Seeing H,A-> SUSY in natural SUSY at FCC-hh

H. Baer, V. Barger, R. Jain, C. Kao, D. Sengupta and X. Tata
arXiv:2112.02232

Why FCC-hh is the right machine for future of HEP and CERN

- Regarding colliders, energy (almost) always wins for discovery
- Expanding tunnel from 27km -> 100 km is most conservative option
- If magnet development 8 T -> 16 T fails (magnet reliability over 5-30 years), can still place reliable 8T magnets in new tunnel and get a 50 TeV collider :)
- If magnet development succeeds, then get 75-100 TeV!
- To discover gluinos, stops: need sqrt(s)>~30 TeV in natural SUSY (DEW<30)

HB, Barger, Gainer, Sengupta, Serce, Tata, arXiv:1808.04844

Status of SUSY in the 21st century

- 20th century: expect m(sparticles)~ m(W)~100 GeV (naturalness)

- computed finetuning in models like mSUGRA/CMSSM: BUT EFT parameters correlated in more UV-complete models e.g. strings: finetuning overestimated by large factors 10-100

  HB, Barger, Mickelson, arXiv:1309.2984

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

- EW naturalness measure: parameter free, depends only on spectra

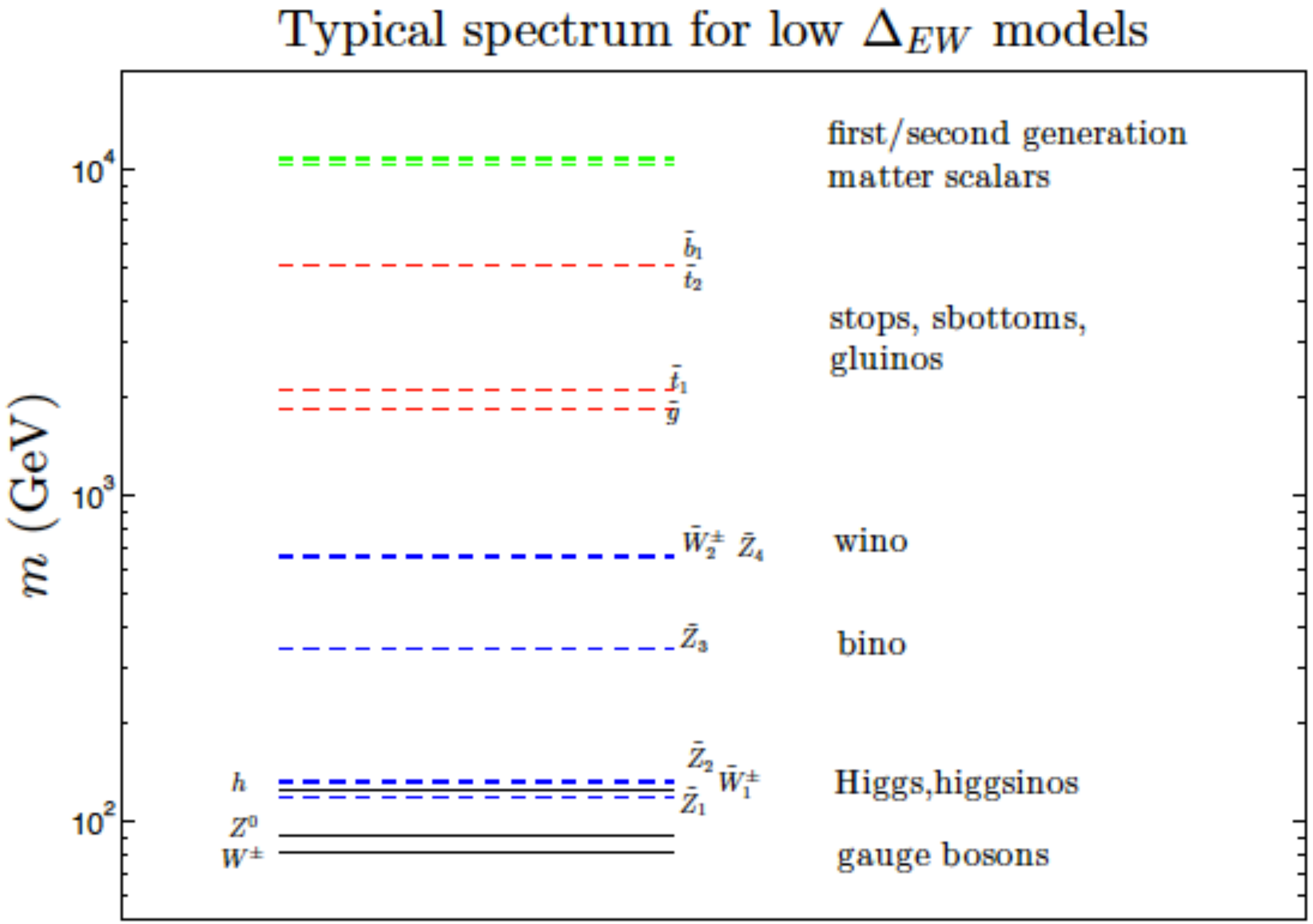
  HB, Barger, Huang, Mustafayev, Tata, PRL109 (2012) 161802

- mu is SUSY conserving: 100-350 GeV => light higgsinos! ; m(gluino)<~6 TeV

- understand Cosm. Constant (Weinberg 1987); emergence of string landscape as manifest in eternally inflating multiverse (Bousso&Polchinski 2000, Susskind, Douglas et al, KKLT, 2000-2005)

- In landscape, statistical draw to large soft terms (Douglas; Susskind; Arkani-Hamed, Dimop, Kachru)

- Tempered by need for pocket universe weak scale ~ our weak scale 100-350 GeV (Agrawal, Barr, Donoghue, Seckel, 1997)



There is a Little Hierarchy, but it is no problem

$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

SUSY predictions from string landscape

dN_vac~msoft^n * f_EWSB

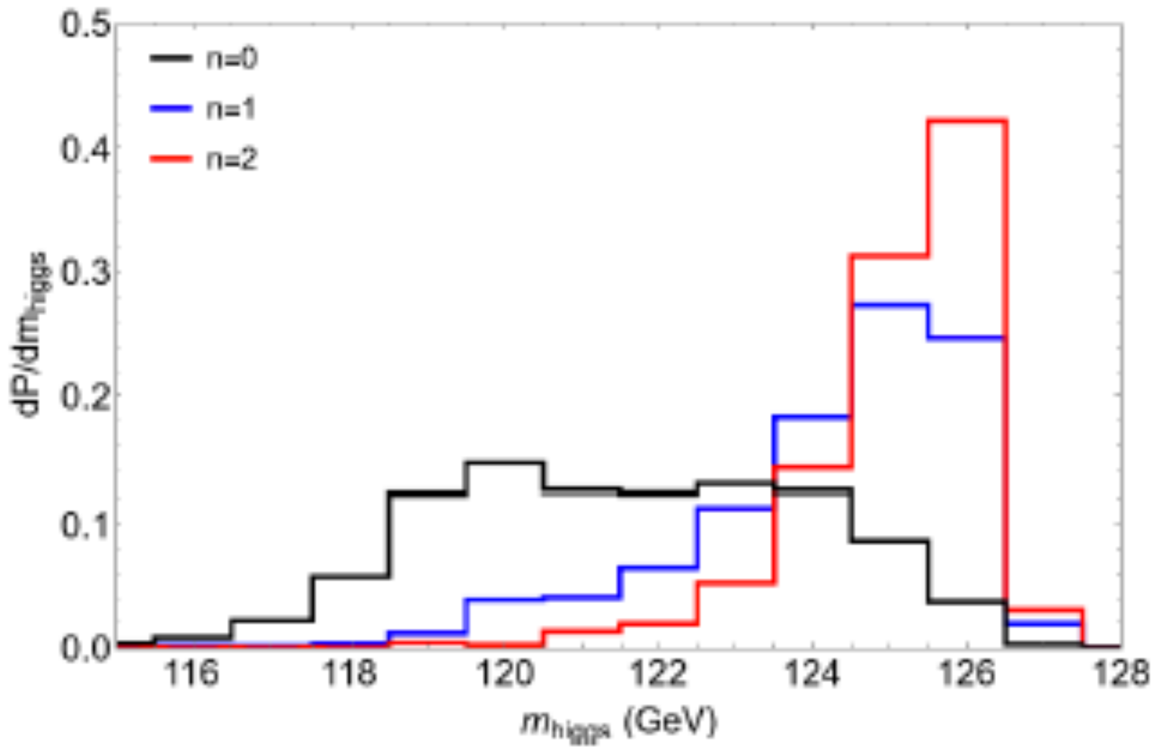


FIG. 18: Distribution in m_h after requiring the anthropic selection of $m_{weak} < 350$ GeV.

