Prospects of Heavy Higgs in the natural SUSY at LHC upgrades

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Overview

- Naturalness and its implication on SUSY
  - How we define naturalness?
  - What's the guidance to look for a natural model.
- Heavy Higgs search in natural SUSY scenario
  - pp-> H/A, H/A -> $\tau\tau$
  - pp-> H/A, H/A -> neutralino/chargino pair, neutralino/chargino -> W/Z/h + MET (special signature in natural SUSY!)
  - pp-> tH^+, H^+ -> $\tau + \nu_\tau$
  - pp-> tH^+, H^+ -> t + b
- Reaches of different Heavy Higgs search channels in the future HL-LHC
  - Model independent xsec x BF vs. m_A
  - Significance reaches on m_A vs. tan(β) plane under natural SUSY

Naturalness implication

No large fine-tuning

- We use m(Z) as representative of weak scale.

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \sim -m_{H_u}^2 - \Sigma_u^u - \mu^2 \qquad (1)$$

- *practical naturalness:* wherein an observable O is natural if all *independent* contributions to O are comparable to or less than O.

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- For natural SUSY, we use the naturalness measure Δ_{EW} defined as

$$\Delta_{EW} \equiv |\text{maximal term on the right} - \text{hand} - \text{side of Eq. } (1)|/(m_Z^2/2)$$

- $|\mu| \sim m(Z)$, $m^2_{Hu} \sim -m(Z)$ for EWSB, radiative corrections not large ~ m(Z).
- $\Delta_{EW} < 30$ and $\mu < 350$ GeV, m(h) ~ 125 GeV, 3-10 % naturalness.

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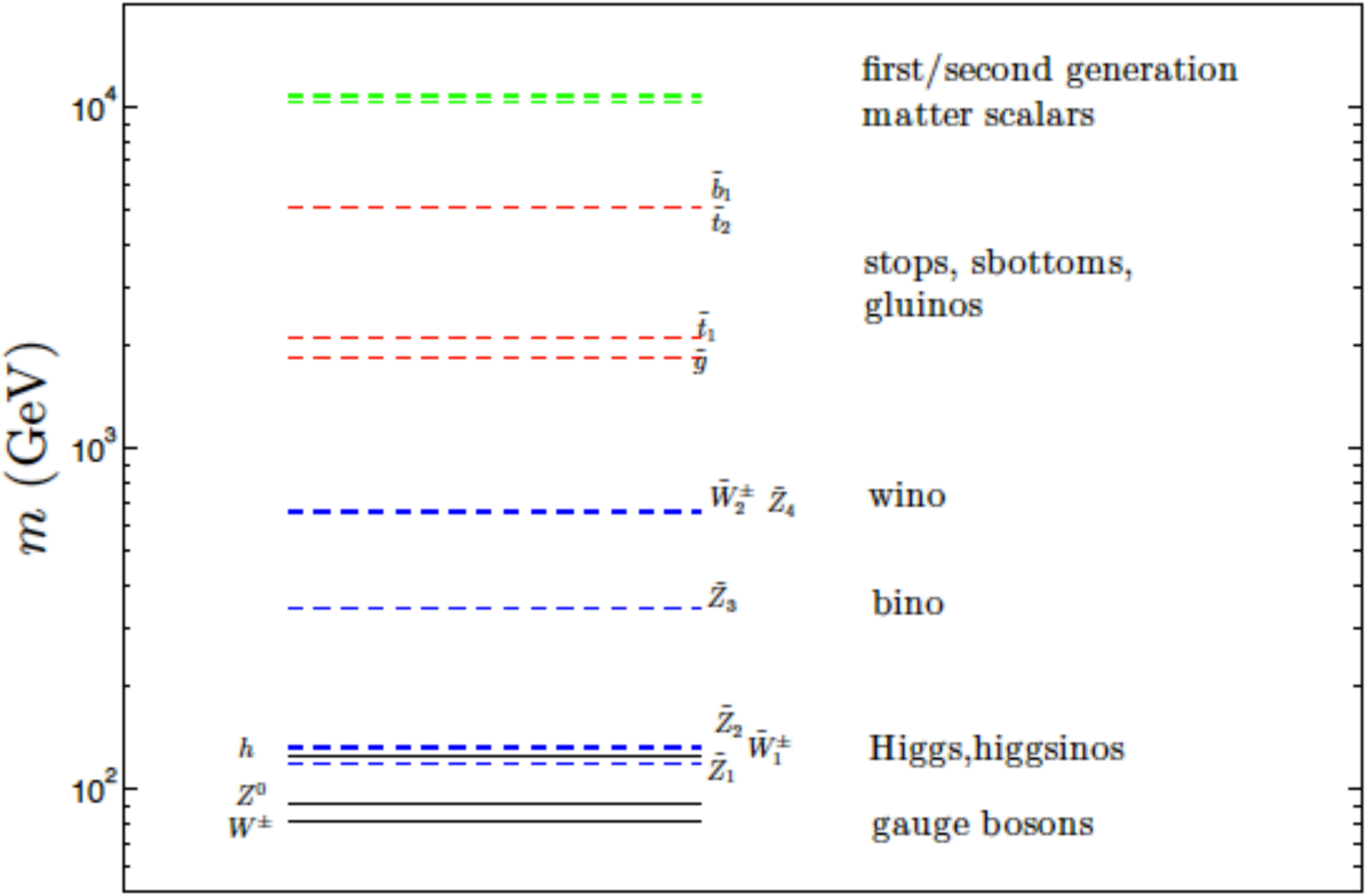
Guidance on choosing “natural” parameters

- m_h ~ 125 GeV
- Respect LHC sparticle search limits ~ usually by assuming supersymmetry breaking in the multi-TeV regime.
- The magnitude of the weak scale also to be natural.

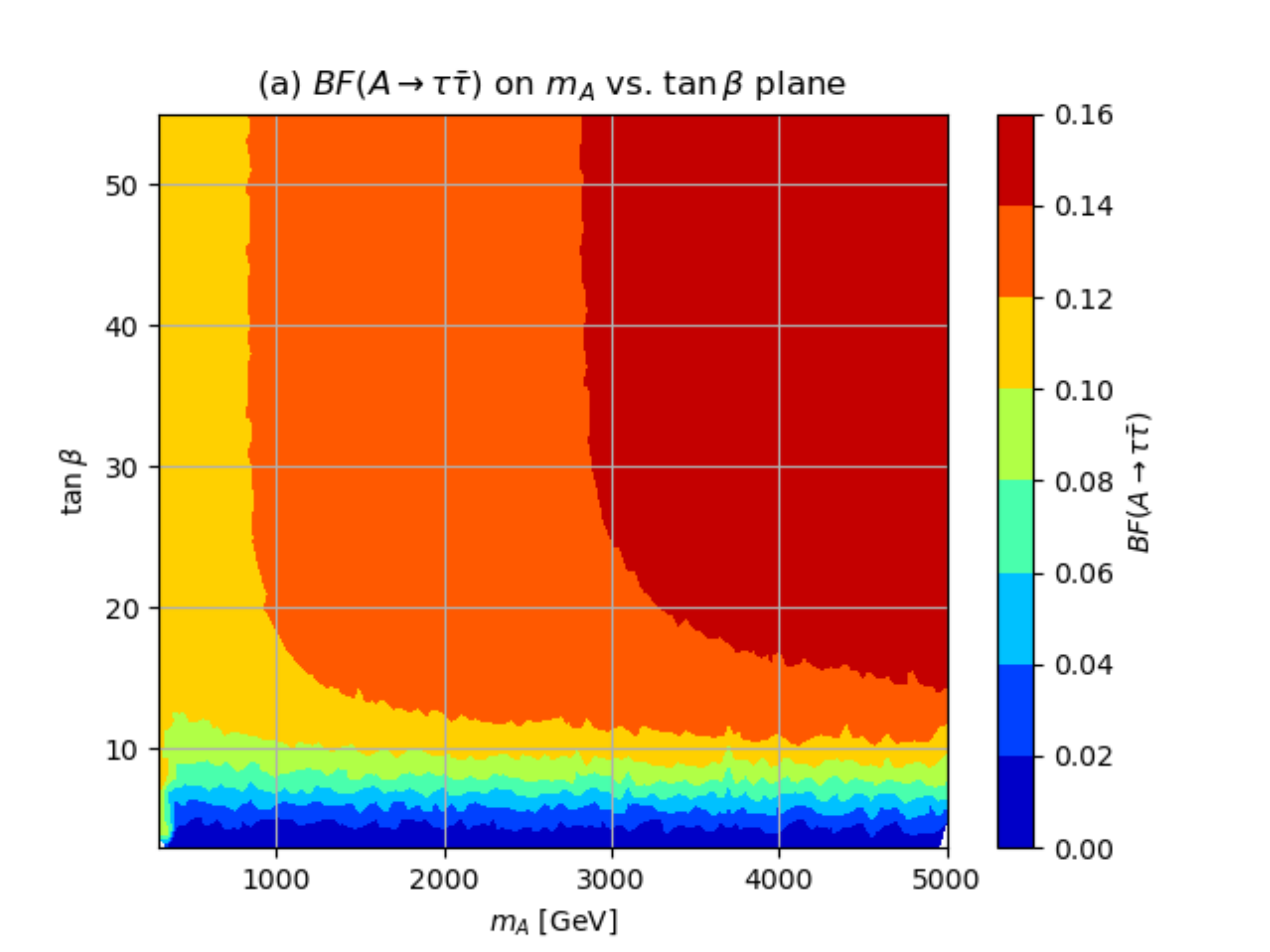
Typical spectrum for low Δ_{EW} models



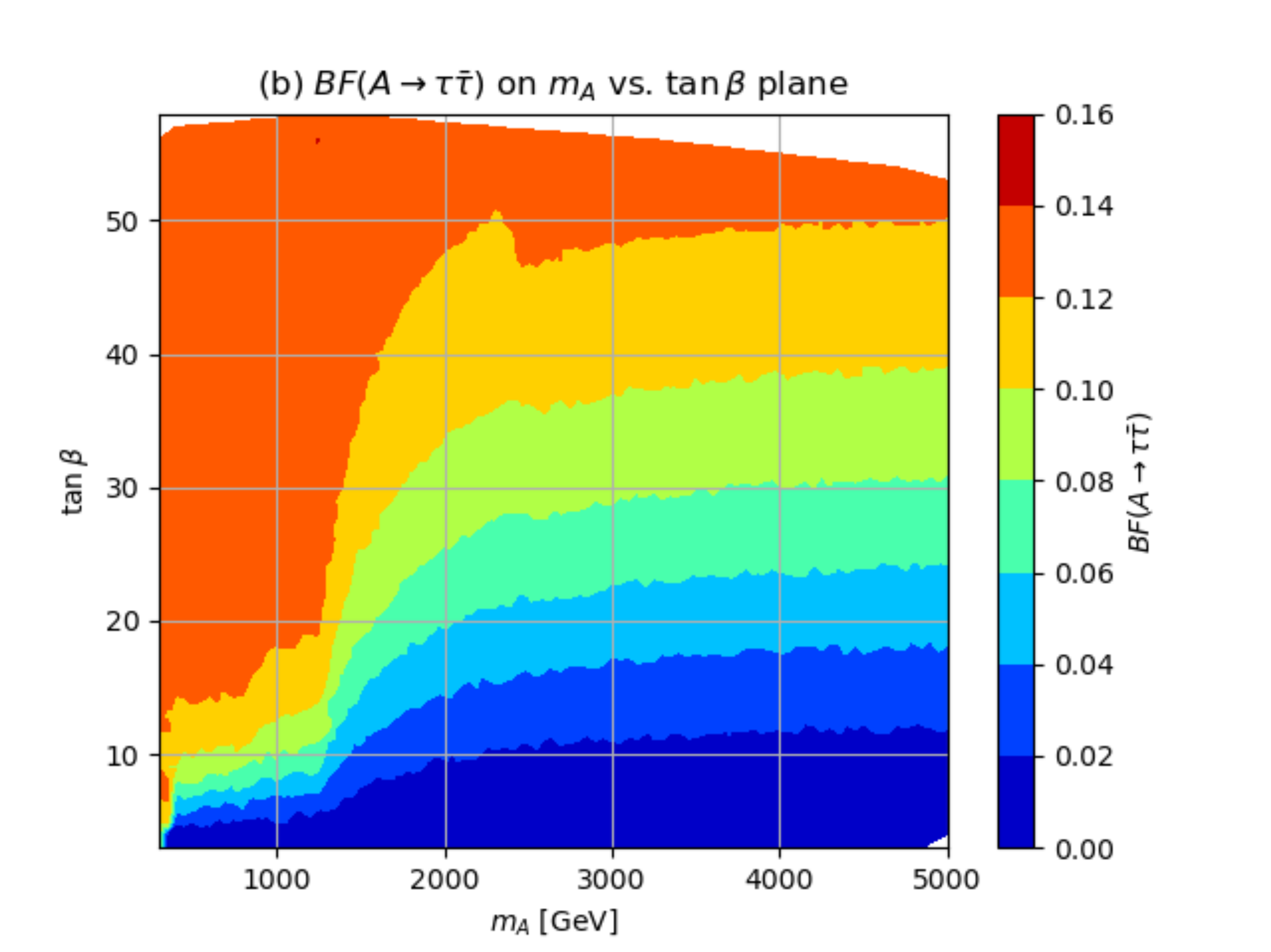
pp-> H/A, H/A -> ττ

BF(A-> ττ) on mA vs tan(β) plane

unnatural SUSY vs. natural SUSY



hMSSM

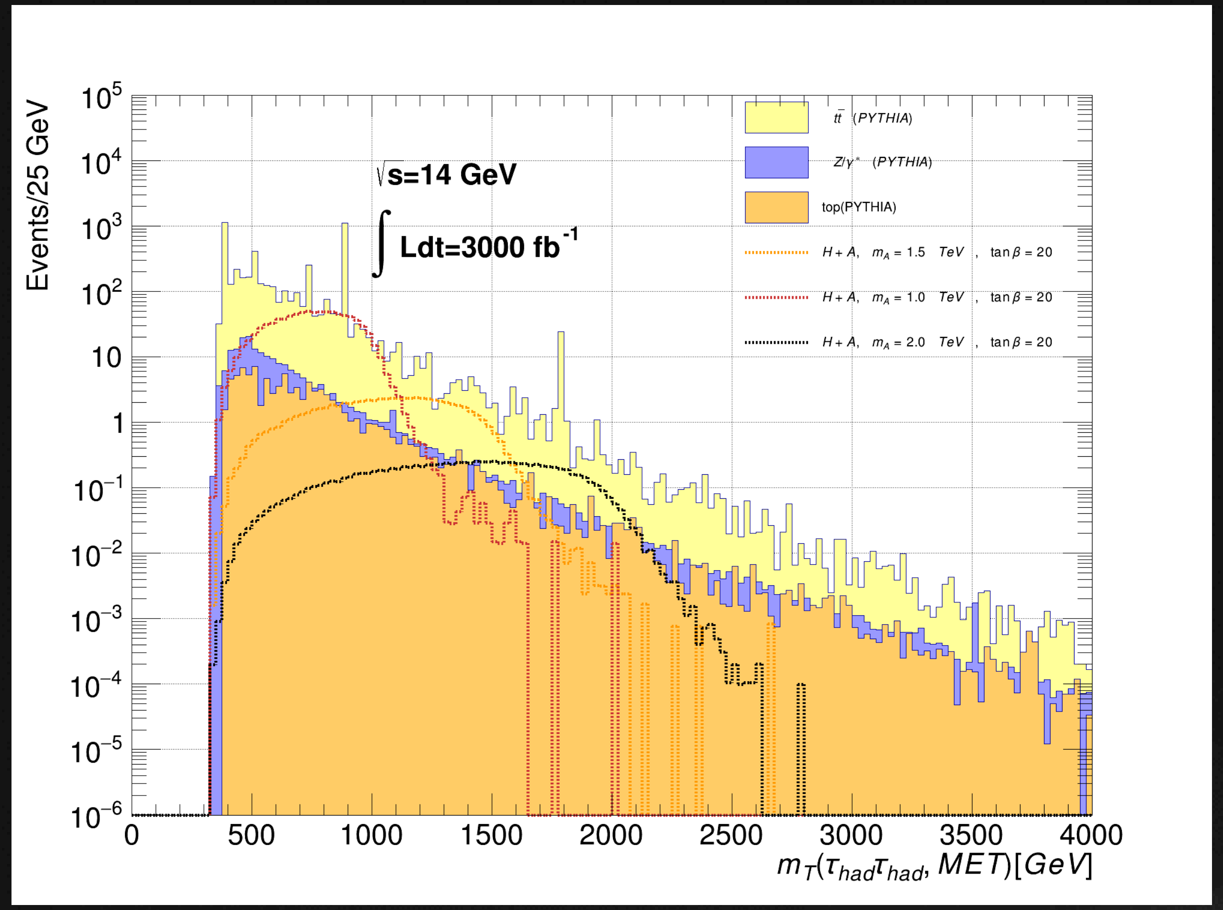


m_h^{125} (nat)

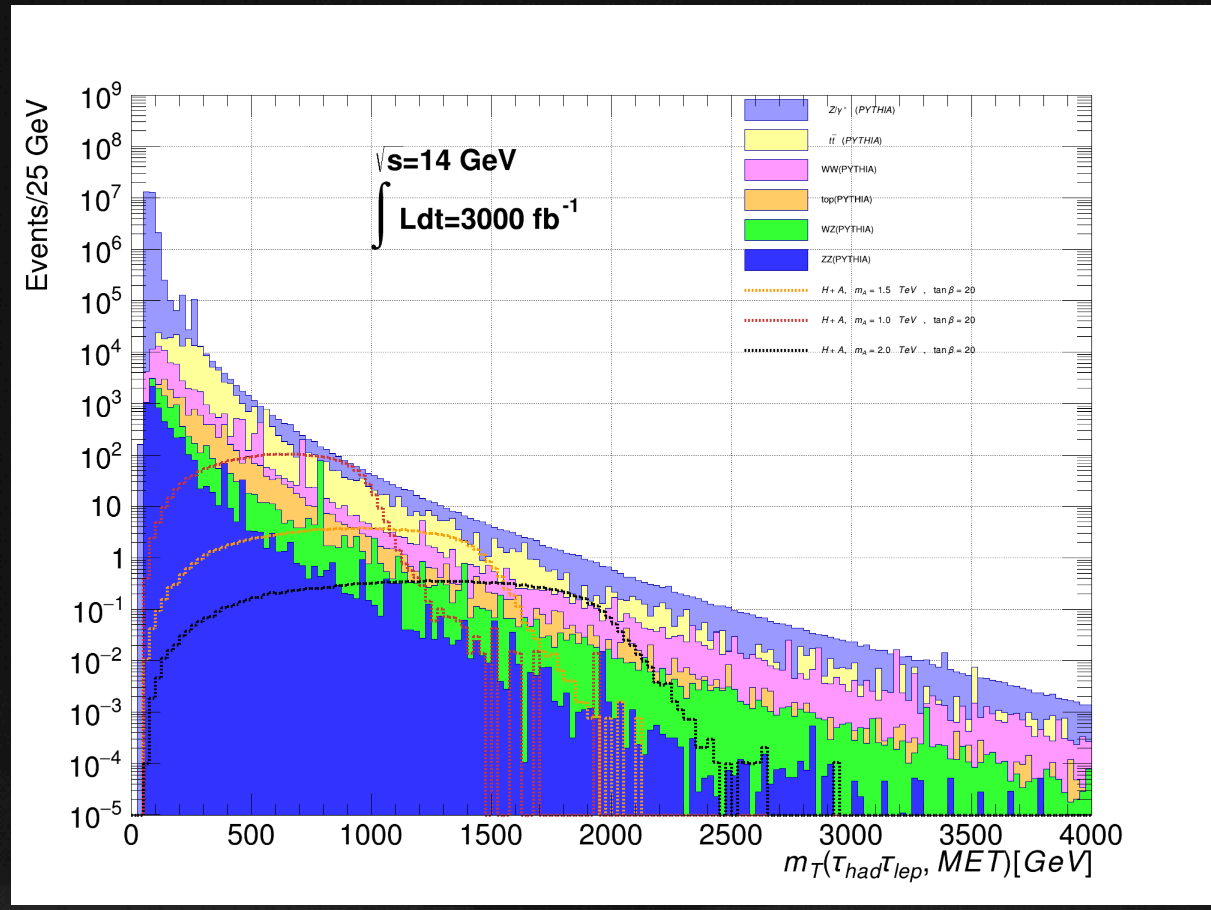
pp-> H/A, H/A -> ττ

- Channels we considered*:
  - $\tau_{had}\ \tau_{had}$
    - $n(\tau_{had}) >= 2$. Two of them are OS.
    - b-tag/b-veto($n_b >= 1/n_b = 0$)
    - back to back (BtB)/non-BtB(acolliner) ($\Delta\phi(\tau\bar{\tau}) > 155°$ / $\Delta\phi(\tau\bar{\tau}) < 155°$)
  - $\tau_{had}\ \tau_{lep}$
    - $n(\tau_{had}) = 1$, $n(l) = 1$. τ_{had} is OS with the lepton.
    - b-tag/b-veto($n_b >= 1/n_b = 0$)
    - back to back (BtB)/non-BtB(acolliner) ($\Delta\phi(\tau\bar{\tau}) > 155°$ / $\Delta\phi(\tau\bar{\tau}) < 155°$)
- SM backgrounds considered: Drell-Yan, ttbar, single top, ZZ, WZ, WW, generated by Pythia.
- For signals, Isajet featuring Isasugra for spectra generation. Resultant outputs in SLHA formats are then fed into Pythia to generate samples. SusHi is used to correct the cross section of the signal to NNLO perturbative QCD.
- The Pythia samples are then interfaced with the Delphes for detector simulation.
- m_T is reconstructed for BtB events; ditau invariant mass is reconstructed for acolinear events.

