ATLAS and CMS Searches for light scalars from direct production and h_{125} decays

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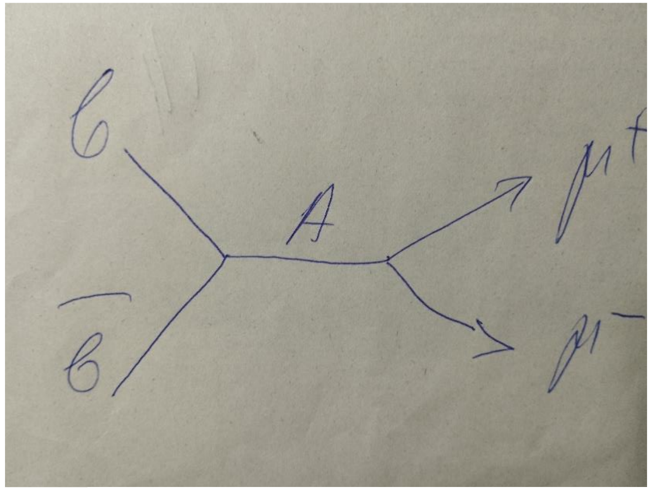
Direct production

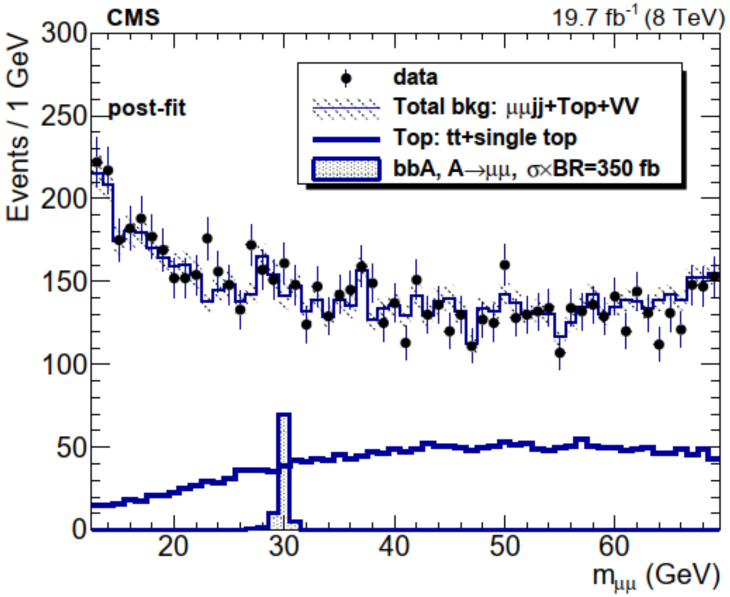
- **I will consider the two following analyses**
  - **$pp \to bbA$, $A \to \mu\mu$, $\tau\tau$, CMS (in the context of WS Yukawa Coupling Scenario in 2HDM Type II)**
    - JHEP 11 (2017) 010,
    - Phys. Lett. B 758 (2016) 296
    - JHEP 05 (2019) 210
  - **$pp \to ttA$, $A \to \mu\mu$ (and $pp \to tt$, $t \to H^{\pm}b$, $H^{\pm} \to W^{\pm}A$, $A \to \mu\mu$), ATLAS**
    - Phys. Rev. D 108 (2023) 092007

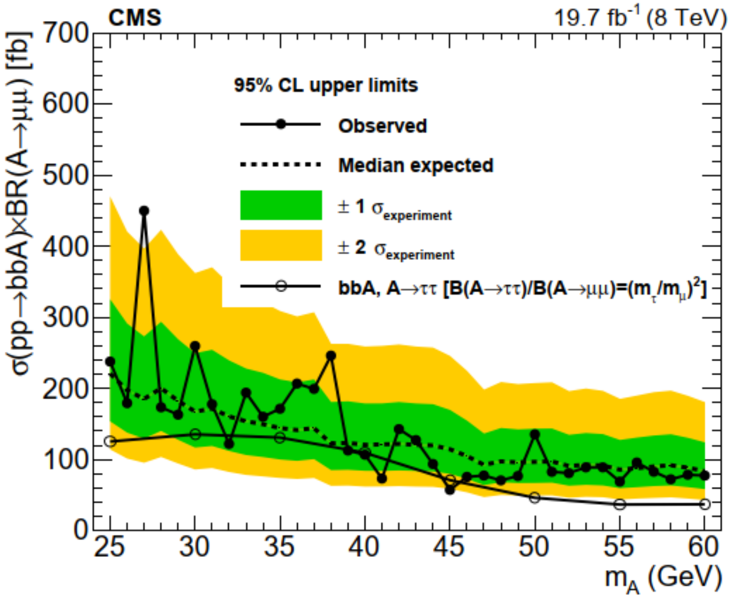
First CMS analyses on 8 TeV data



Selection optimized for pp→bbA, A→μμ signal model

- $p_T^{\mu_1} > 25\,\text{GeV}, |\eta_{\mu_1}| < 2.1;$
- $p_T^{\mu_2} > 5\,\text{GeV}, |\eta_{\mu_2}| < 2.4;$
- $p_T^{\text{b jet}} > 20\,\text{GeV}$ and $|\eta| < 2.4;$
- $p_T^{\text{miss}} < 40\,\text{GeV}.$





μμ and ττ final states have similar sensitivity assuming their BRs are related as $(m_\tau/m_\mu)^2$

Quick reminder on Wrong Sign Yukawa Coupling Scenario (WS) and pp→bbA, A→μμ,ττ (I)

Two solutions to have h compatible with h_{125} in Type II 2HDM

plot provided by P. Ferreira (in 2019), see also P. Ferreira et al arXiv1410.1926

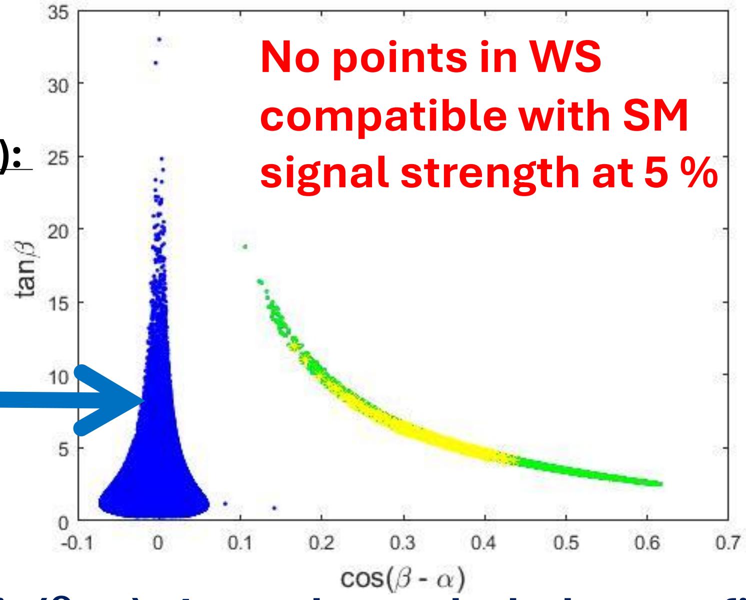
- Blue – alignment or decoupling limit, 20% compatibility with SM signal strength
- Green and Yellow – cos(β+α)≈0, Wrong Sign Yukawa Scenario:
  - $C_D \approx -1$, $C_V = C_U \approx 1$
  - Green – 20 % compatibility
  - Yellow – 10 % compatibility

In the "Higgs basis" (see J. Bernon et al., arXIv:1507.00933):

$$c_{\beta-\alpha} = -\,\mathrm{sgn}(Z_6)\sqrt{\frac{Z_1 v^2 - m_h^2}{m_H^2 - m_h^2}} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}},$$

Alignment limit – $Z_6 \to 0$
Decoupling limit – $m_H >> v$

2HDM Type II scan by P. Ferreira



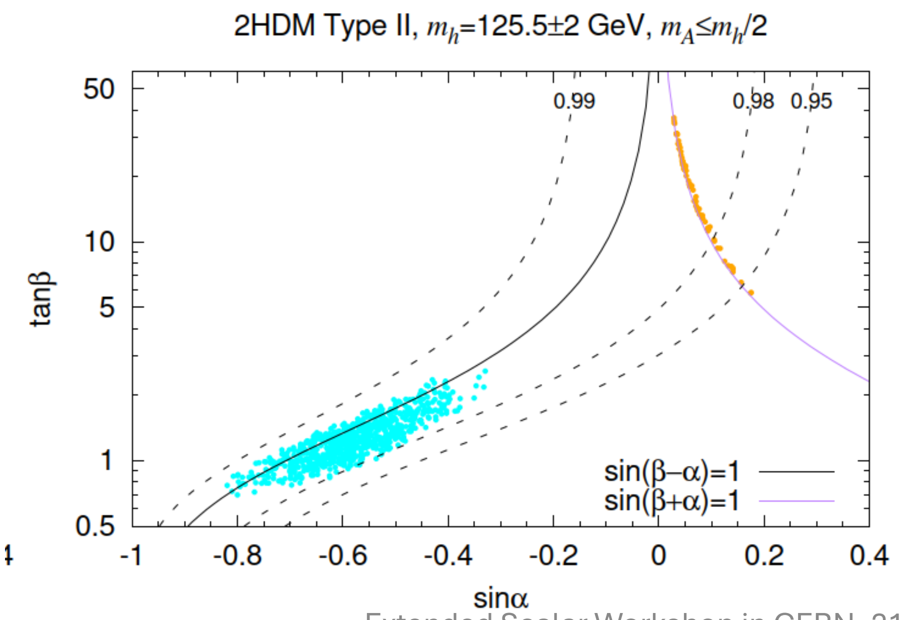
Wrong sign Yukawa coupling ($C_D \approx -1$, $C_V = C_U \approx 1$) scenario, sin(β+α)≈1, can be excluded or confirmed with h→γγ at HL-LHC,3 ab^{-1} where the h_{125} signal strength accuracy measurement of ≈5 % can be reached (FTR-19-001)

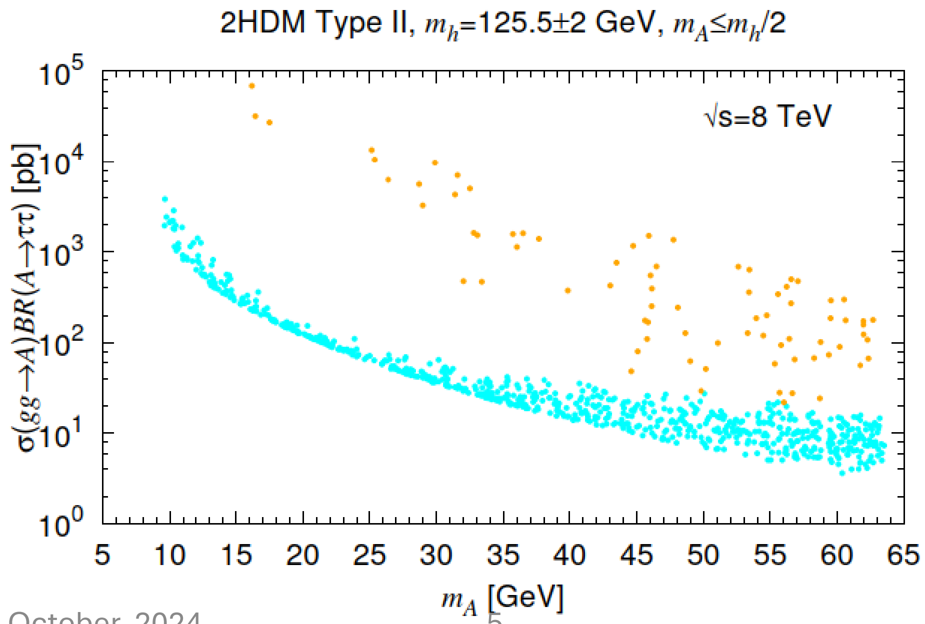
Quick reminder on Wrong Sign Yukawa Coupling Scenario (WS) and pp→bbA, A→μμ,ττ (II)

can Wrong Sign Yukawa Coupling Scenario be probed with a search for additional bosons ?