pull A0 to maximal mixing

m(h)~125 GeV

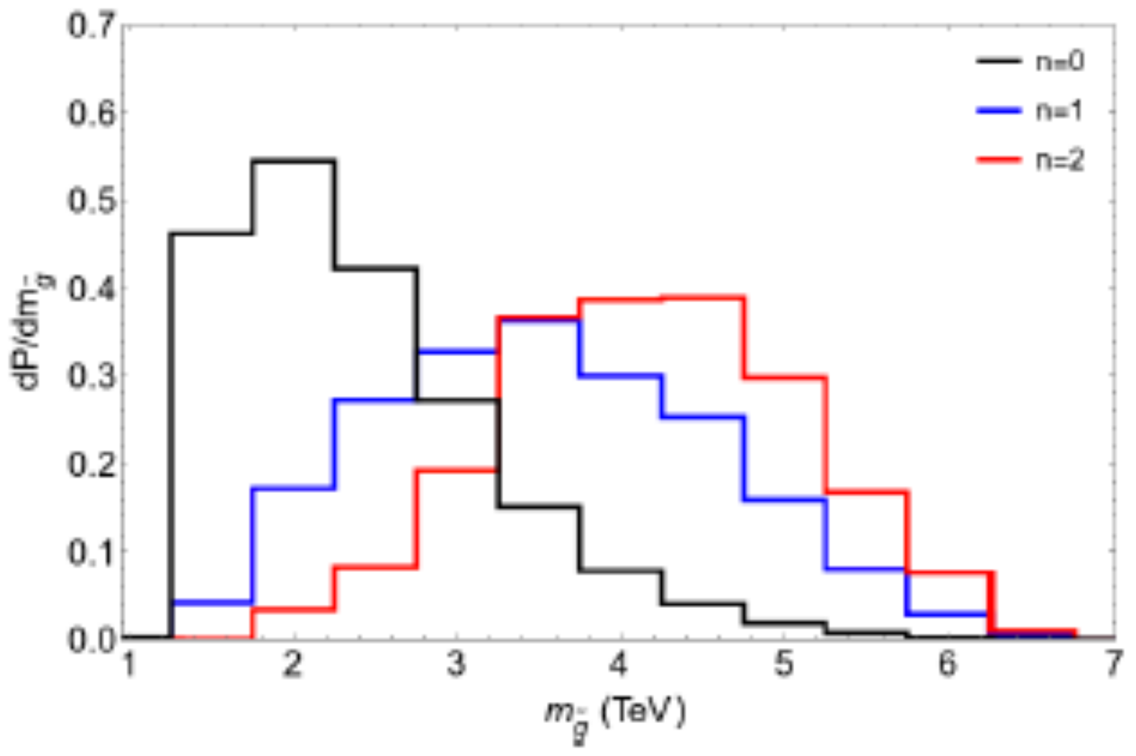
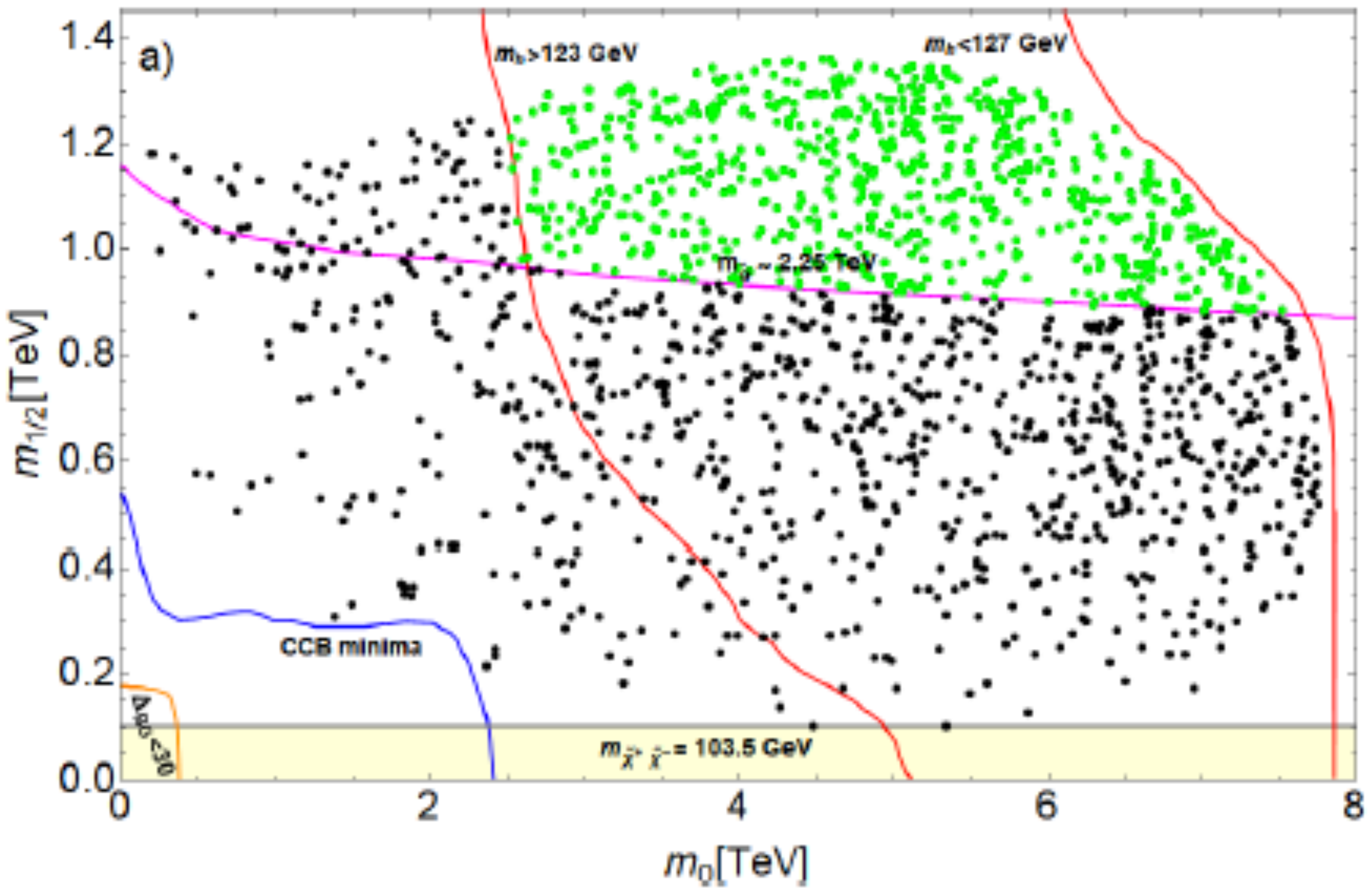


FIG. 19: Distribution in $m_{\tilde{g}}$ after requiring the anthropic selection of $m_{weak} < 350$ GeV.

m(glno)>2 TeV

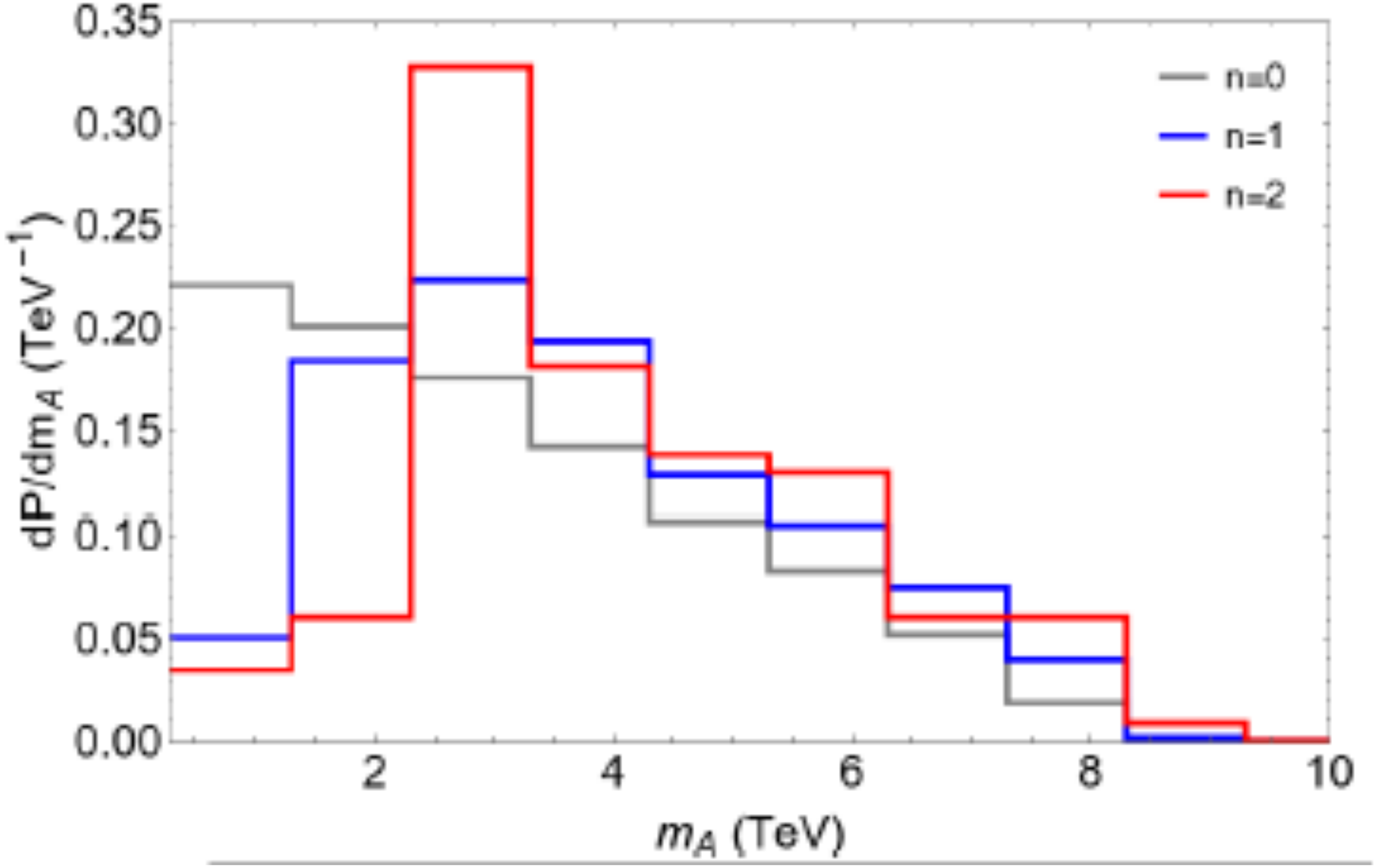
HB, Barger, Serce, Sinha, 2017



more stringy natural-
greater density of points:
heavy sparticles favored so long as mZ^PU<~4*mZ^OU

