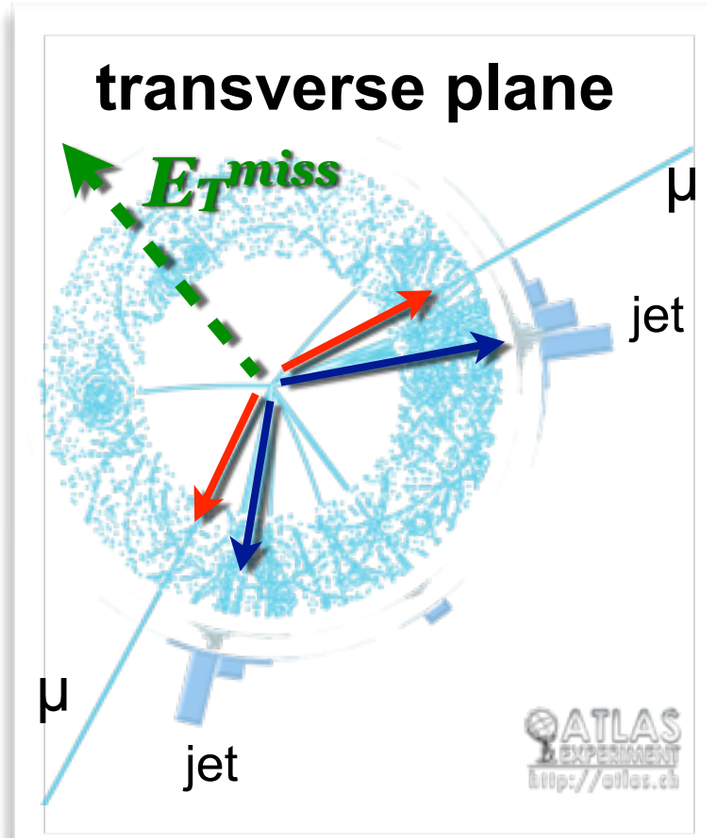
Black line consistent with relic density

Red region consistent Fermi-LAT data

tt background

- Neutrinos leave no trace in the detector:
  - Missing transverse energy: E_T^{miss}
  - Presence of non-interacting particles induced through momentum conservation in the transverse plane