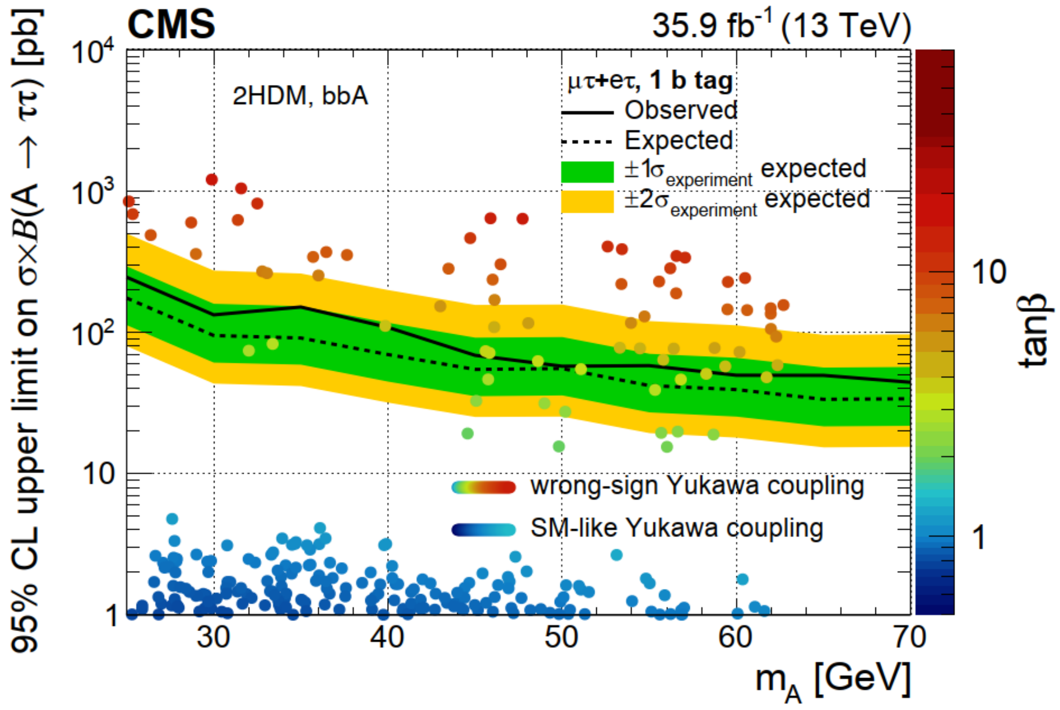
- 2HDM Type II scan with constraints (see J. Bernon et al. arXiv:1412.3385)
  - $m_A < m_h/2$
  - BR(h->AA) < 0.3
  - Dark yellow color – WS scenario

Very large cross-section for bbA, A->ττ in WS

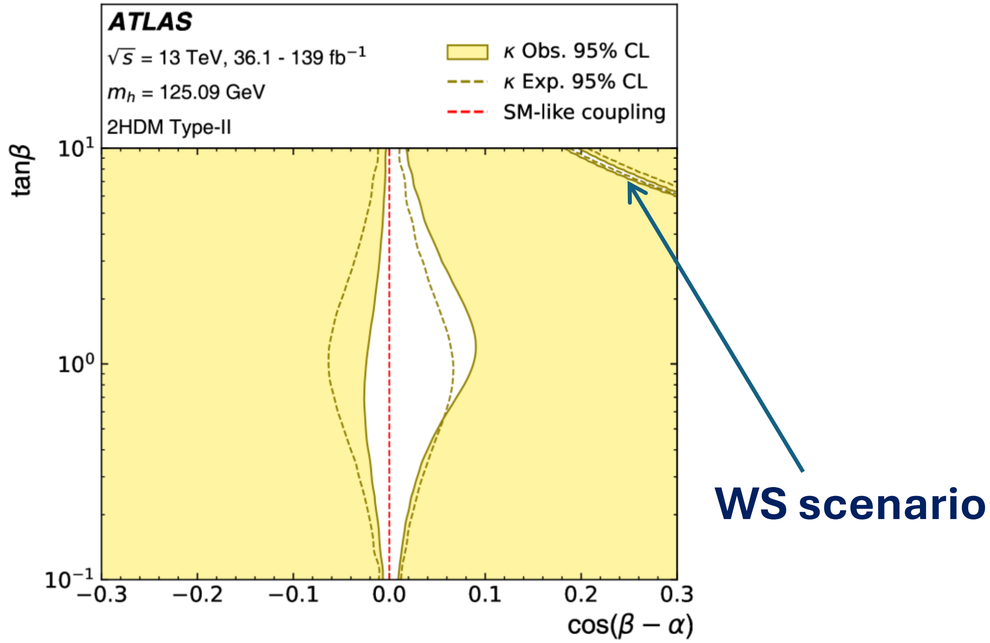




WS scenario: CMS searches for light A in bbA, A->$\tau\tau$ at 13 TeV and complementarity with h_{125} measurements



arXiv:2402.05742



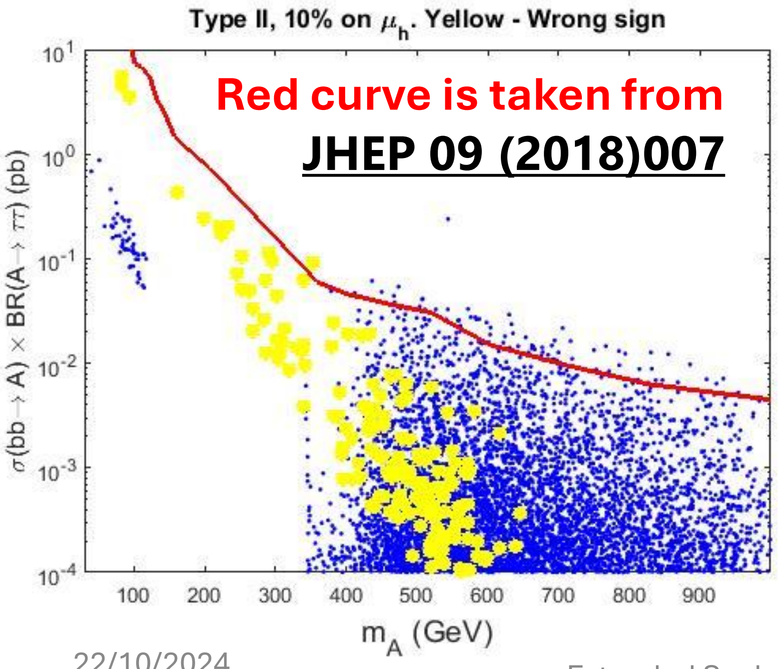
- most of the points in WS scenario with tanβ > 3 are excluded by pp→bbA, A->$\tau\tau$
- region tanβ < 3 in WS scenario is excluded by h_{125} measurements
- can conclude that WS scenario is excluded for $m_A < m_h/2$
- what's about $m_A > m_h/2$ region ? One should check ATLAS/CMS A/H→$\tau\tau$ searches

Comparison of experimental limits with predictions in 2HDM and WS scenario: bbϕ, ϕ->ττ

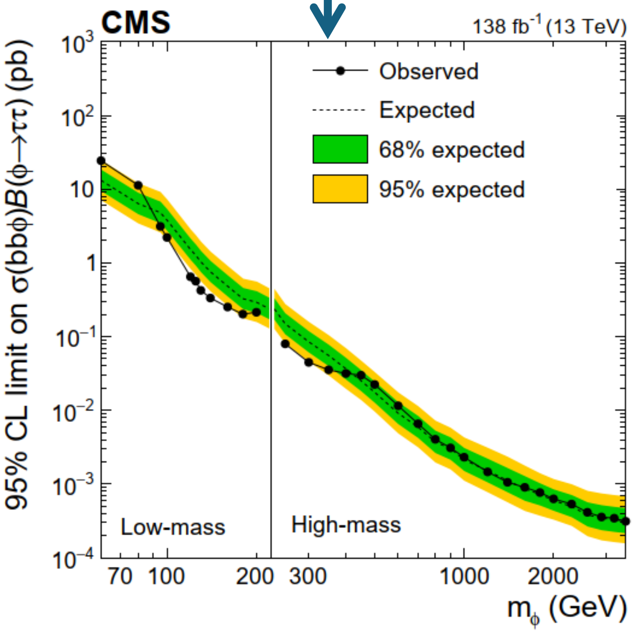
- Scans of 2019 by Pedro Ferreira (see also J. Bernon et al., arXiv:1507.00933)
  - Blue – 2HDM Type II, compatibility 20 % with SM signal strength
  - Yellow – WS scenario in 2HDM Type II, compatibility with SM signal strength 10 %

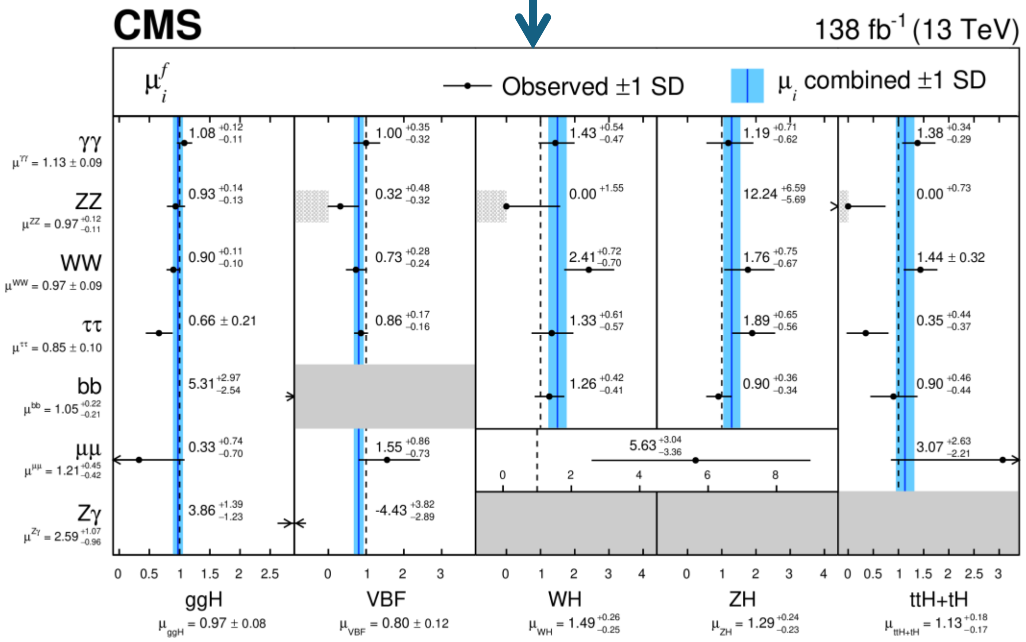
Need to be updated for

1. latest h_{125} measurements
2. latest A/H→ττ searches

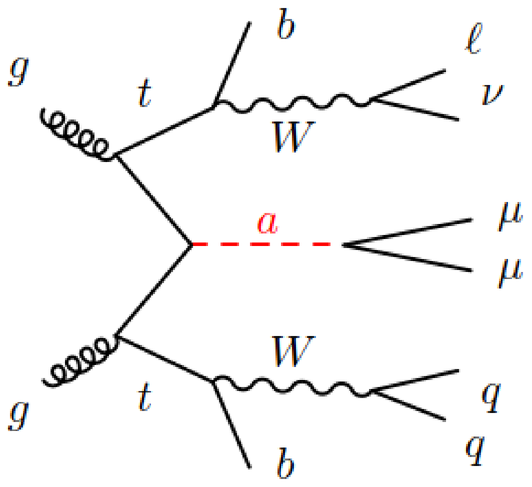


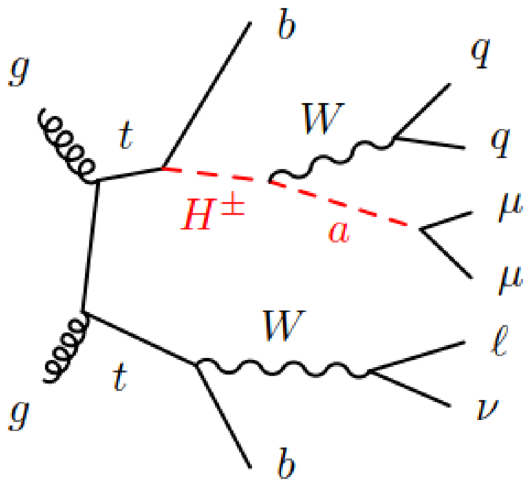
Red curve is taken from **JHEP 09 (2018)007**





ATLAS search for pp→ttA, A→μμ (and pp→tt, t→ H±b, H±→W±A, A→μμ) with full Run II data

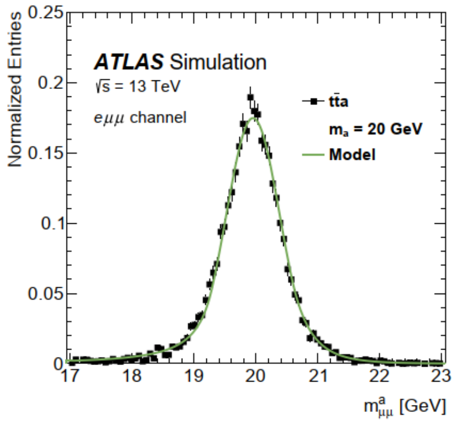




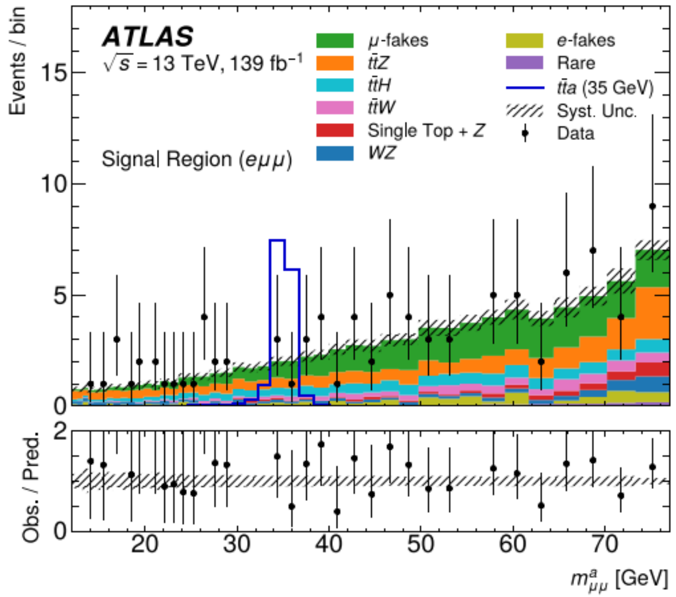
Motivated, in particular by [Mirkoantonio Casolino](), [Trisha Farooque](), [Aurelio Juste](), [Tao Liu](), [Michael Spannowsky]() «Probing a light CP-odd scalar in di-top-associated production at the LHC" [arXiv:1507.07004]()