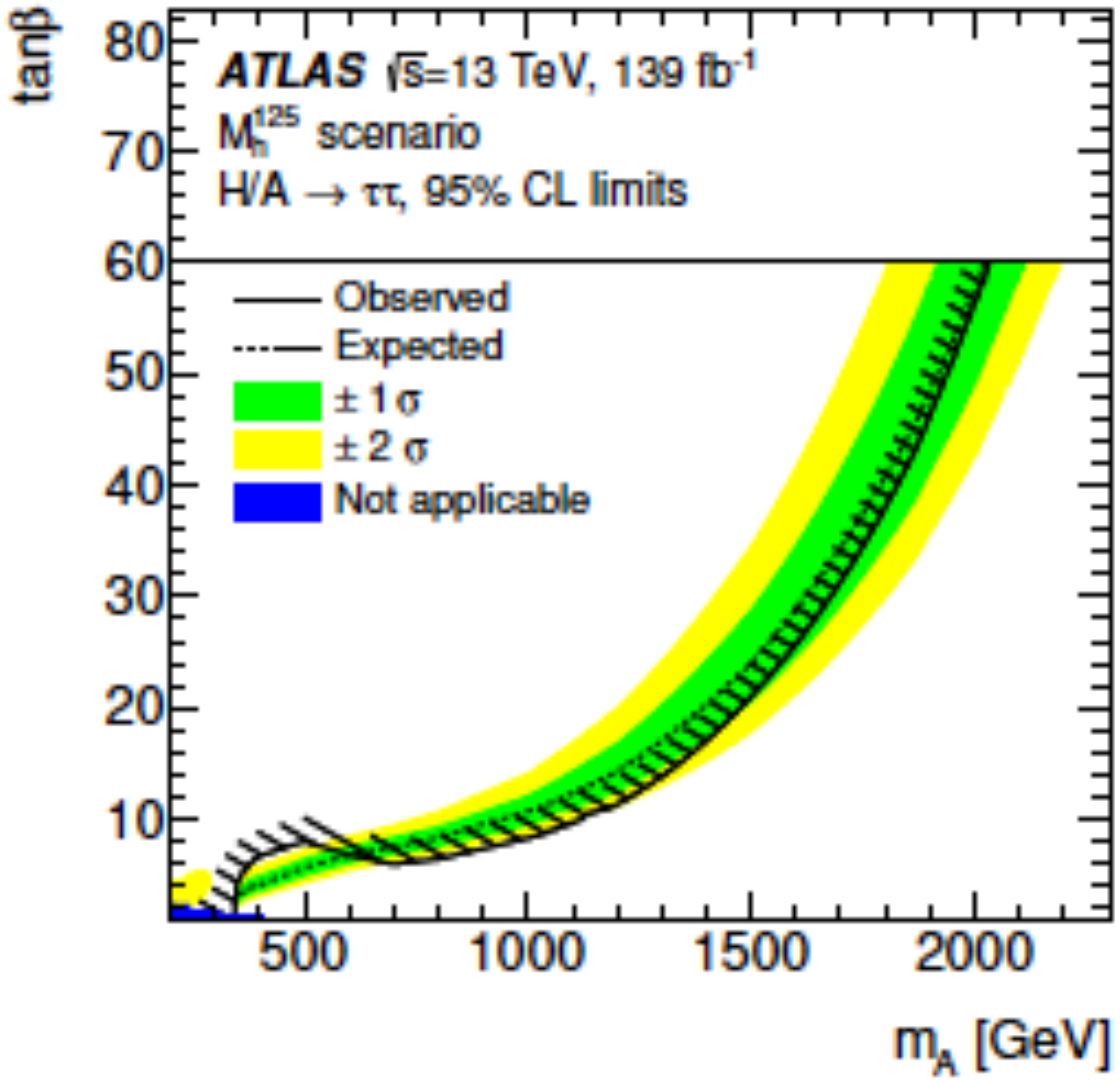
HB, Barger, Salam, 2019

What about SUSY Higgs bosons?



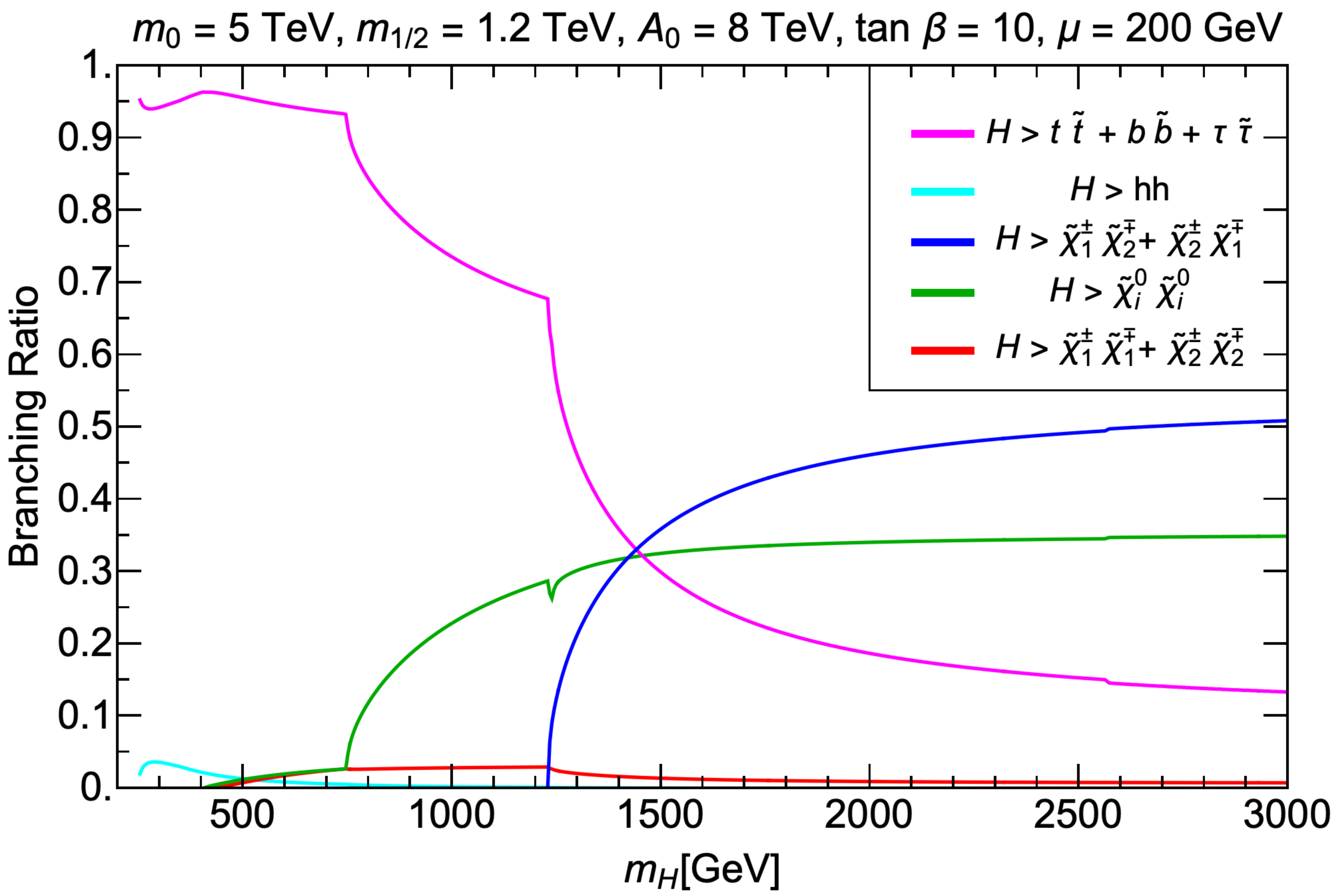
m(A,H)~ 1-8 TeV so decays to SUSY should be open

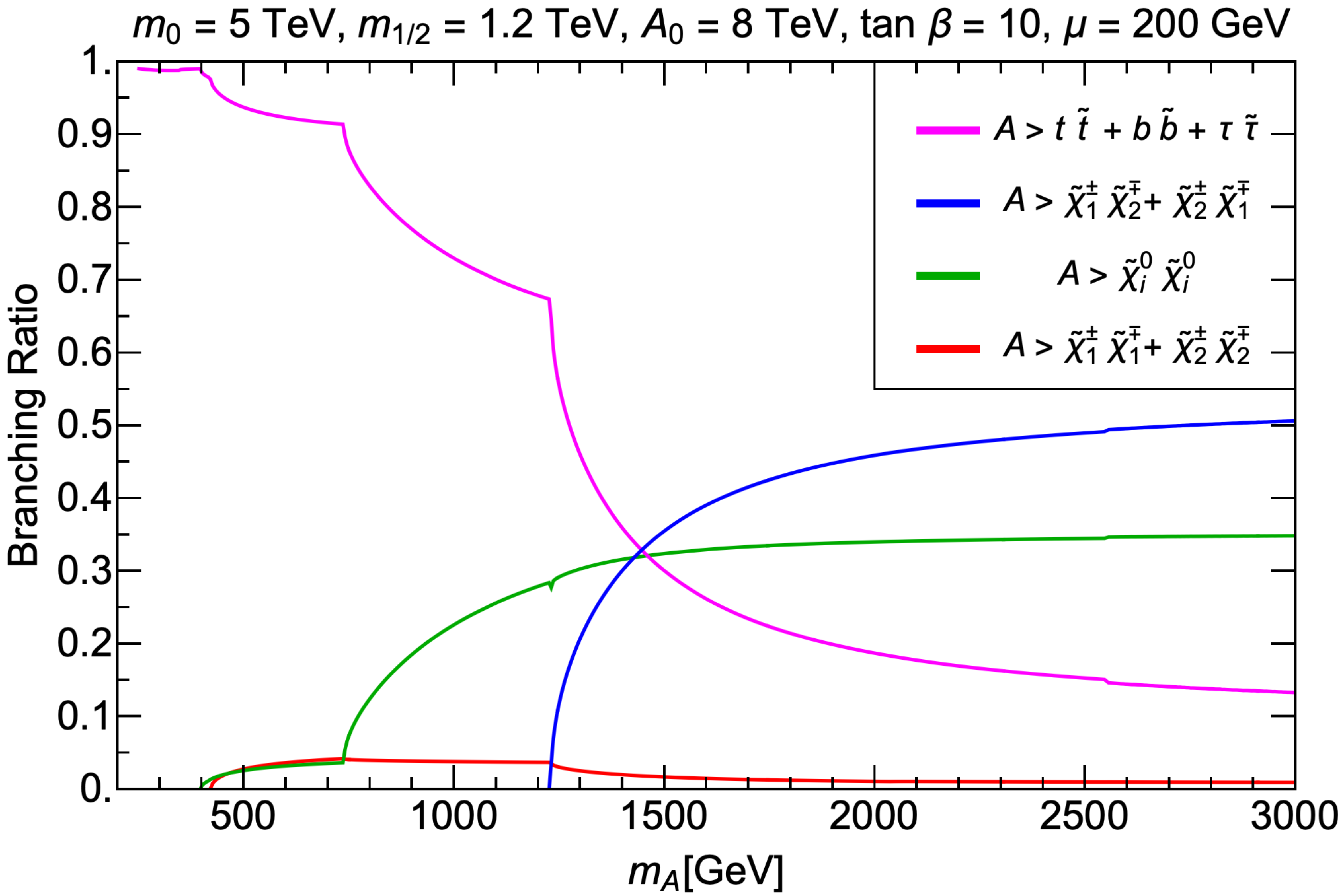
Best heavy Higgs discovery mode
-> tau+taubar