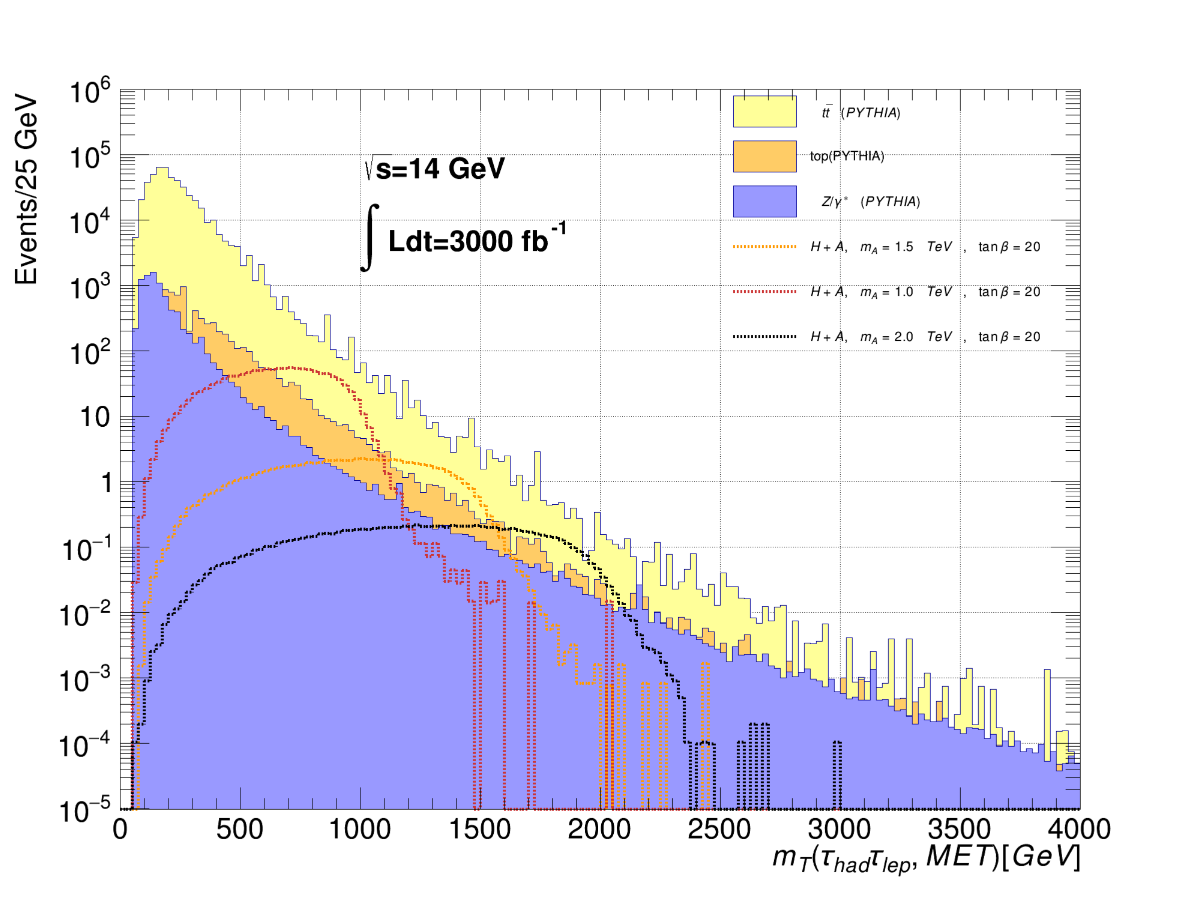
* Detailed selection criterias, isolation requirements and kinematics cuts can be found in our paper arXiv:2209.00063v1 [hep-ph] arXiv:2212.09198v1 [hep-ph]



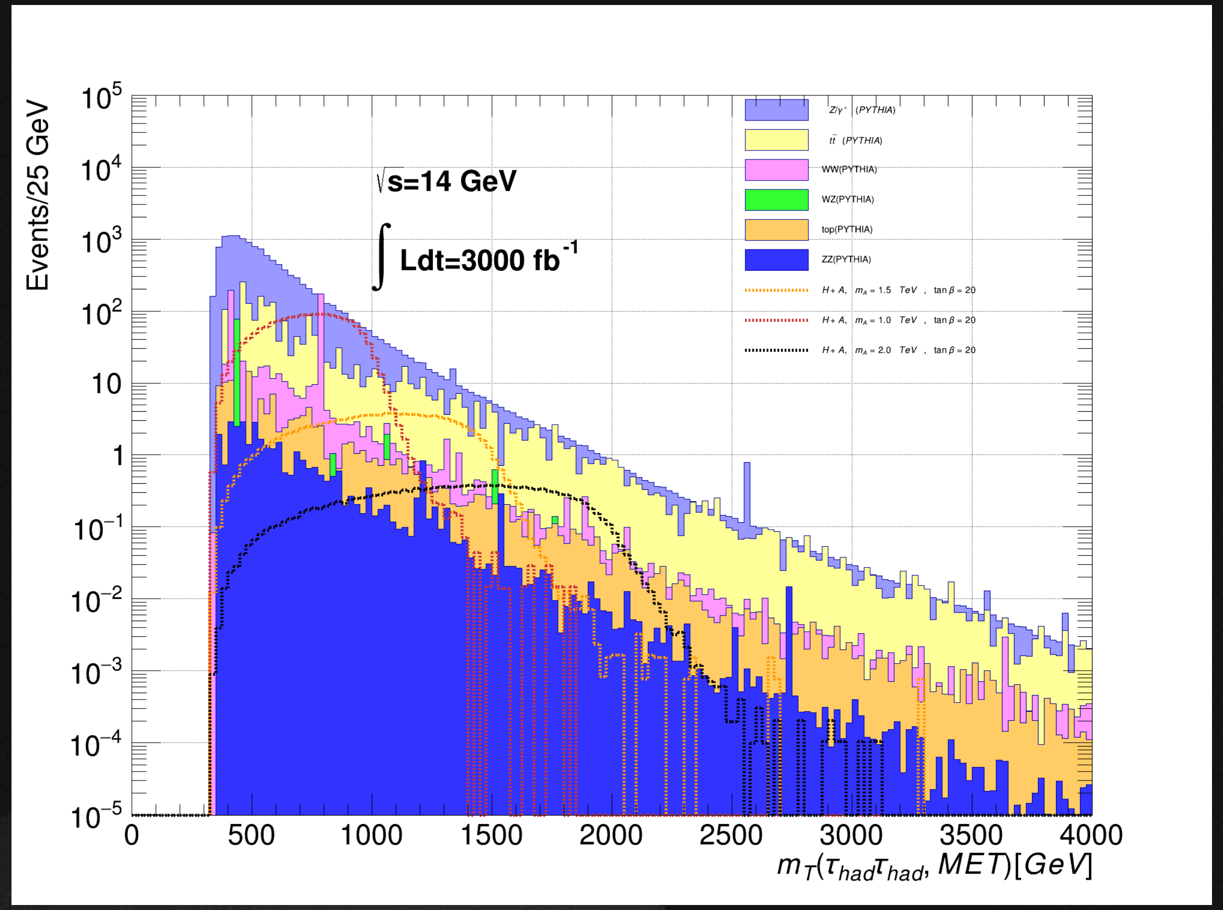
had-had, b-tag (BtB)



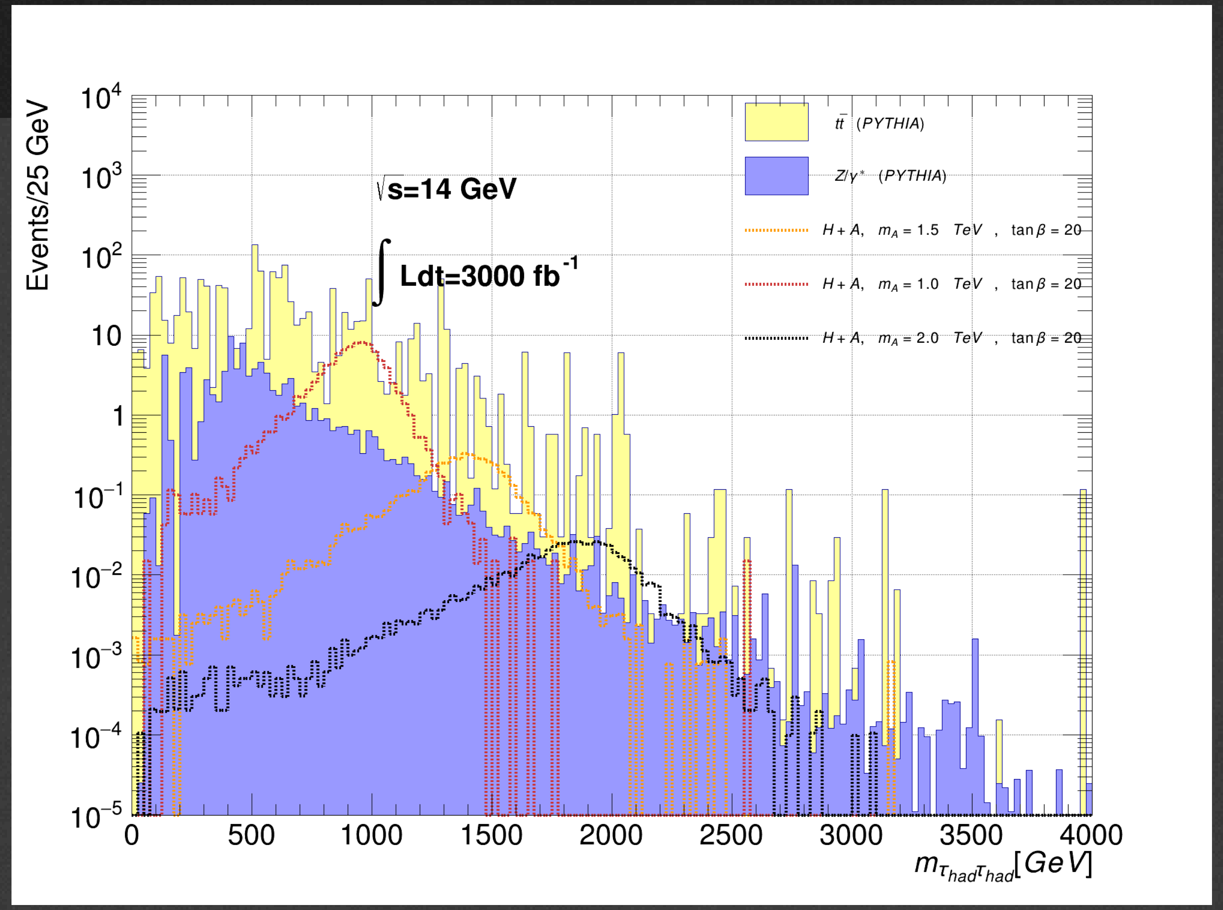
had-lep, b-veto (BtB)



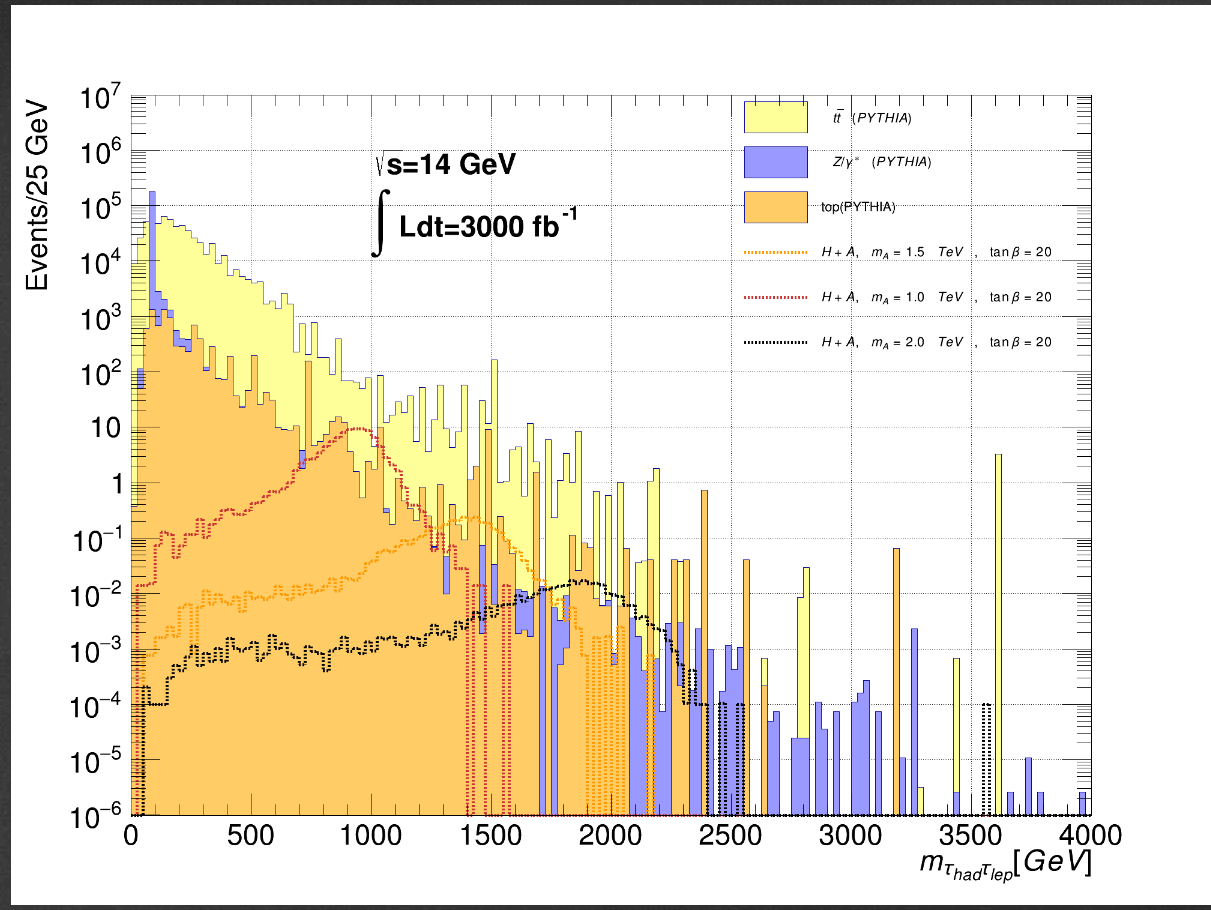
had-lep, b-tag (BtB)



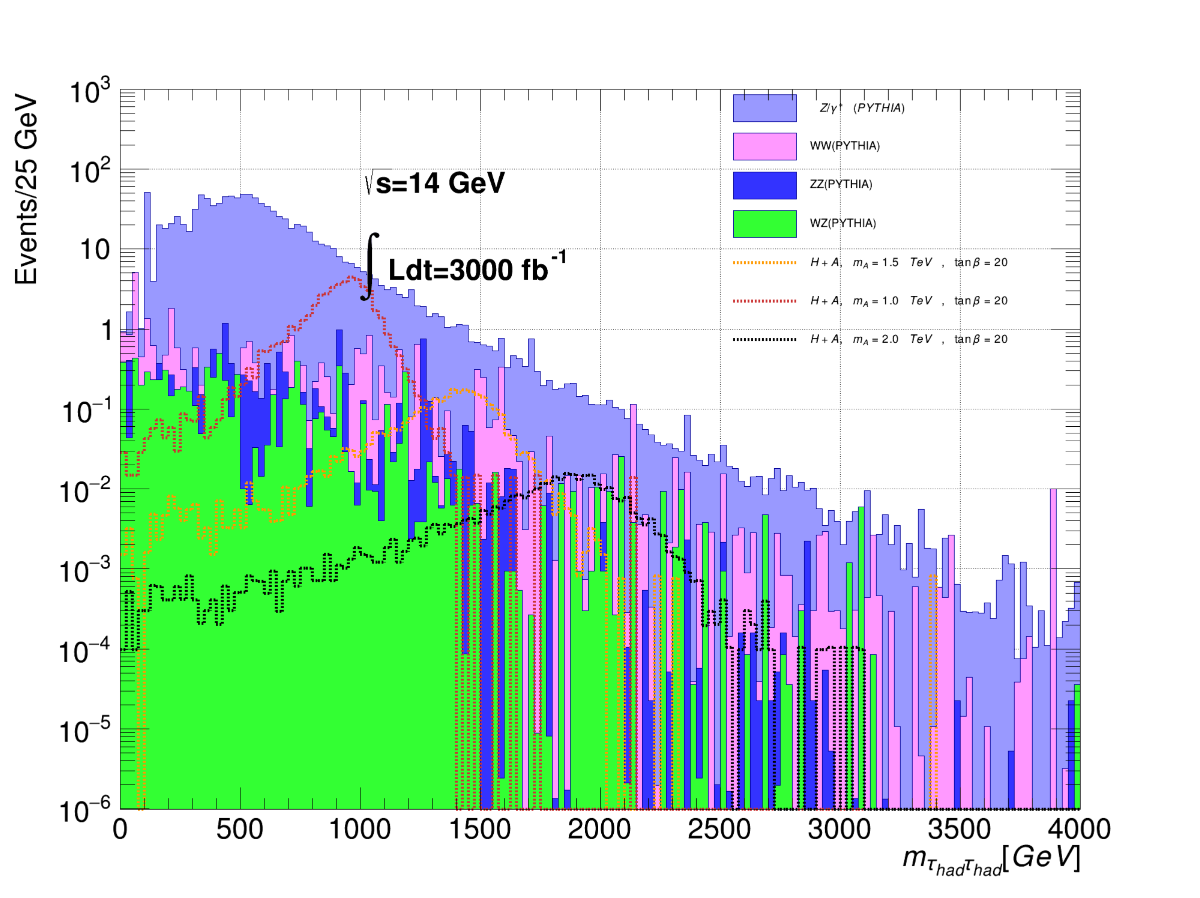
had-had, b-veto (BtB)



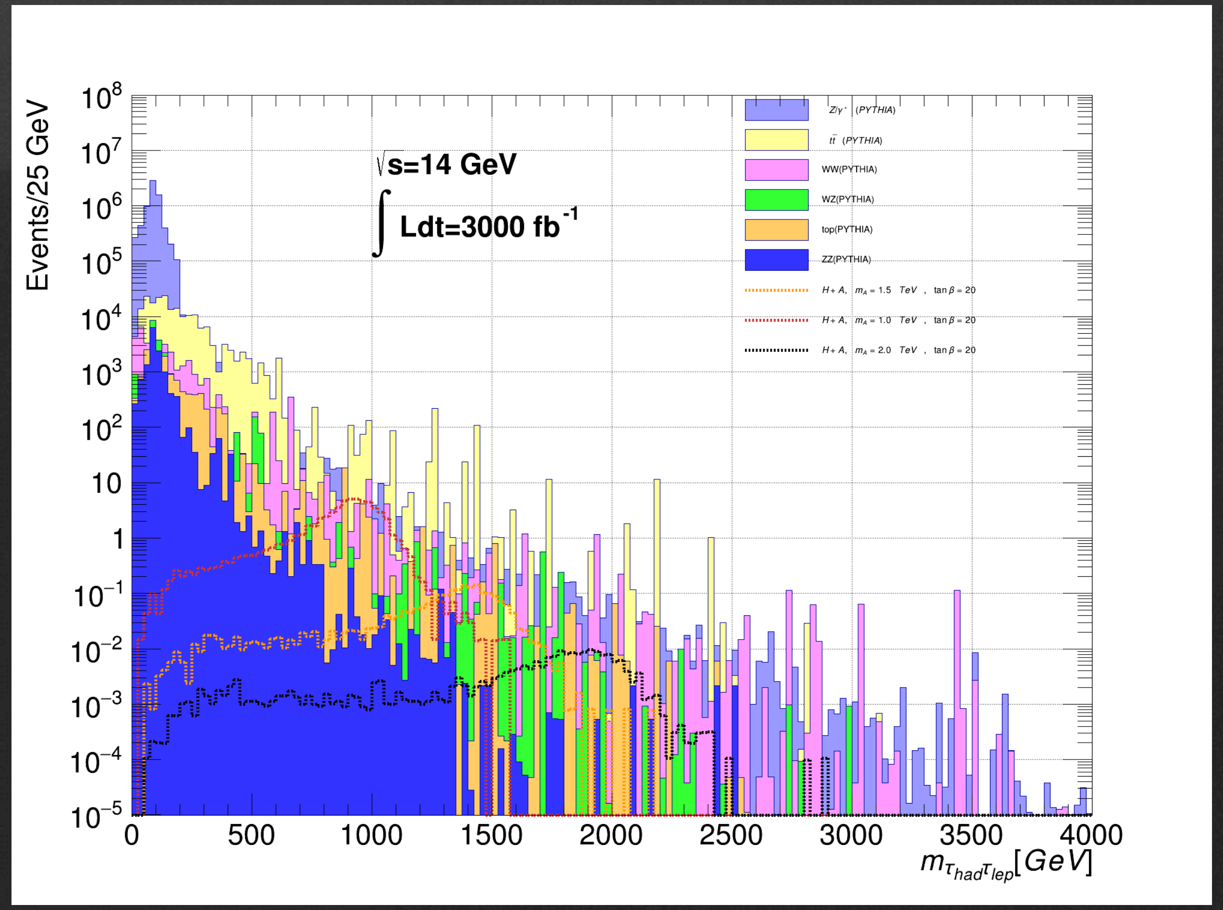
had-had, b-tag (acoliner)



had-lep, b-tag (acoliner)

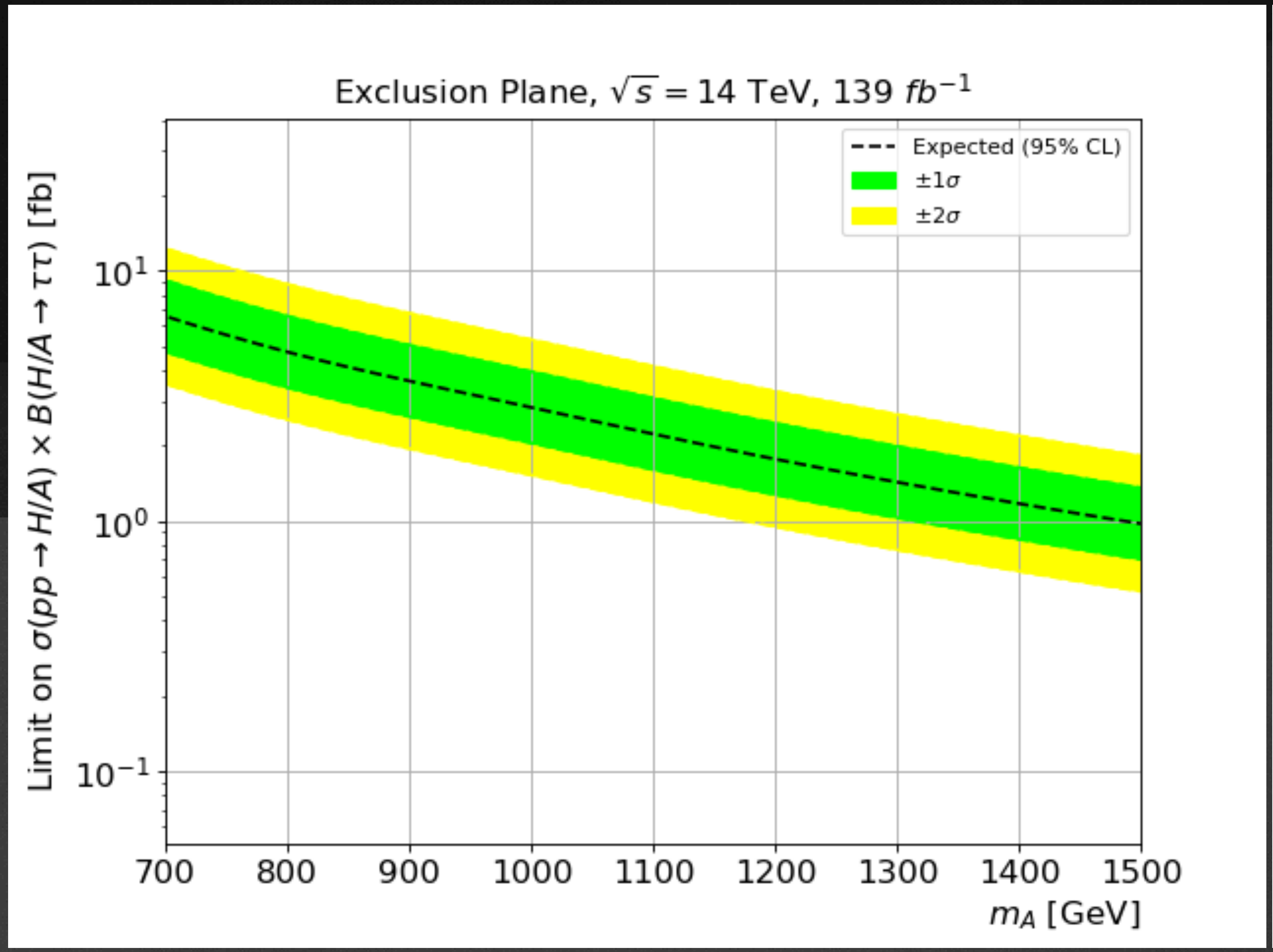


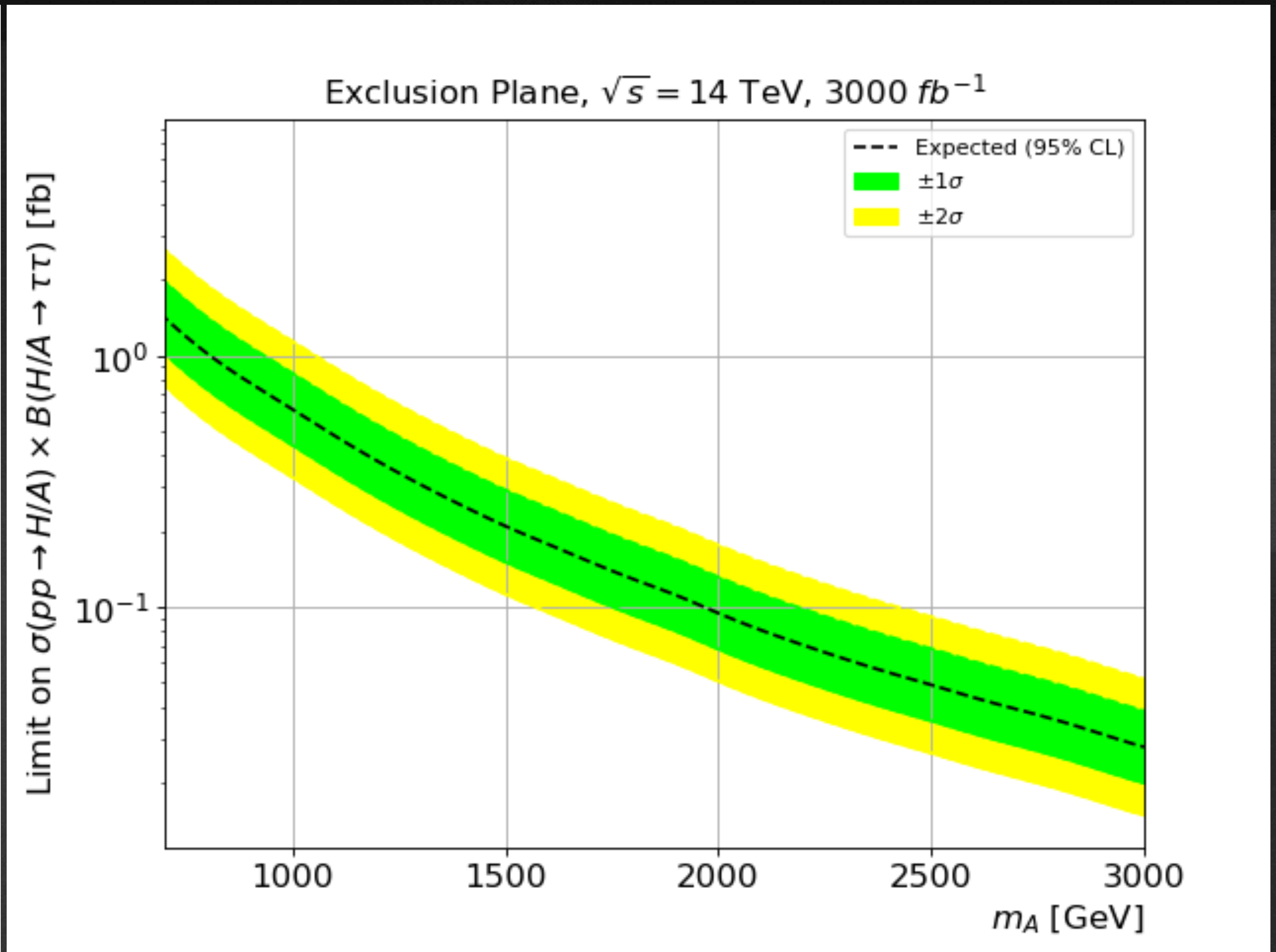
had-had, b-veto (acoliner)