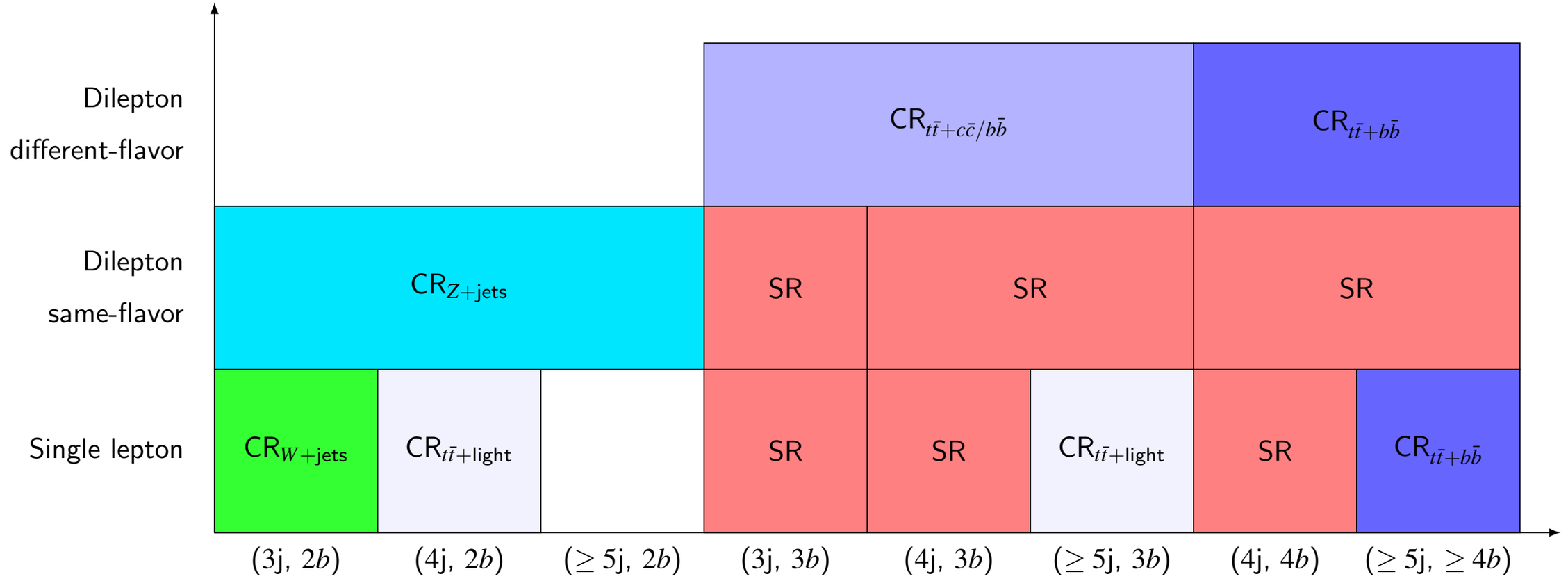




h→aa→4b

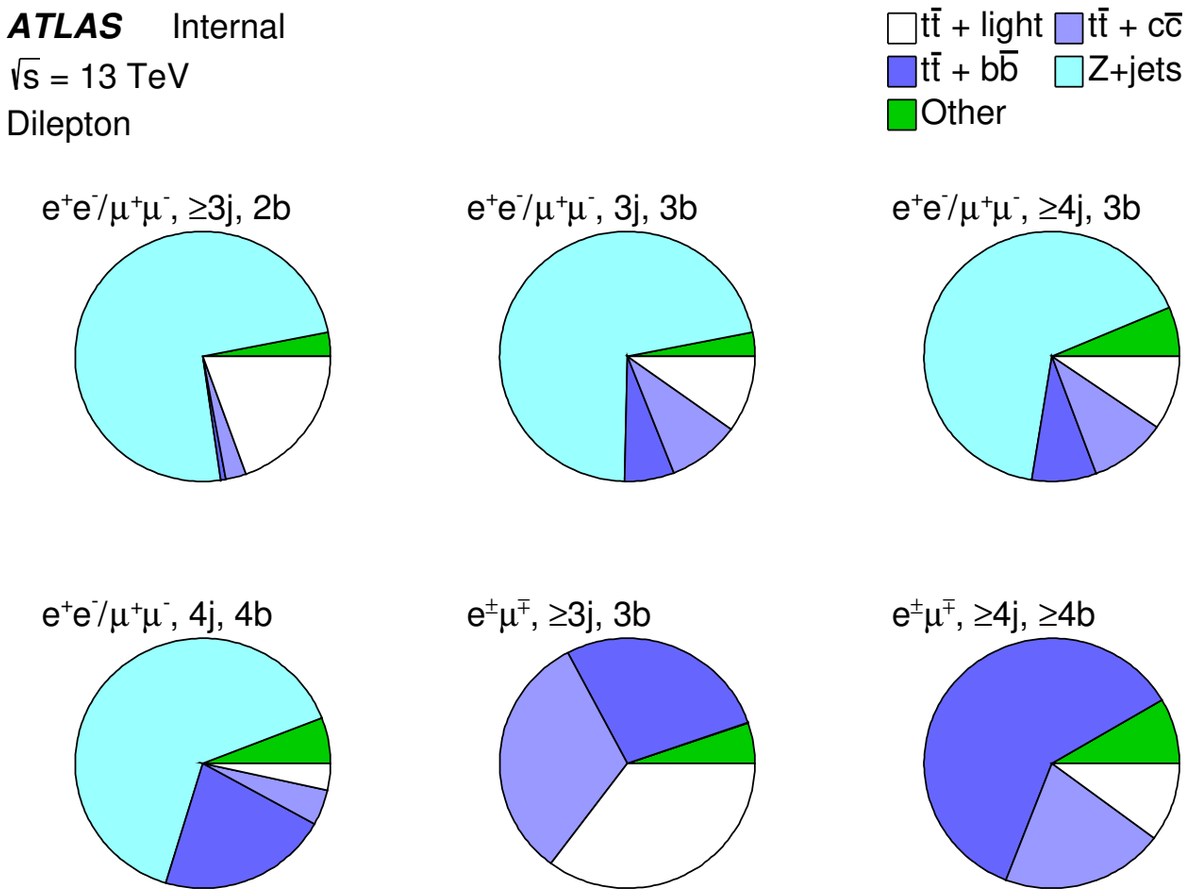
Analysis regions

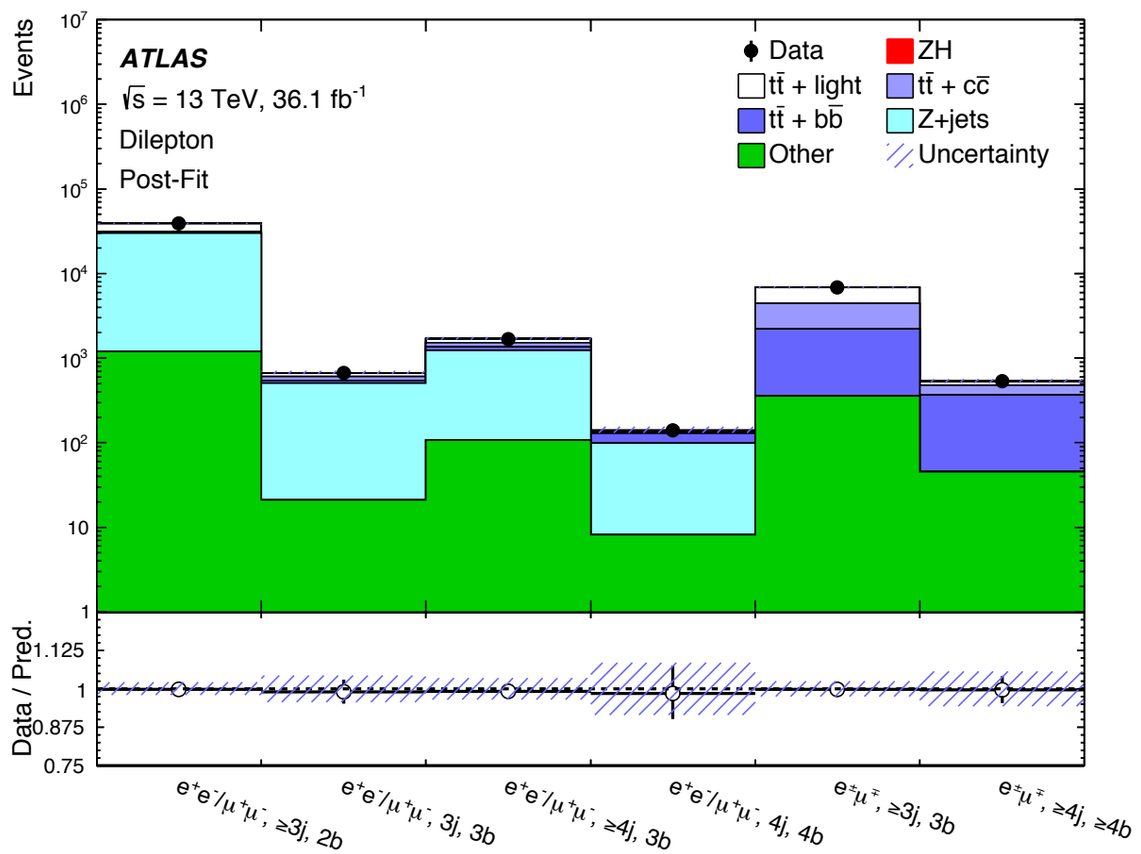
- Bin events based on:
  - Total number of jets (nj)
  - Number of b-tagged jets (nb)
  - Signal-enhanced bins are the ones with 3b or 4b (& <5j)