ATLAS: m(H,A)>~1 TeV for tanb~10

H, A -> natSUSY BFs





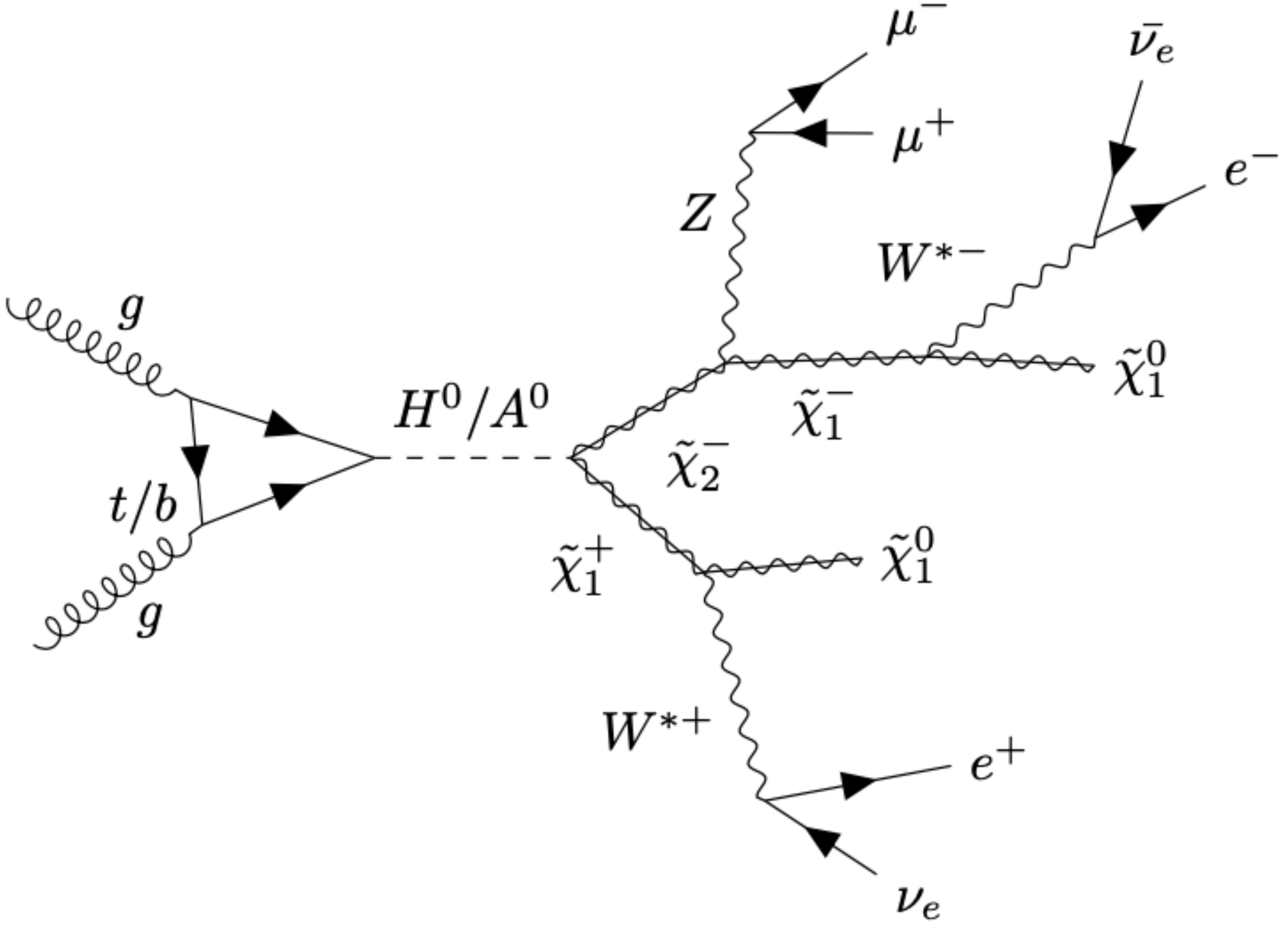
$$\mathcal{L} \ni -\sqrt{2}\sum_{i,A} \mathcal{S}_i^\dagger g t_A \bar{\lambda}_A \frac{1-\gamma_5}{2}\psi_i + h.c.$$