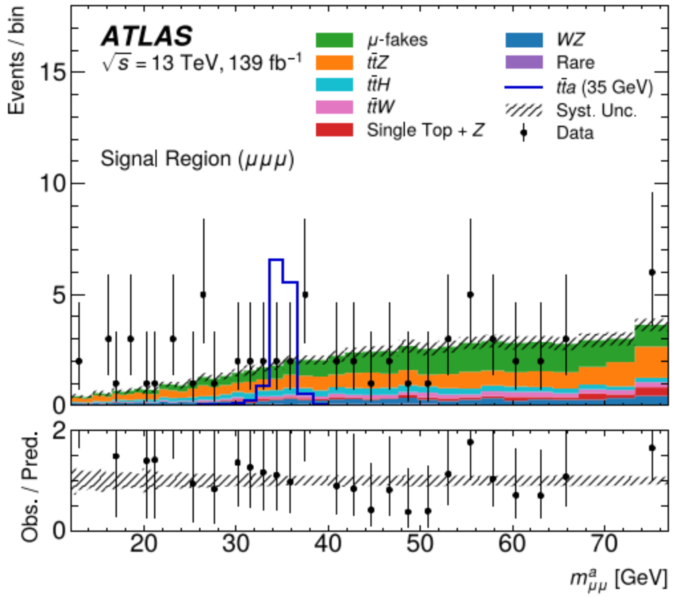
Signal selections

- $e^{\pm}\mu^{+}\mu^{-}$, $\mu\mu\mu$ selected with single electron and single muon triggers
  - Σ μ charge = ±1 for $\mu\mu\mu$
  - for $\mu\mu\mu$ final state «a-muons» are muons with $m_{\mu\mu}$ closest to m_a. Other muon is «top-muon».
    - a-muons p_T > 15, 10 GeV,
    - top-muon p_T > 27 GeV, $|\eta_\mu|$< 2.5
- signal region
  - 12 < $m^a{}_{\mu\mu}$< 77 GeV, $m^{other}{}_{\mu\mu}$ < 77 GeV or > 107 GeV to reject $Z \rightarrow \mu\mu$
  - ≥ 3 jets p_T > 20 GeV, $|\eta|$<2.5; ≥ 1 b-tagged jet



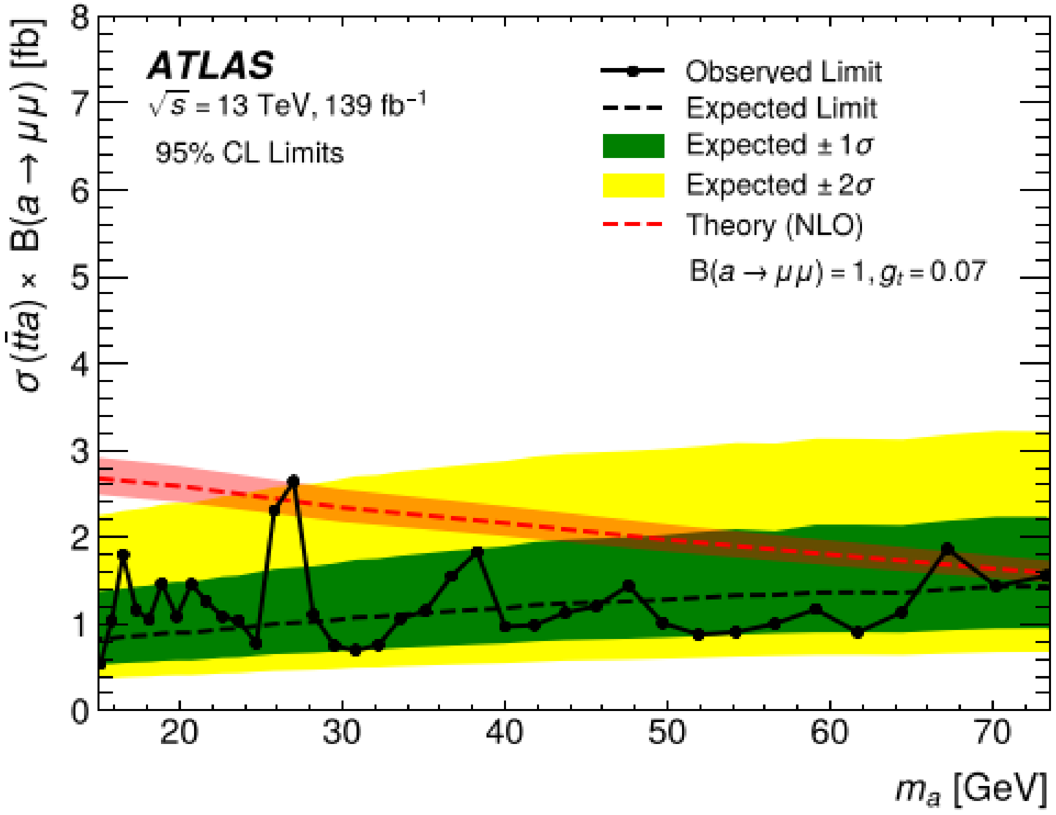
width assumed to be dominated by detector resolution





Result for pp→tta, a→μμ model

Minimal p-value = 0.008 (2.4 σ) at m_a=27.0 GeV,

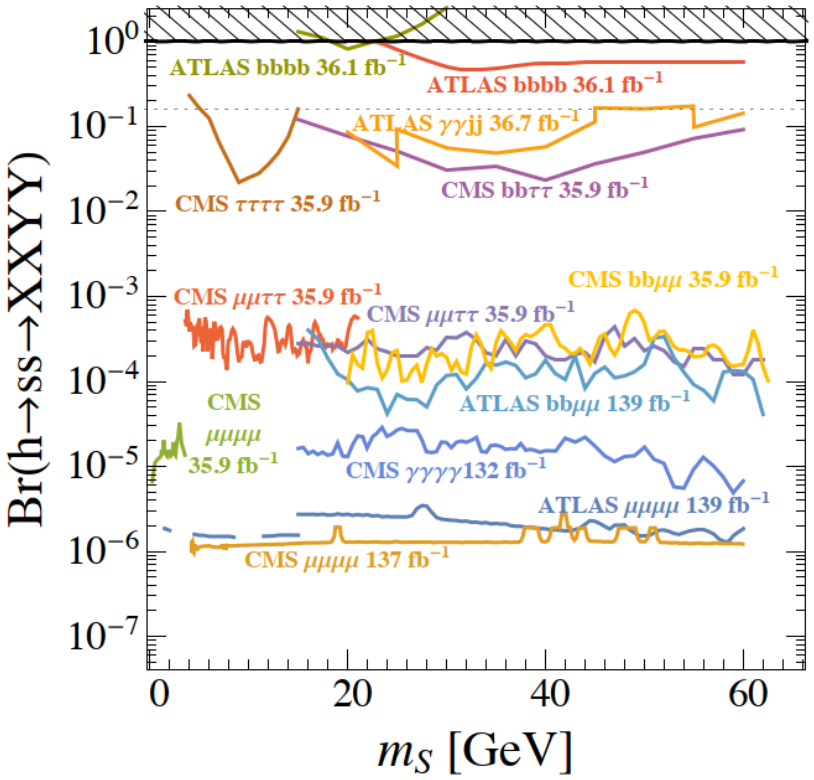


Searches for the light scalars from h_{125} decay

CMS and ATLAS searches for $h_{125} \to ss \to xxyy$ on one plot

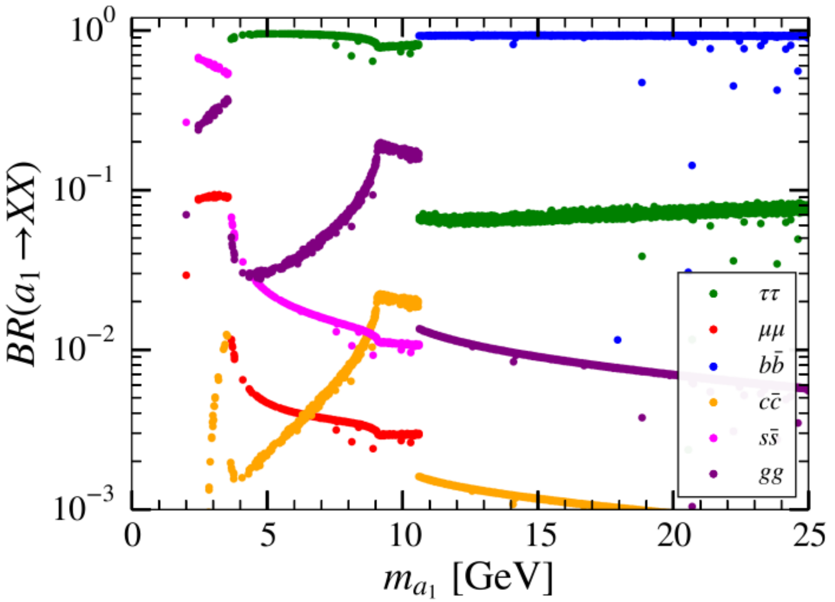
M. Carena et al arXIv:2203.08206

see also M. Cepeda at el arXiv:2111.12751



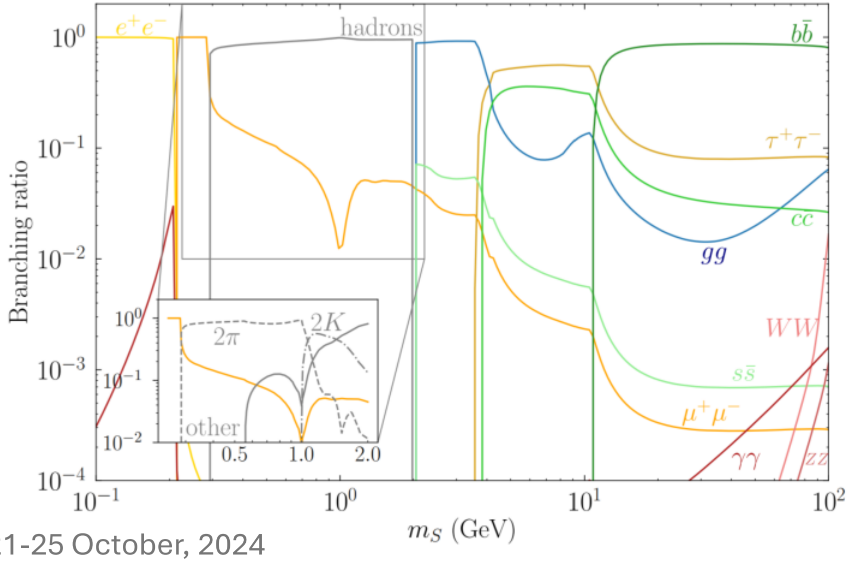
- **Recent ATLAS analyses of 2024**
  - $h_{125} \to aa \to 4\gamma$
  - $h_{125} \to Za \to ll\gamma\gamma$

R. Aggleton at al, arXiv:1609.06089 Br's in NMSSM

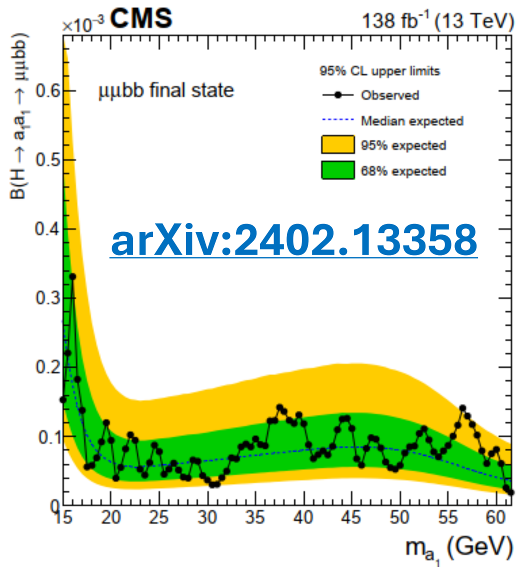


M. Carena et al arXIv:2203.08206

Br's in h125+singlet model

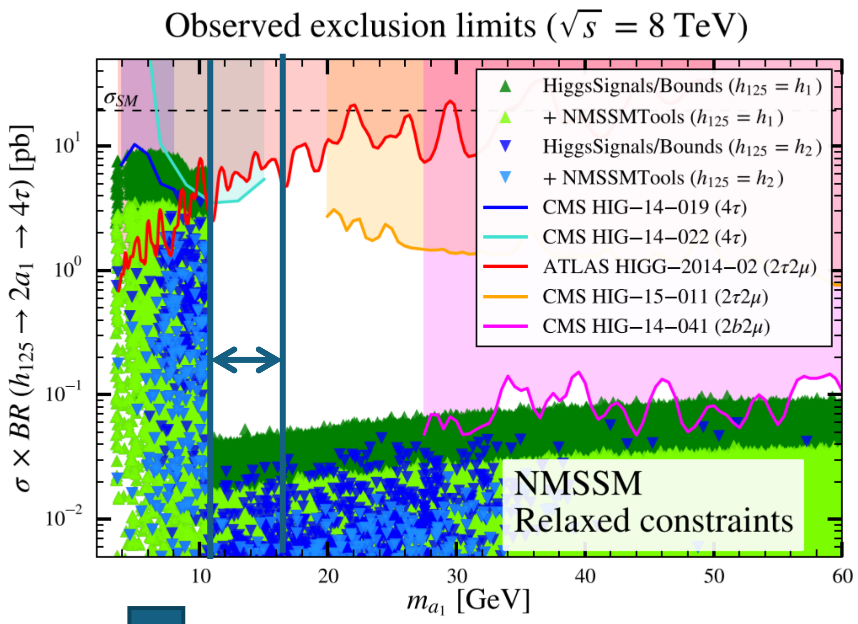


Searches for h_{125} decay to aa(hh) vs models (I)