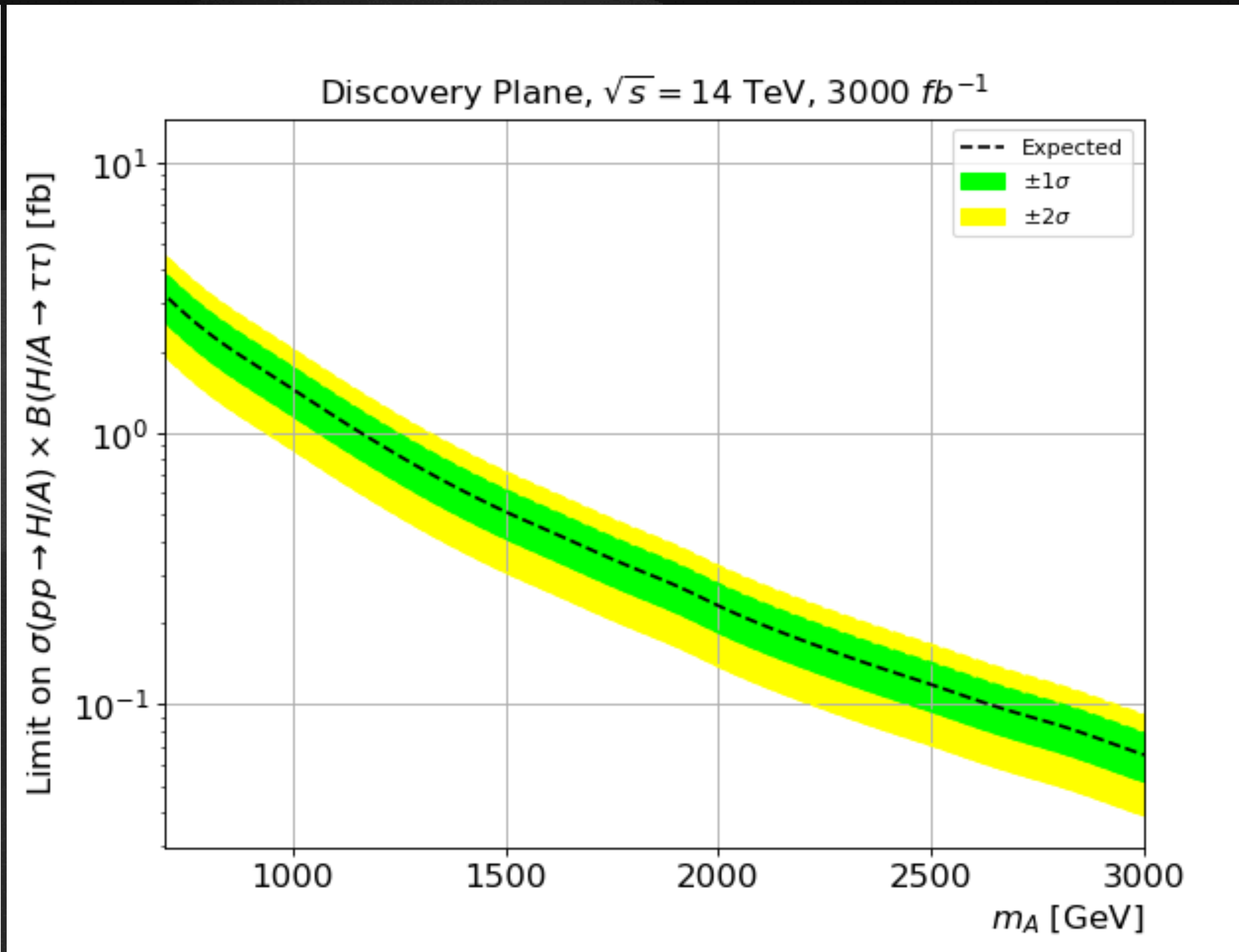


had-lep, b-veto (acoliner)

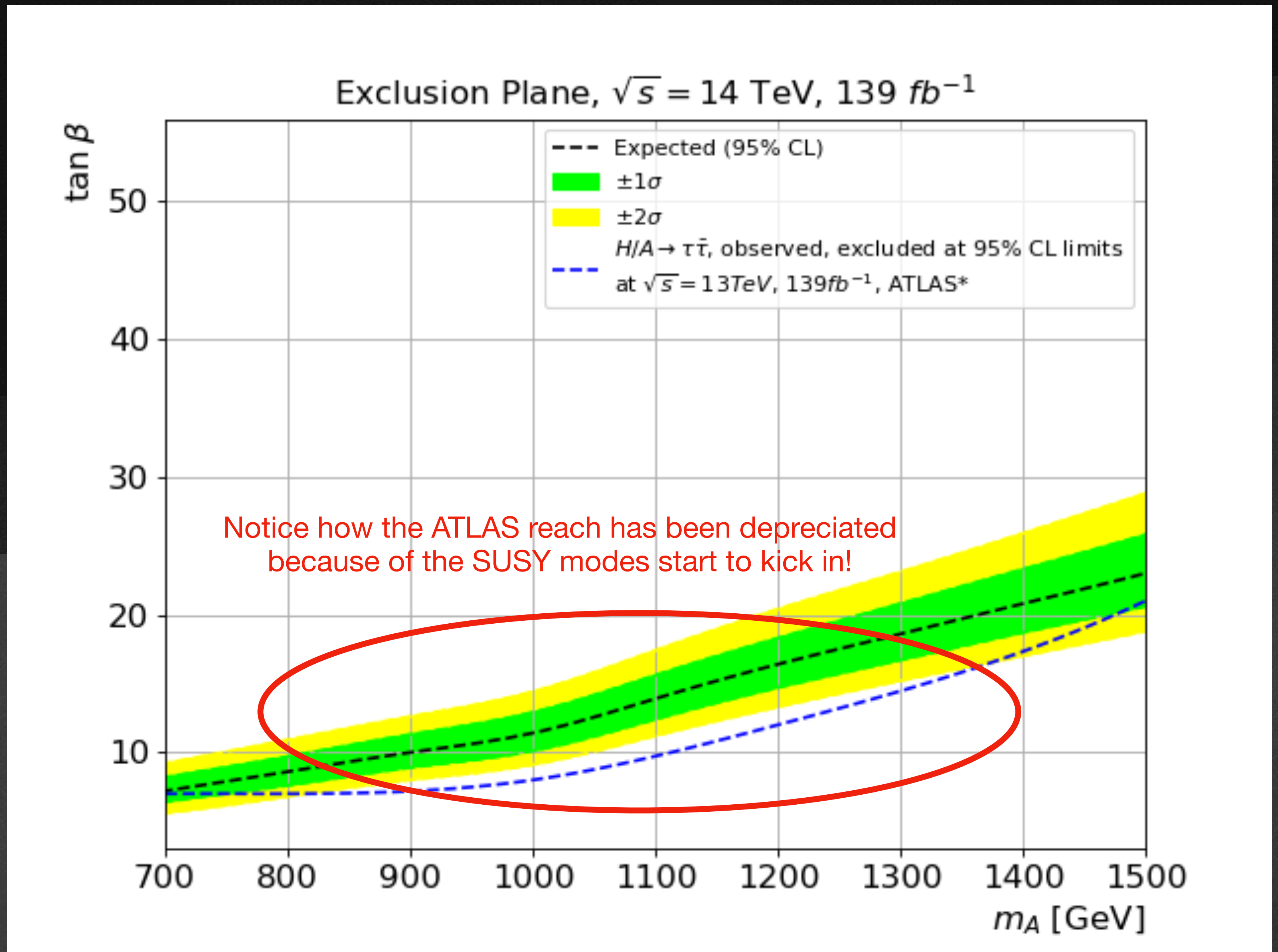
Reach on xsec(pp->H/A) x BF(H/A-> ττ) vs. m_A

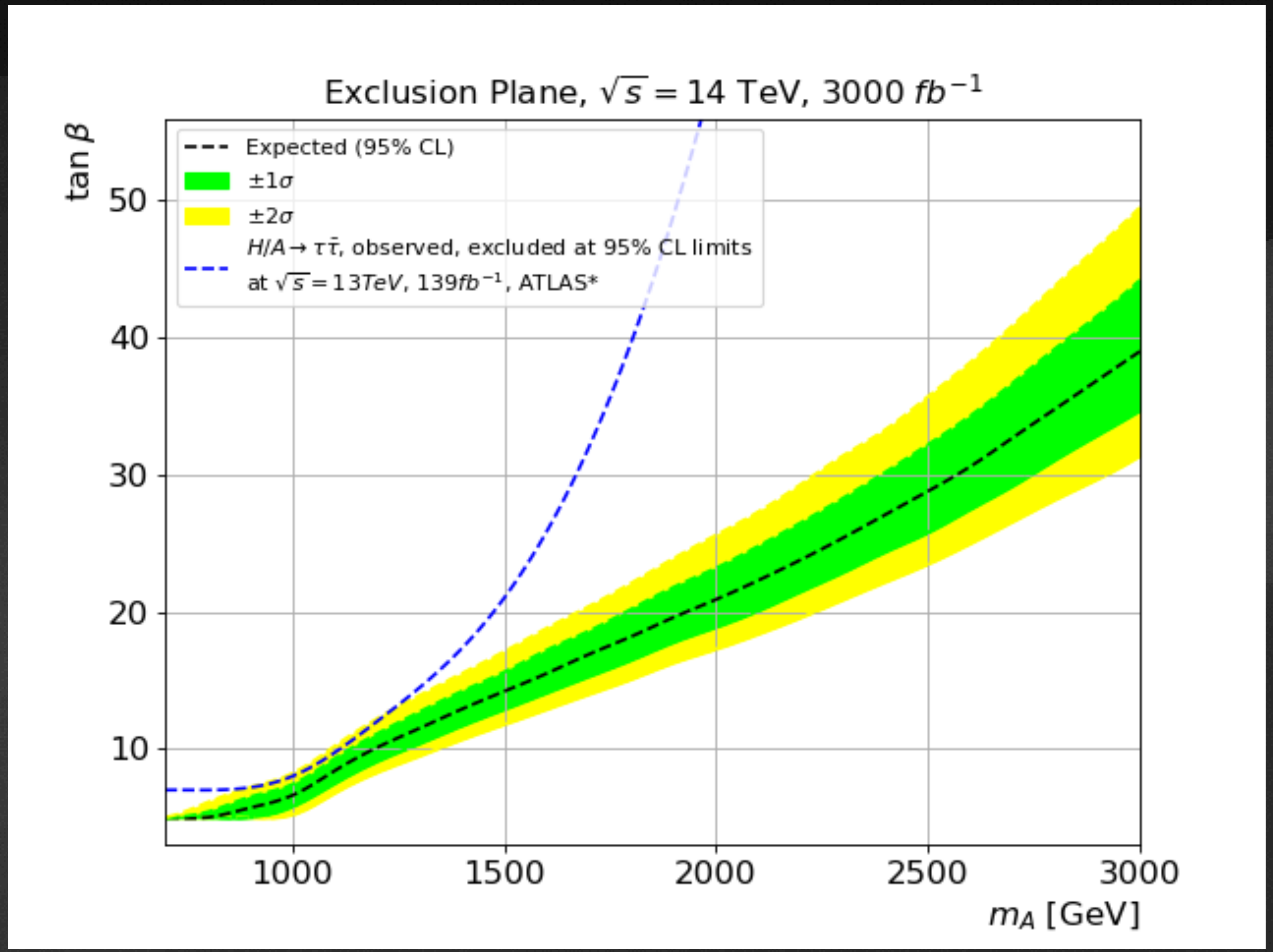


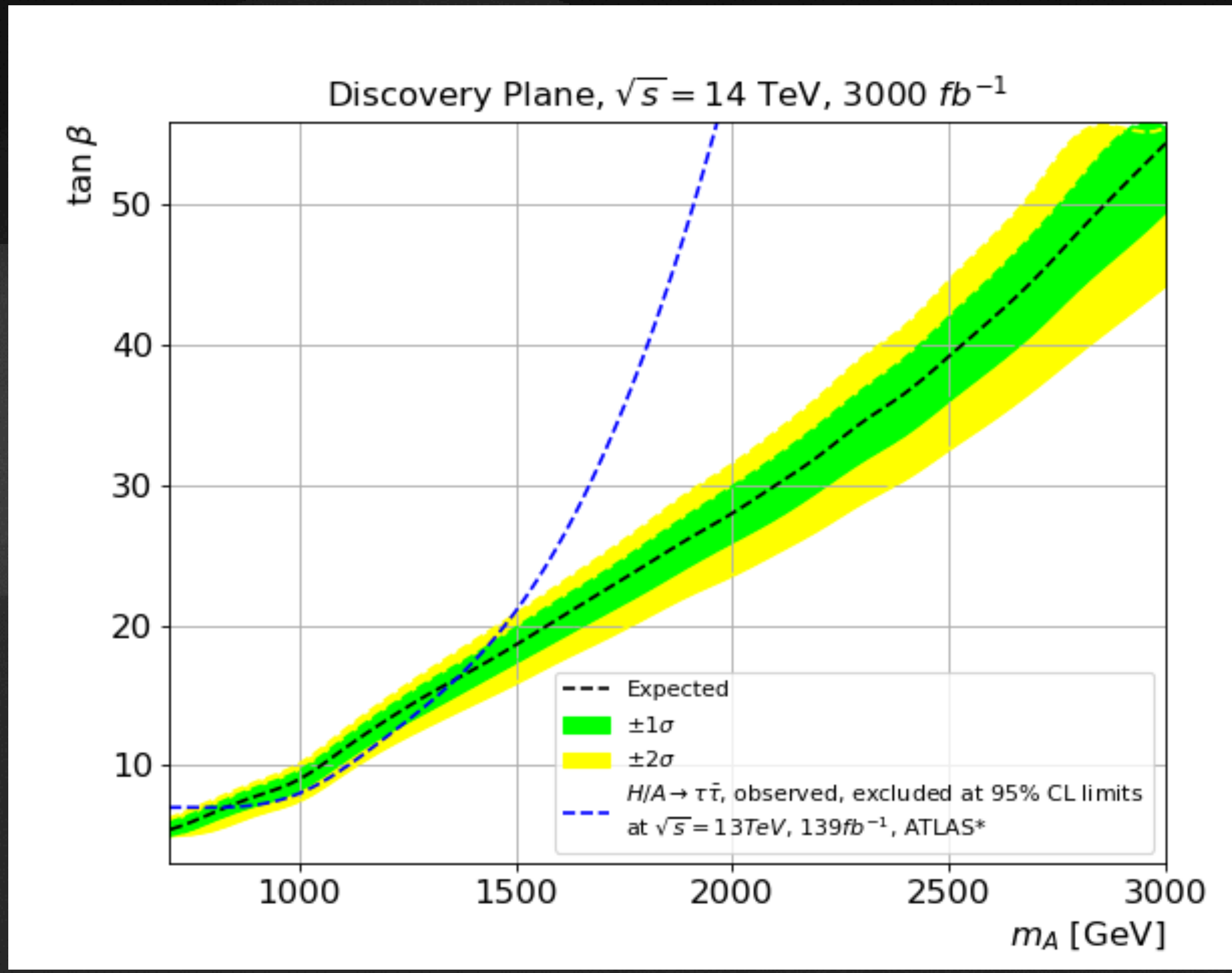




Significance reaches on m_A vs. tan(β) plane





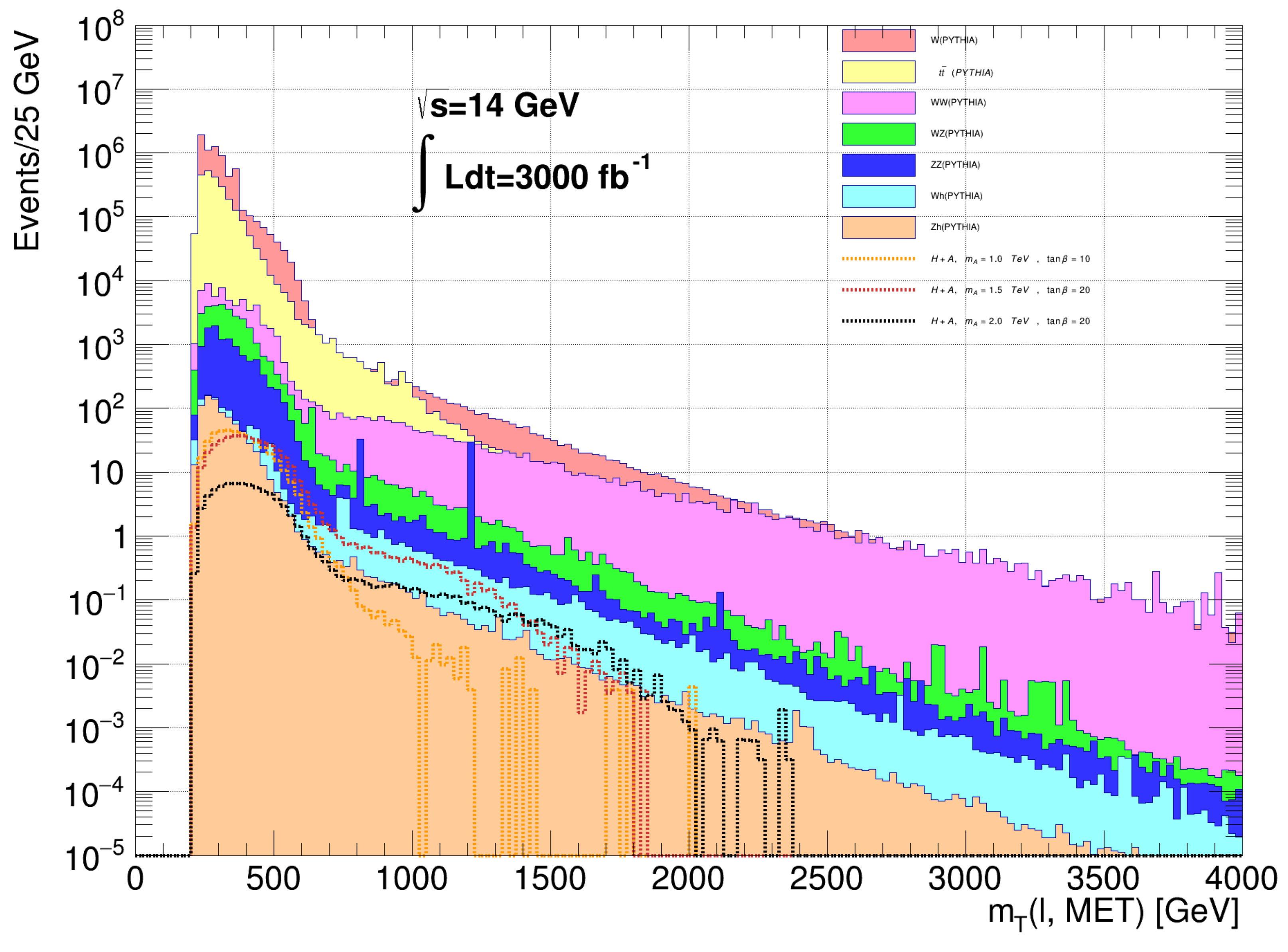


*ATLAS resutls from arXiv:2002.12223v2 [hep-ex] pp-> H/A, H/A -> neutralino/chargino pair, neutralino/chargino -> W/Z/h + MET

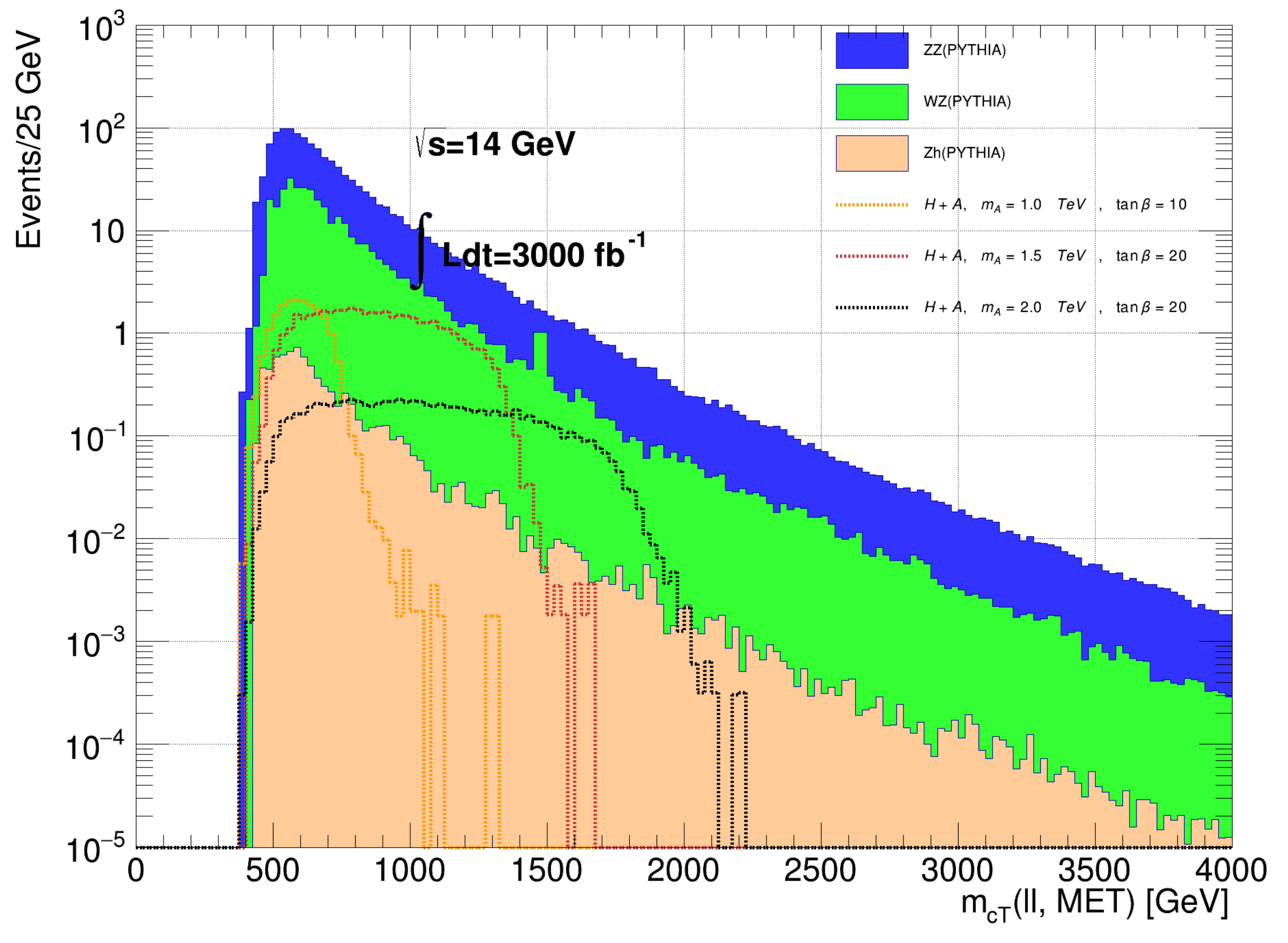
pp-> H/A, H/A -> neutralino/chargino pair, neutralino/chargino -> W/Z/h + MET

- Channels we considered*:
  - 1l (from intermediate W decay) + MET
  - 1l + 1 boosted fat jet J + MET
  - 2l (from Z) + MET
  - 2l + 1 soft l (2l from Z with the soft l from sparticle decay) + MET
  - 2b (2b from h) + MET
  - 2b + 1 soft l (2b from h with the soft l from sparticle decay) + MET
- SM backgrounds considered: ttbar, WW, WZ, ZZ, Zh, Wh, W+jets, generated by Pythia.
- For signals, Isajet featuring Isasugra for spectra generation. Resultant outputs in SLHA formats are then fed into Pythia to generate samples. SusHi is used to correct the cross section of the signal to NNLO perturbative QCD.
- The Pythia samples are then interfaced with the Delphes for detector simulation.
- m_T reconstructed for all channels.