dominant decay modes once kinematically allowed: H,A -> gaugino+higgsino,

*SUSY modes reduce H,A-> SM modes

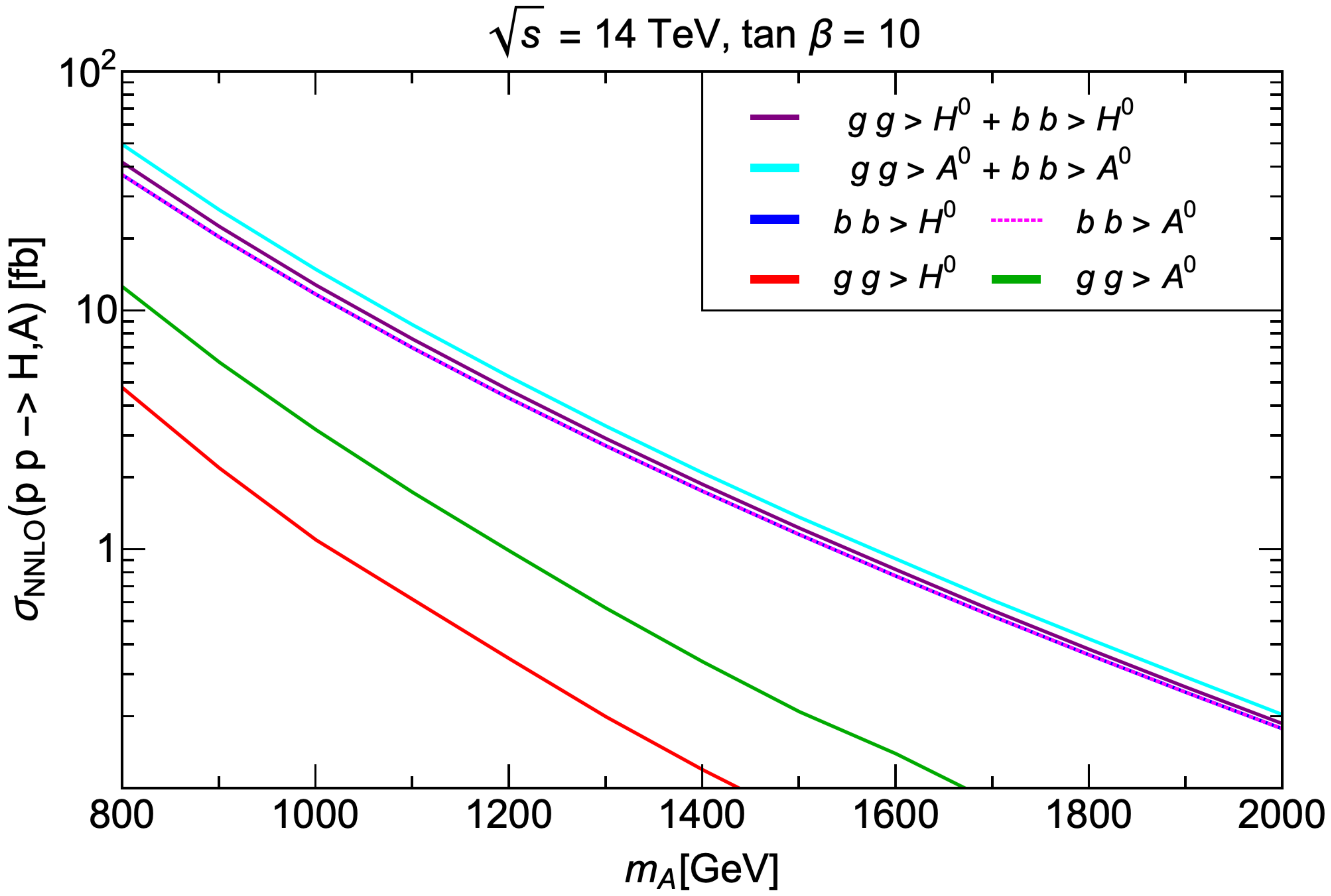
*but new discovery possibilities arise

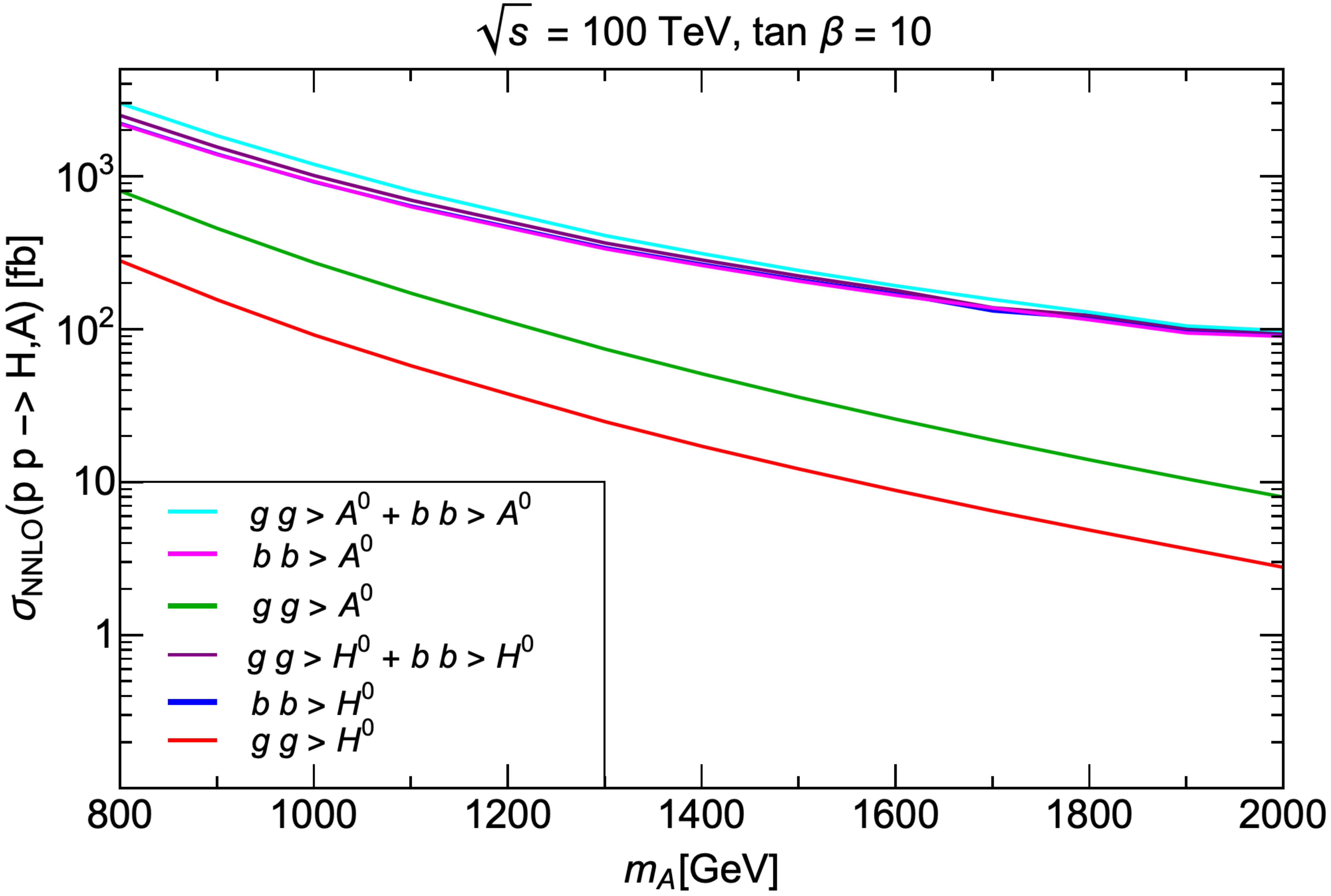
Can we see H,A-> SUSY at hadron colliders?



real Z->llbar plus 2 softer leptons+MET

gg,bbbar fusion cross sections

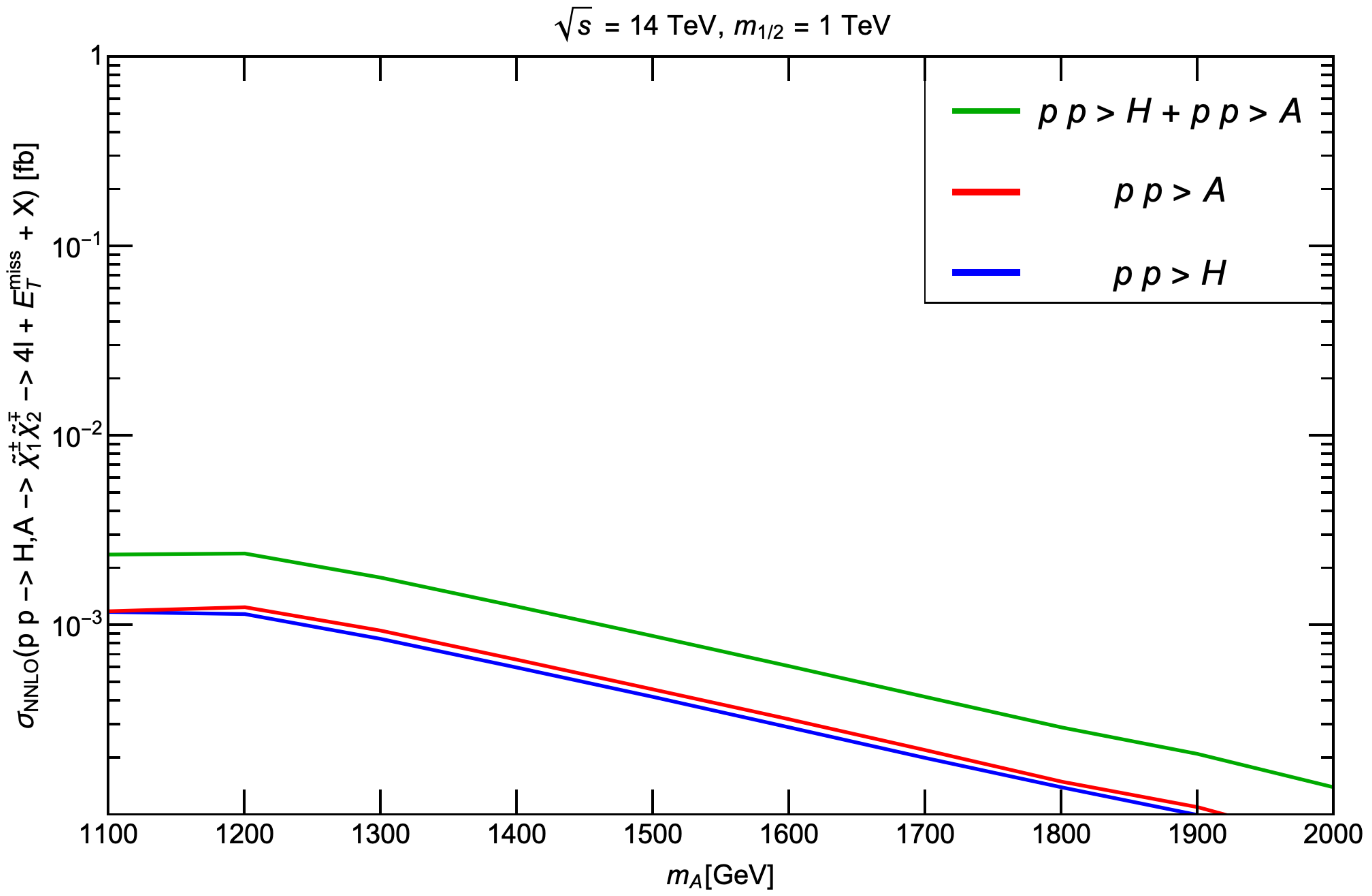


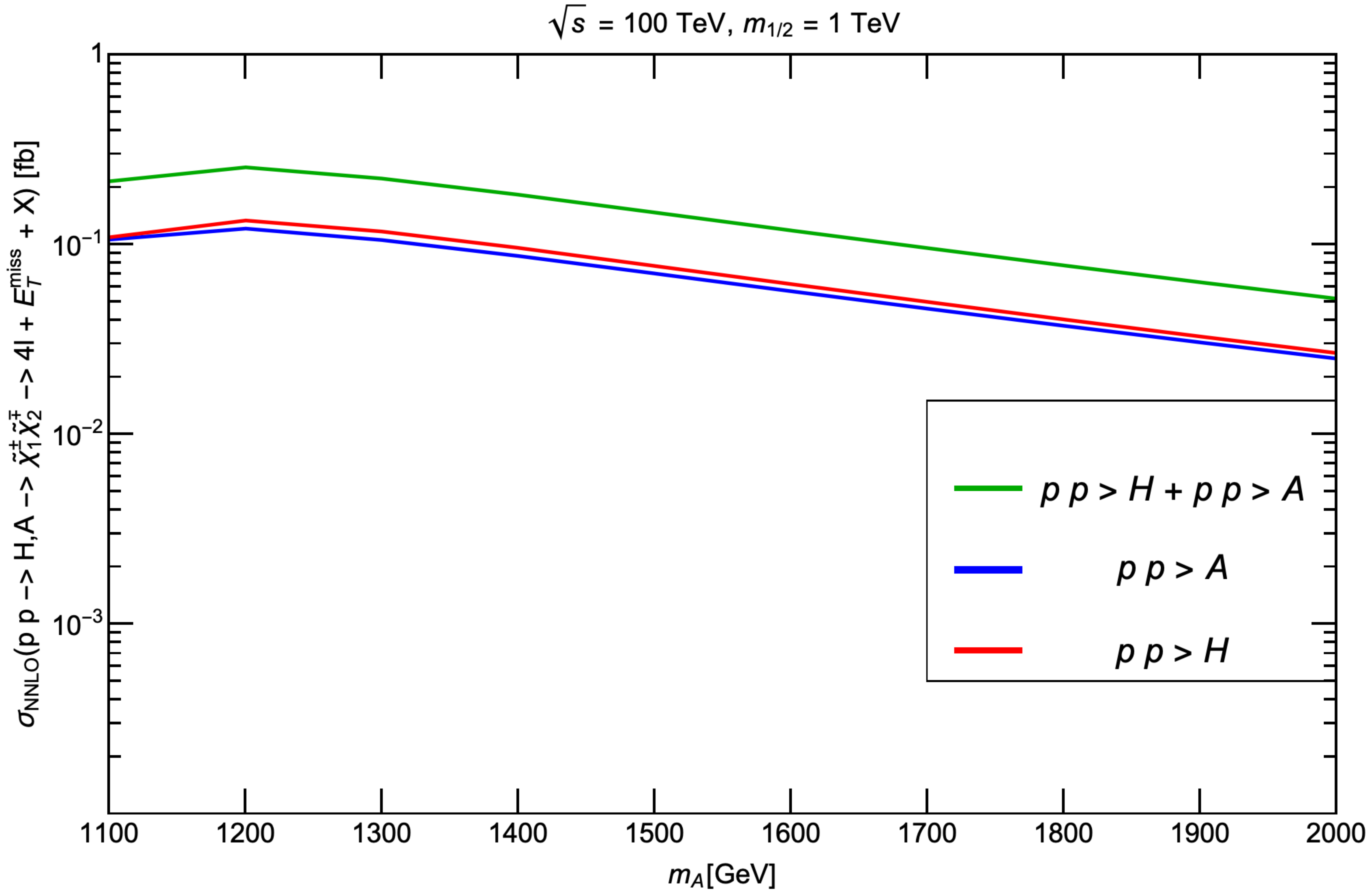


probably need FCC-hh to do the job; rates too low at HL-LHC

total cross sections jump by ~75-200 in moving from 14->100 TeV

fold in BFs to 4-lepton final states (but no cuts yet)