[arXiv:2402.13358](https://arxiv.org/abs/2402.13358)

[R. Aggleton at al, arXiv:1609.06089](https://arxiv.org/abs/1609.06089)

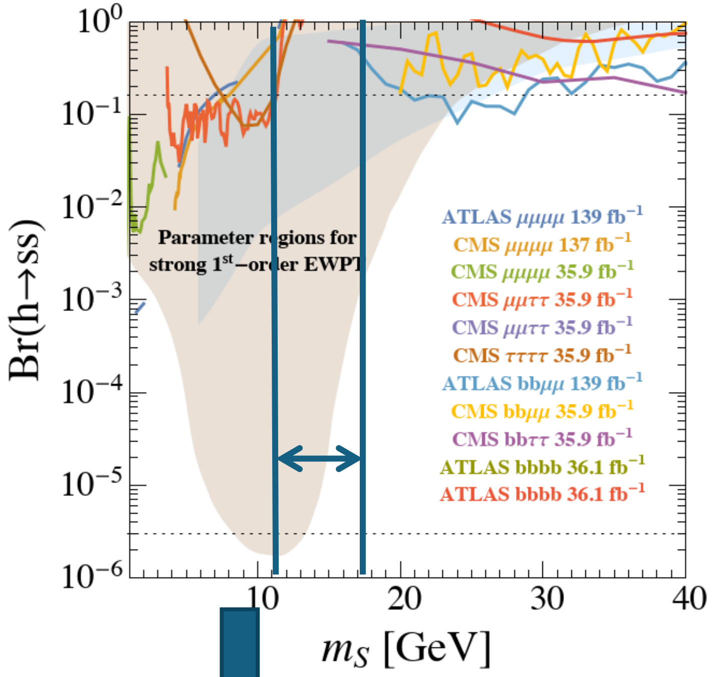


already sensitive to NMSSM

this plot need to be updated for 13 TeV (Run II) analyses. CMS:

- μμbb: [arXiv:2402.13358](https://arxiv.org/abs/2402.13358) – m_a range is 20-60 GeV
- ττbb: [arXIv:2402.13358](https://arxiv.org/abs/2402.13358) – m_a range is 15-60 GeV
- μμττ: arXiv:2005.08694 – m_a range is 3.6-21 GeV
- ττττ : arXiv:1907.07235 – m_a range is 4.0-15 GeV
- μμμμ: [arXiv:1812.00380](https://arxiv.org/abs/1812.00380) – m_a range is 0.25-8.5 GeV
- bbbb: [arXiv:2403.10341](https://arxiv.org/abs/2403.10341) – m_a range is 15-60 GeV

M. Carena et al arXiv:2203.08206

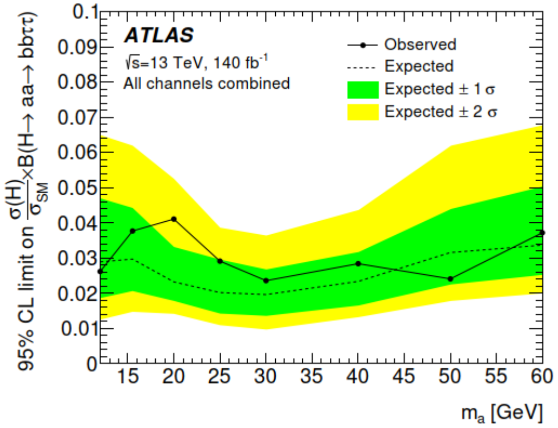


[h125+singlet model](#)

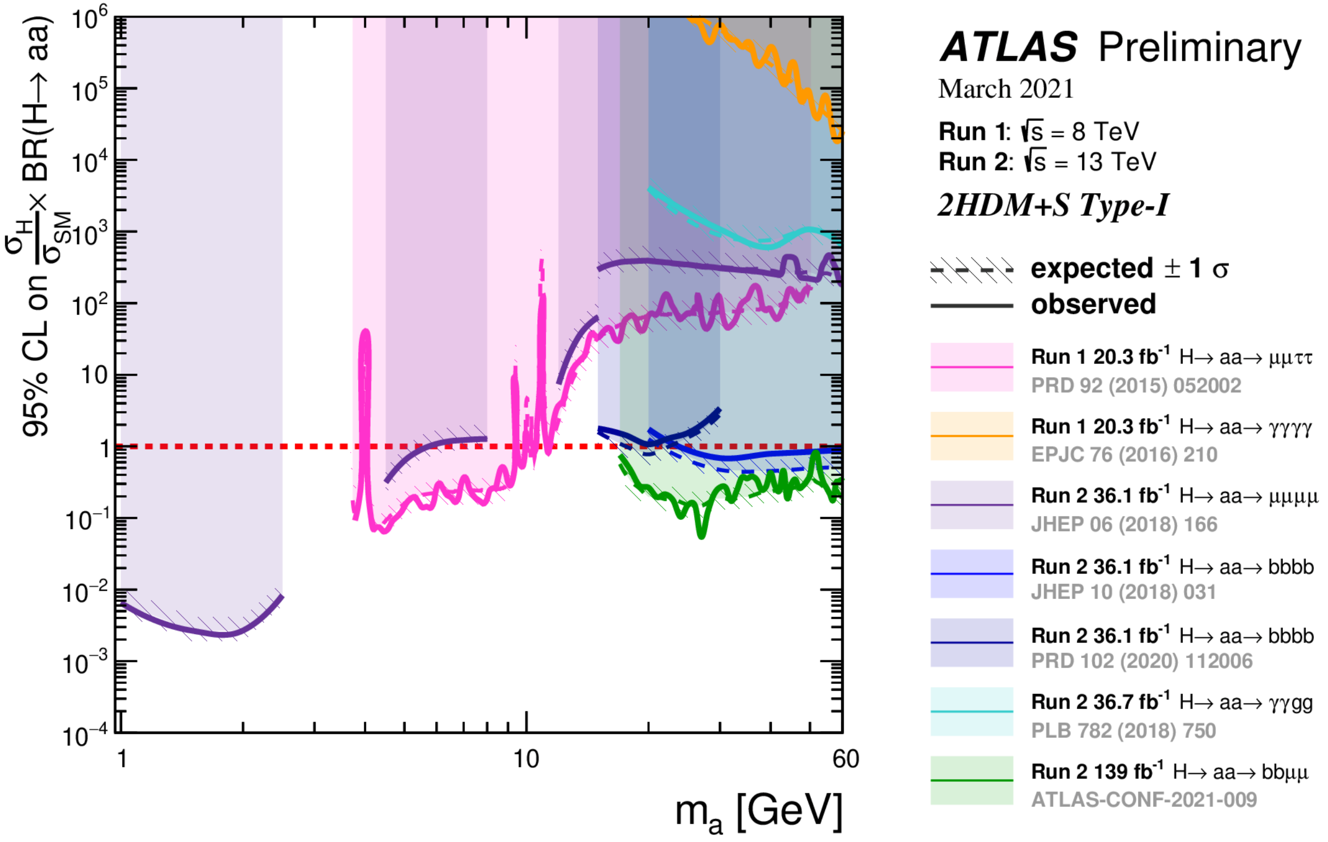
Already sensitive to parameter regions for strong 1st order EWPT

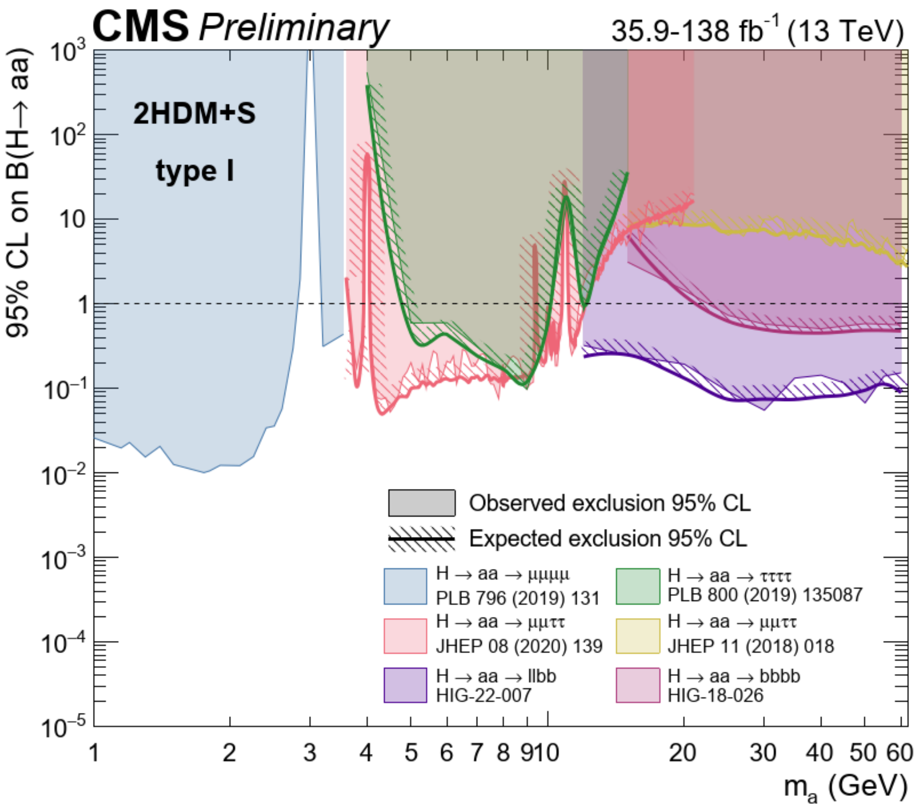
mass range, m_a≈10-15 GeV was not accessible. μμ(ττ)bb could do it using a «fat jet», with two b-quarks inside.

arXiv:2407.01335
ATLAS, DeXTer method



Searches for h_{125} decay to aa(hh) vs models (II)





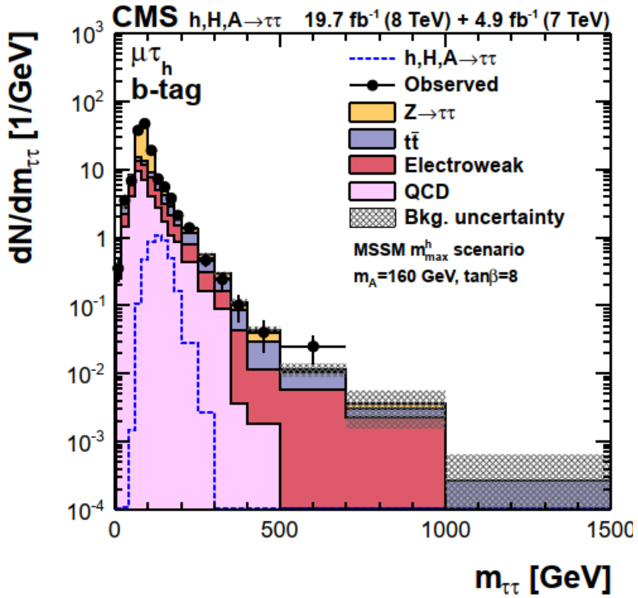
Regions 3-5, 9-11 GeV are covered with calculations taking into account effect of mixing of pseudoscalar and η_c, η_b states (h->$\eta_b\eta_c$->aa, η_ba->aa, ...). U. Haisch et al. arXiv:1802.02156

Search for dimuon resonance with mass of ≈28 GeV in $\mu^+\mu^-$ + b-jet events using CMS Run I and Run II data