Background composition

- Having different backgrounds dominating different njnb bins helps constrain all the background components

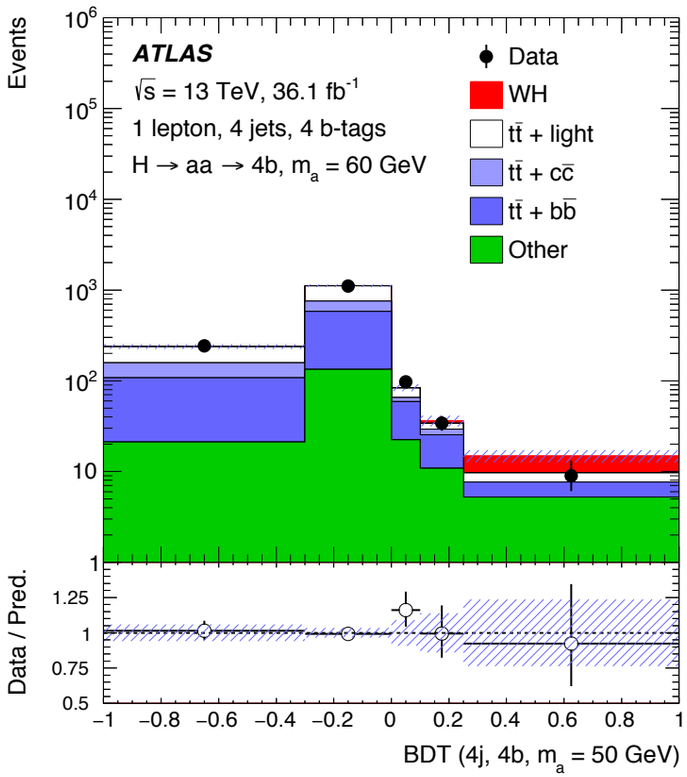




BDT

Variable	$(1\ell, 3j, 3b)$	$(1\ell, 4j, 3b)$	$(1\ell, 4j, 4b)$	$(2\ell, 3j, 3b)$	$(2\ell, \geq 4j, 3b)$	$(2\ell, \geq 4j, \geq 4b)$
m_{bbb}	✓	✓		✓	✓	
m_{bbbb}			✓			✓
m_{bb1}			✓			✓
m_{bb2}			✓			✓
average $\Delta R(b,b)$	✓	✓	✓	✓	✓	✓
H_{T}	✓	✓	✓			
p_{T}^{W}	✓					
m_{bbj}		✓				
m_{T2}	✓	✓	✓			
$\Delta R(\ell,\ell)$				✓	✓	✓
$\Delta R(Z,H)$				✓	✓	
$\cos\theta^{*}$						✓
$E_{\mathrm{T}}^{\mathrm{miss}}$				✓	✓	✓

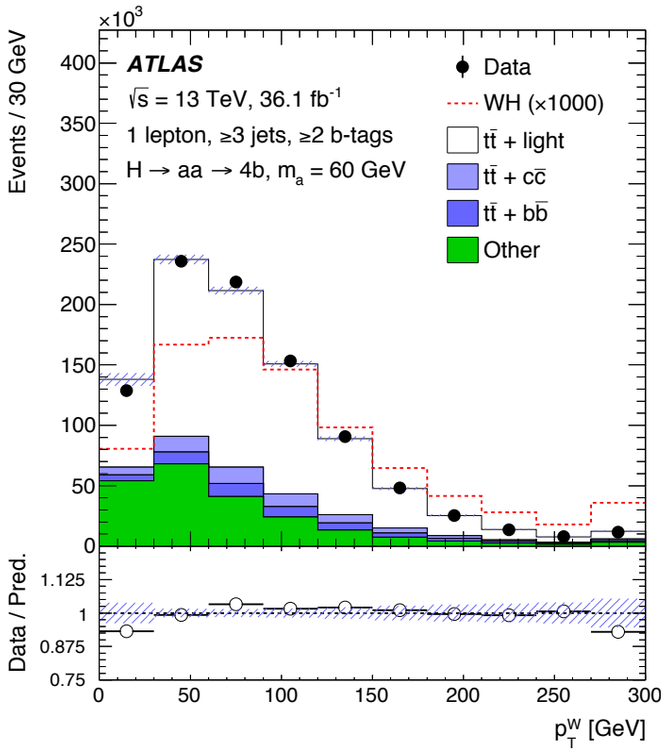
Table 2: List of variables used to train the BDT multivariate discriminant for each signal region.