rates for pp-> H,A -> 4l+MET pretty low at 14 TeV; need FCC-hh

various cuts for m(H,A)~1 TeV

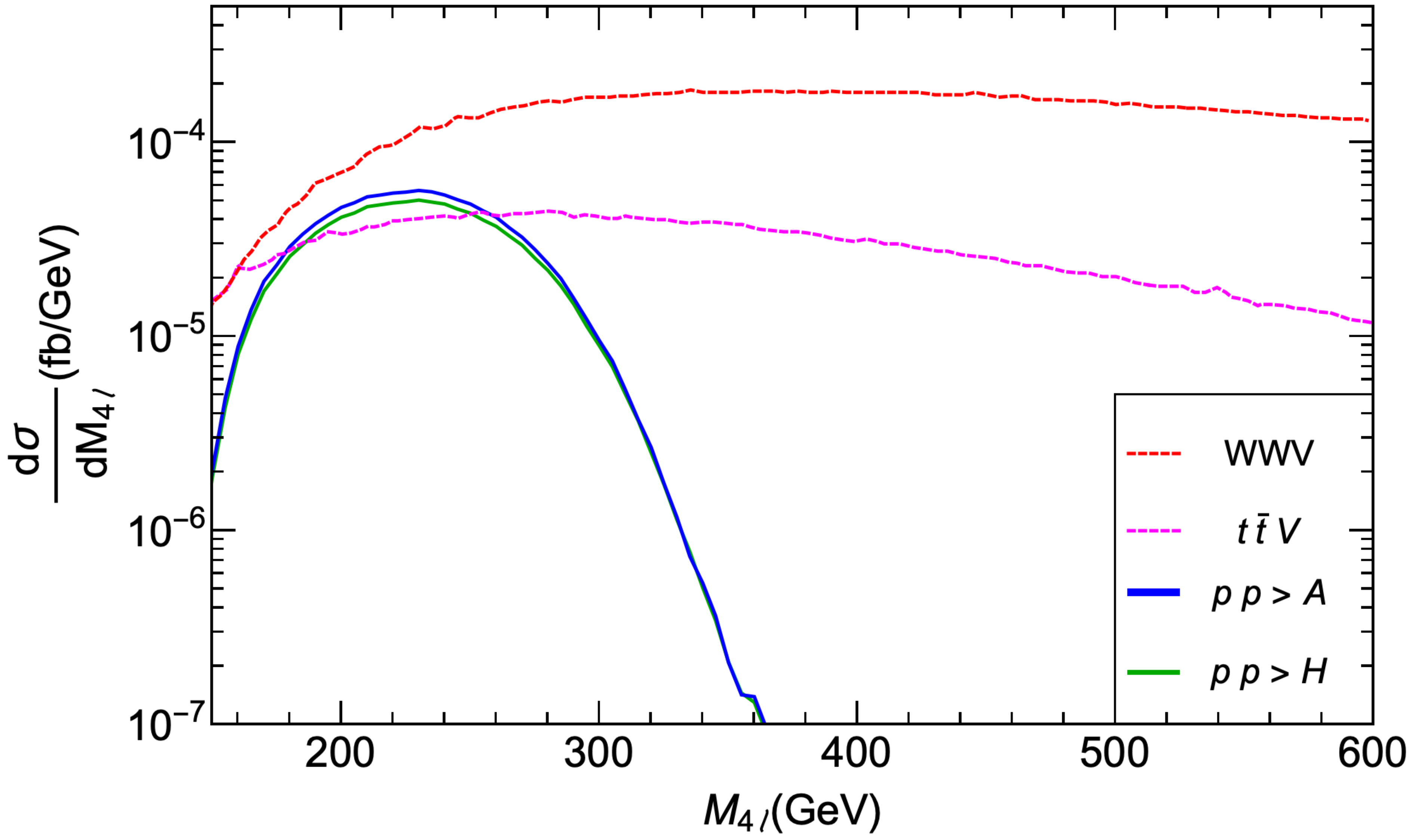
BGs: WWV, ttbarV, Zh, ZZV (V=W,Z,gamma^*)

- p_T $(\ell_1, \ell_2, \ell_3, \ell_4) > 20$ GeV, 10 GeV, 10 GeV, 10 GeV;
- $|\eta|$ $(\ell_1, \ell_2, \ell_3, \ell_4) < 2.5$.

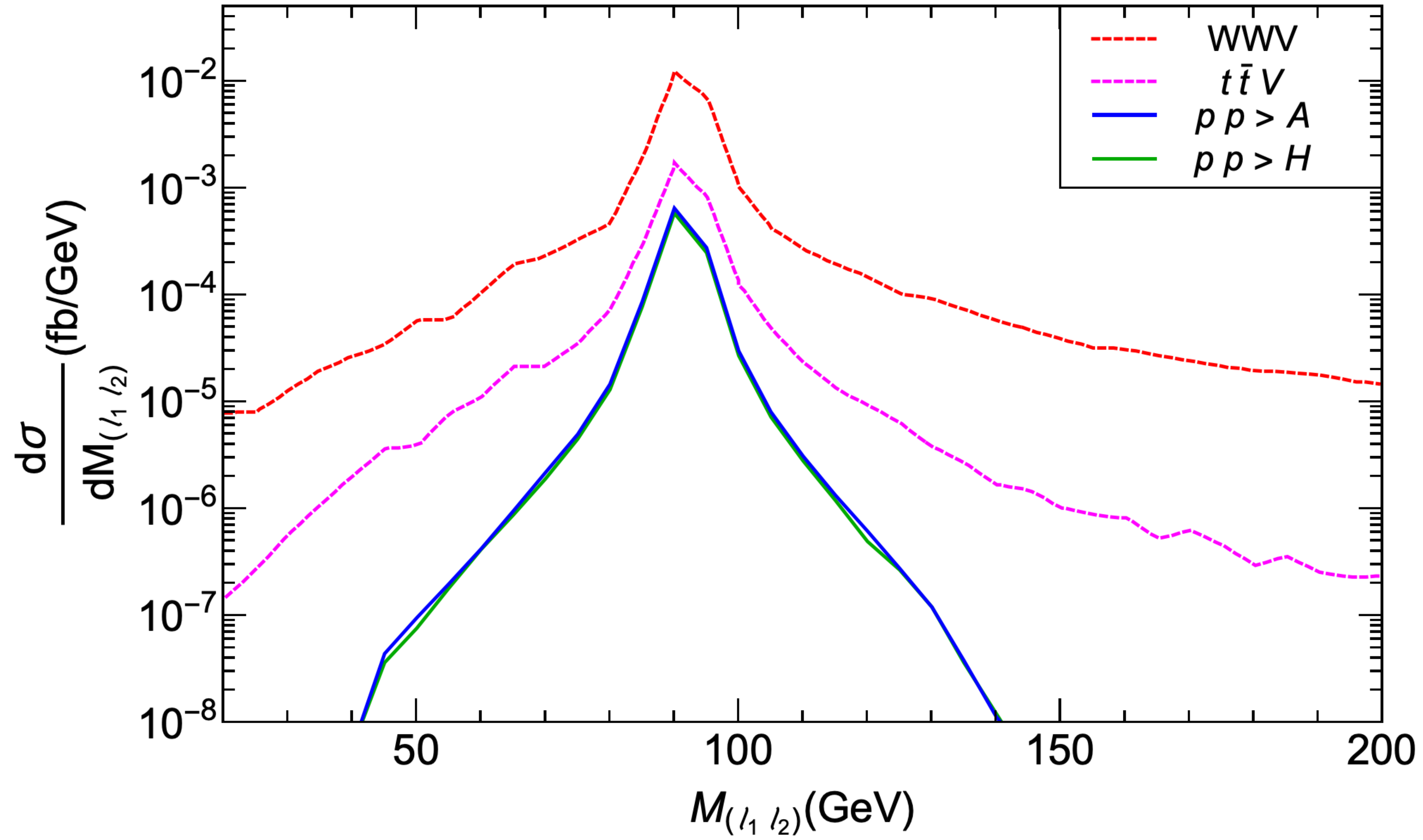
cut set A

- Veto events with b-jets p_T (jet) > 20 GeV and $|\eta|$ (jet) < 2.5 as already mentioned;
- $\Delta_R(j, \ell) > 0.4$, where j denotes a b-quark with $p_T < 20$ GeV or with $|\eta_b| > 0.4$, to mimic lepton isolation;
- Invariant mass for two opposite sign same flavor leptons $m_{\ell^+\ell^-} > 10$ GeV, to reduce the background from $\gamma^* \to \ell\bar{\ell}$;
- $\not{E}_T > 125$ GeV.