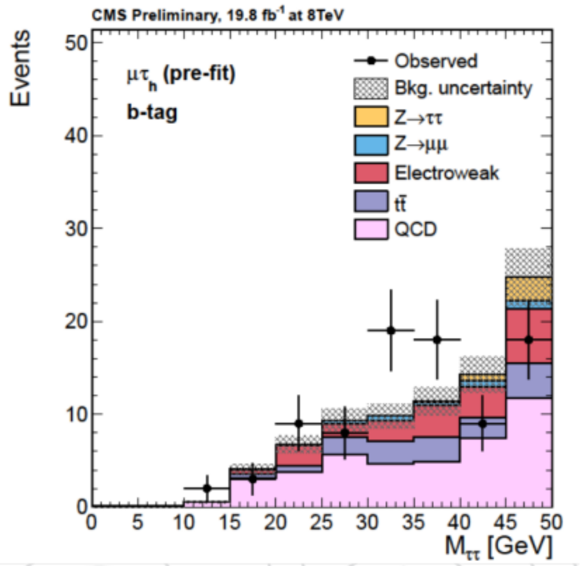
Motivation of $\mu^+\mu^-$+b analysis

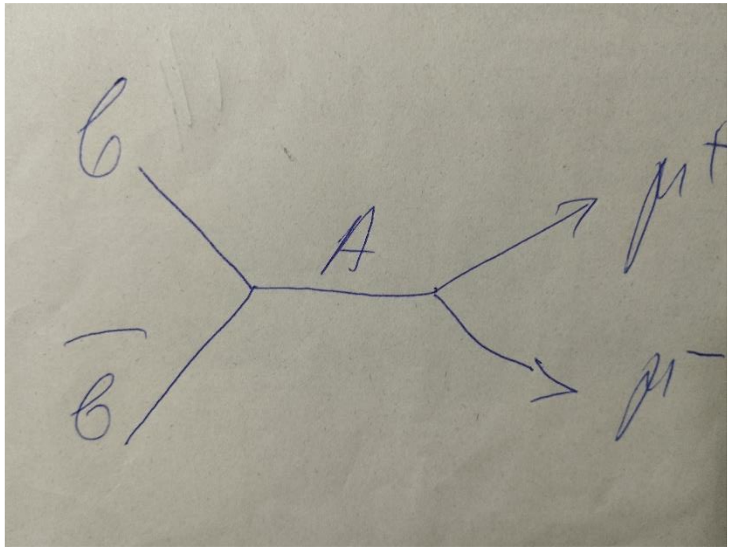
- **M.M. Almarashi and S. Moretti,**
  "Low mass Higgs signals at the LHC in NMSSM" ,
  [Eur. Phys. J. C71 (2011) 1618]
- **J. Bernon, J. F. Gunion, Y. Jiang, and S. Kraml,**
  "Light Higgs bosons in two-Higgs-doublet models",
  [Phys. Rev. D 91 (2015) 075019]

JHEP 10 (2014) 160



zoom at low mass

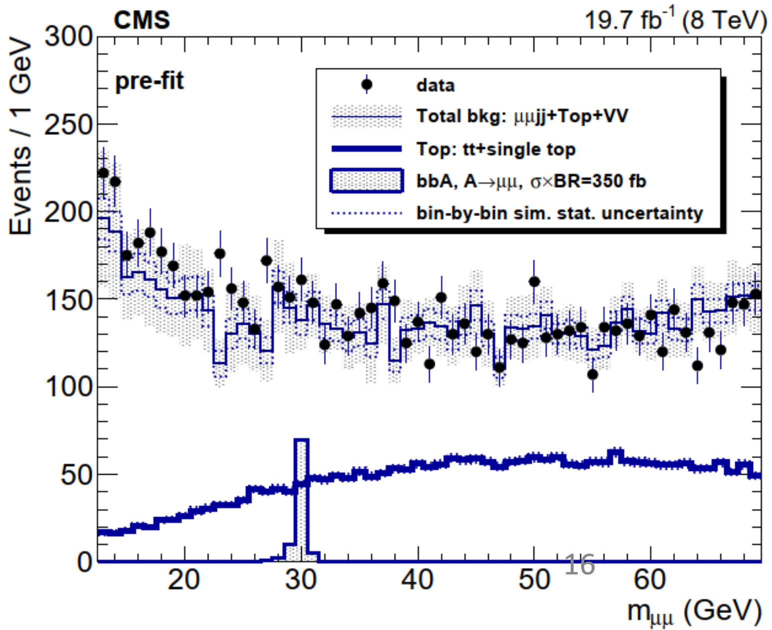




Selections

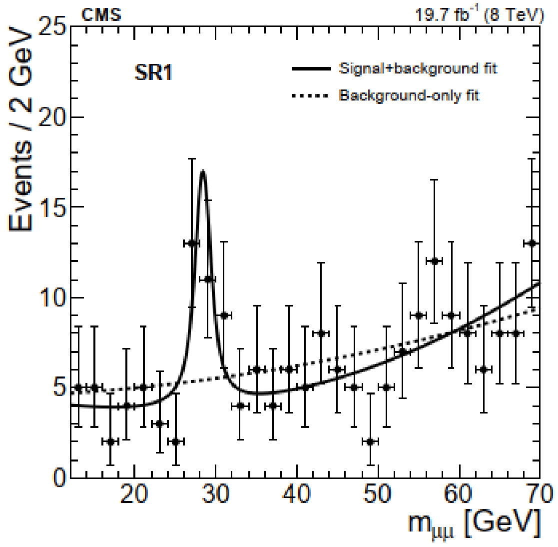
- $p_T^{\mu_1} > 25\,\text{GeV},\ |\eta_{\mu_1}| < 2.1;$
- $p_T^{\mu_2} > 5\,\text{GeV},\ |\eta_{\mu_2}| < 2.4;$
- $p_T^{\text{b jet}} > 20\,\text{GeV}$ and $|\eta| < 2.4;$
- $p_T^{\text{miss}} < 40\,\text{GeV}.$

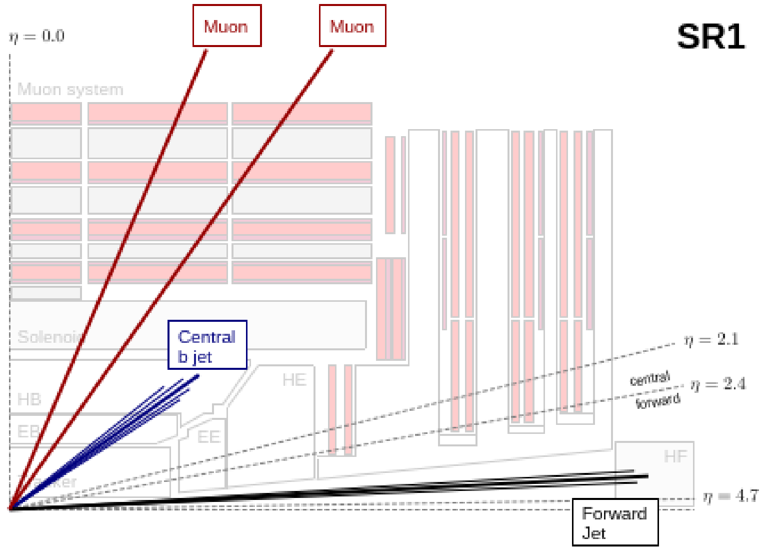
JHEP 11 (2017) 010

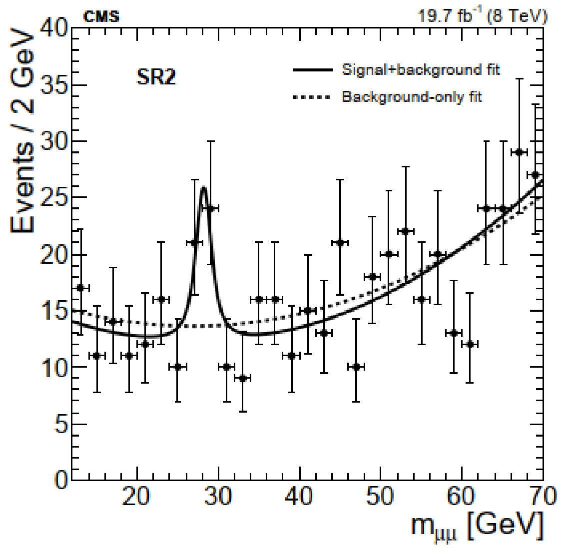


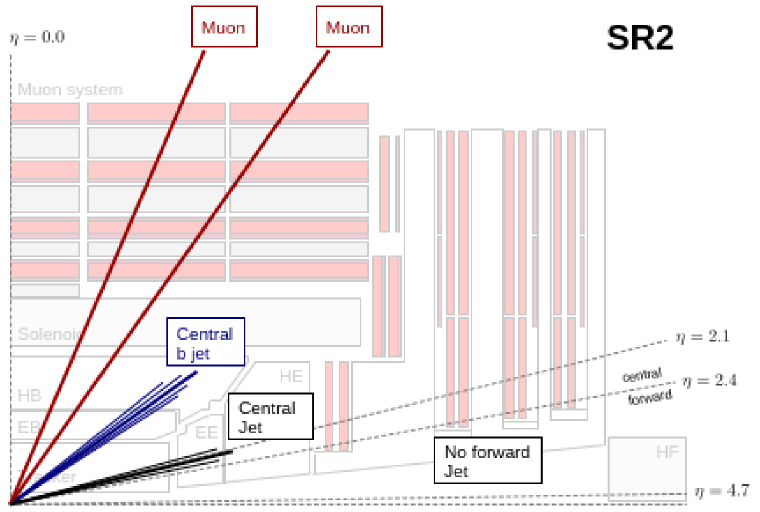
Observation of event excess at 8 TeV in 2014

- due to good luck: selection $p_T^{\mu 1,2}$>25 GeV instead of 25,10 GeV was applied due to typo in code for Search Region 1 (SR1)
- once bump was observed in SR1 Higgs PAG conveners wanted to be convinced by finding the same bump in different event category (SR2). It was done.

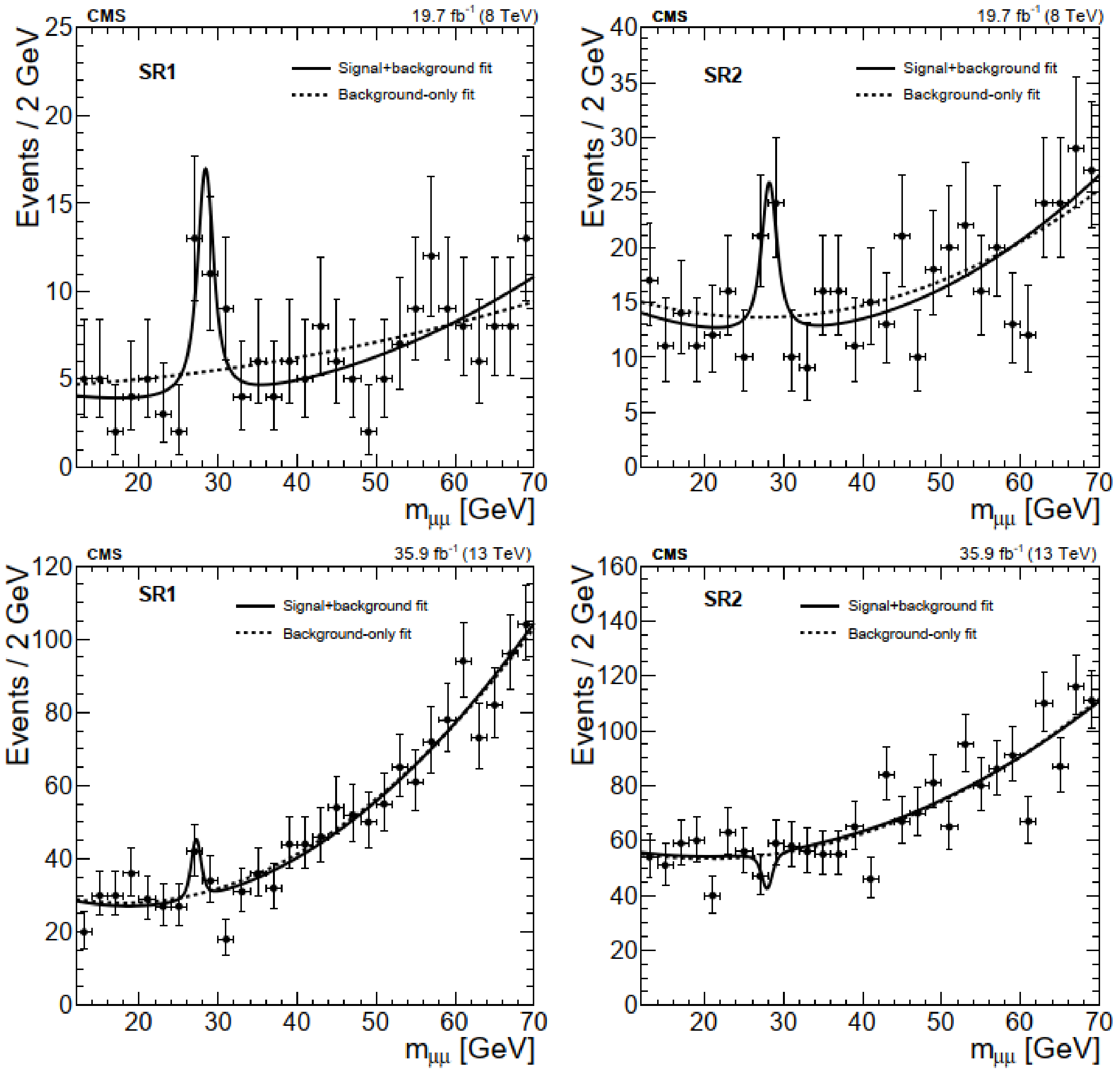








Once paper of 8 TeV analysis was ready to be out in 2016 we were requested to add 13 TeV 2016 data with the same selection. We published analysis (JHEP 11 (2018) 161) 2 years later in 2018.