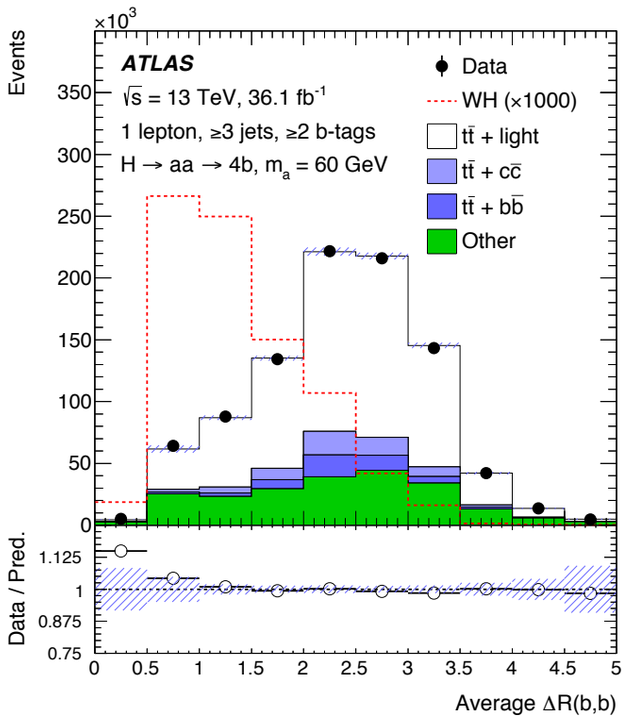


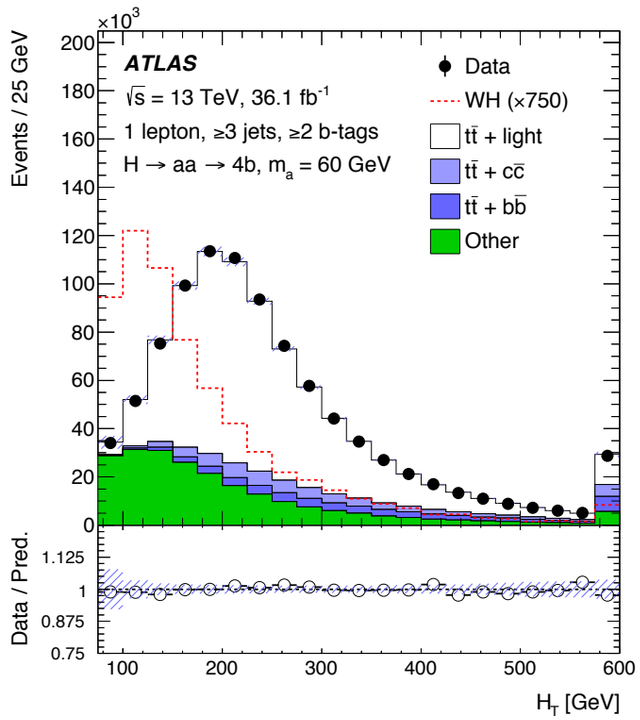
Kinematic variables

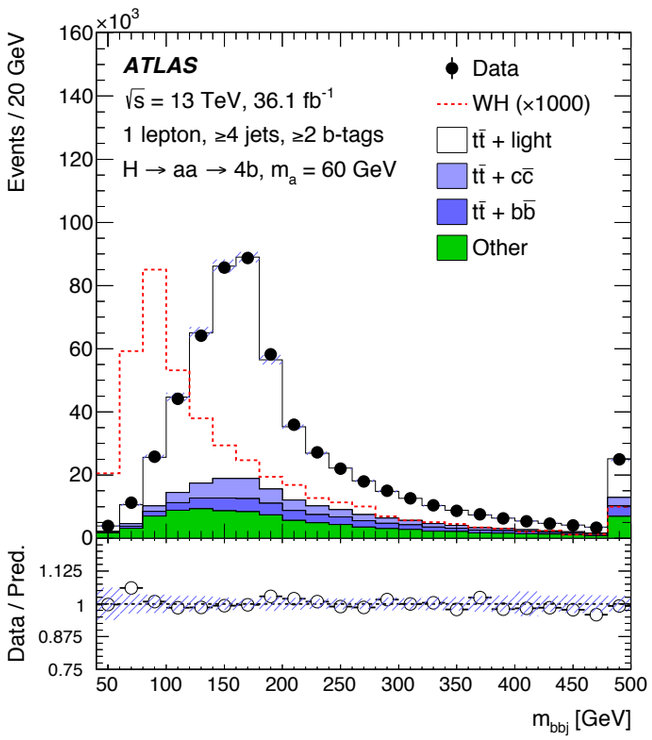
(a)

(b)