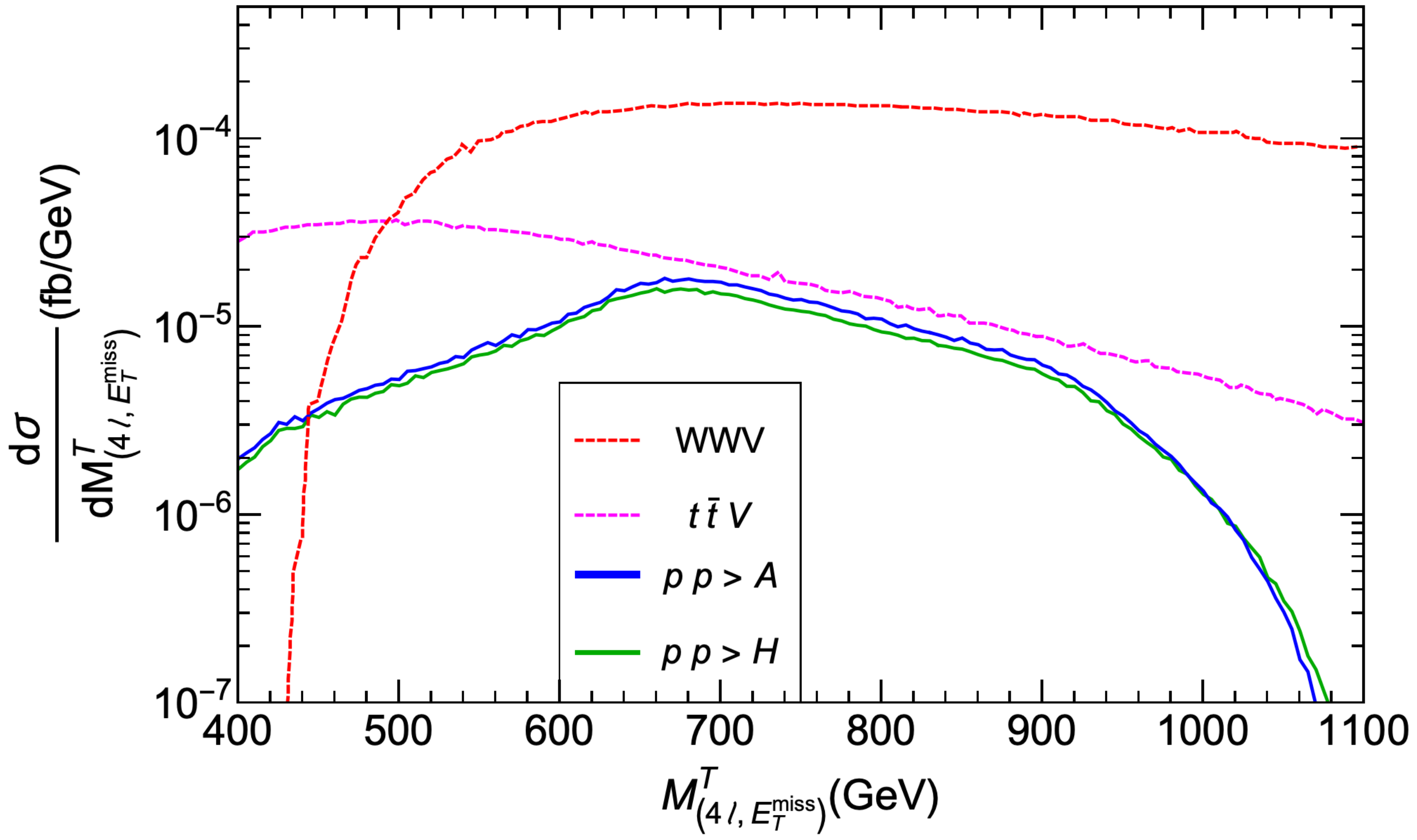
(c) $\sqrt{s}$ = 100 TeV



(a) $\sqrt{s}$ = 100 TeV



(d) $\sqrt{s}$ = 100 TeV



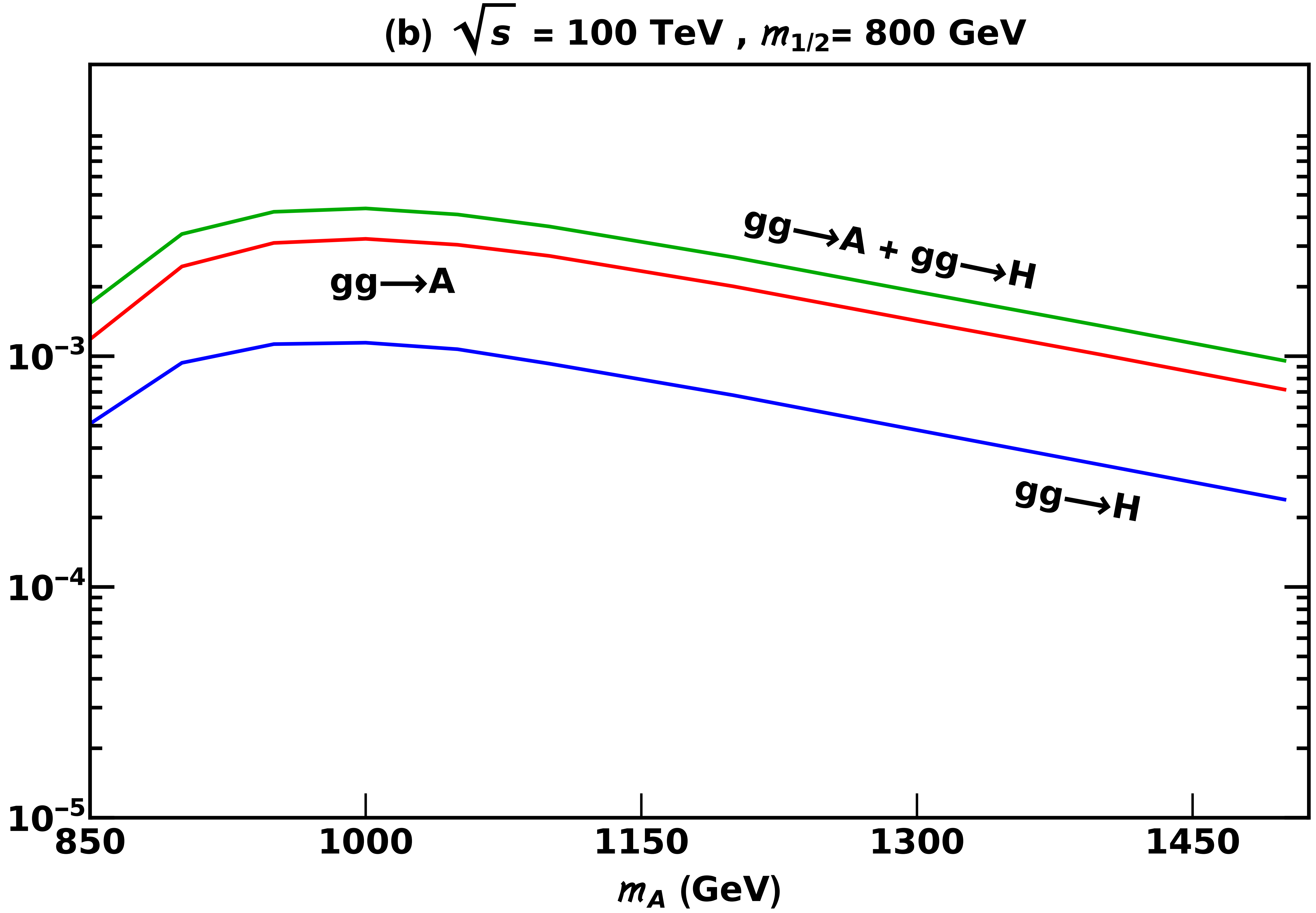
cuts motivated by distributions

- We define ℓ_1 and ℓ_2 as the two leptons whose invariant mass is closest to M_Z and require $|M(\ell_1, \ell_2) - M_Z| < 10$ GeV since the signal includes one Z boson;[6]
- $10 < M(\ell_3, \ell_4) < 75$ GeV, where ℓ_3 and ℓ_4 denotes the remaining leptons.
- $0.14 m_A < M(4\ell) < 0.34 m_A$
- $\not{E}_T > 200$ GeV.

cut set B

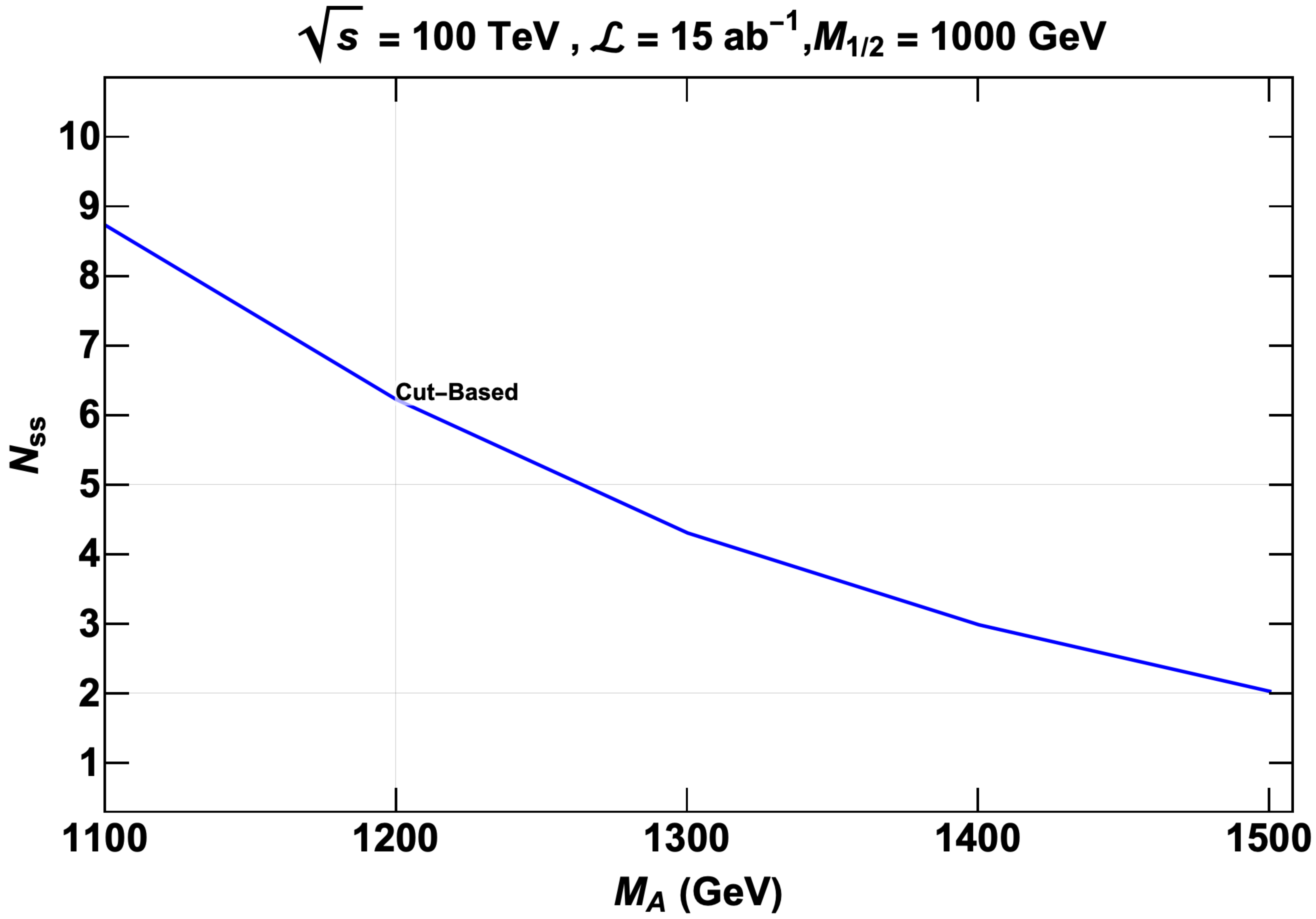
(get mA from e.g. H,A -> tautaubar)