Event category	SR1 Additional forward jet	SR2 Additional central jet
Muons	OS, $p_T > 25$ GeV, $\lvert\eta\rvert < 2.1$	
$m_{\mu\mu}$	$m_{\mu\mu} > 12$ GeV	
b-tagged jet	$p_T > 30$ GeV, $\lvert\eta\rvert \leq 2.4$	
Additional jet	$p_T > 30$ GeV, $2.4 < \lvert\eta\rvert < 4.7$	$p_T > 30$ GeV, $\lvert\eta\rvert \leq 2.4$
Jet veto	No other jets $p_T > 30$ GeV, $\lvert\eta\rvert \leq 2.4$	No jets $p_T > 30$ GeV, $2.4 < \lvert\eta\rvert < 4.7$
p_T^{miss}	—	$<$40 GeV
$\Delta\phi(\mu\mu, jj)$	—	$>$2.5 rad

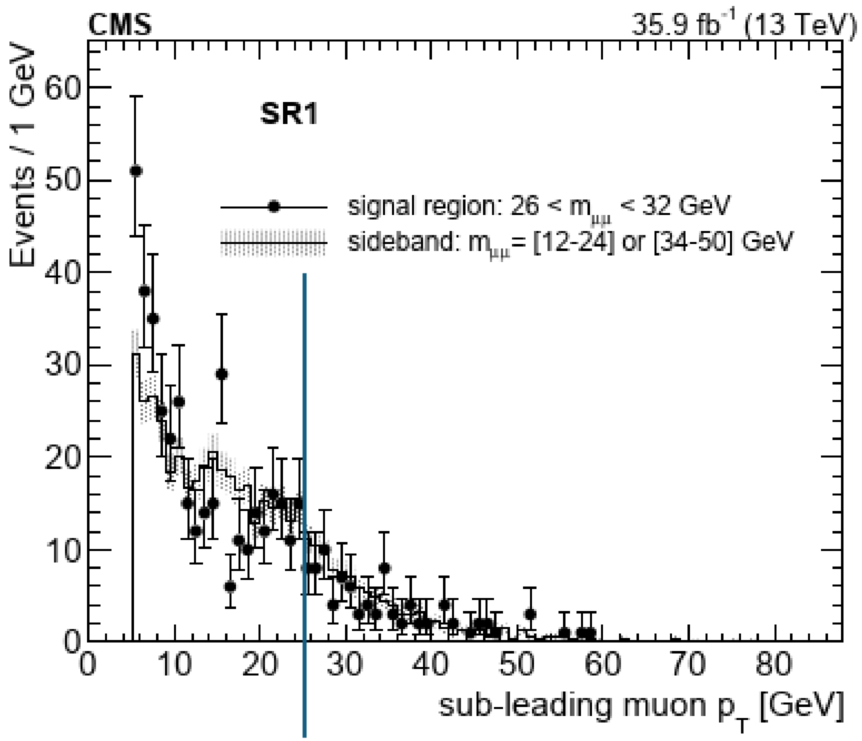
Event category	SR1 Additional forward jet	SR2 Additional central jet
m_X (GeV)	28.4± 0.6	28.2± 0.7
$\Gamma_{\mu\mu}$ (GeV)	1.9±1.3	1.9±1.1

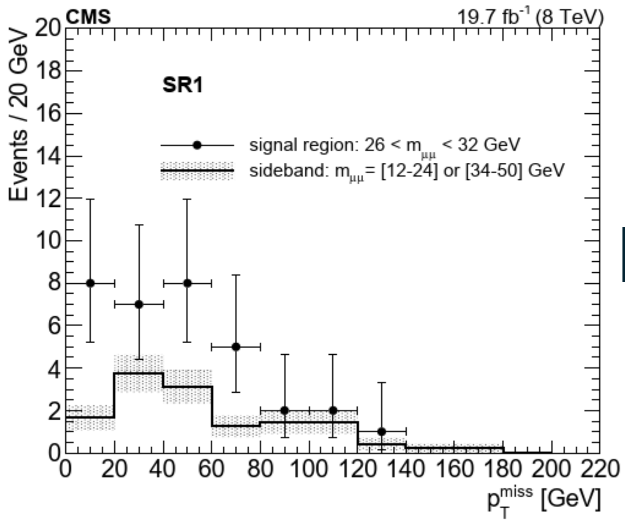
$\sqrt{s}$ (TeV)	8		13	
Event category	SR1	SR2	SR1	SR2
Local significance (s.d.)	4.2	2.9	2.0	1.4 deficit
m_X (GeV)	28.3± 0.4		27.2±0.6	
$\Gamma_{\mu\mu}$ (GeV)	1.8±0.8		0.7±1.0	
N_S	22.0 ± 7.6	22.8 ± 9.5	14.5 ± 9.3	-14.9 ± 10.1

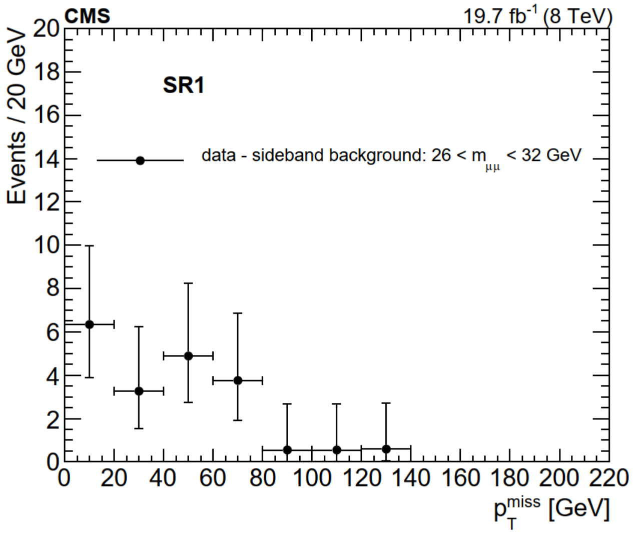
M. Mangano: no observation at 13 TeV might be explained by the increase of tt background by a factor of 3.3

Analysis is on the way with full Run II data.

What we can learn from public plots of the previous analysis ?







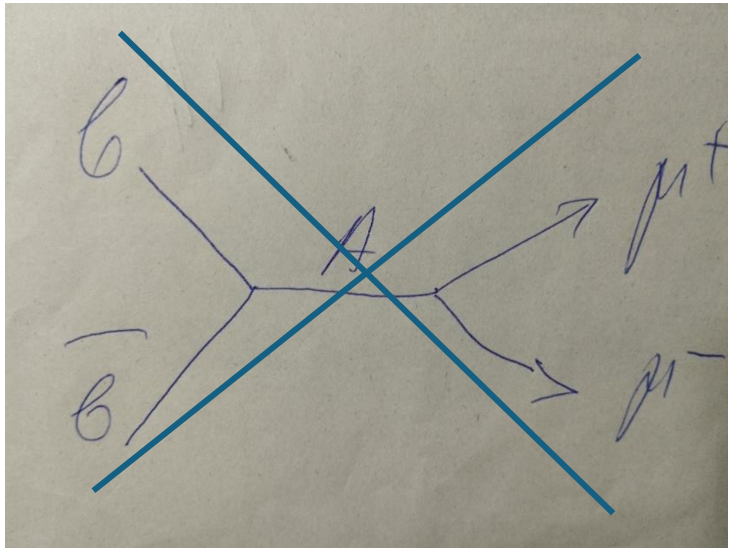
- **bumpy structure in $p_T^{\mu 2}$=[18-25] GeV in the signal region is not present in sidebands**
  - **therefore previous analysis cut of $p_T^{\mu 2}$ > 25 GeV is not optimal for the «signal» in 13 TeV data**
  - **«signal» is produced from the decay of heavy object (to be shown later)**
- **"signal" has non zero soft missing p_T in the range of ≈ [0-80] GeV**

Signal models we considered based on 8 TeV and 13 TeV 2016 data

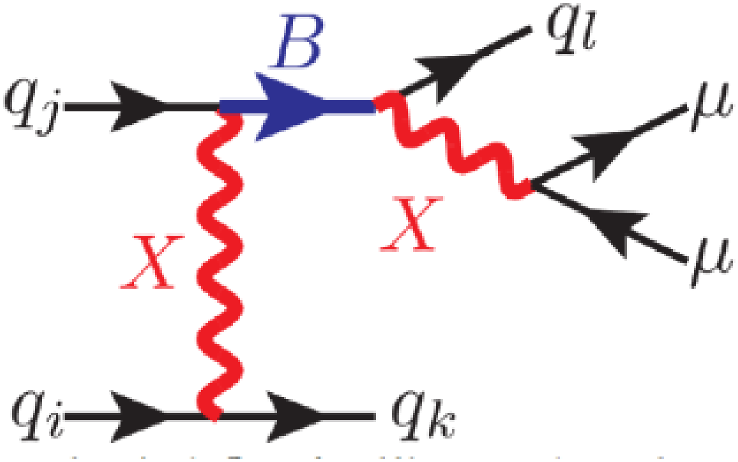
In collaboration with Stefano Moretti, Luca Panizzi, Daniele Barducci

Does signal originate from the direct production or not ?
Is it a scalar or vector ?