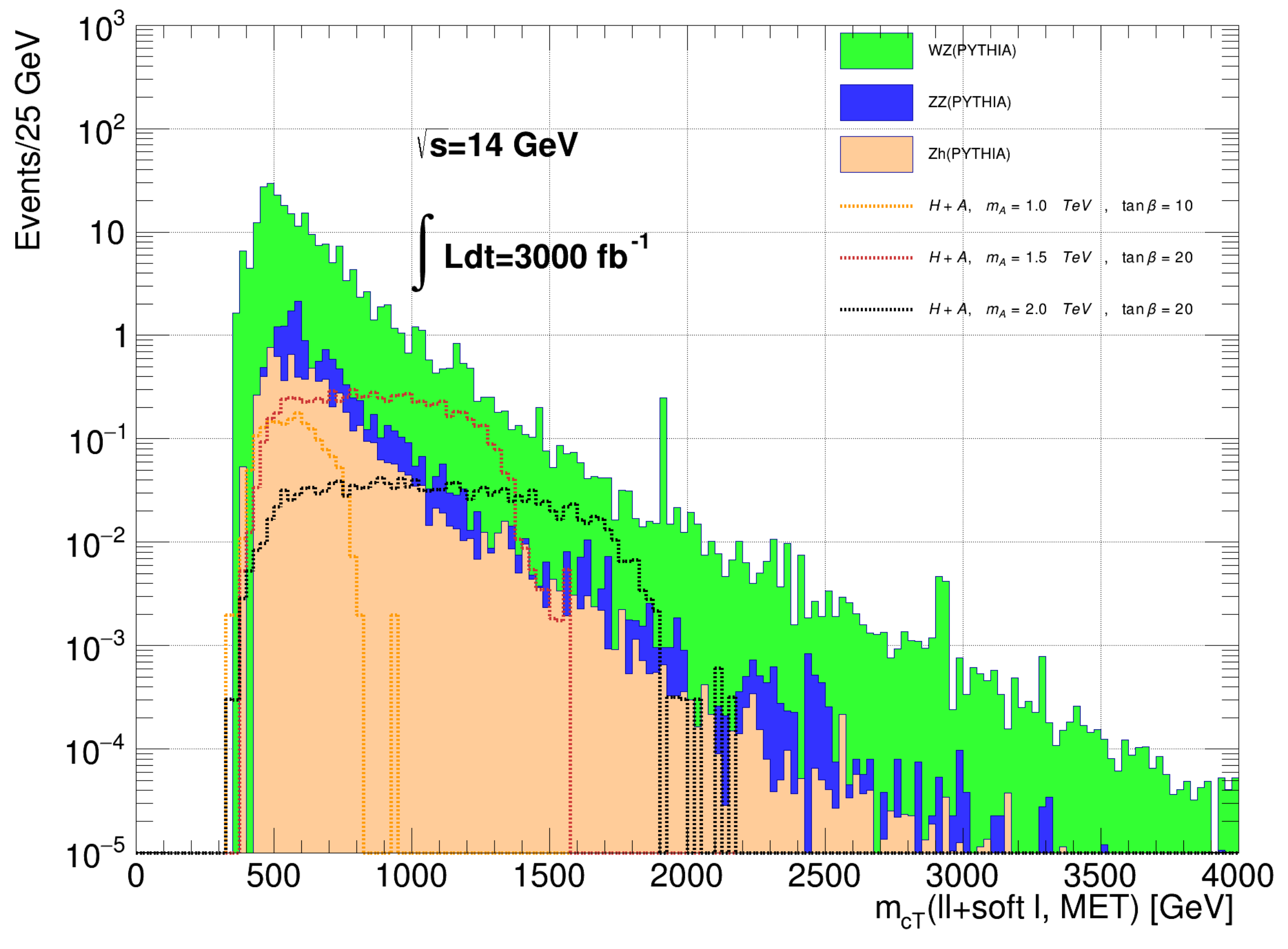
* Detailed selection criterias, isolation requirements and kinematics cuts can be found in our paper arXiv:2209.00063v1 [hep-ph] arXiv:2212.09198v1 [hep-ph]



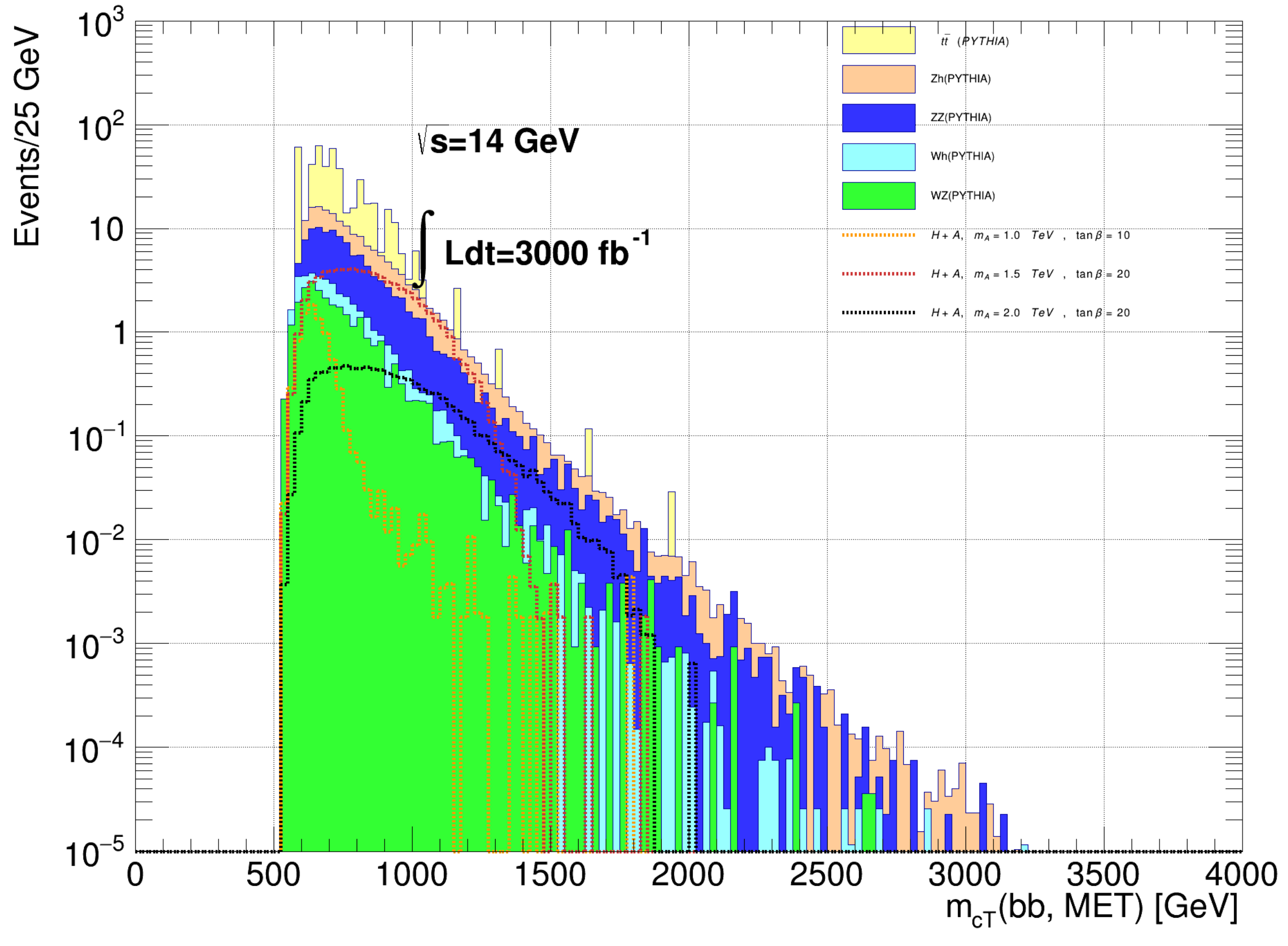
1l



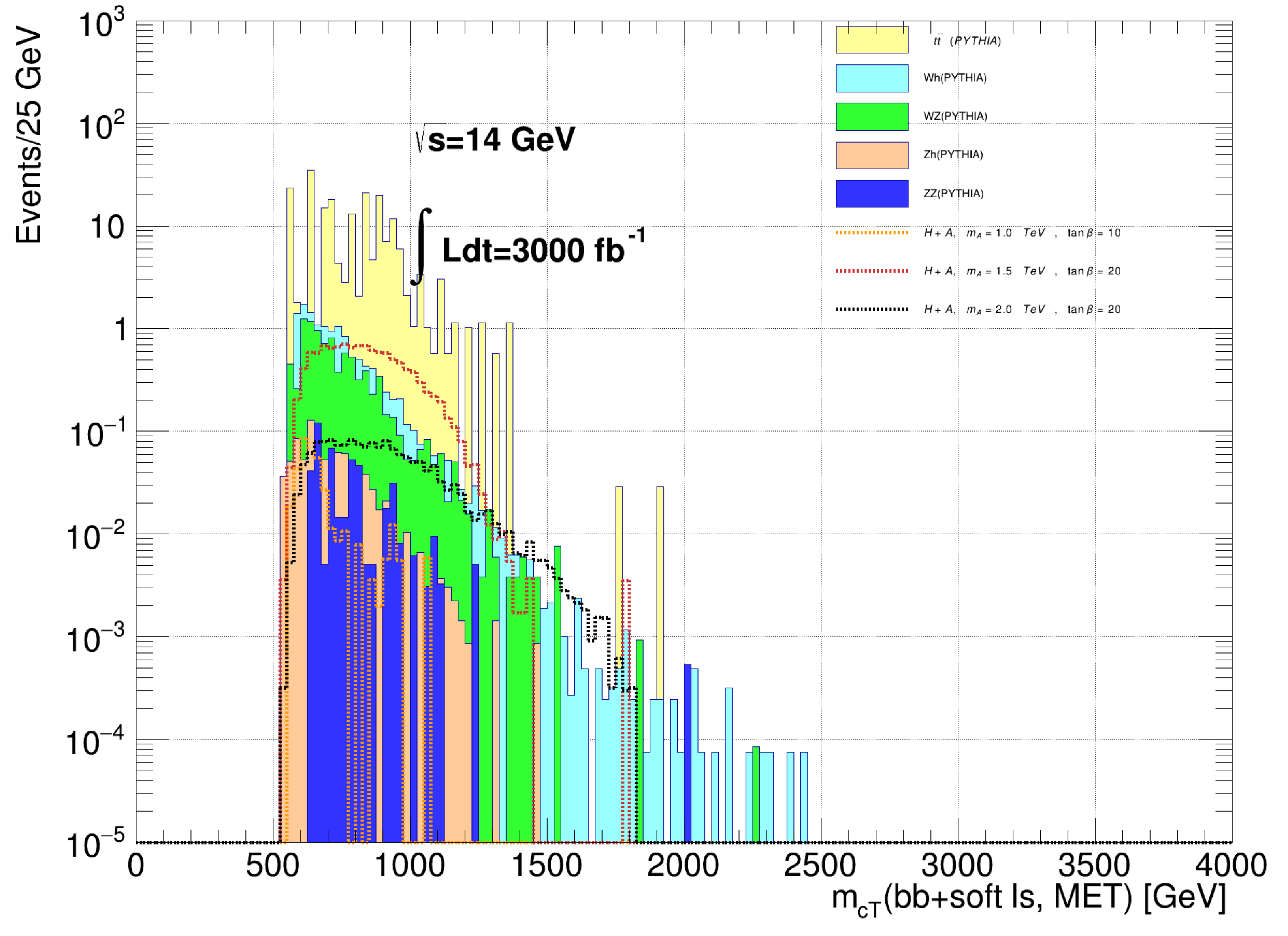
2l



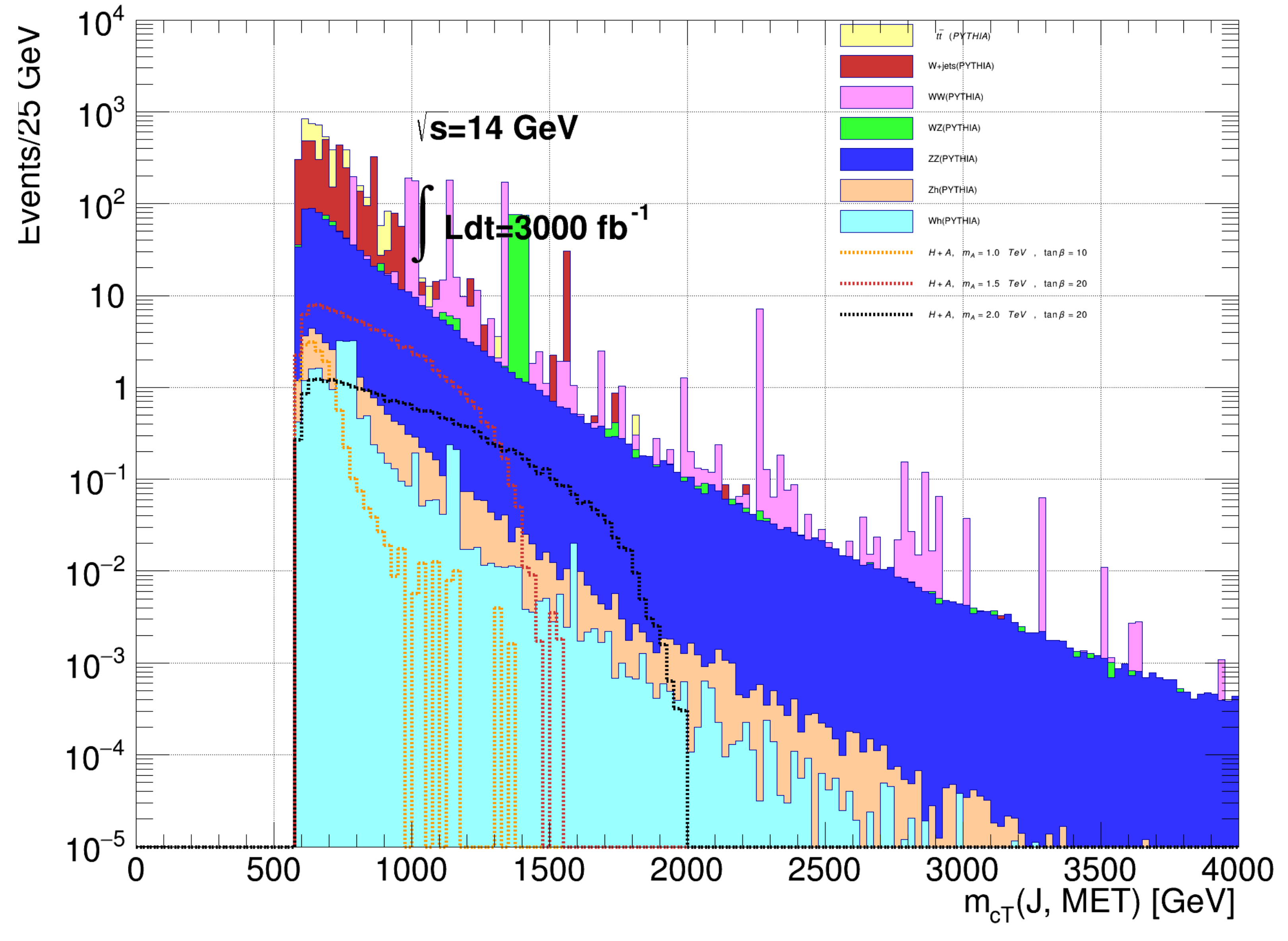
2l+1 soft l



2b

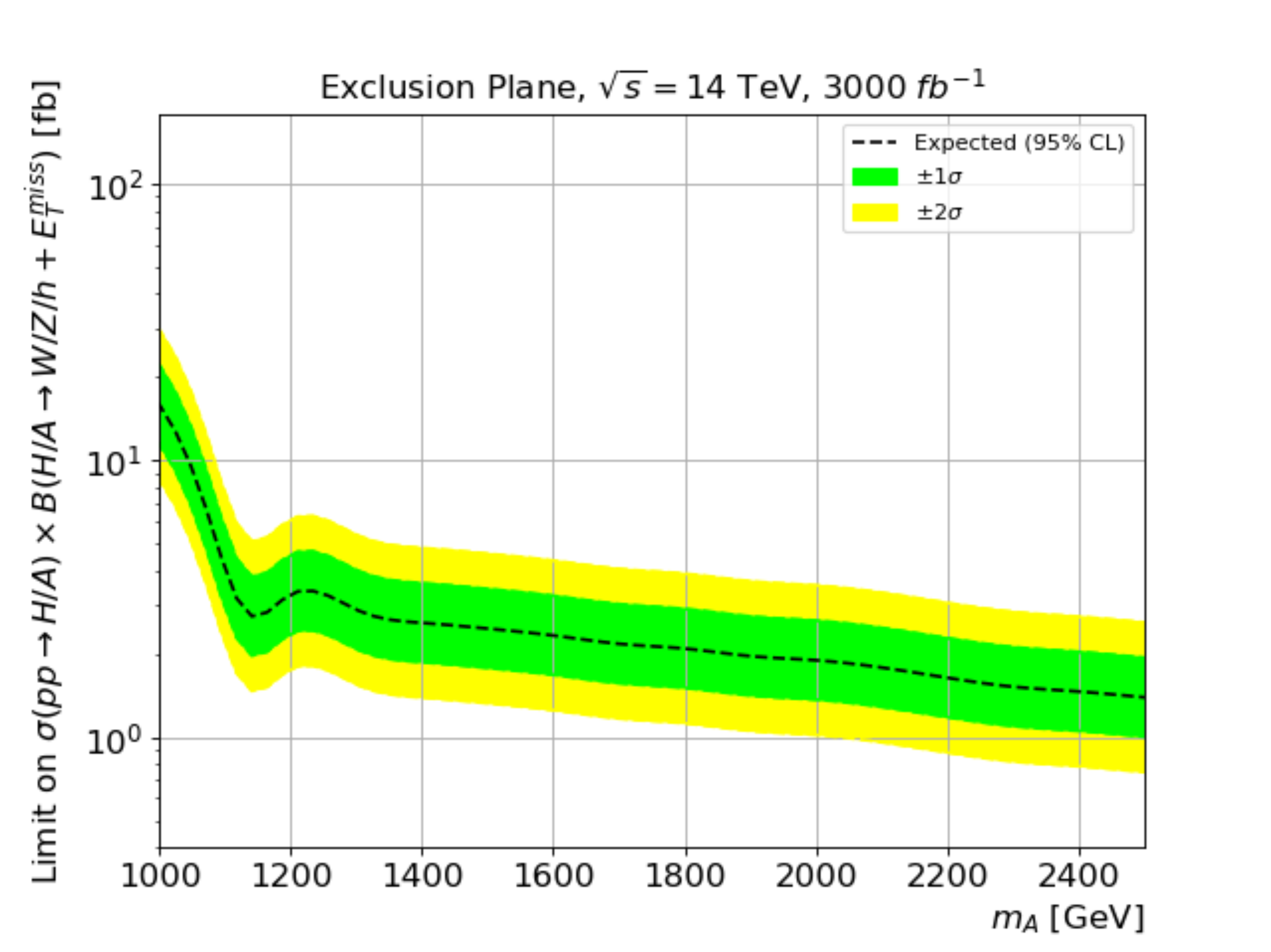


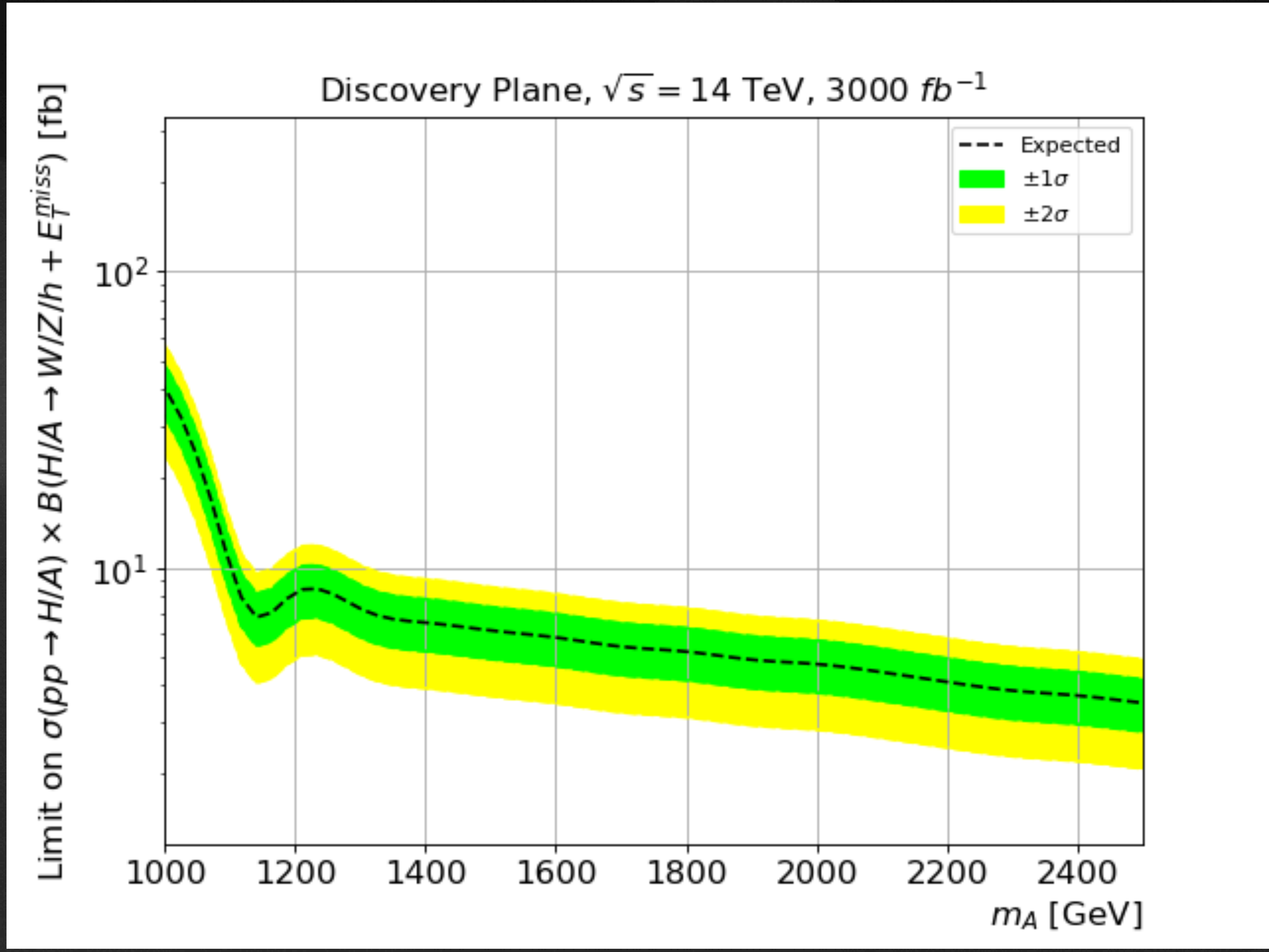
2b+1 soft l



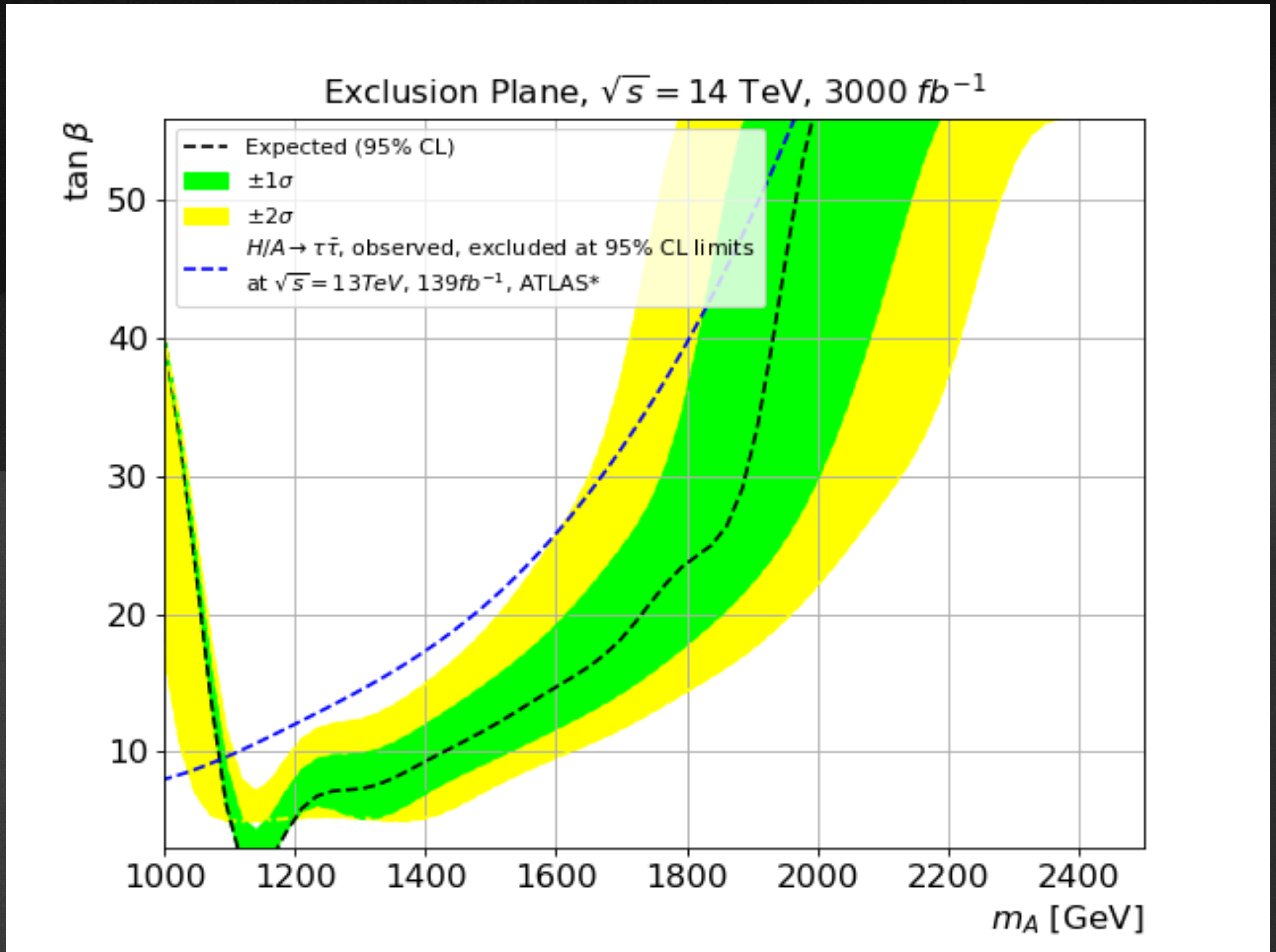
1J + 1 tau

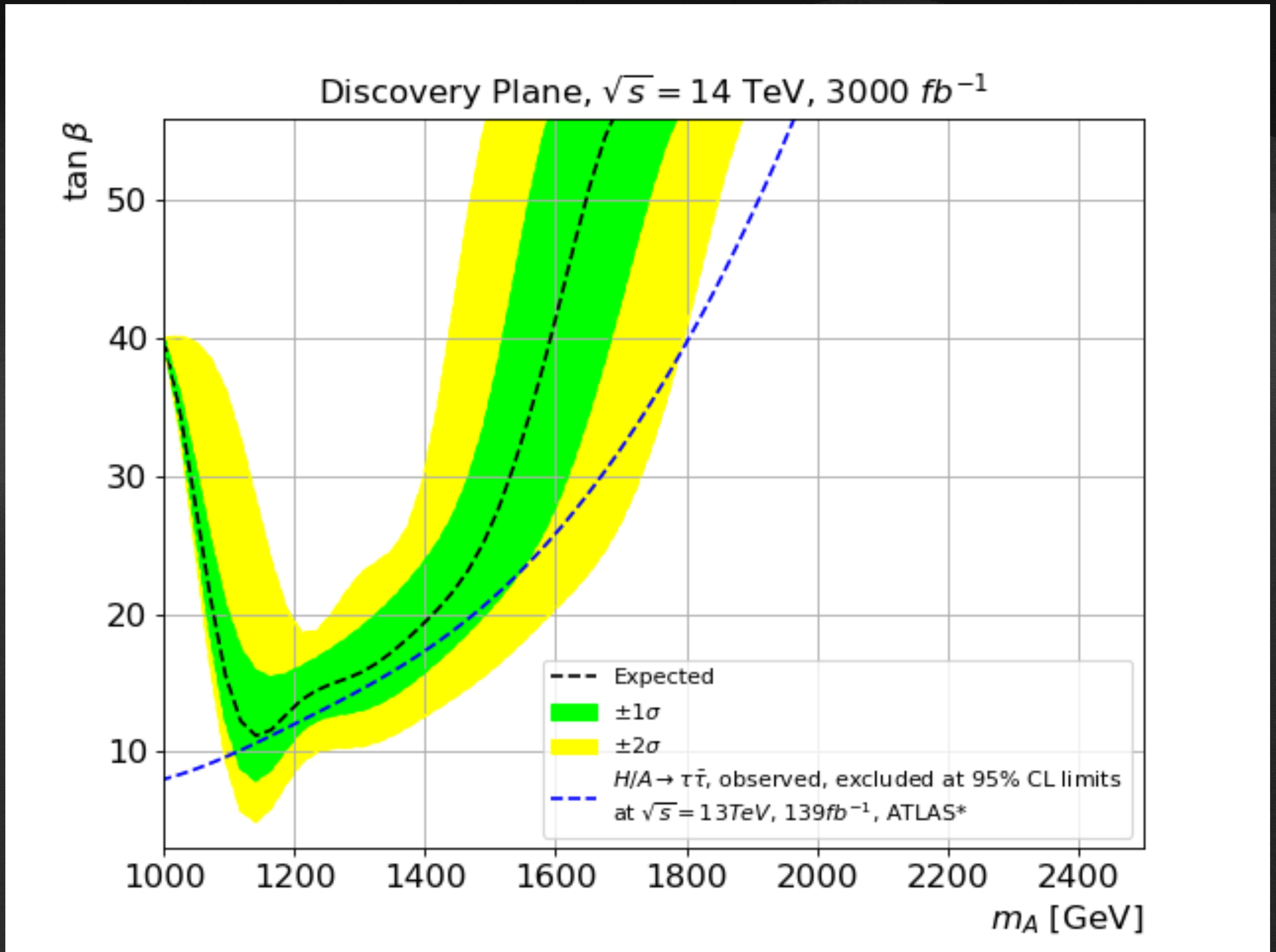
Reach on xsec(pp->H/A) x BF(H/A-> W/Z/h + MET) vs. m_A