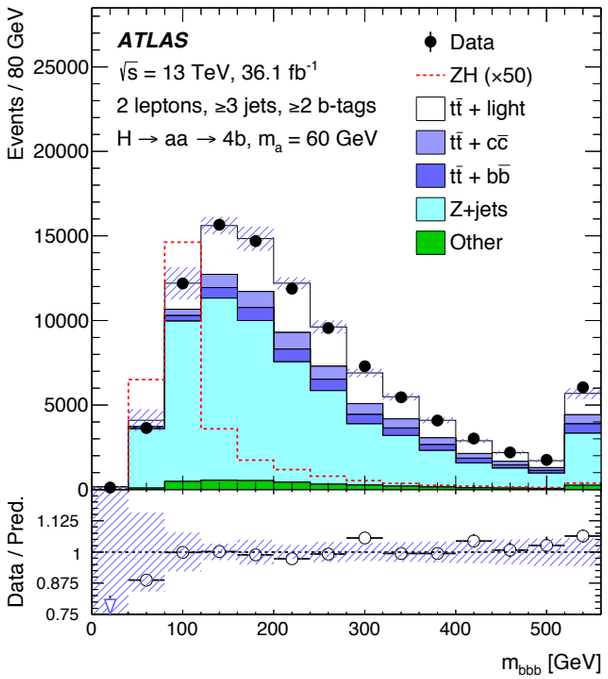




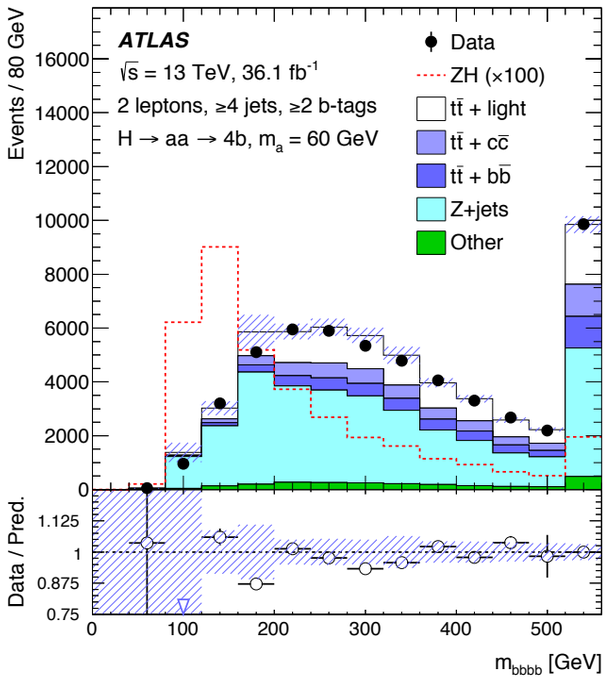




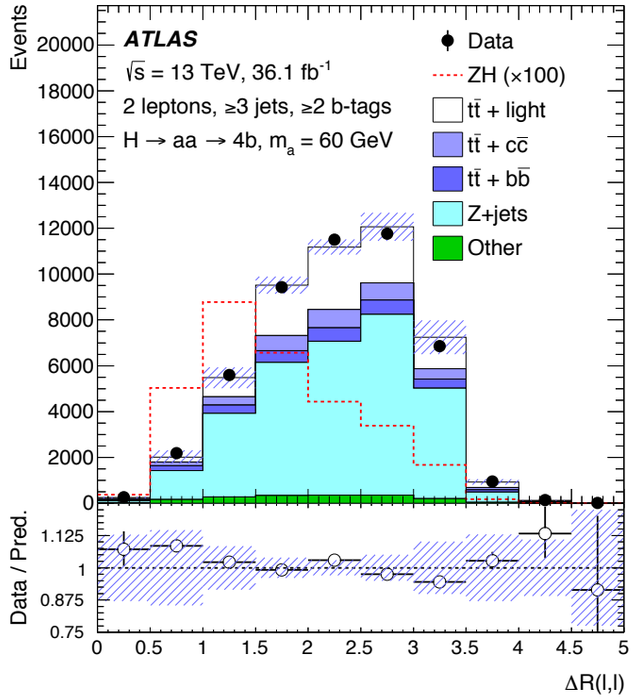
Kinematic variables

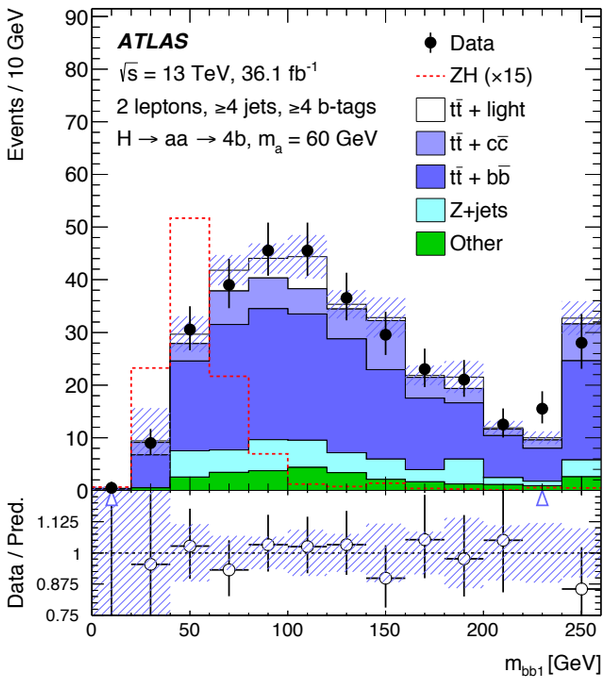


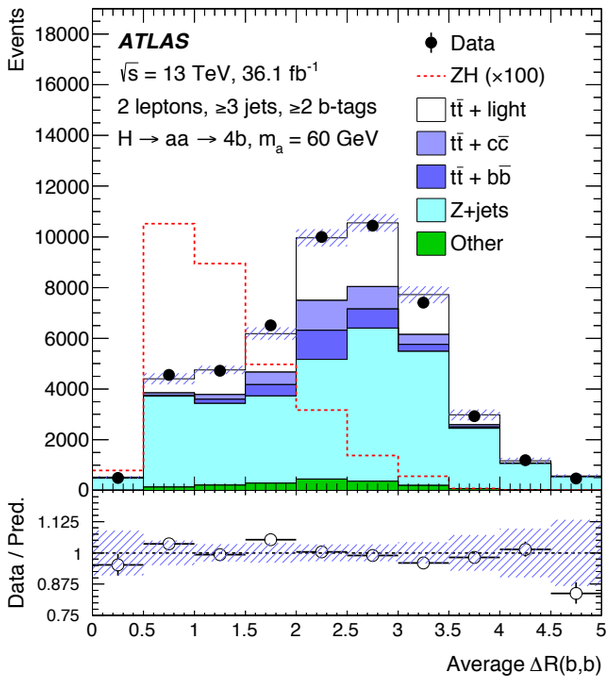
(a)