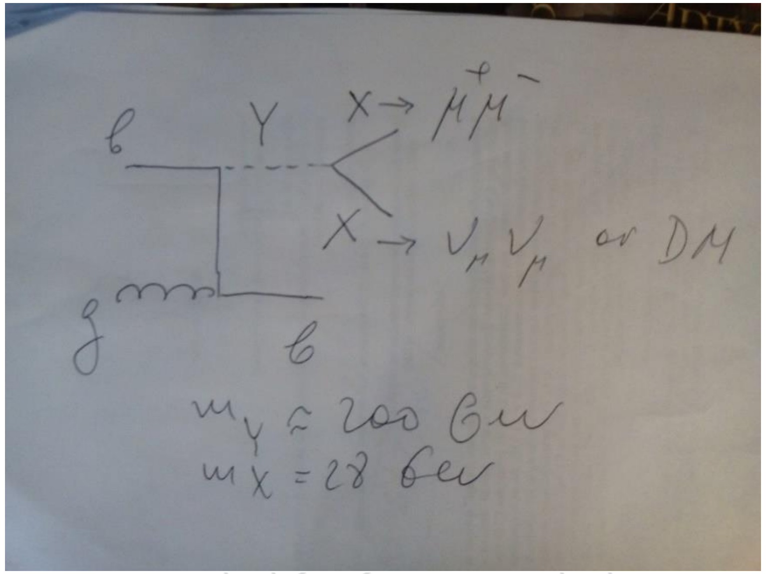
Direct production

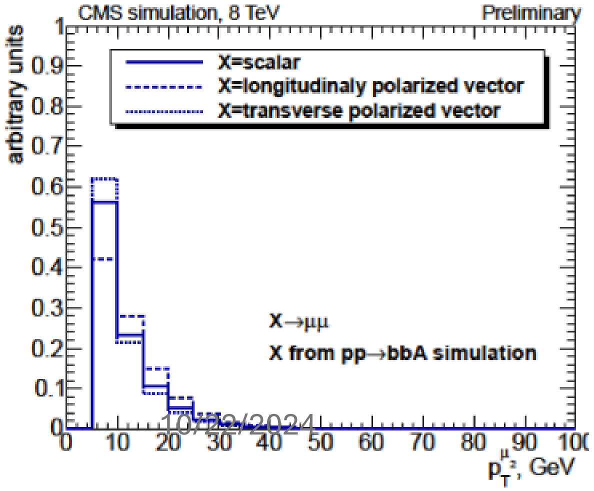


VLQ model

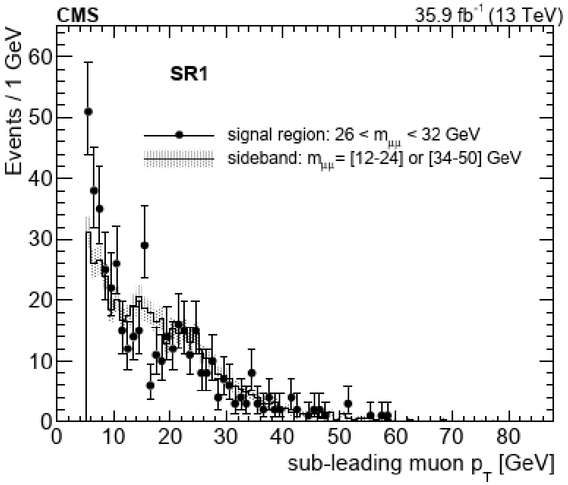


«XY» model

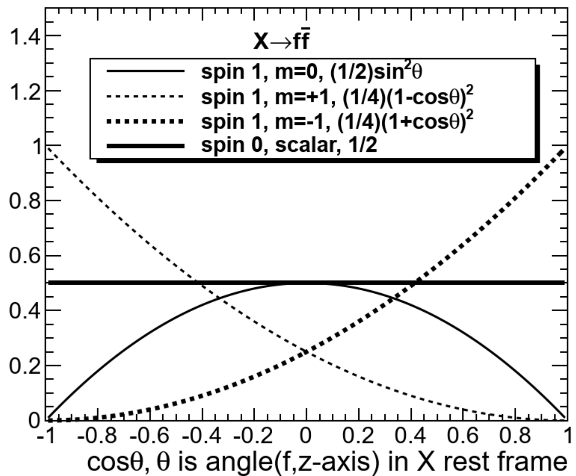


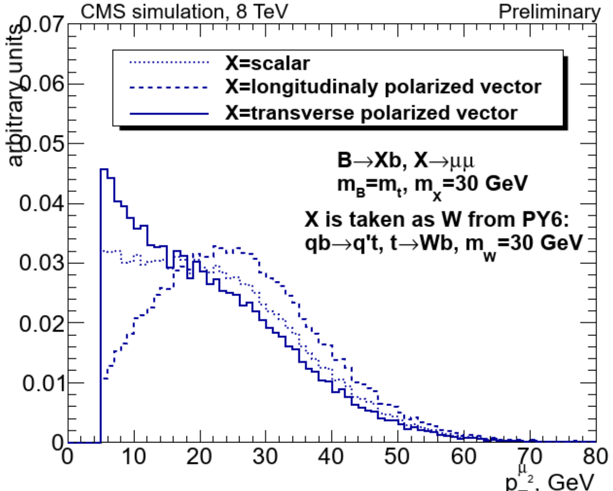


data



dimuon

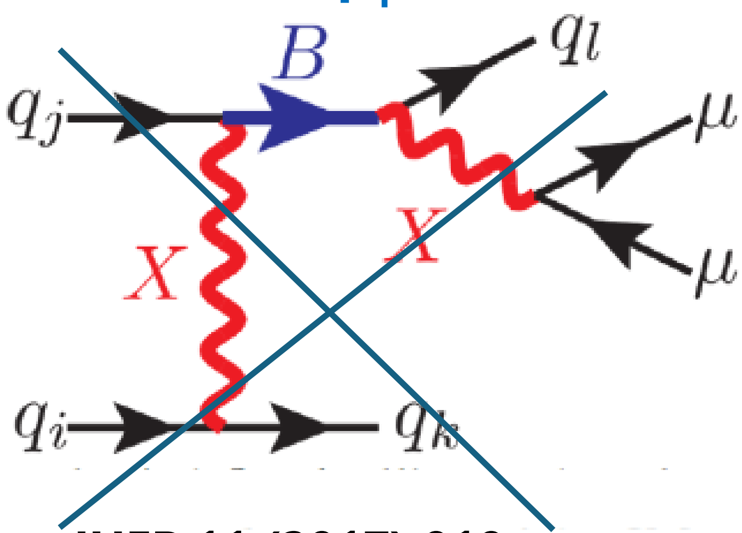




Signal has some missing p_T

VLQ model

zero real p_T^{miss}



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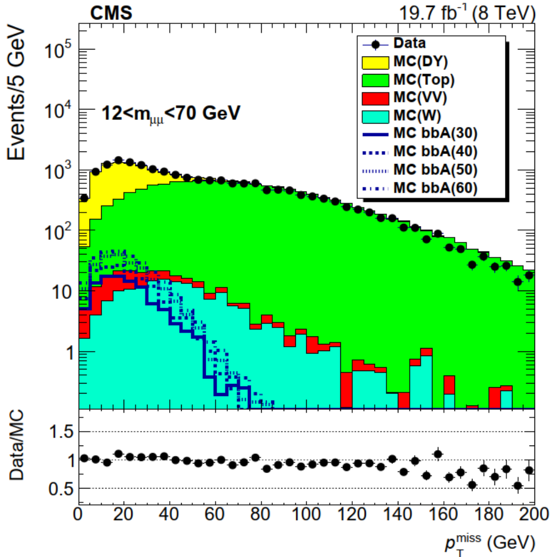
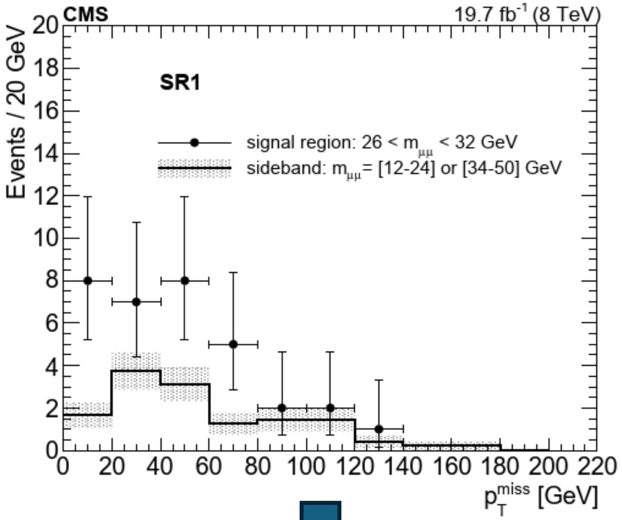
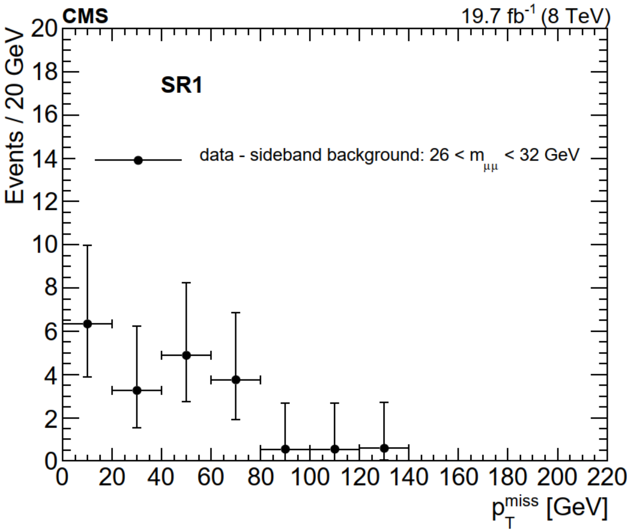
from bbA→A, A→μμ analysis



Run I, 8 TeV data

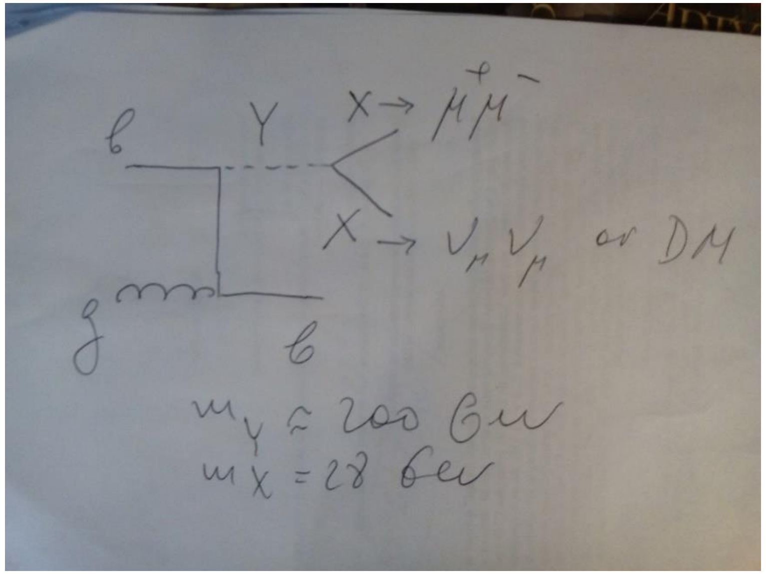
soft missing p_T

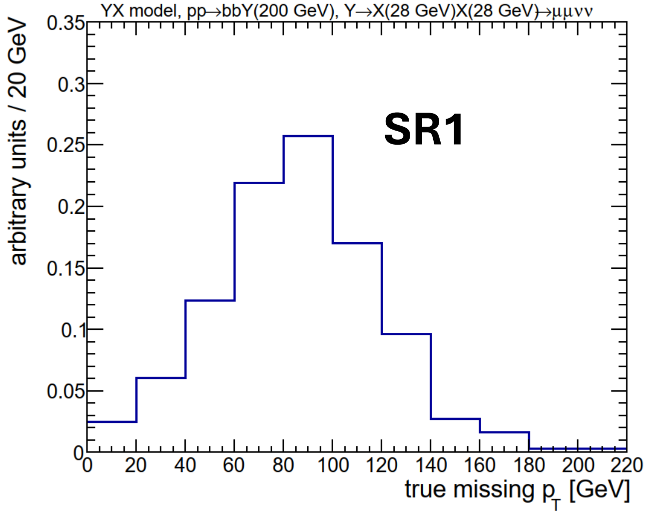




«XY» model:bbY prod.

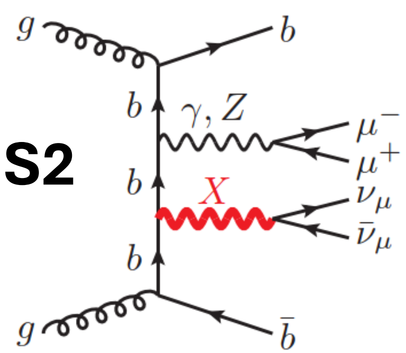
too large real missing p_T



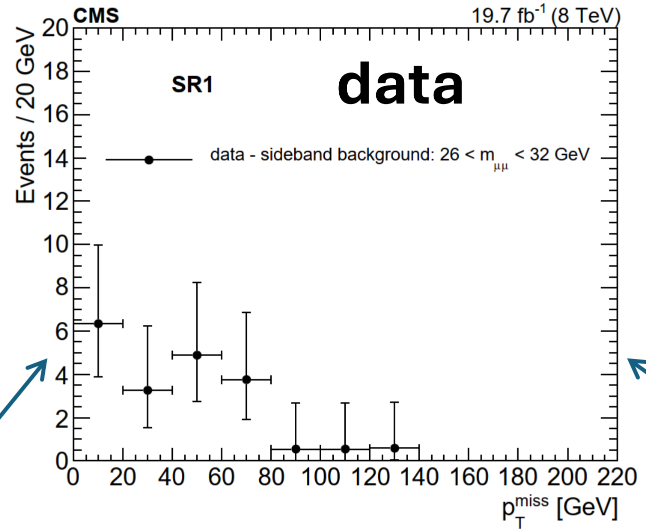


YX model: true missing p_T in SR1, 8 TeV

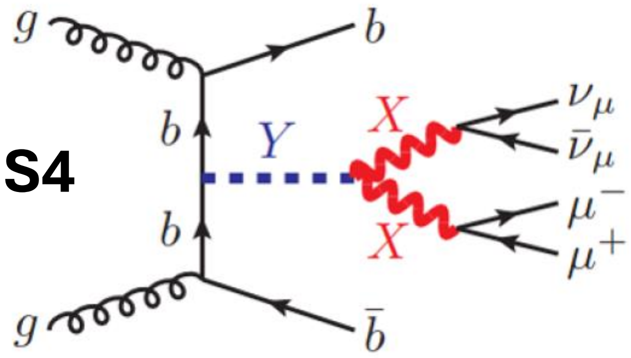
S2



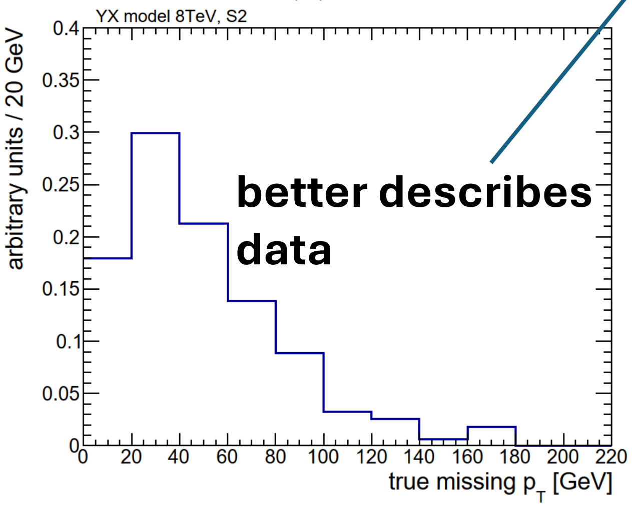
$\mathcal{A} \propto g_{X\nu_\mu\nu_\mu}\, g_{Xbb}$



S4

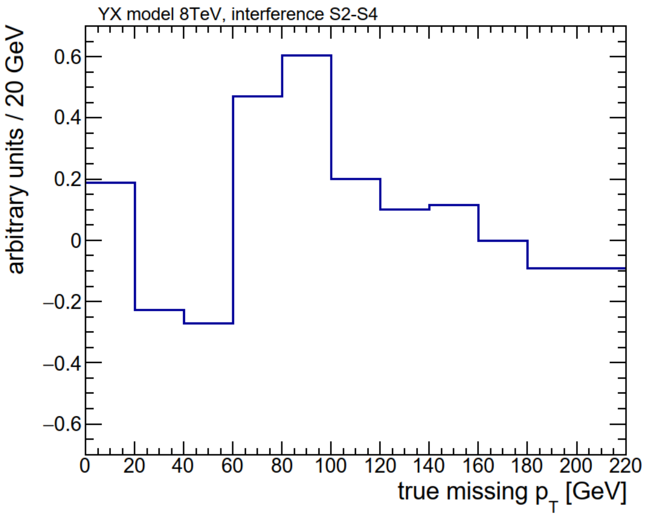


S2, $20<m_{\mu\mu}<40$ GeV

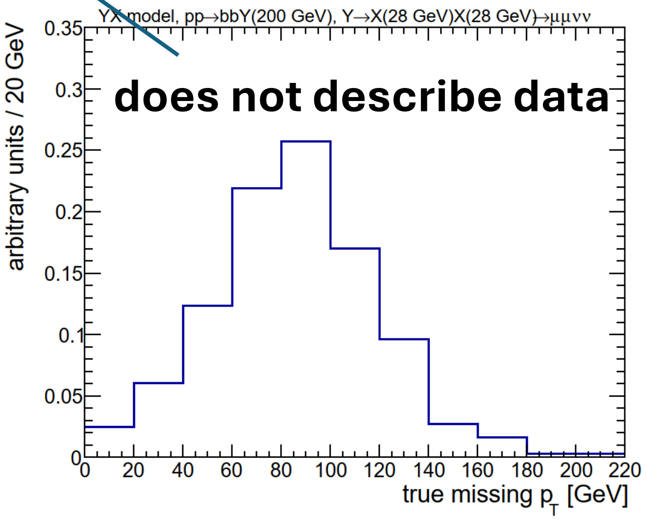


better describes data

Int. S2-S4, $20<m_{\mu\mu}<40$ GeV



S4

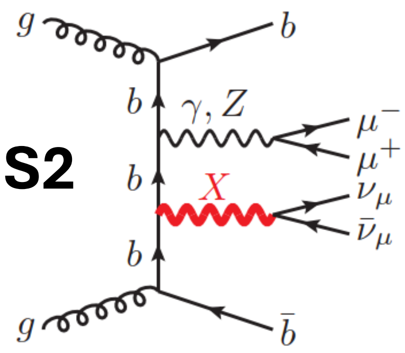


does not describe data

It seems S2 is a dominant contribution, but ... (next slide)