Significance reaches on m_A vs. tan(β) plane



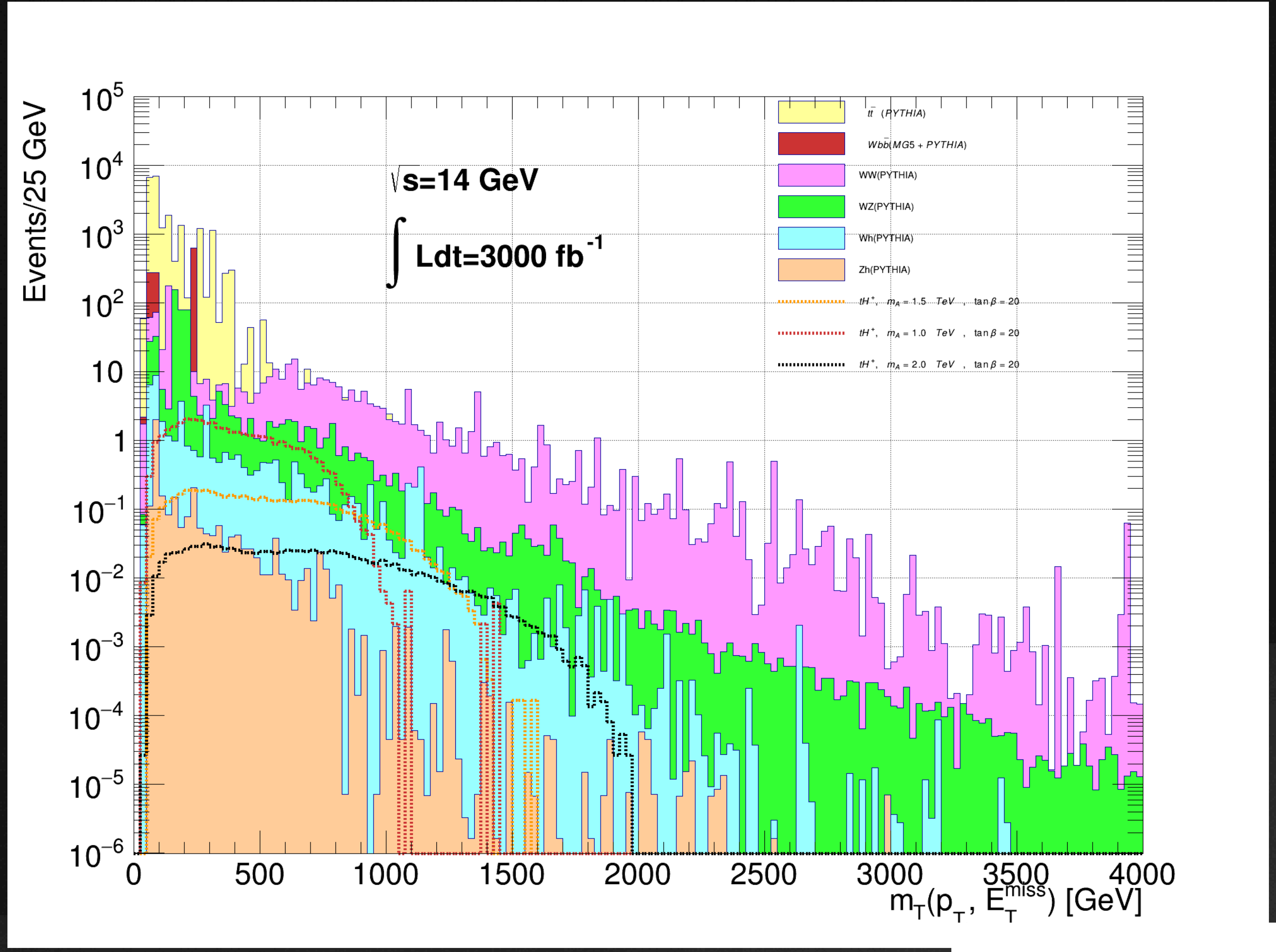


$pp \to tH^+$, $H^+ \to \tau + \nu_\tau$

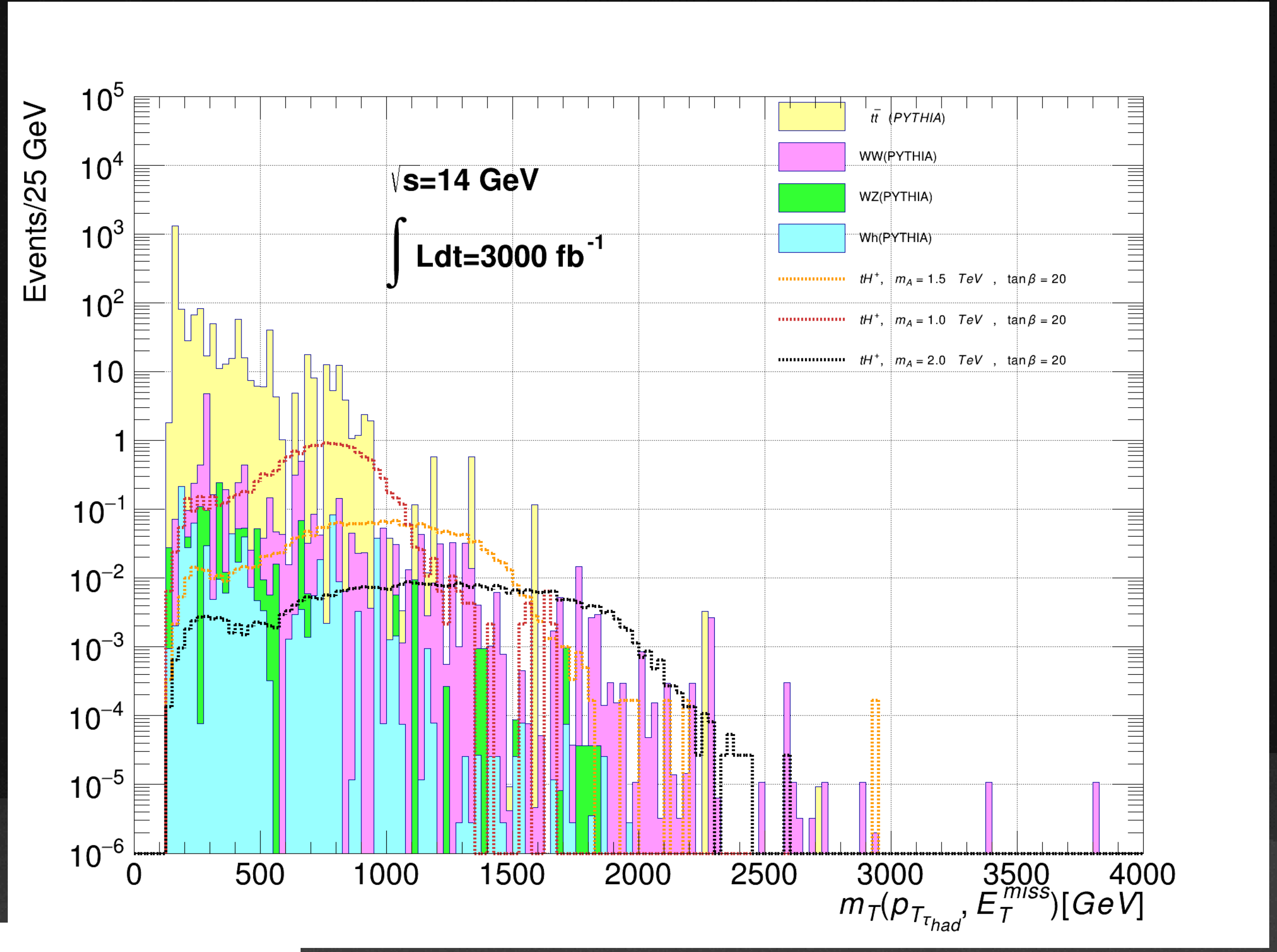
pp-> tH^+, $H^+ \rightarrow \tau + \nu_\tau$

- Channels we considered*:
  - 1l + MET (+ 1b)
  - 1τ + MET (+ 1b)
  - 1τ + 1l + MET (+ 1b)
- SM backgrounds considered: ttbar, single top, WW, WZ, ZZ, Zh, Wh, httbar, generated by Pythia and Wbb by Madgraph.
- For signals, Isajet featuring Isasugra for spectra generation.Resultant outputs in SLHA formats are then fed into Pythia to generate samples.
- The Pythia samples are then interfaced with the Delphes for detector simulation.
- m_T reconstructed for all channels.

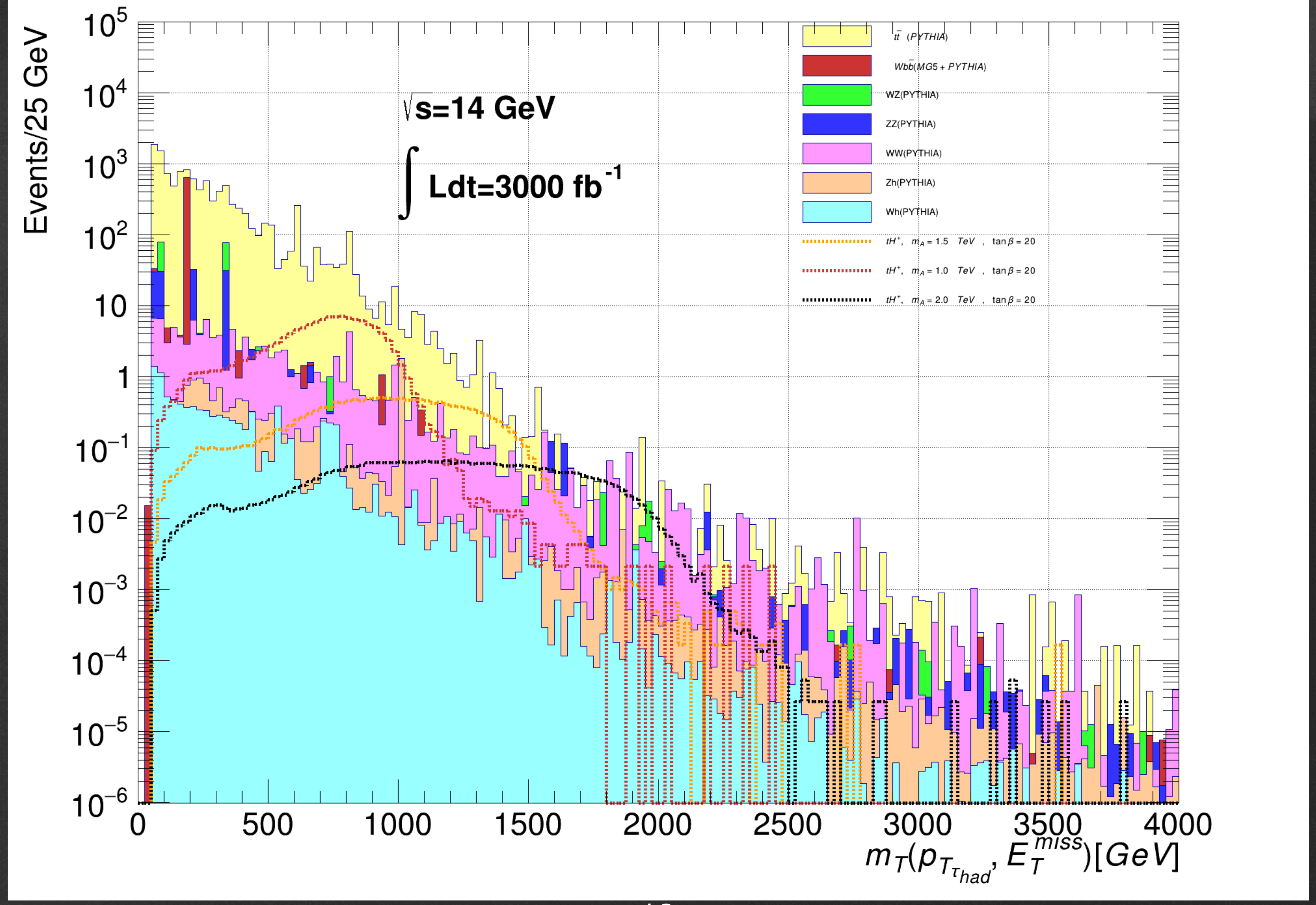
* Detailed selection criterias, isolation requirements, tagging and kinematics cuts are listed in backup slides