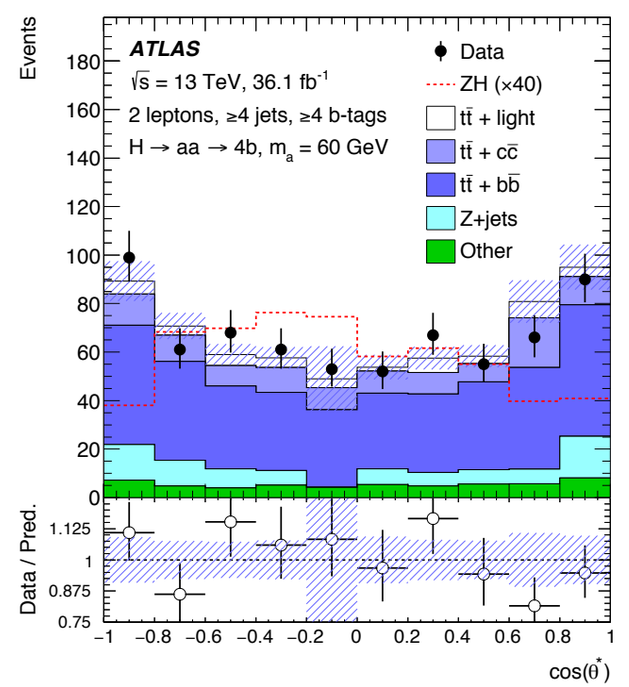


(b)