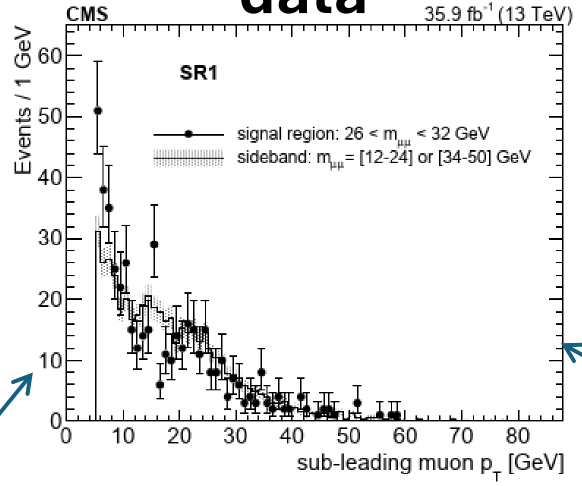
YX model, $p_T^{\mu 2}$ in SR1, 13 TeV

S2

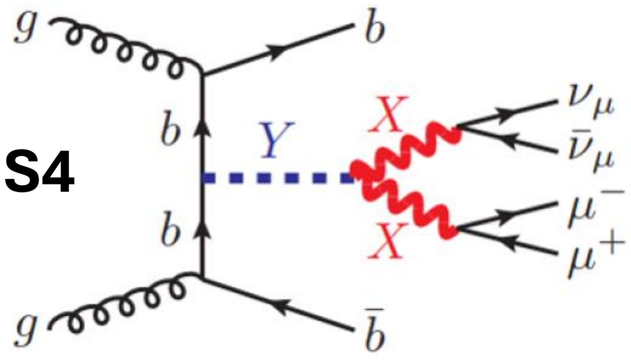


$\mathcal{A} \propto g_{X\nu_\mu\nu_\mu}\ g_{Xbb}$

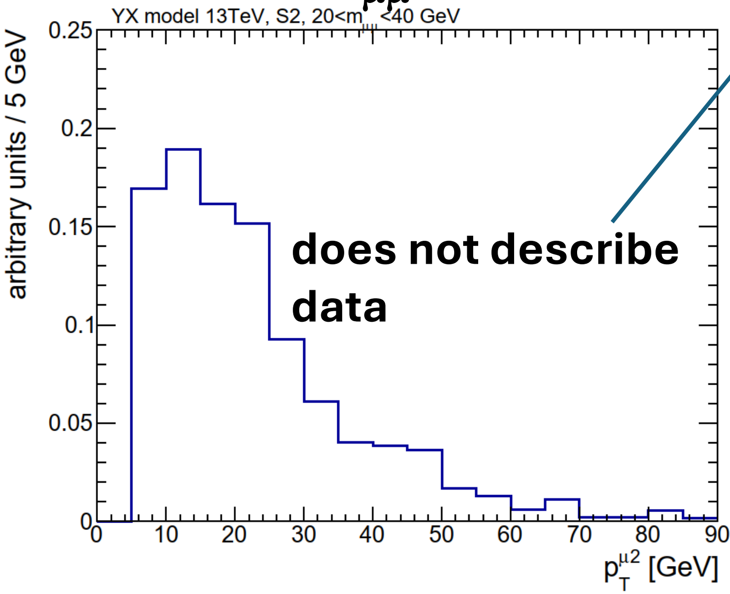
data



S4

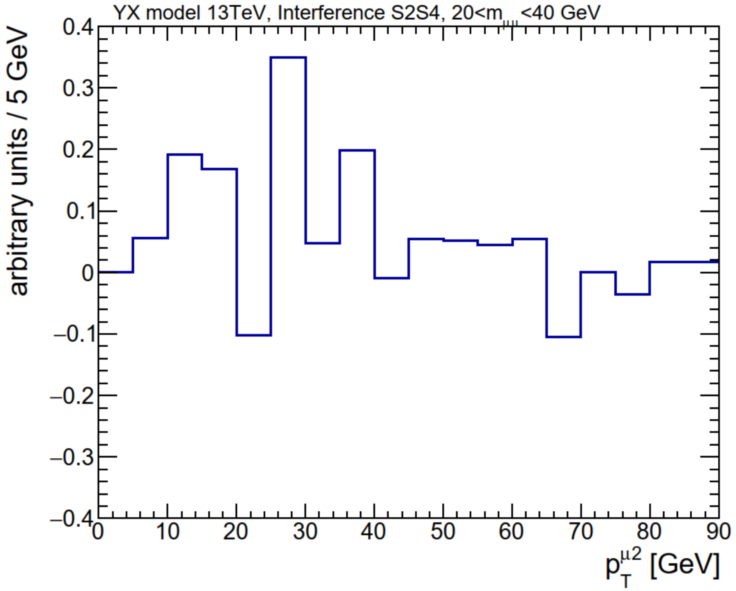


S2, 20<$m_{\mu\mu}$<40 GeV

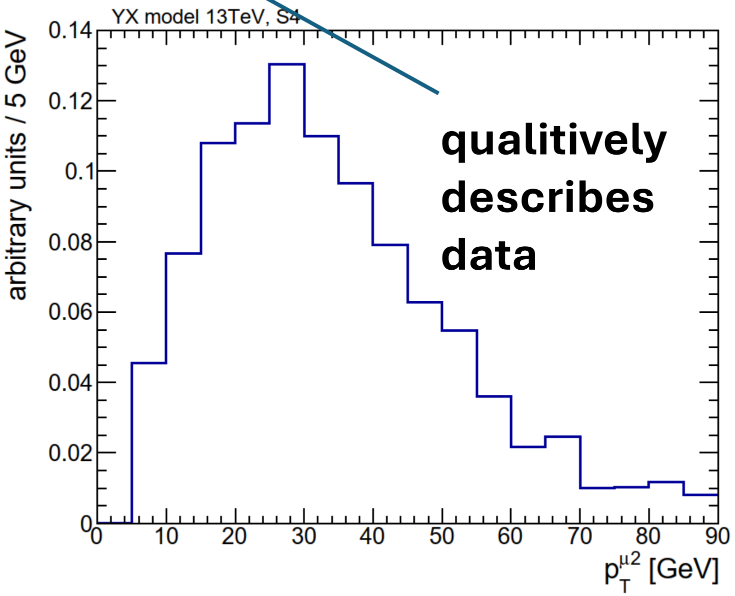


does not describe data

S2-S4, 20<$m_{\mu\mu}$<40 GeV



S4



qualitively describes data

Analysis is on the way with full Run II data

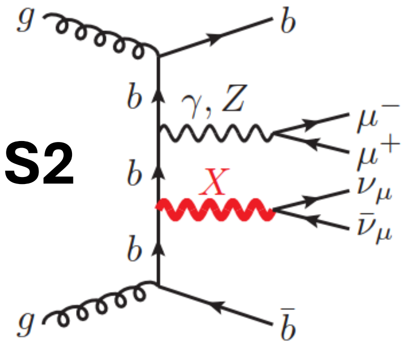
Stay tuned.

Conclusions

- **no light scalars found yet in a direct production or from h_{125} decays**
  - **need to improve sensitivity in $10 < m_a < 20$ GeV mass range with merged b-jets**
- **most significant excess is found in $\mu\mu$+b-jet analysis at $m_{\mu\mu} \approx 28$ GeV in two event categories at 8 TeV (local significance 4.2 σ and 2.9 σ)**
  - **analysis is on the way with full Run II data**

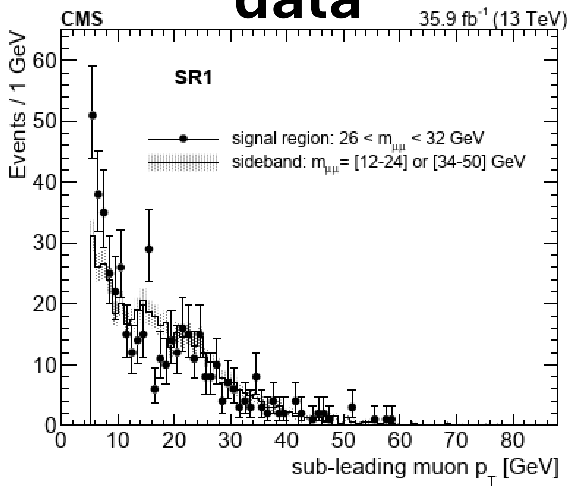
YX model, $p_T^{\mu 2}$ in SR1, 13 TeV

S2

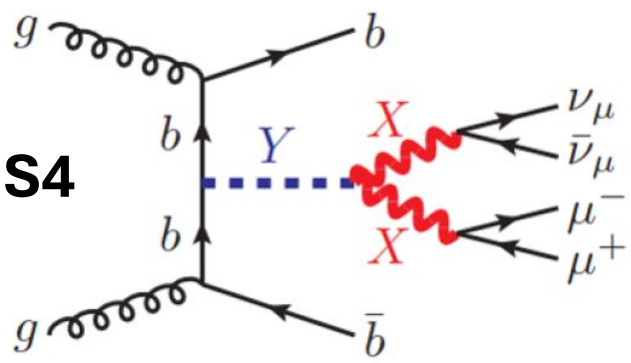


$\mathcal{A} \propto g_{X\nu_\mu\nu_\mu}\ g_{Xbb}$

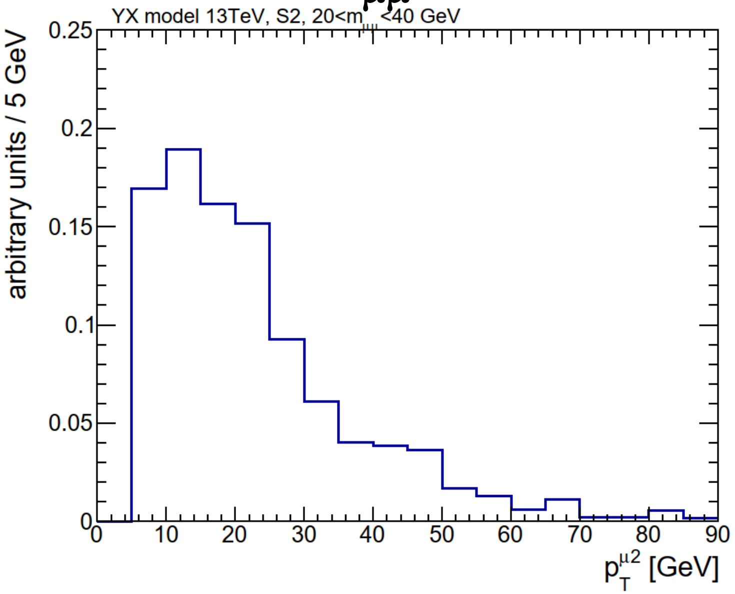
data



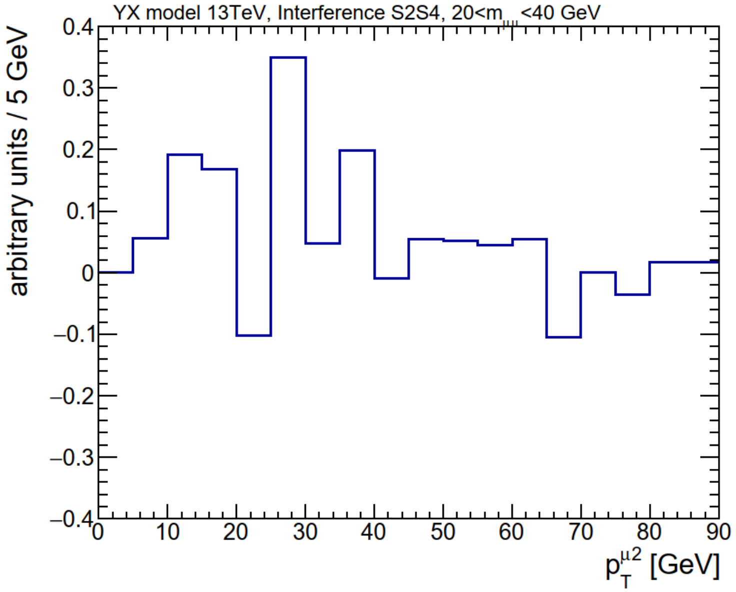
S4



S2, $20<m_{\mu\mu}<40$ GeV



S2-S4, $20<m_{\mu\mu}<40$ GeV



S4