1l

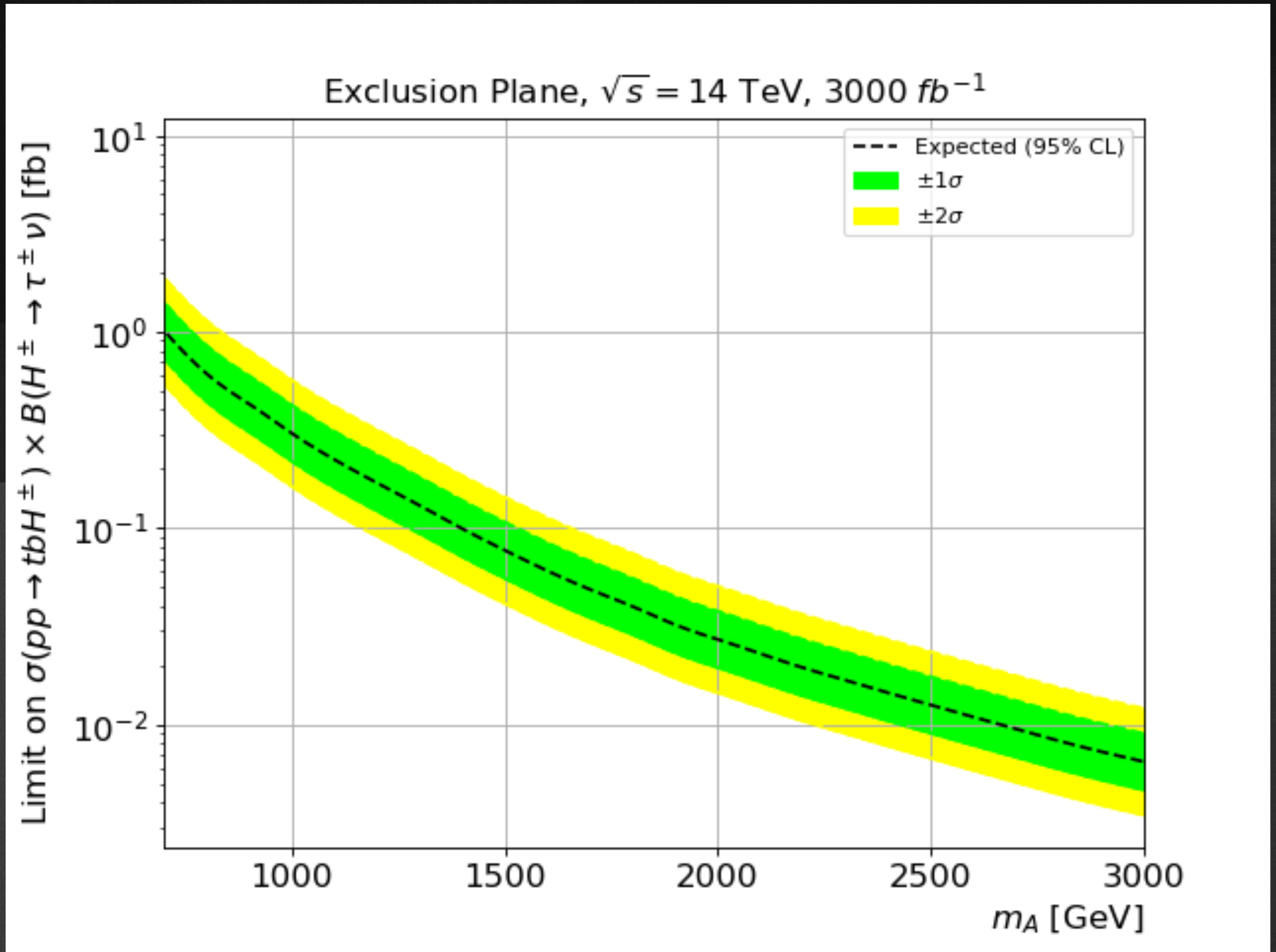


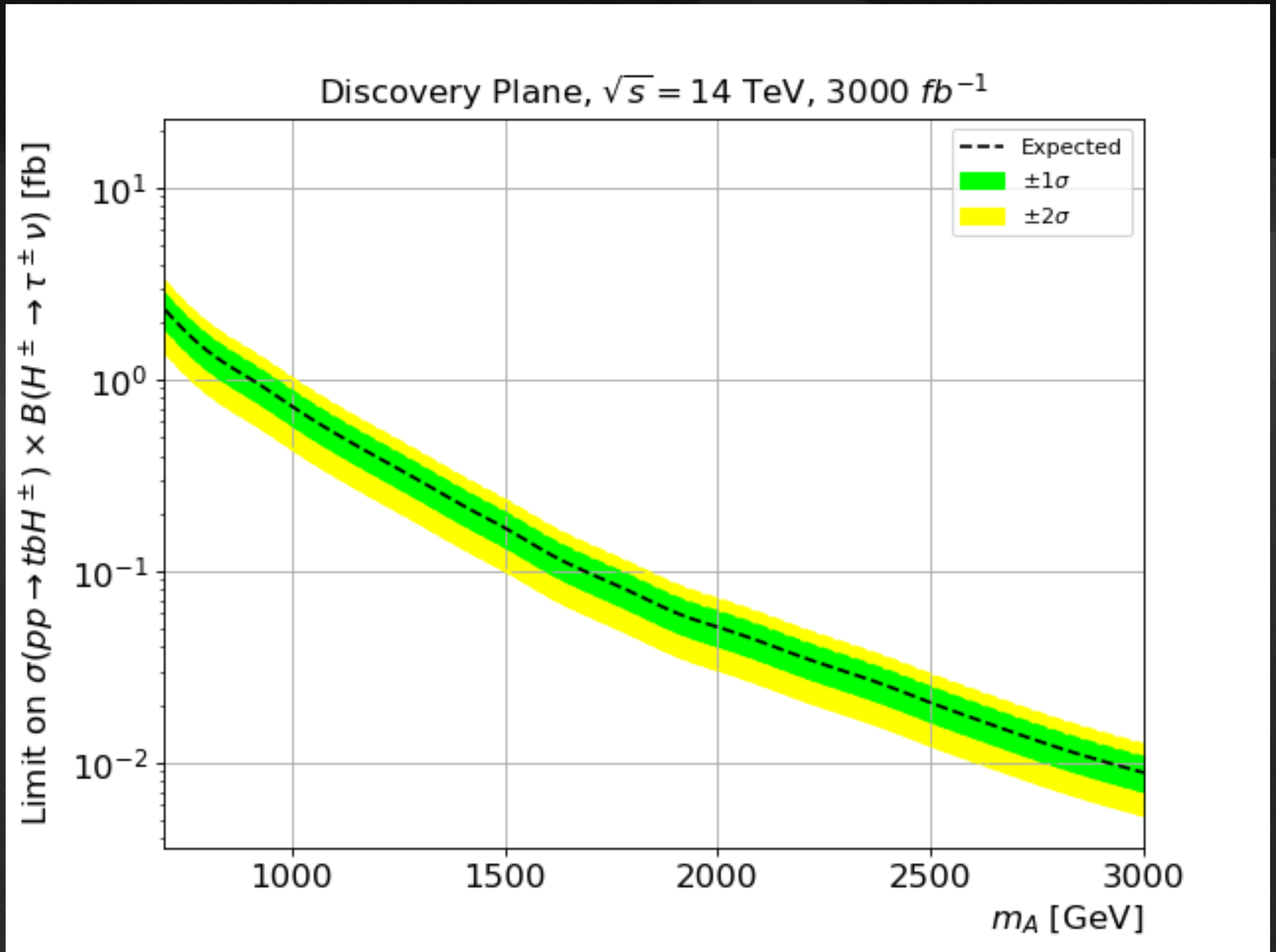
1l+1tau



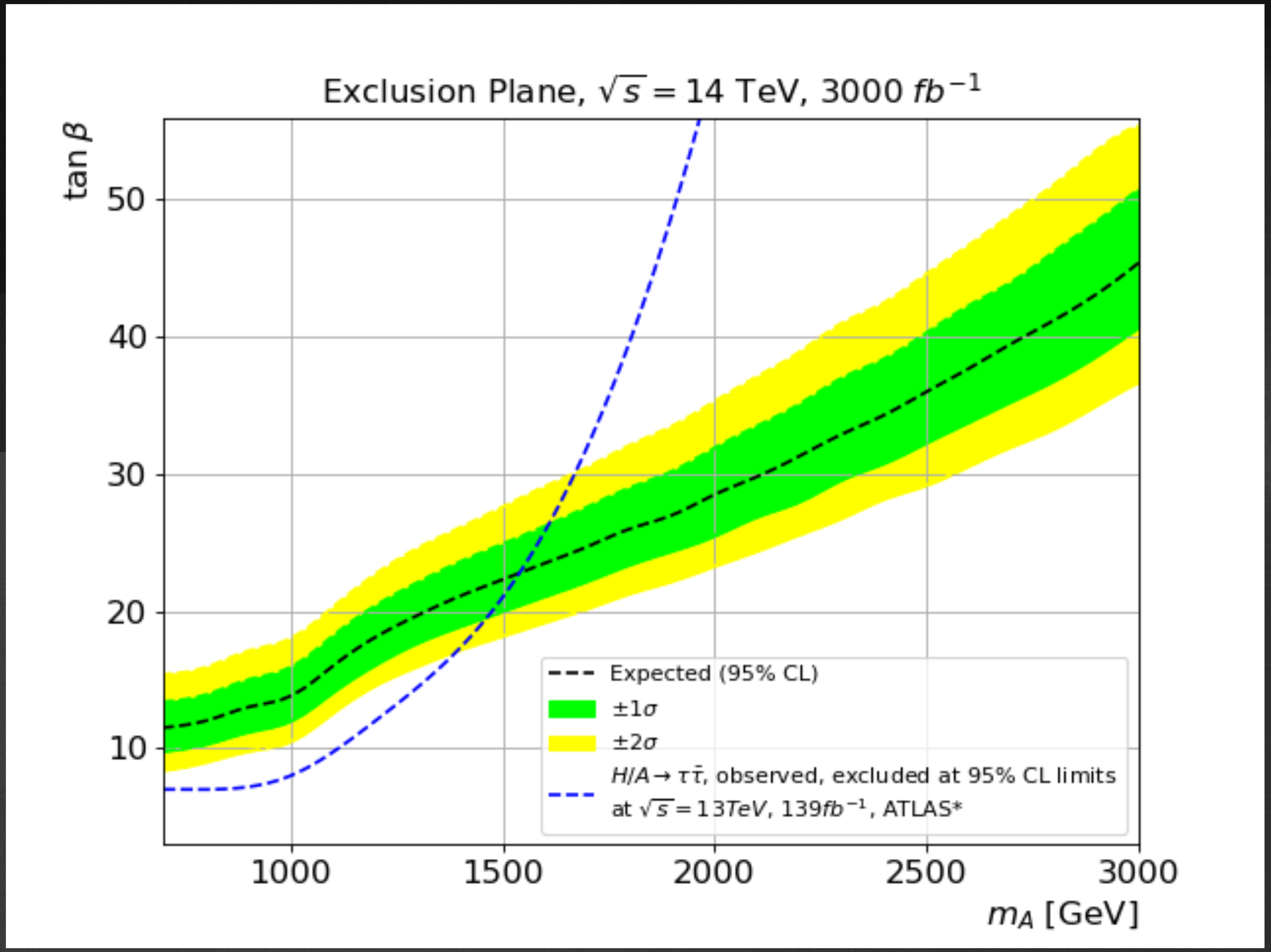
1tau

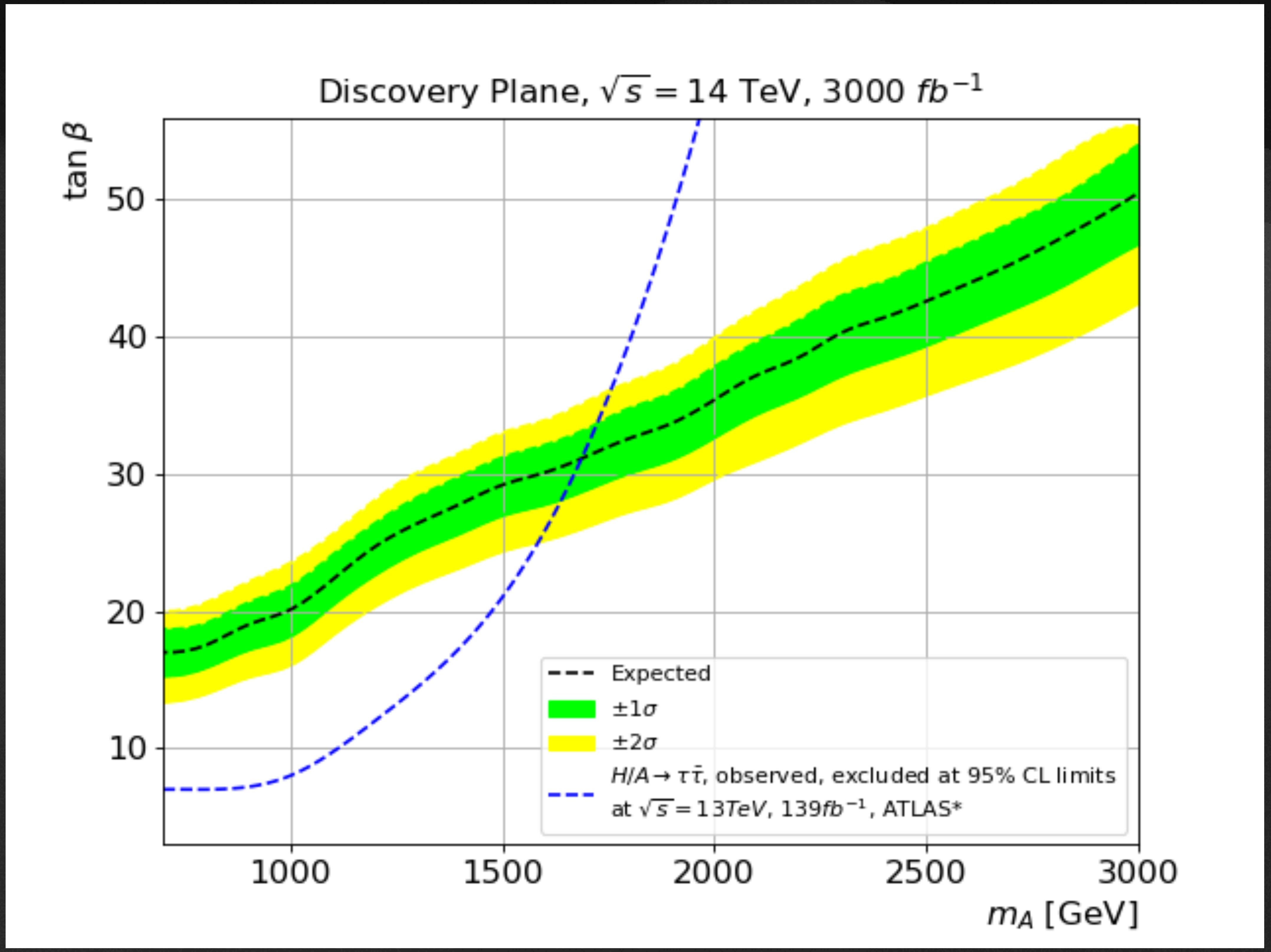
Reach on xsec(pp->tH$^+$) x BF(H$^+$-> τ + ν_τ) vs. m_A





Significance reaches on m_A vs. tan(β) plane



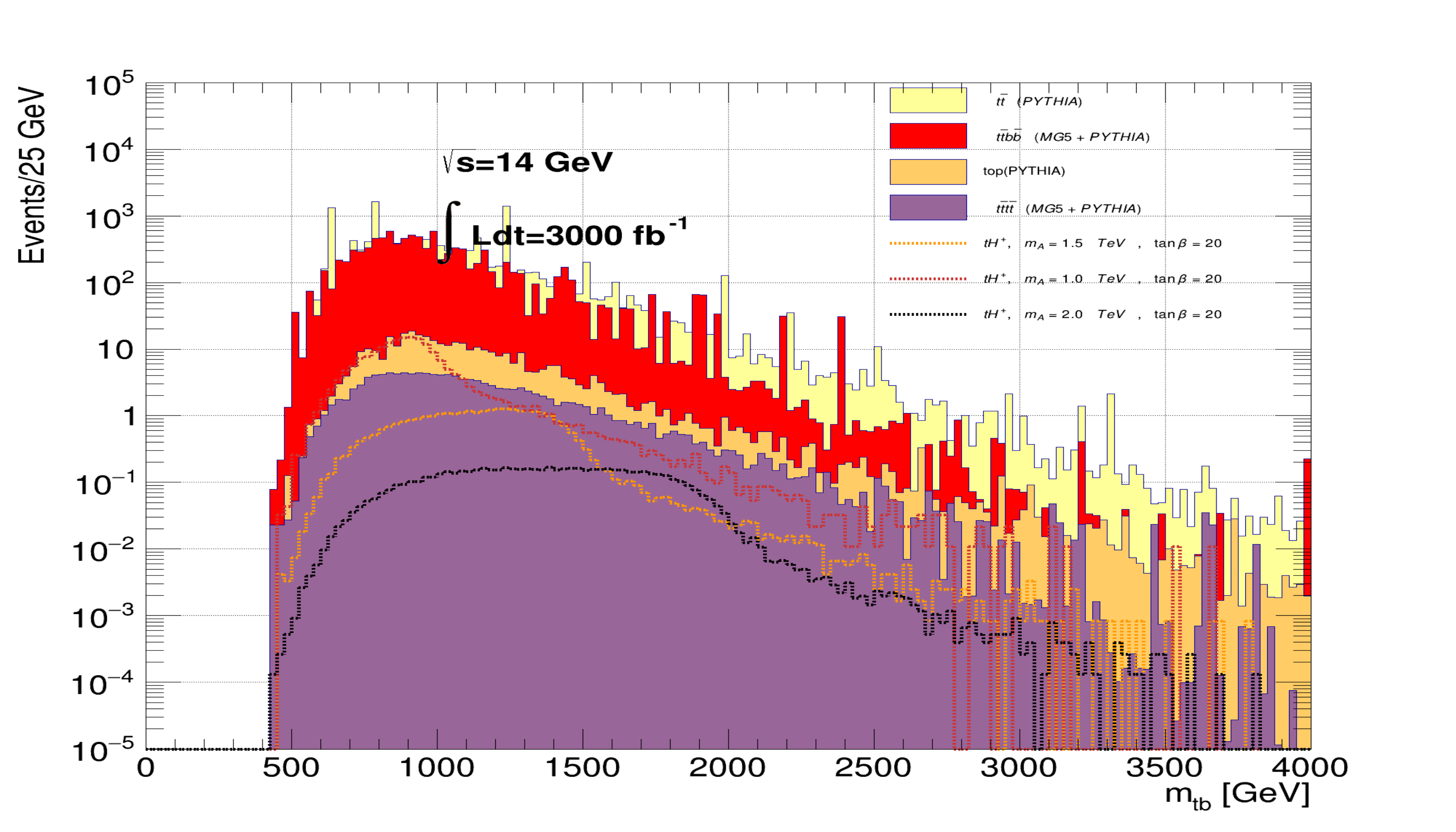


pp-> tH^+, H^+ -> t + b

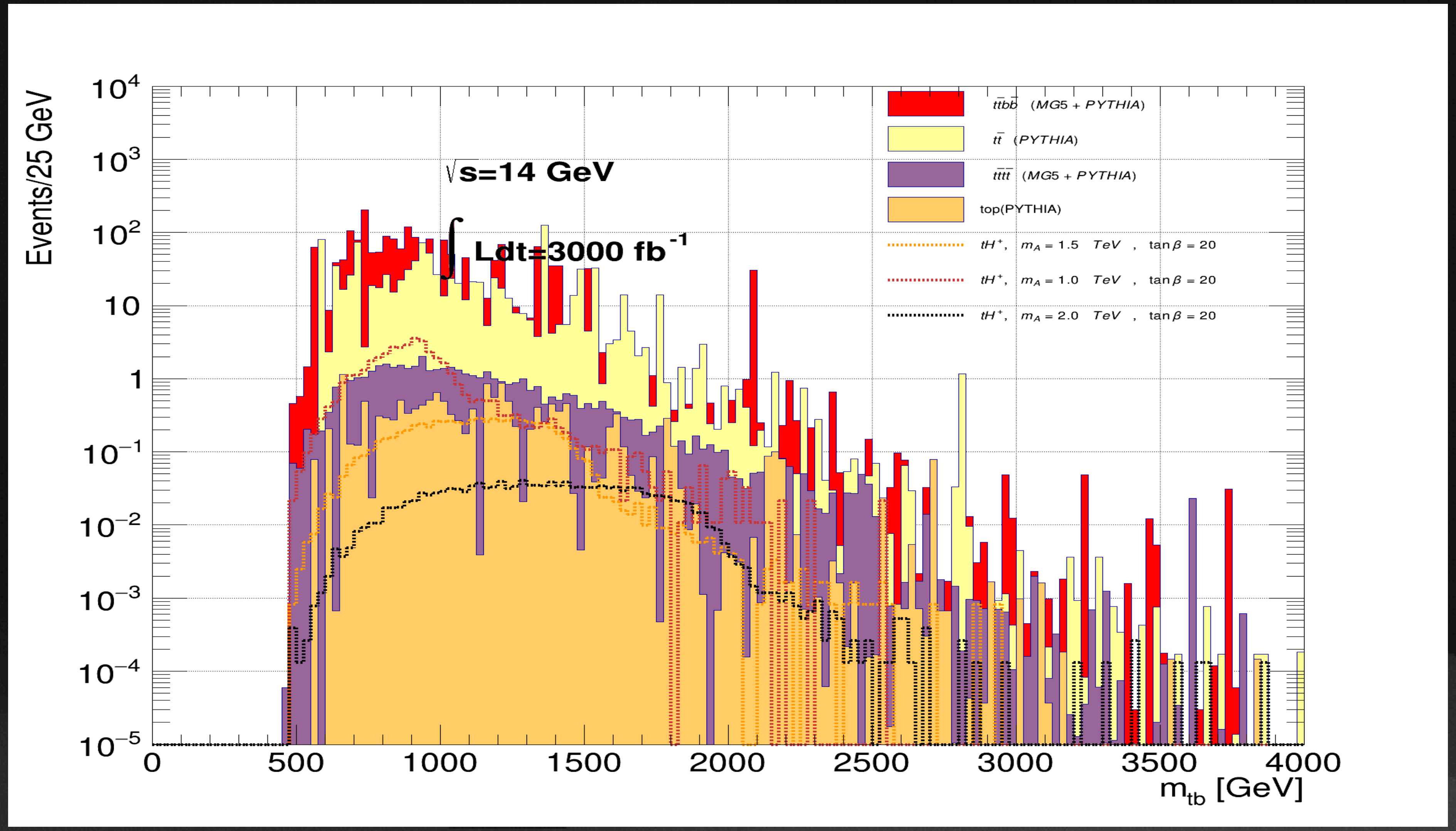
pp-> tH+, H+ -> t + b

- Channels we considered*:
  - Single top + 3b
    - n(top) = 1, tagged by HEPTopTagger2
    - If HEPTopTagger fails to tag, at least one boosted (pT>300 GeV) fat J with 145 GeV < m_J < 300 GeV, and at least one b jet within the cone of that big J
  - Single top + 1l + 3b
    - n(top) = 1, tagged by HEPTopTagger2
    - If HEPTopTagger fails to tag, one boosted (pT>300 GeV) with 145 GeV < m_J < 300 GeV, and at least one b jet within the cone of that big J
- SM backgrounds considered: ttbar (truth 3b vetoed to avoid double counting) generated by Pythia and ttbb, tttt by Madgraph.
- For signals, Isajet featuring Isasugra for spectra generation. Resultant outputs in SLHA formats are then fed into Pythia to generate samples.
- The Pythia samples are then interfaced with the Delphes for detector simulation.
- invariant mass m_{tb} reconstructed for all channels.

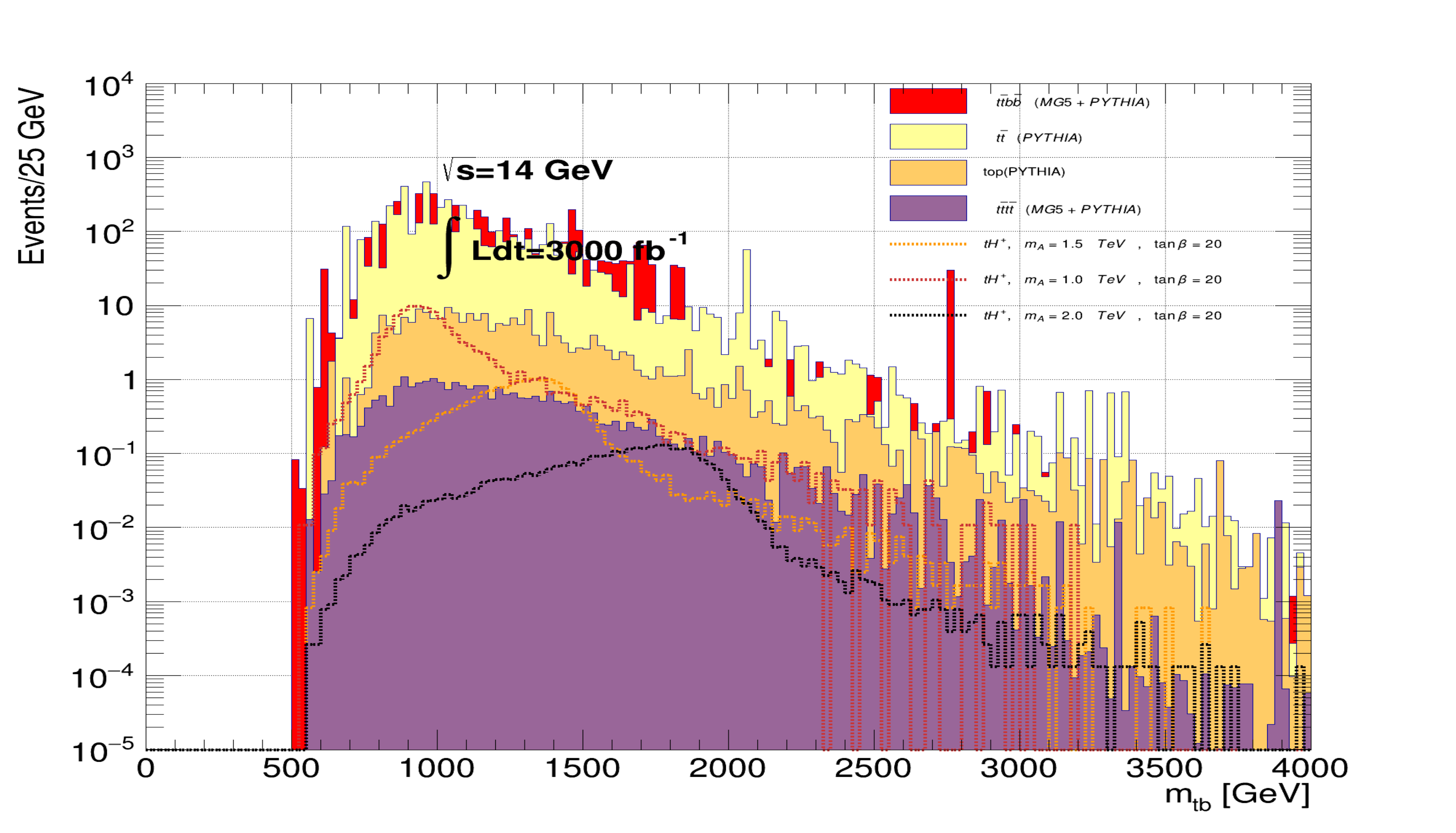
* Detailed selection criterias, isolation requirements and kinematics cuts can be found in our paper arXiv:2209.00063v1 [hep-ph] arXiv:2212.09198v1 [hep-ph]



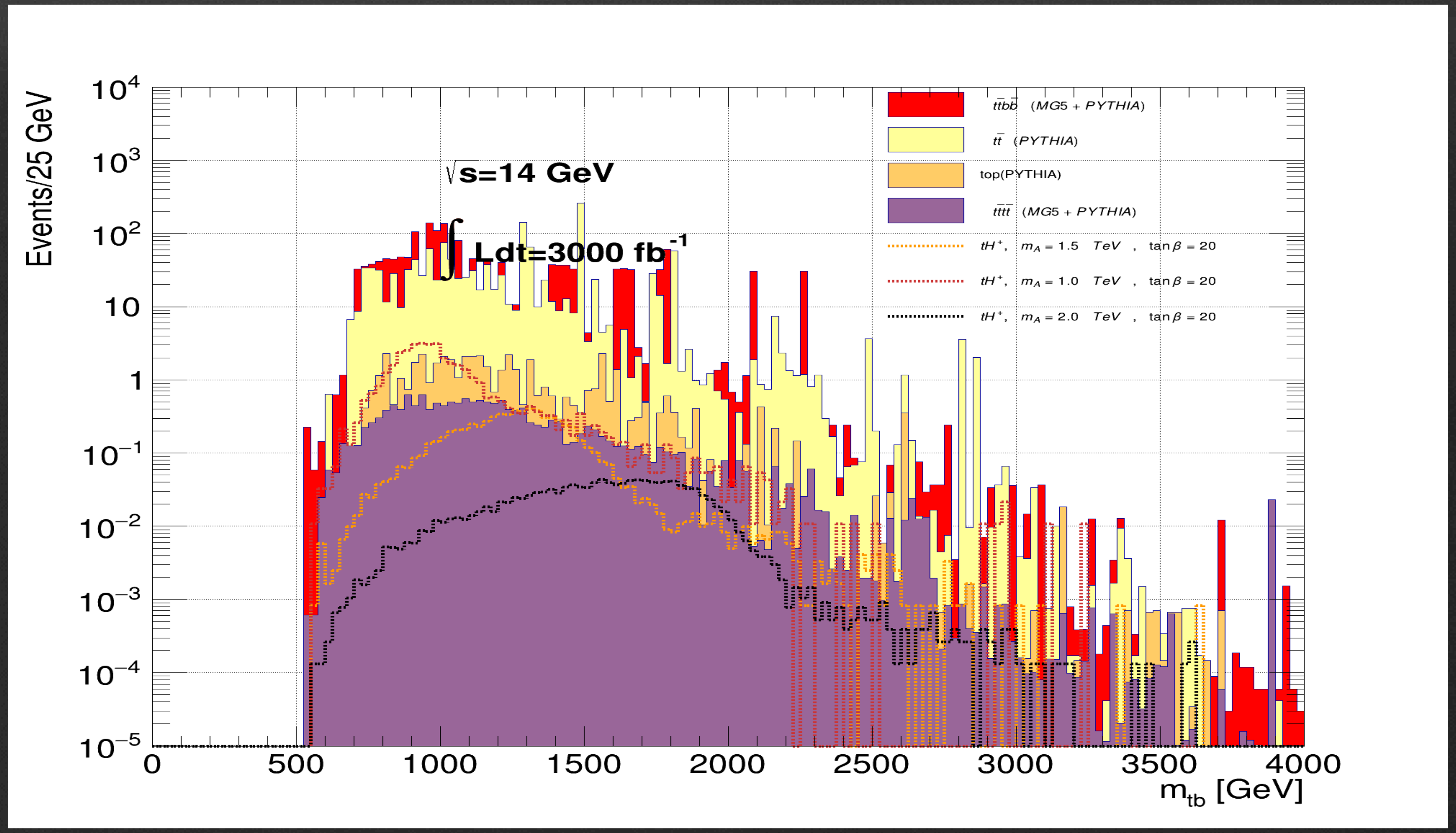
1t(tagged)