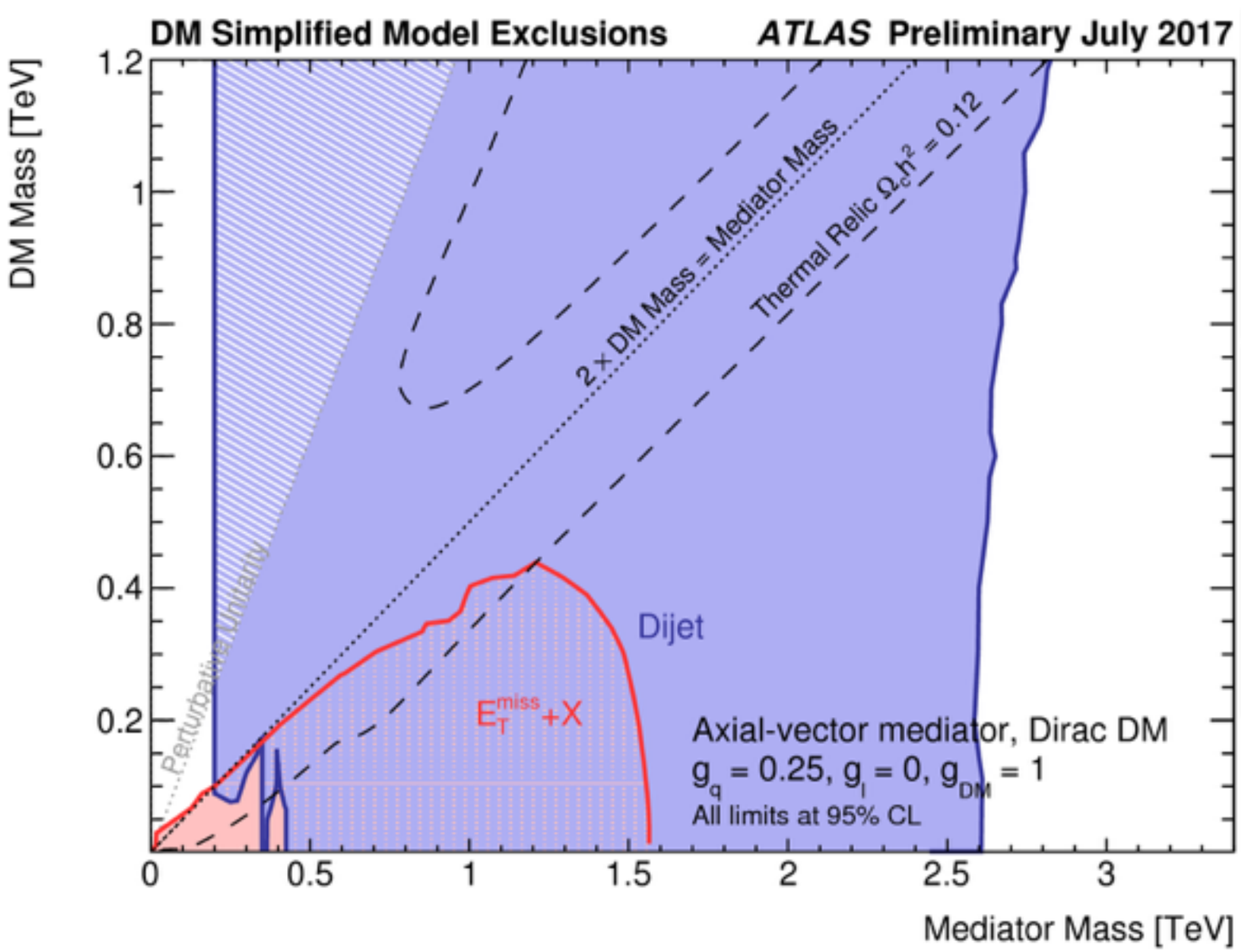


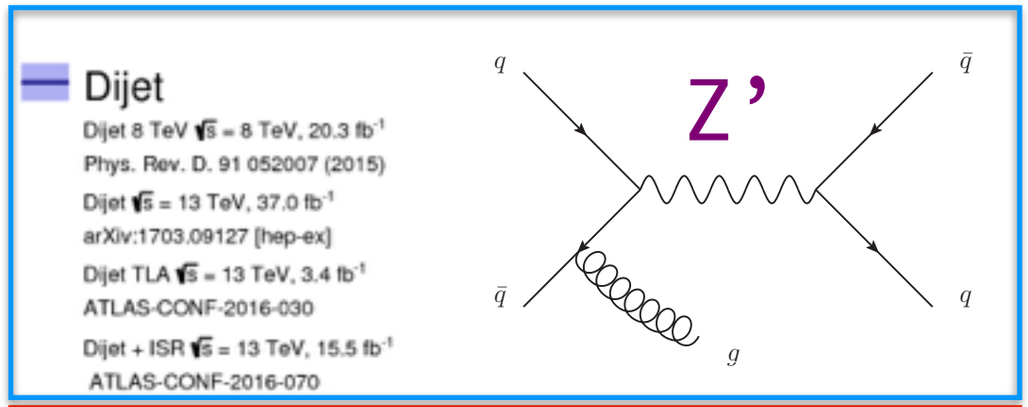


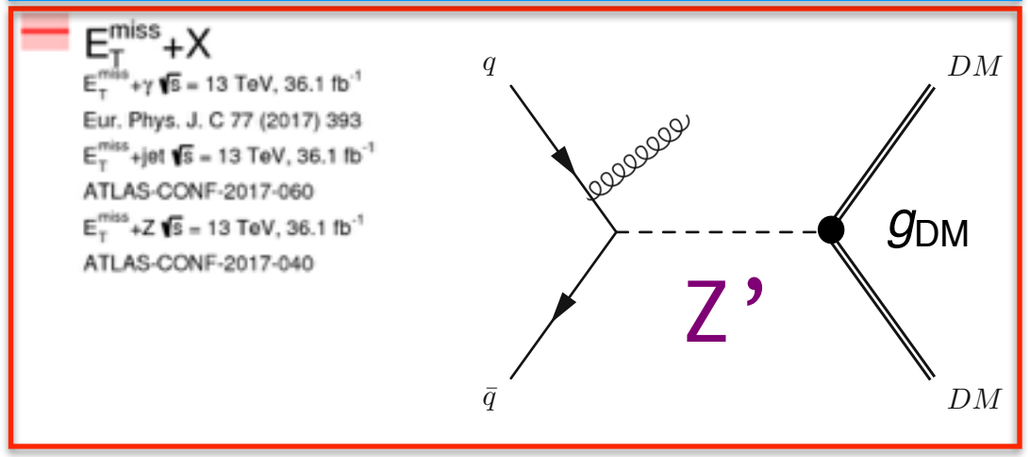


ATLAS DM searches

- Assuming a leptophobic axial-vector mediator (arXiv:1703.05703)