1t(tagged)+1l

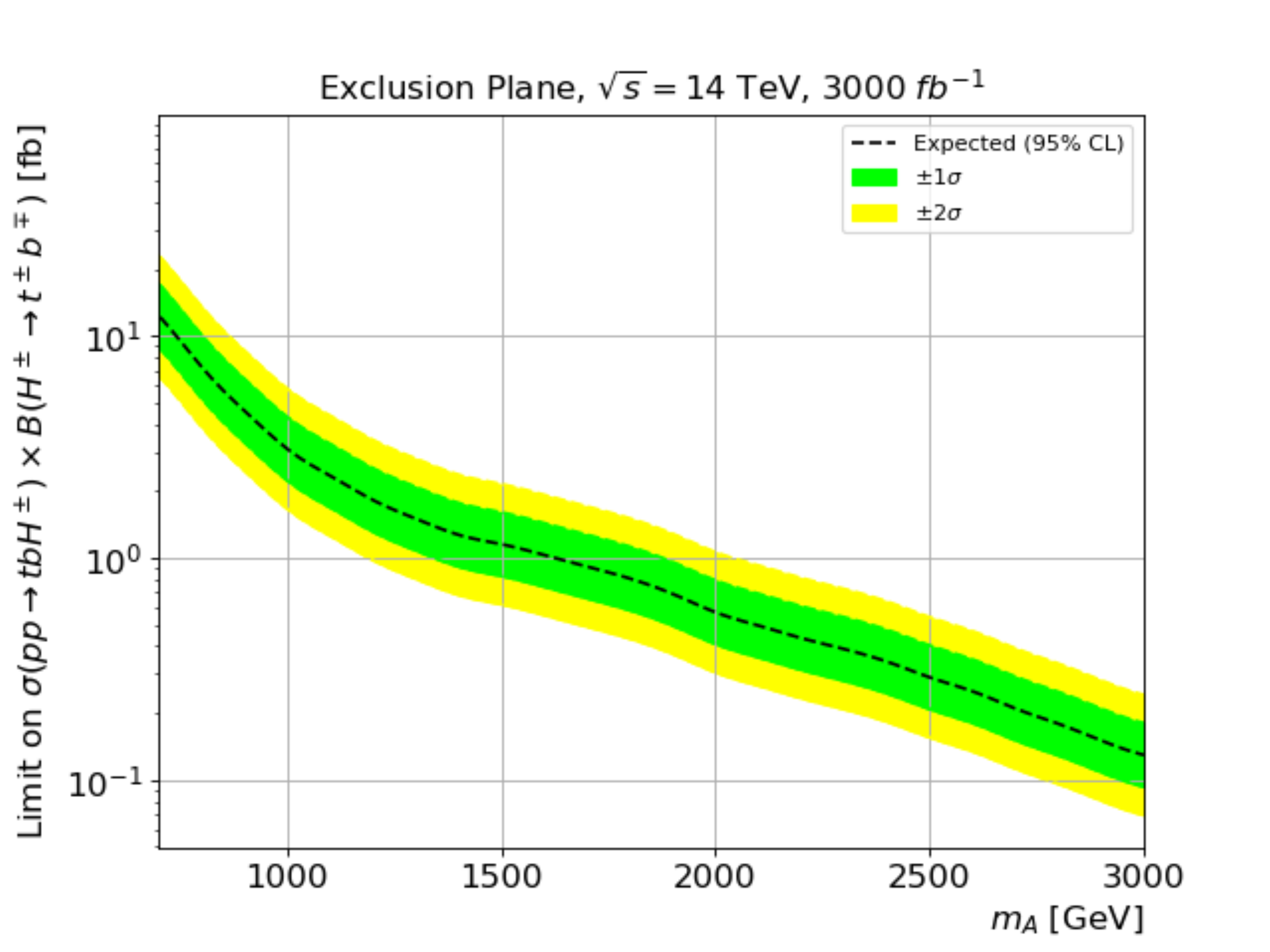


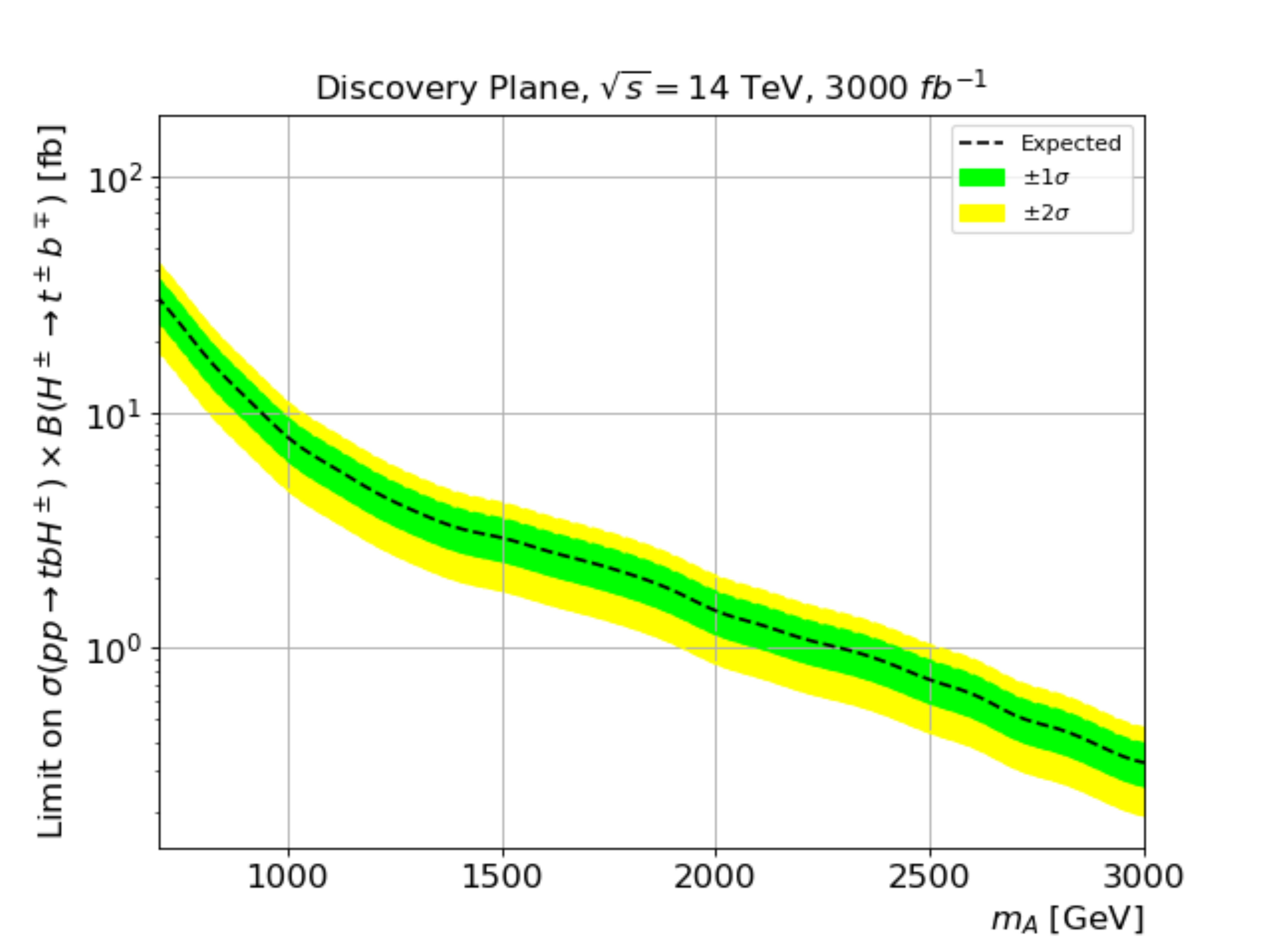
1t(no tagged)



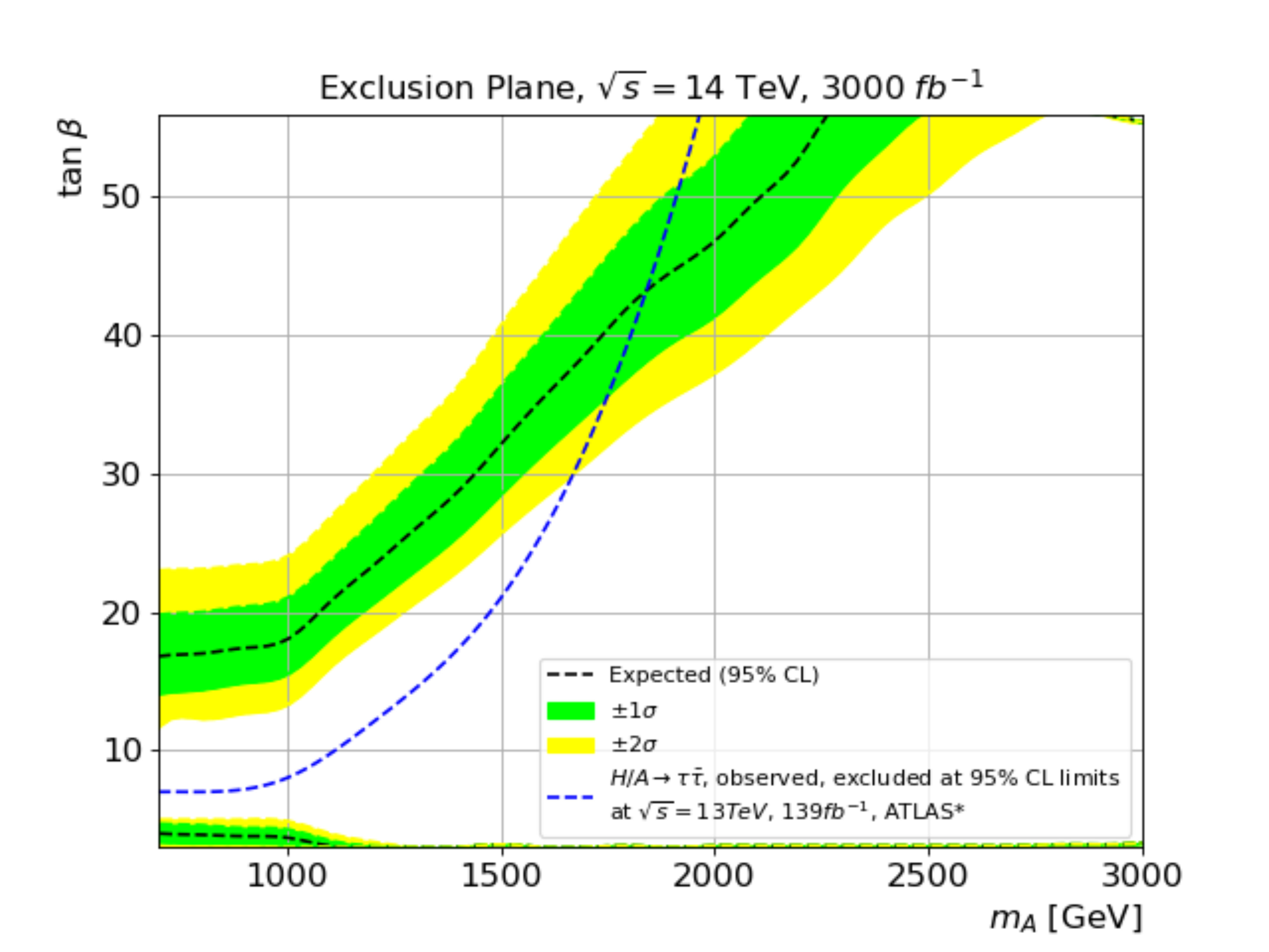
1t(no tagged)+1l

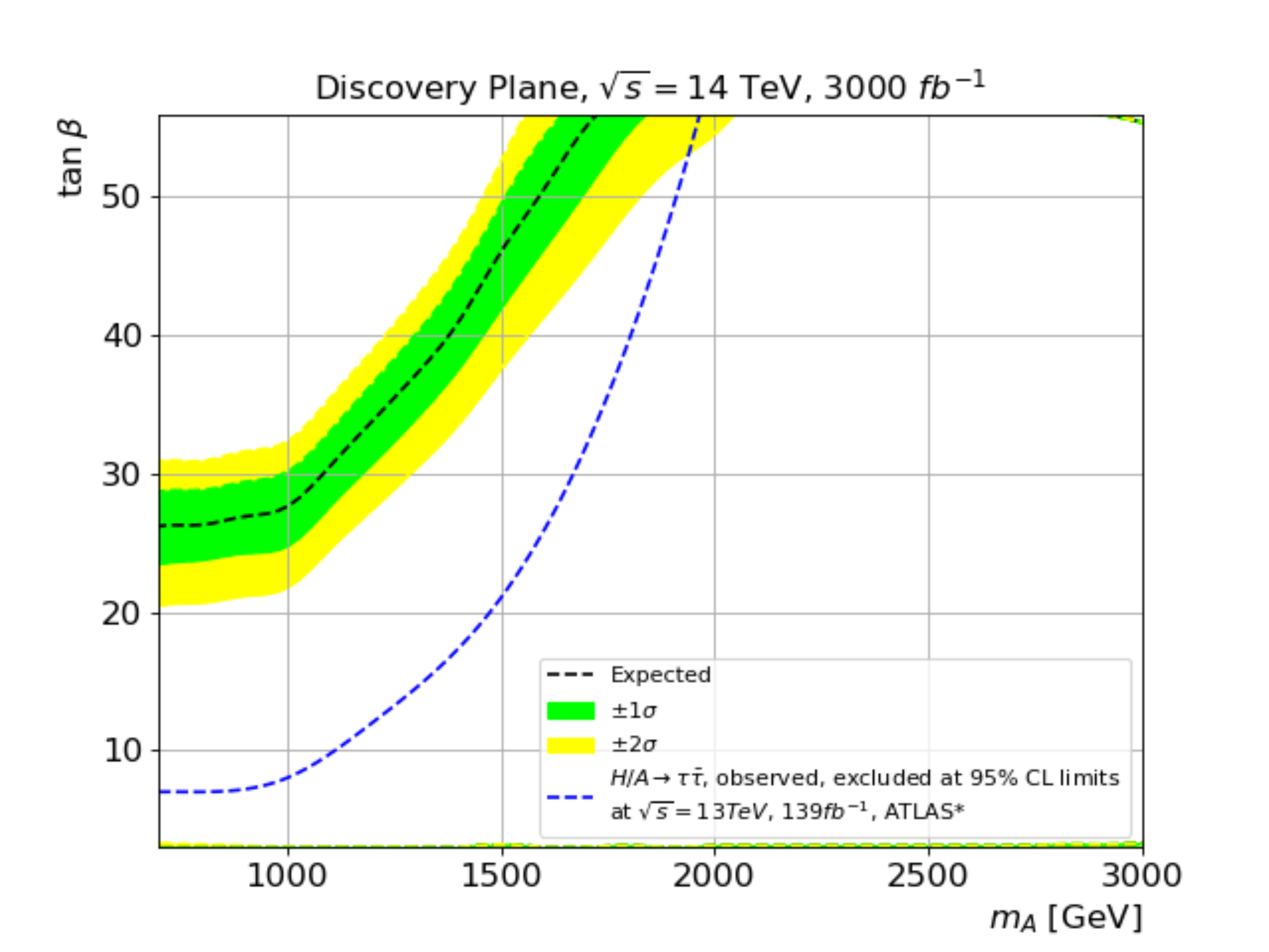
Reach on xsec(pp->tH+) x BF(H+-> t + b) vs. m_A



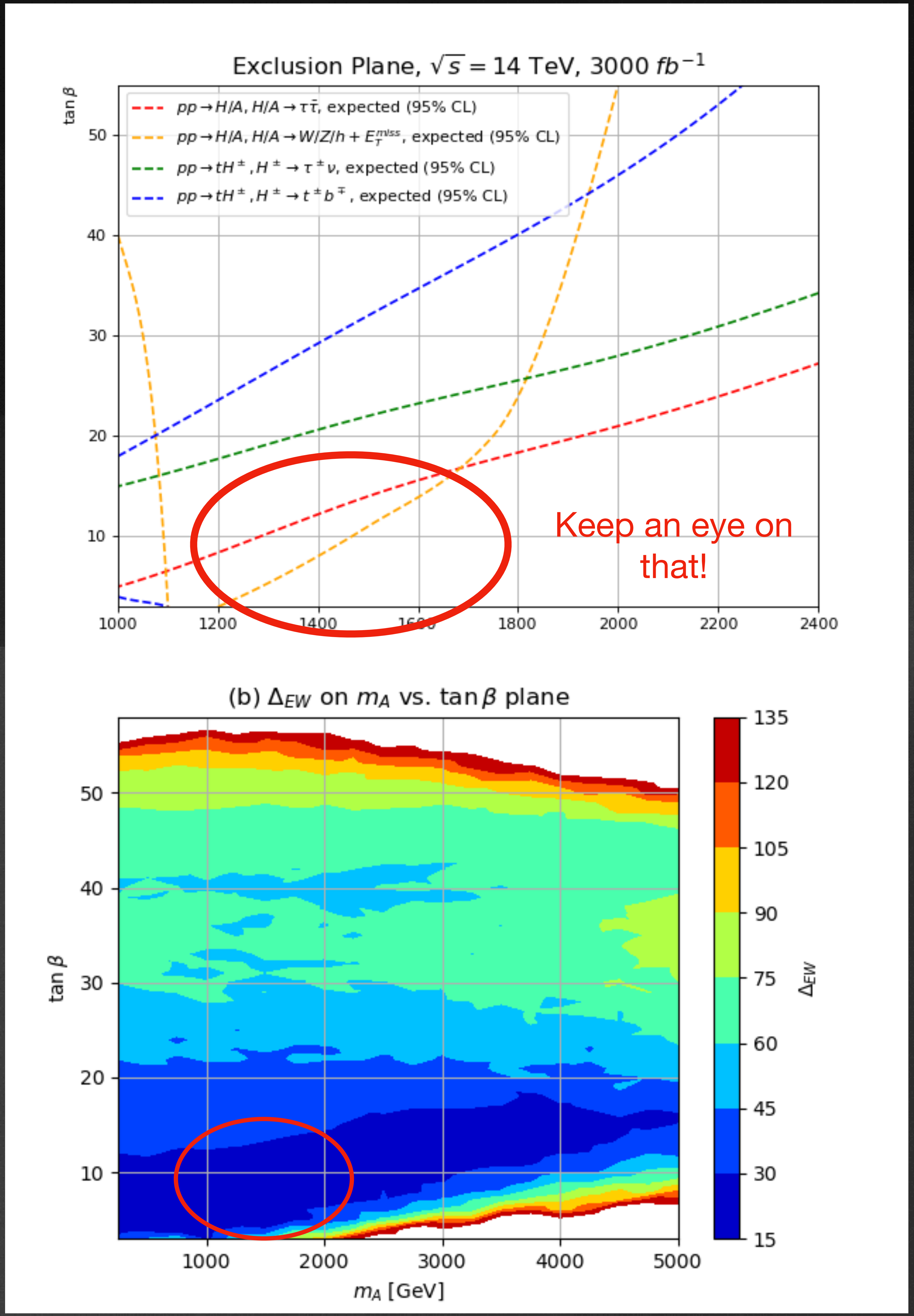


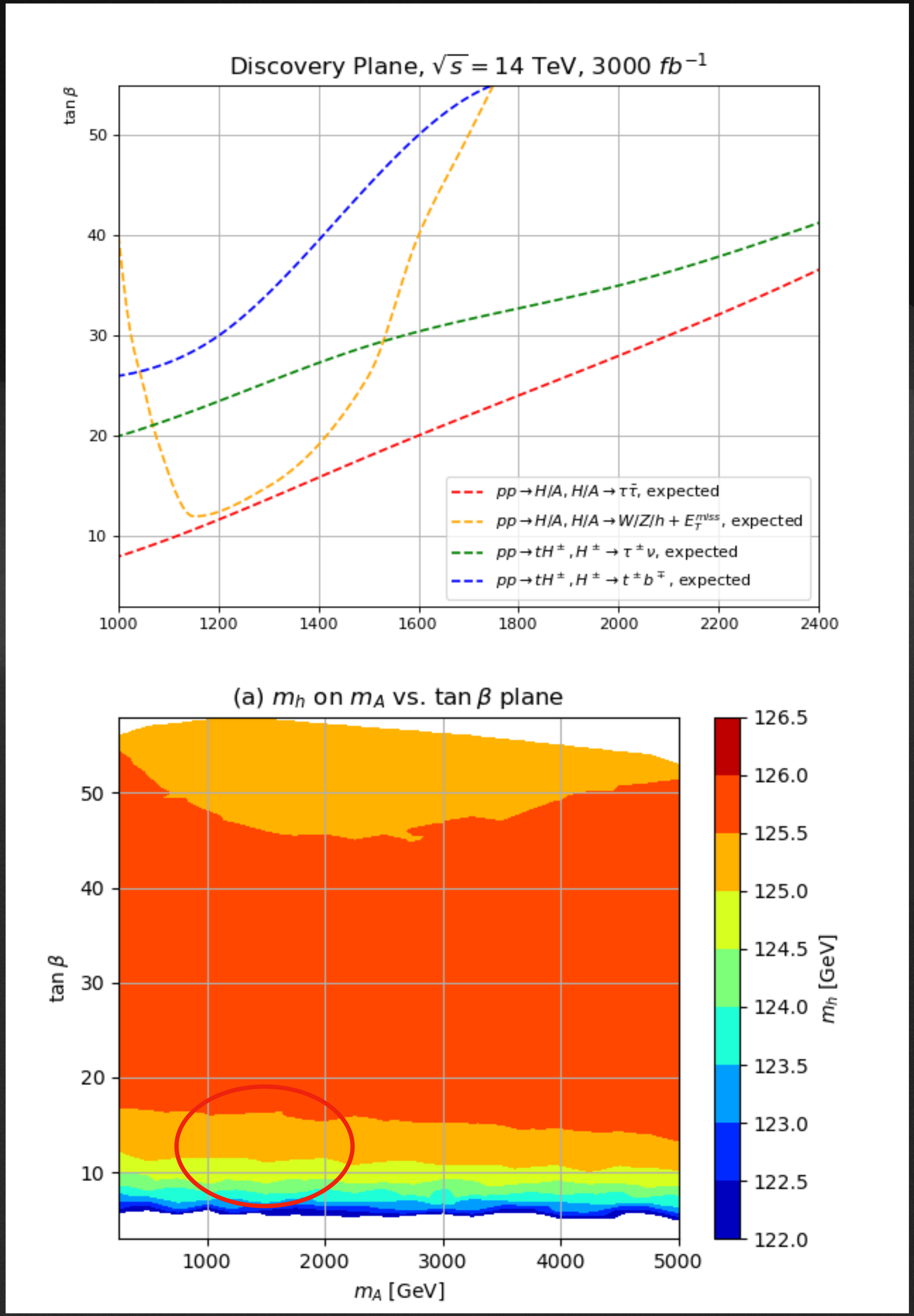
Significance reaches on m_A vs. tan(β) plane





The Grand Search Picture in HL-LHC

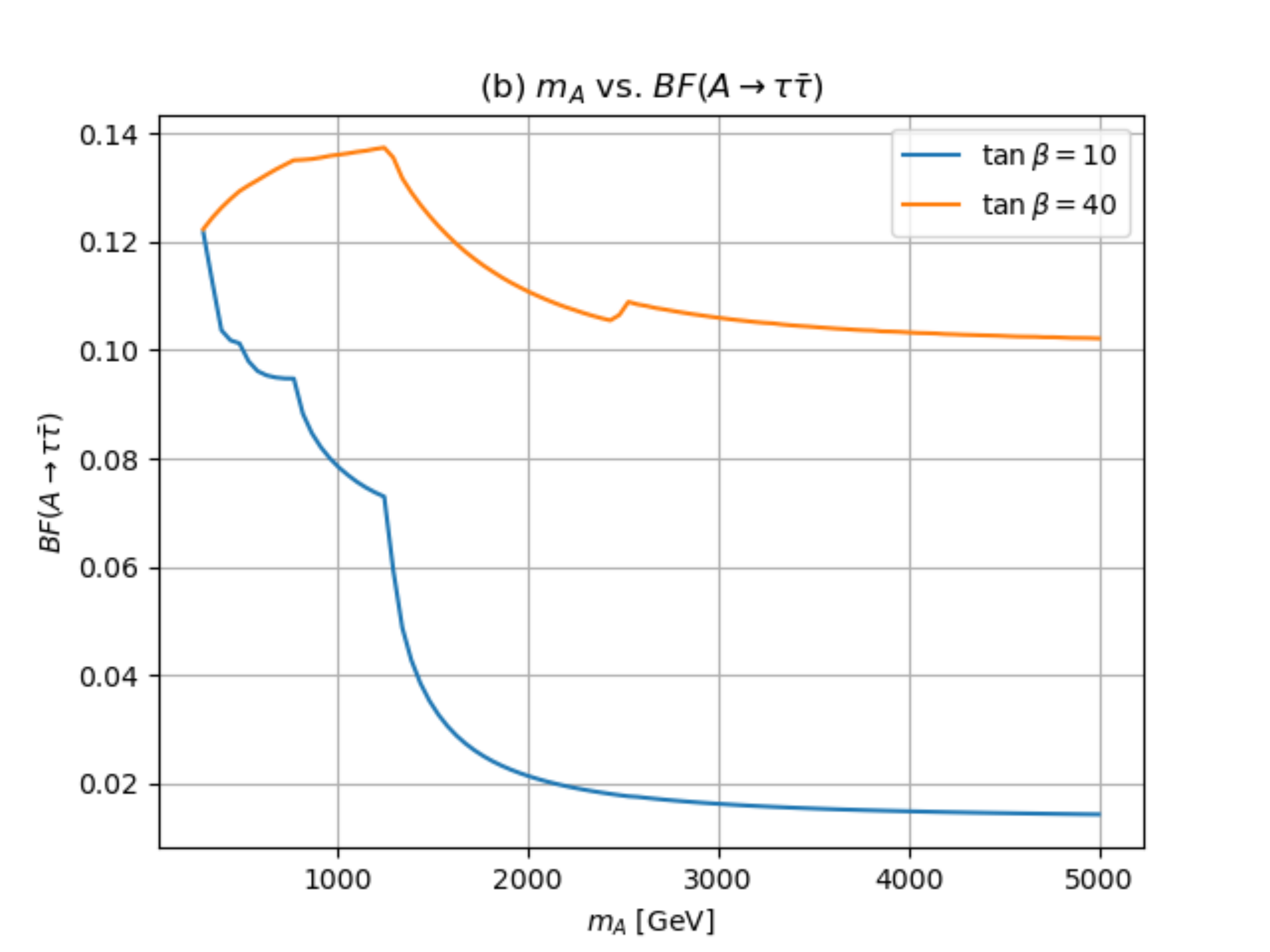


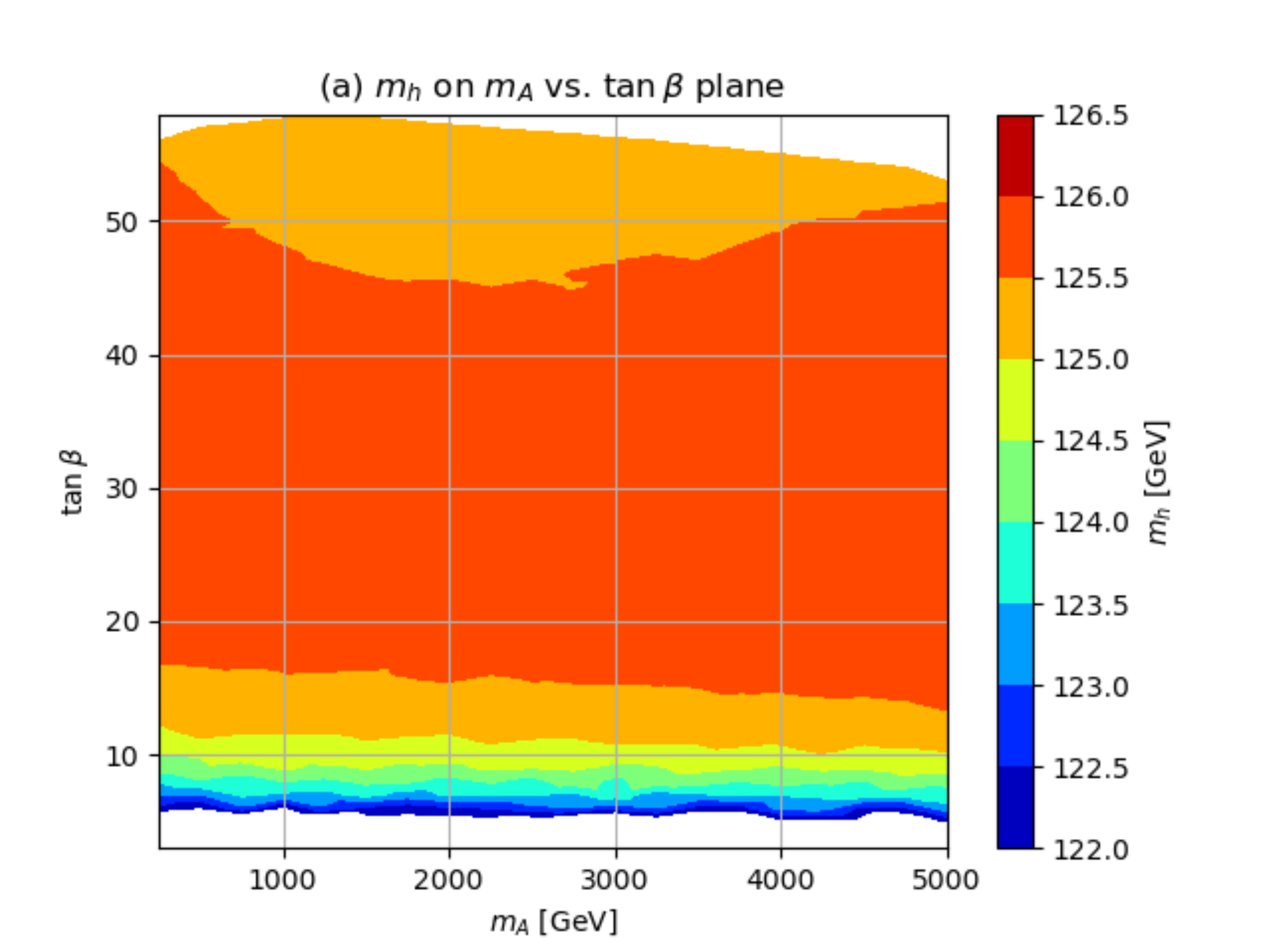


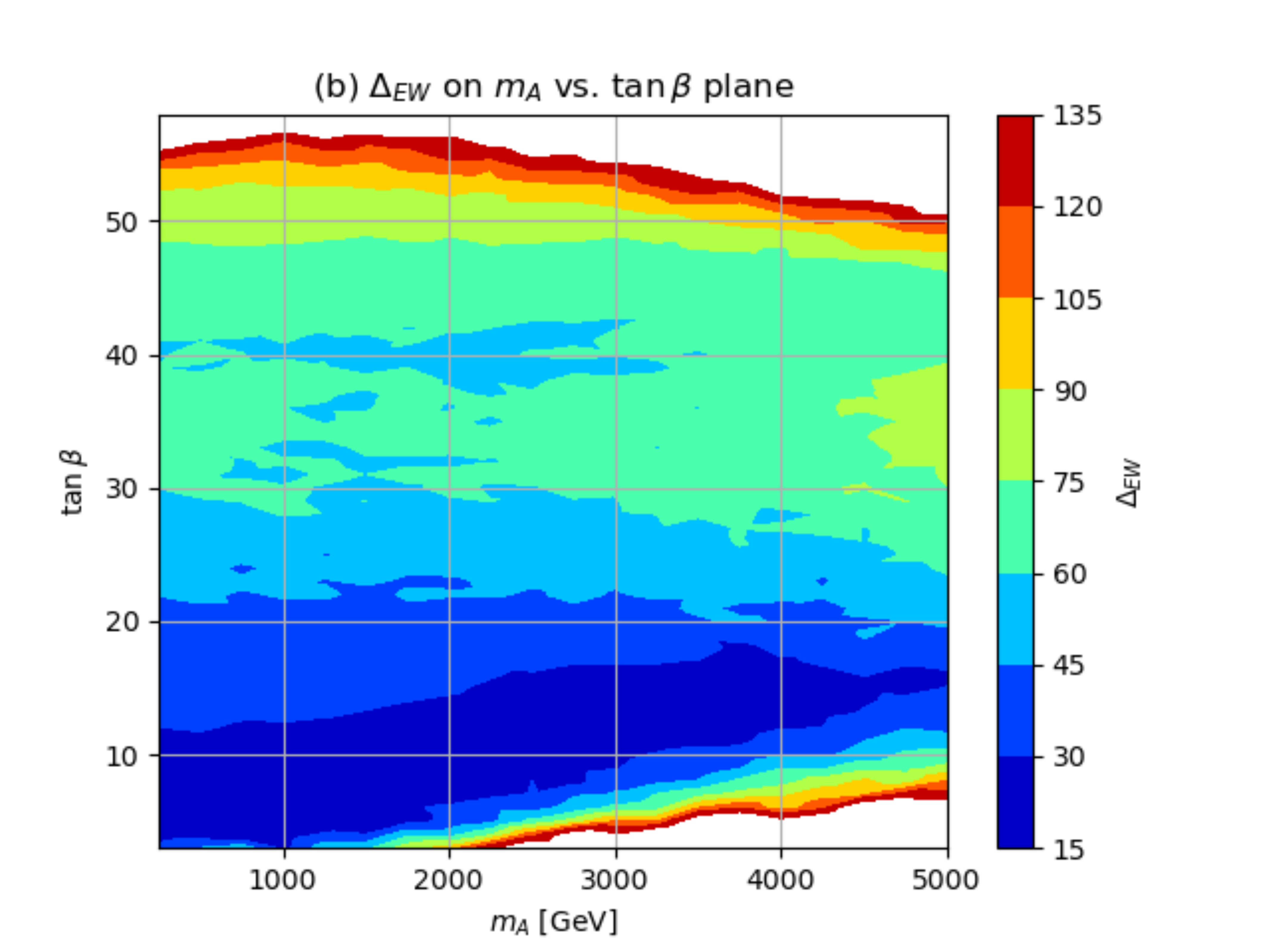
Conclusion

- Vast parameter space in natural SUSY.
- New phenomenology
- Keep an eye on H/A->sparticles
  - It's a special signature for natural SUSY
  - It covers reach in low tan(β) region, which is not accessible by H/A-> ττ.
  - It's a special signature for natural SUSY and is also preferred in the parameter space for low DEW and m_h~125 GeV!

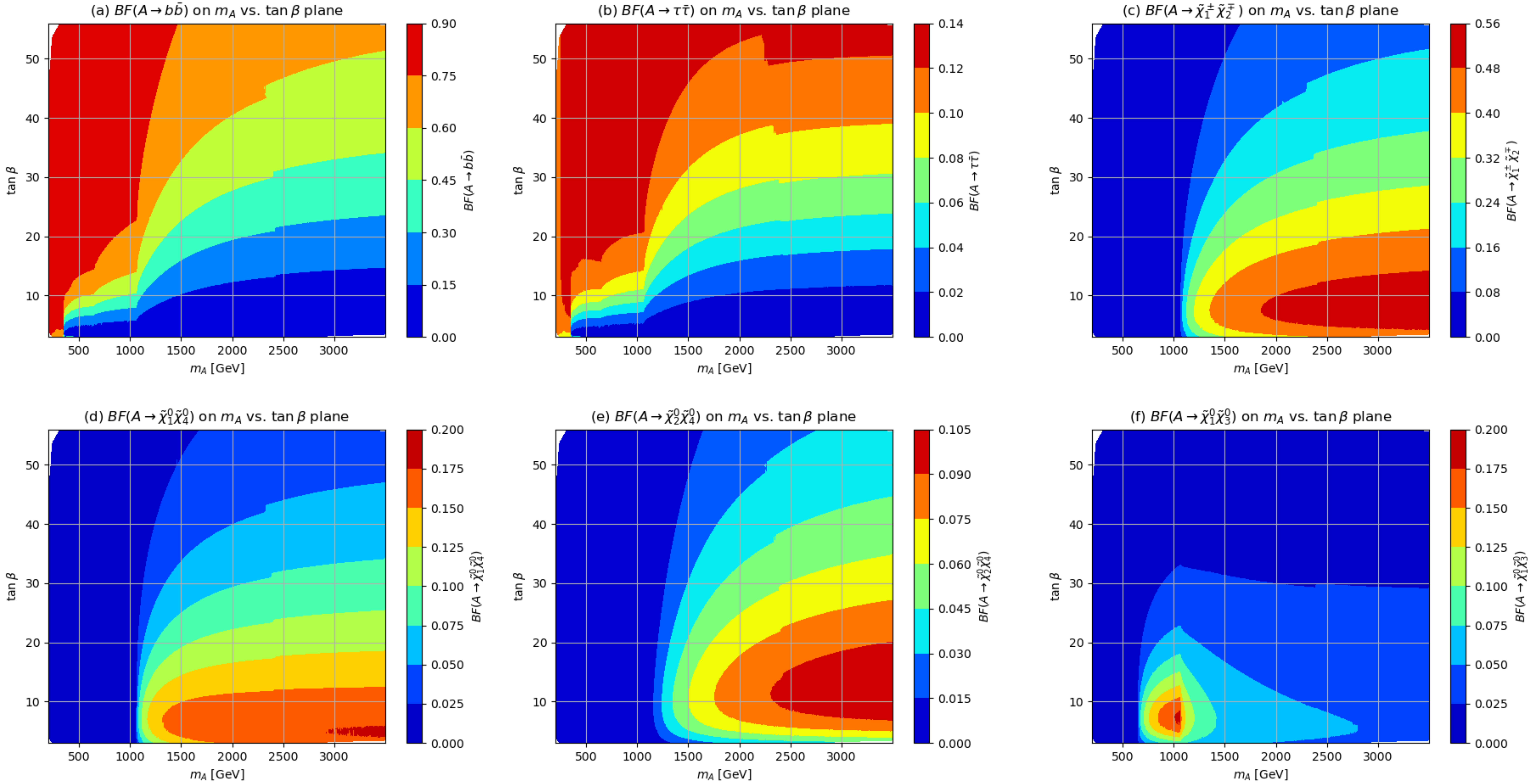
Backup

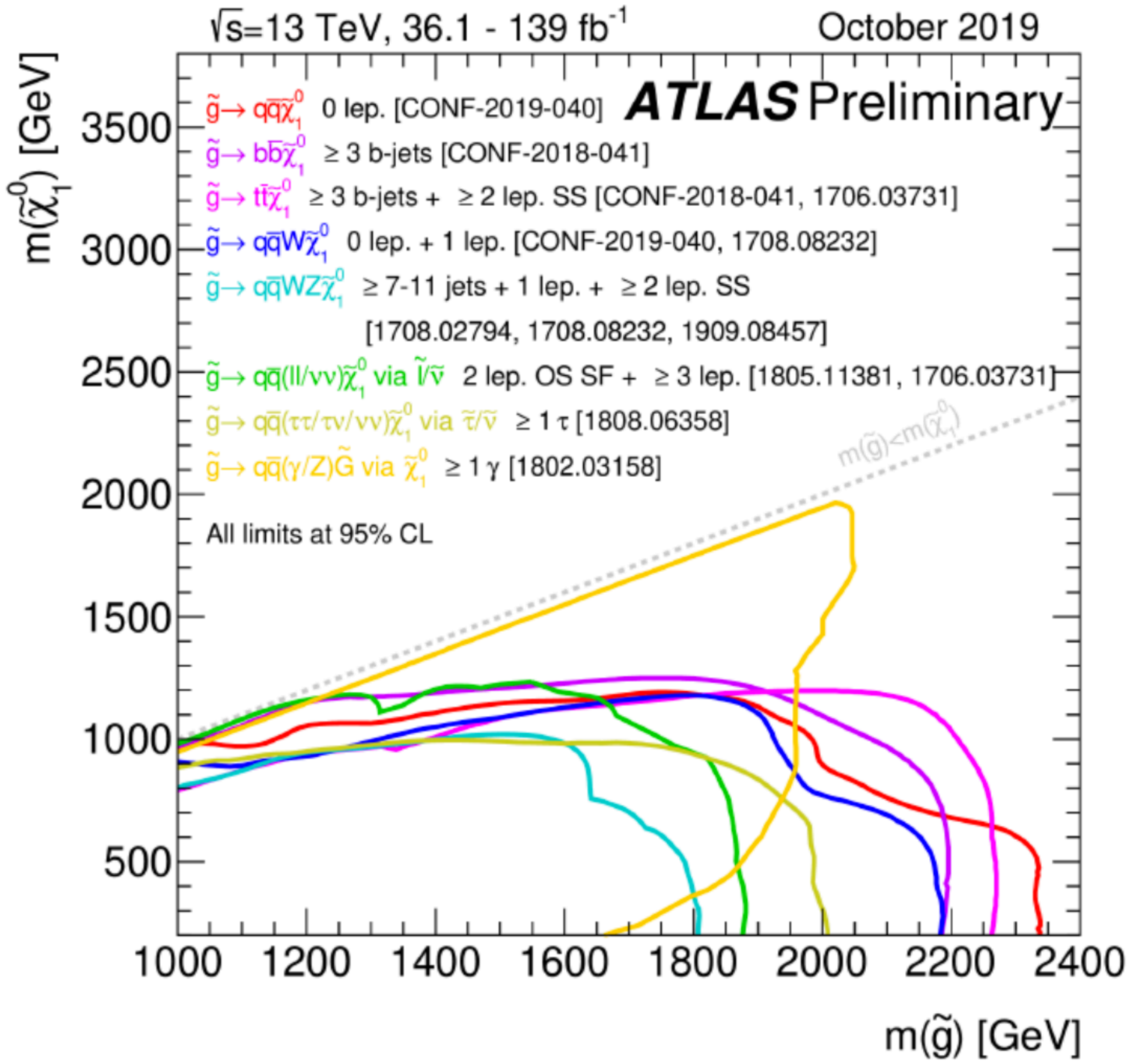

(b) m_A vs. $BF(A \to \tau\bar{\tau})$
0.14
0.12
0.10
0.08
0.06
0.04
0.02
$BF(A \to \tau\bar{\tau})$
1000
2000
3000
4000
5000
m_A [GeV]
$\tan\beta = 10$
$\tan\beta = 40$

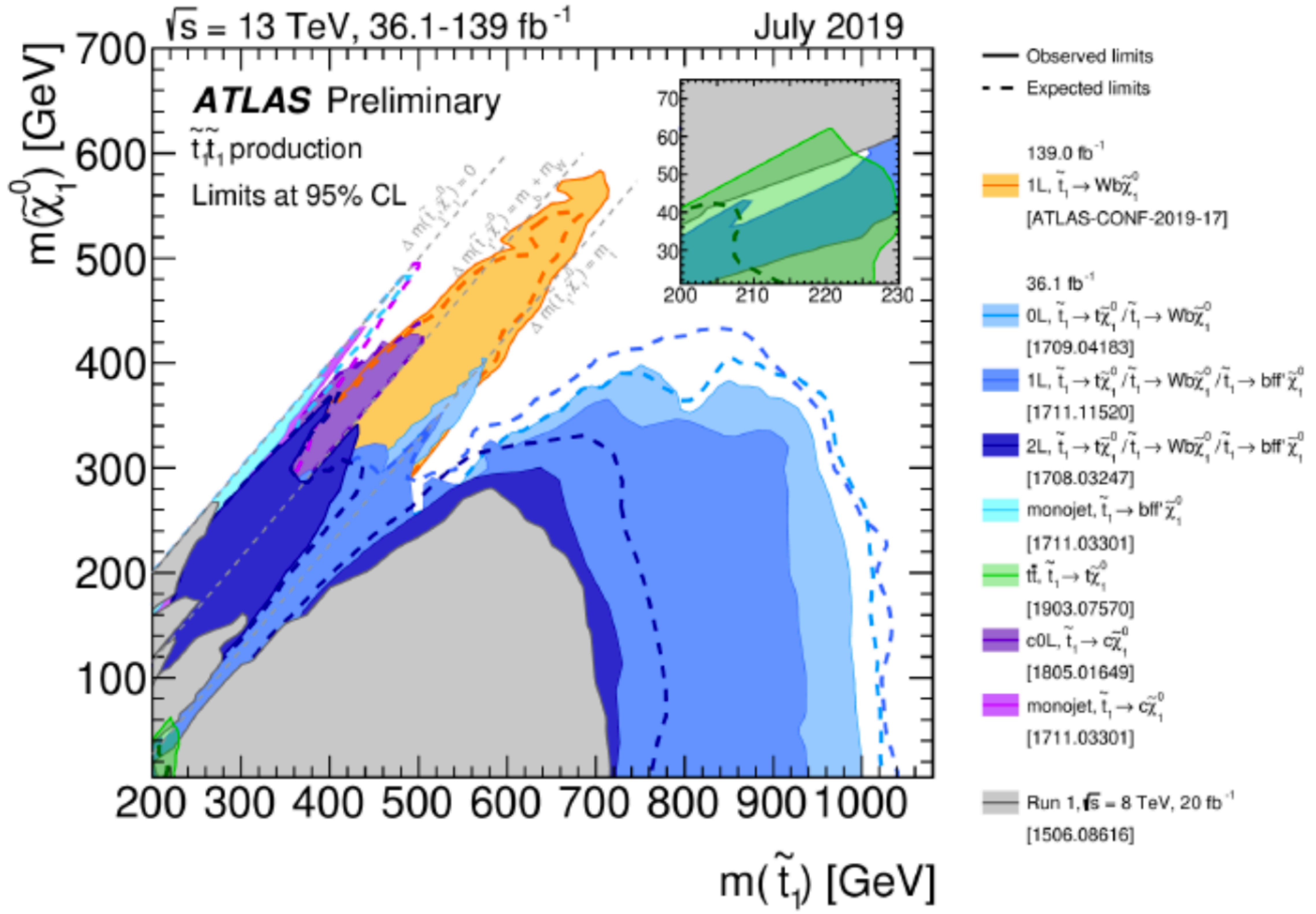




mh~125 GeV, Δ_{EW} <30 will be good!


(a) $BF(A \to b\bar{b})$ on m_A vs. $\tan\beta$ plane
(b) $BF(A \to \tau\bar{\tau})$ on m_A vs. $\tan\beta$ plane
(c) $BF(A \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp})$ on m_A vs. $\tan\beta$ plane
(d) $BF(A \to \tilde{\chi}_1^0\tilde{\chi}_4^0)$ on m_A vs. $\tan\beta$ plane
(e) $BF(A \to \tilde{\chi}_2^0\tilde{\chi}_4^0)$ on m_A vs. $\tan\beta$ plane
(f) $BF(A \to \tilde{\chi}_1^0\tilde{\chi}_3^0)$ on m_A vs. $\tan\beta$ plane
$\tan\beta$
m_A [GeV]
$BF(A \to b\bar{b})$
$BF(A \to \tau\bar{\tau})$
$BF(A \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp})$
$BF(A \to \tilde{\chi}_1^0\tilde{\chi}_4^0)$
$BF(A \to \tilde{\chi}_2^0\tilde{\chi}_4^0)$
$BF(A \to \tilde{\chi}_1^0\tilde{\chi}_3^0)$





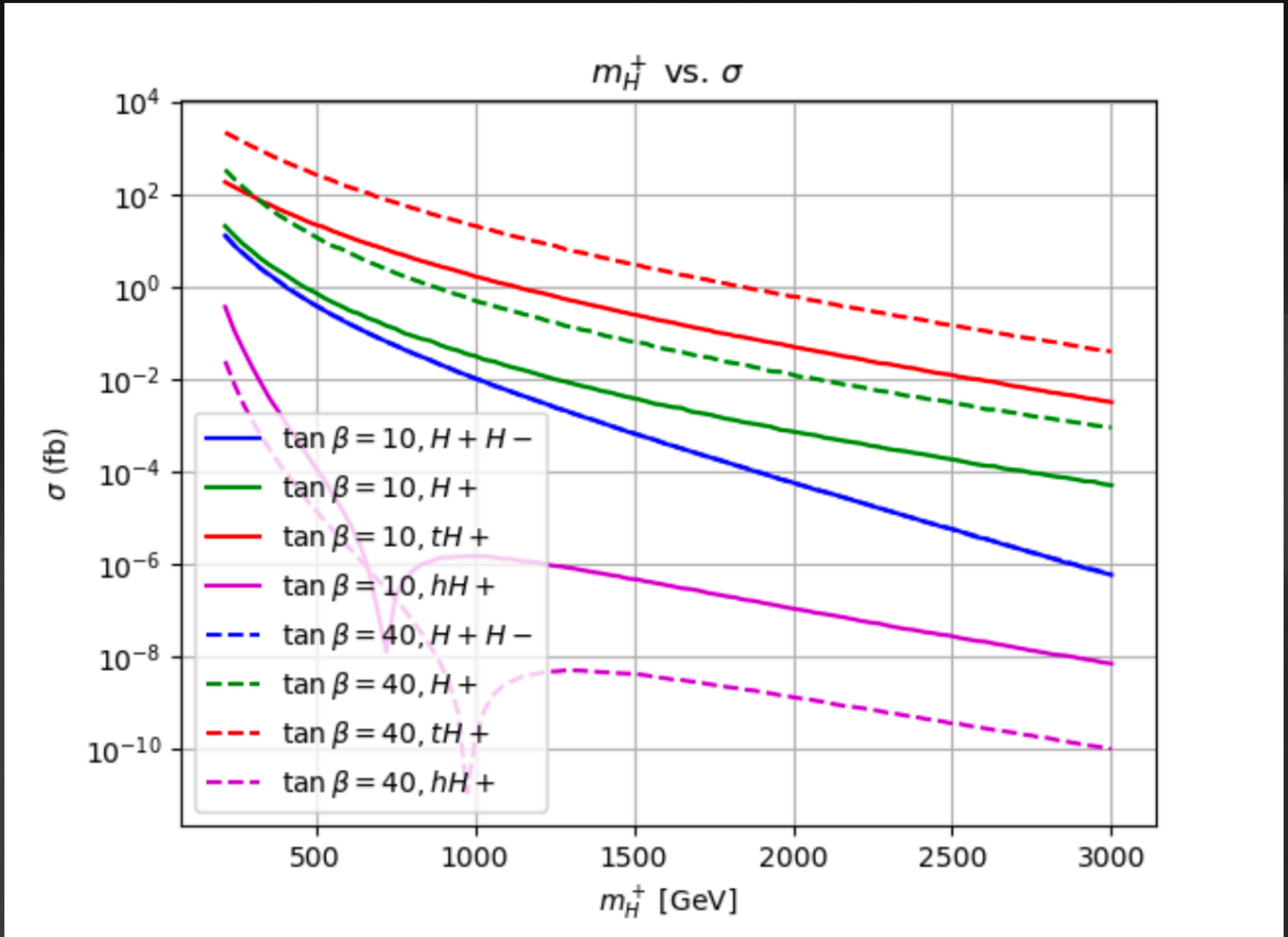
$$m_{\tilde{g}} > 2.25 \text{ TeV}$$

$$m_{\tilde{t}_1} > 1.1 \text{ TeV}$$

Input parameters and mass spectrum for natural SUSY scenario m_h^{125}(nat)

parameter	m_h^{125}(nat)
m_0	5 TeV
$m_{1/2}$	1.2 TeV
A_0	-8 TeV
$\tan\beta$	10
μ	250 GeV
m_A	2 TeV
$m_{\tilde{g}}$	2830 GeV
$m_{\tilde{u}_L}$	5440 GeV
$m_{\tilde{u}_R}$	5561 GeV
$m_{\tilde{e}_R}$	4822 GeV
$m_{\tilde{t}_1}$	1714 GeV
$m_{\tilde{t}_2}$	3915 GeV
$m_{\tilde{b}_1}$	3949 GeV
$m_{\tilde{b}_2}$	5287 GeV
$m_{\tilde{\tau}_1}$	4746 GeV
$m_{\tilde{\tau}_2}$	5110 GeV
$m_{\tilde{\nu}_\tau}$	5107 GeV
$m_{\tilde{\chi}_1^\pm}$	261.7 GeV
$m_{\tilde{\chi}_2^\pm}$	1020.6 GeV
$m_{\tilde{\chi}_1^0}$	248.1 GeV
$m_{\tilde{\chi}_2^0}$	259.2 GeV
$m_{\tilde{\chi}_3^0}$	541.0 GeV
$m_{\tilde{\chi}_4^0}$	1033.9 GeV
m_h	124.7 GeV
$\Omega_{\tilde{z}_1}^{std}h^2$	0.016
$BF(b\to s\gamma)\times 10^4$	3.1
$BF(B_s\to\mu^+\mu^-)\times 10^9$	3.8
$\sigma^{SI}(\tilde{\chi}_1^0,p)$ (pb)	2.2×10^{-9}
$\sigma^{SD}(\tilde{\chi}_1^0,p)$ (pb)	2.9×10^{-5}
$\langle\sigma v\rangle\|_{v\to 0}$ (cm^3/sec)	1.3×10^{-25}
$\Delta_{\rm EW}$	22

Inputs for NUHM2 model with mt = 173.2 GeV using Isajet 7.88,
we then scan through m_A, tan(β).


m_H^+ vs. σ
σ (fb)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
500
1000
1500
2000
2500
3000
m_H^+ [GeV]
$\tan\beta = 10, H+H-$
$\tan\beta = 10, H+$
$\tan\beta = 10, tH+$
$\tan\beta = 10, hH+$
$\tan\beta = 40, H+H-$
$\tan\beta = 40, H+$
$\tan\beta = 40, tH+$
$\tan\beta = 40, hH+$