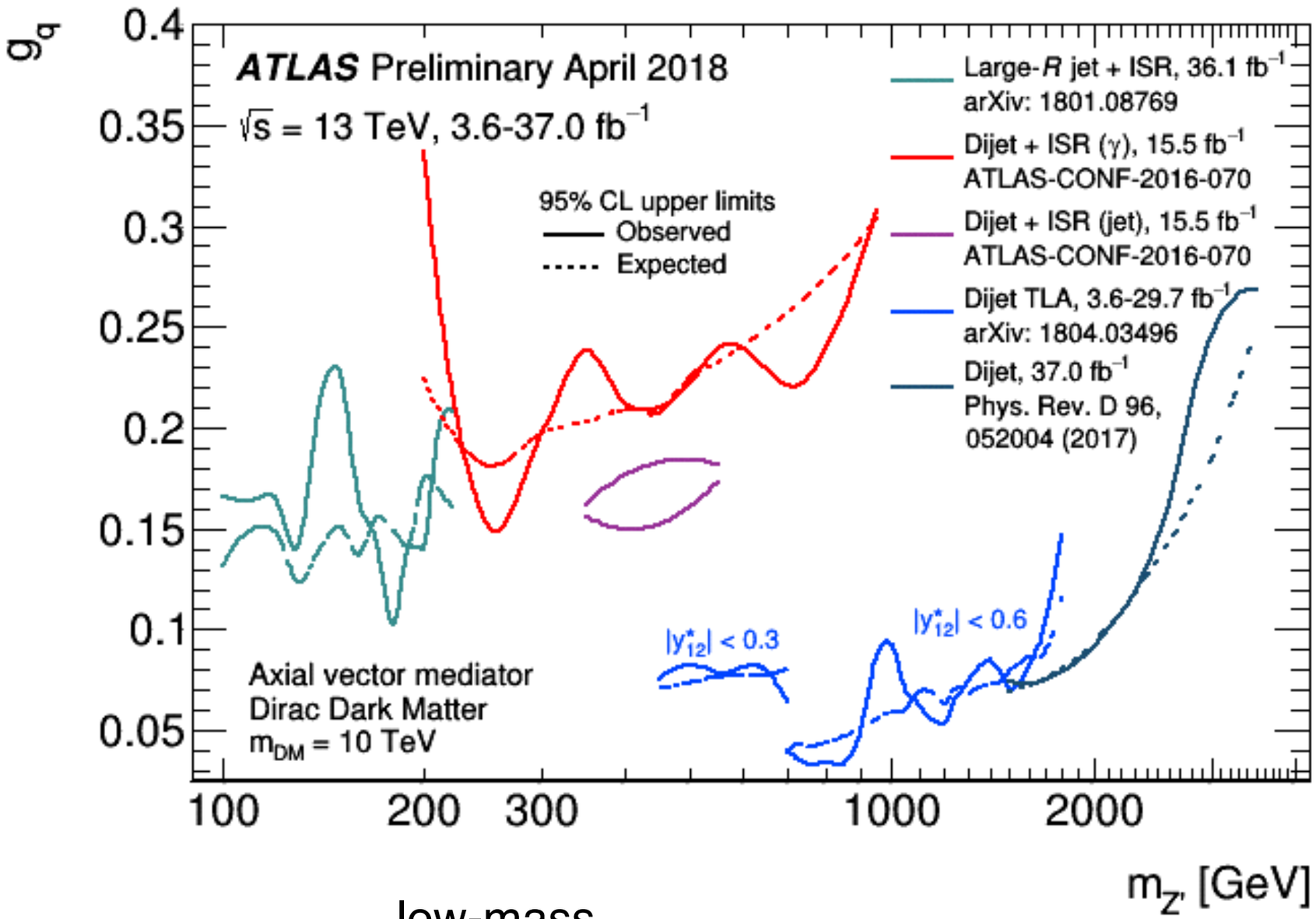






ATLAS DM searches

- Assuming a leptophobic axial-vector mediator Z' (arXiv:1507.00966)



Low-mass resonance
=> boosted

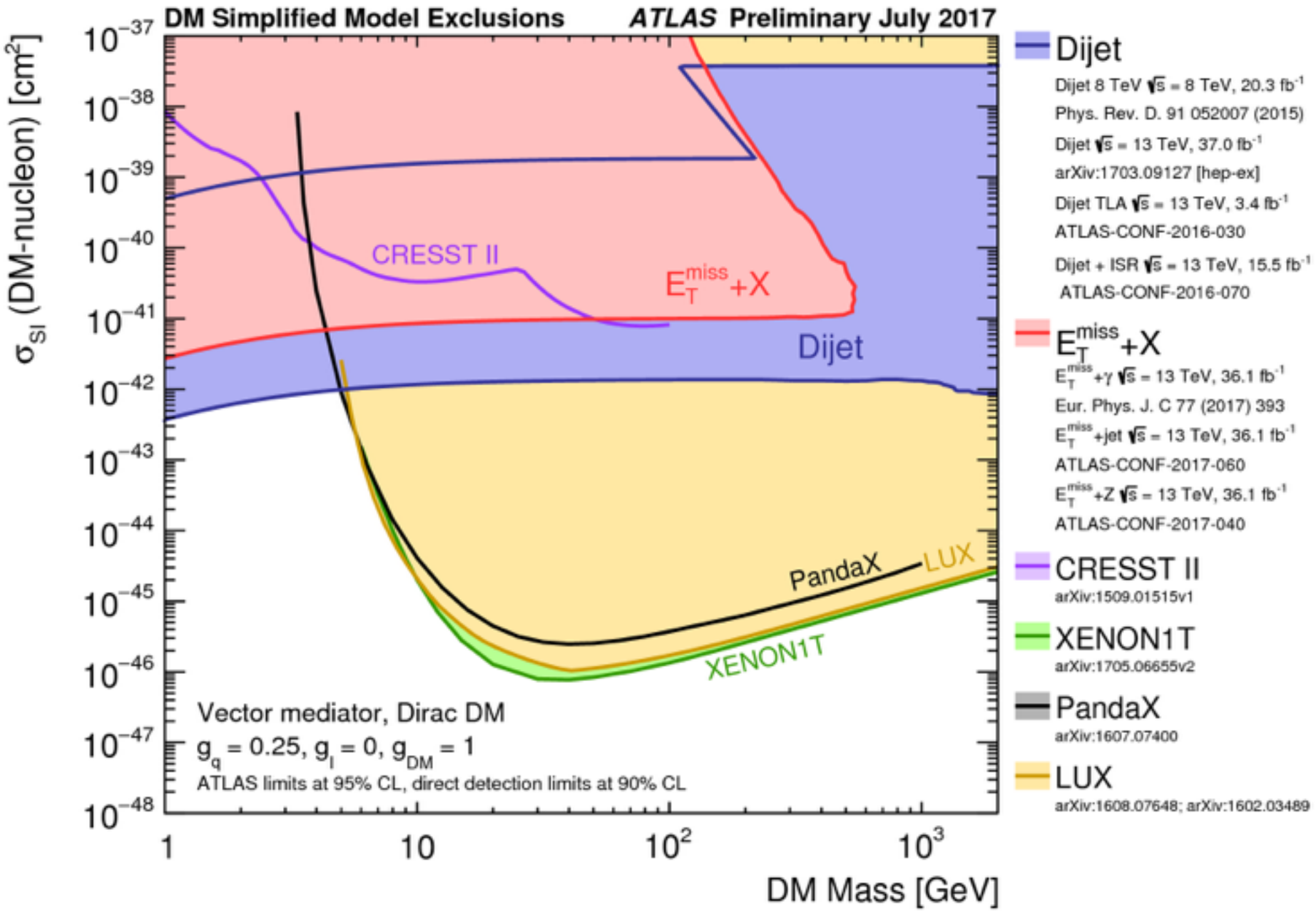
low-mass resonance, triggering on ISR

Trigger-level-analysis

High-mass analysis

ATLAS DM searches

- Spin-independent WIMP-nucleon scattering cross section in the context of the Z'-like simplified model with vector couplings



ATLAS DM searches

- Spin-dependent WIMP-neutron scattering cross section in the context of the Z'-like simplified model with axial-vector couplings