sigma after cut set B (fb)



cut based analysis

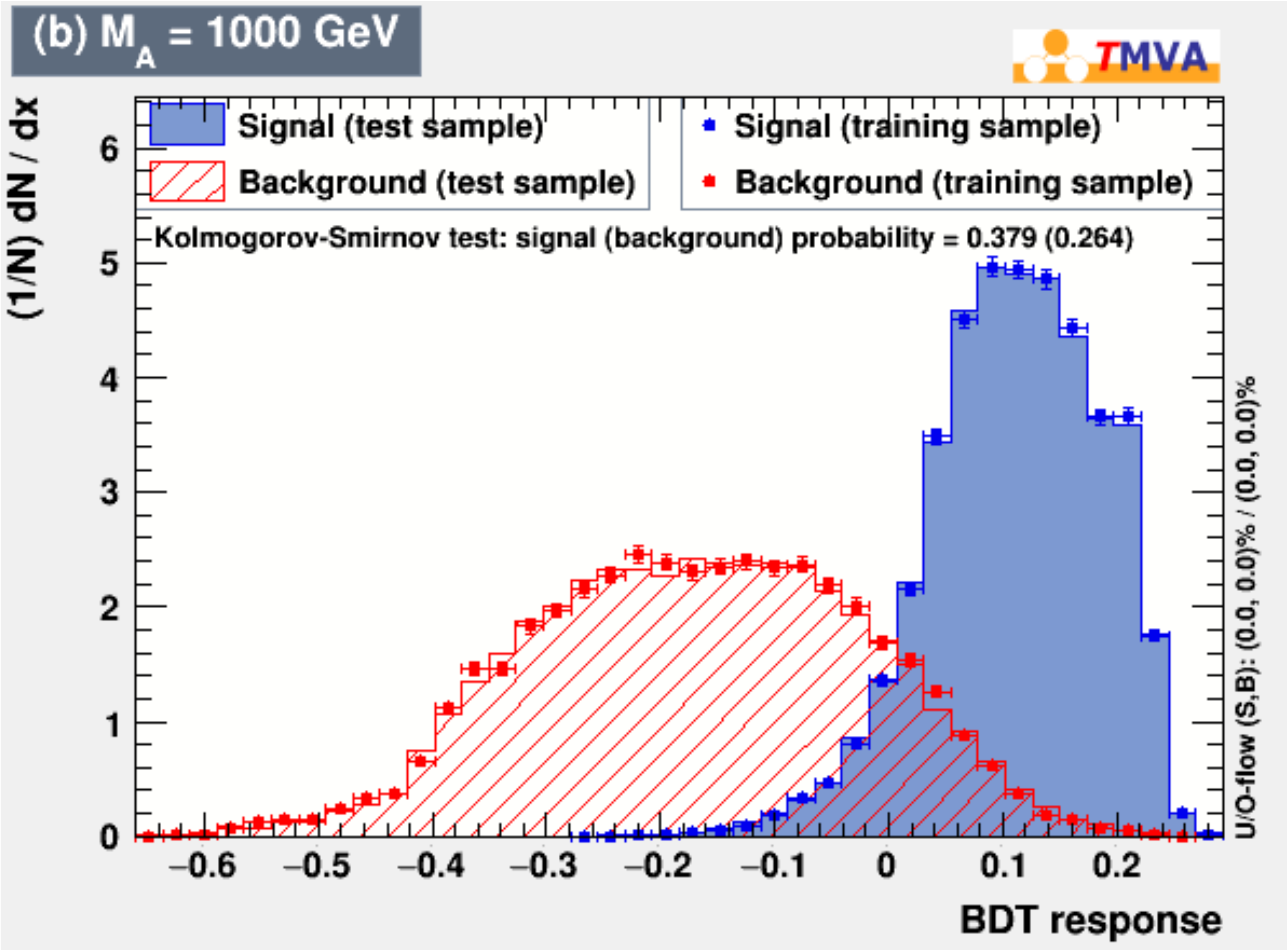
statistical significance

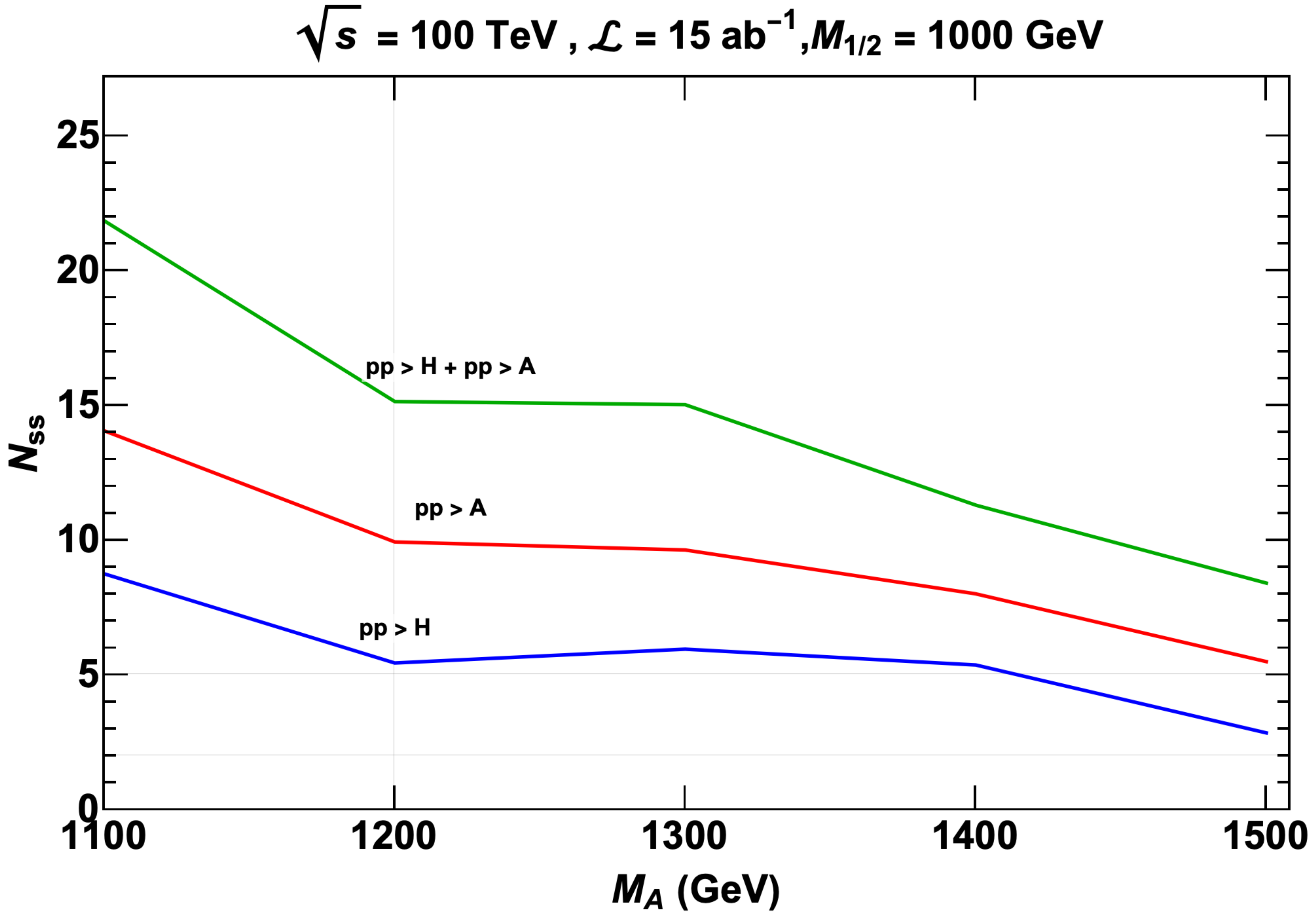


5-sigma reach to m(H,A)~1250 GeV

(gg,bb -> H,A)

boosted decision tree analysis (BDT)





(gg,bbbar -> H,A)

(works better than our conventional cuts)

conclusions

- natural SUSY from landscape: m(h)~125 GeV and sparticles beyond LHC reach
- maybe discover SUSY at HL-LHC via light higgsinos: soft dilepton analysis
- otherwise, need hadron collider energy upgrade: sqrt(s)>30 TeV
- FCC-hh most conservative: sqrt(s)~50-100 TeV
- in addition to sparticle/heavy Higgs discovery, can see H,A -> SUSY via 4l+MET cascade decays to gaugino+higgsino states
- can see 4l+MET signature over range m(H,A)~800-1200 GeV; more using BDT

Backup slides

#1: Simplest SUSY measure: Δ_{EW}

No large uncorrelated cancellations in m(Z) or m(h)

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

$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200$ GeV at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200$ GeV

CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

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PRL109 (2012) 161802

High scale (HS, stop mass) measure

$$m_h^2 \simeq \mu^2 + m_{H_u}^2(weak) = \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/m_{SUSY}^2\right)$$

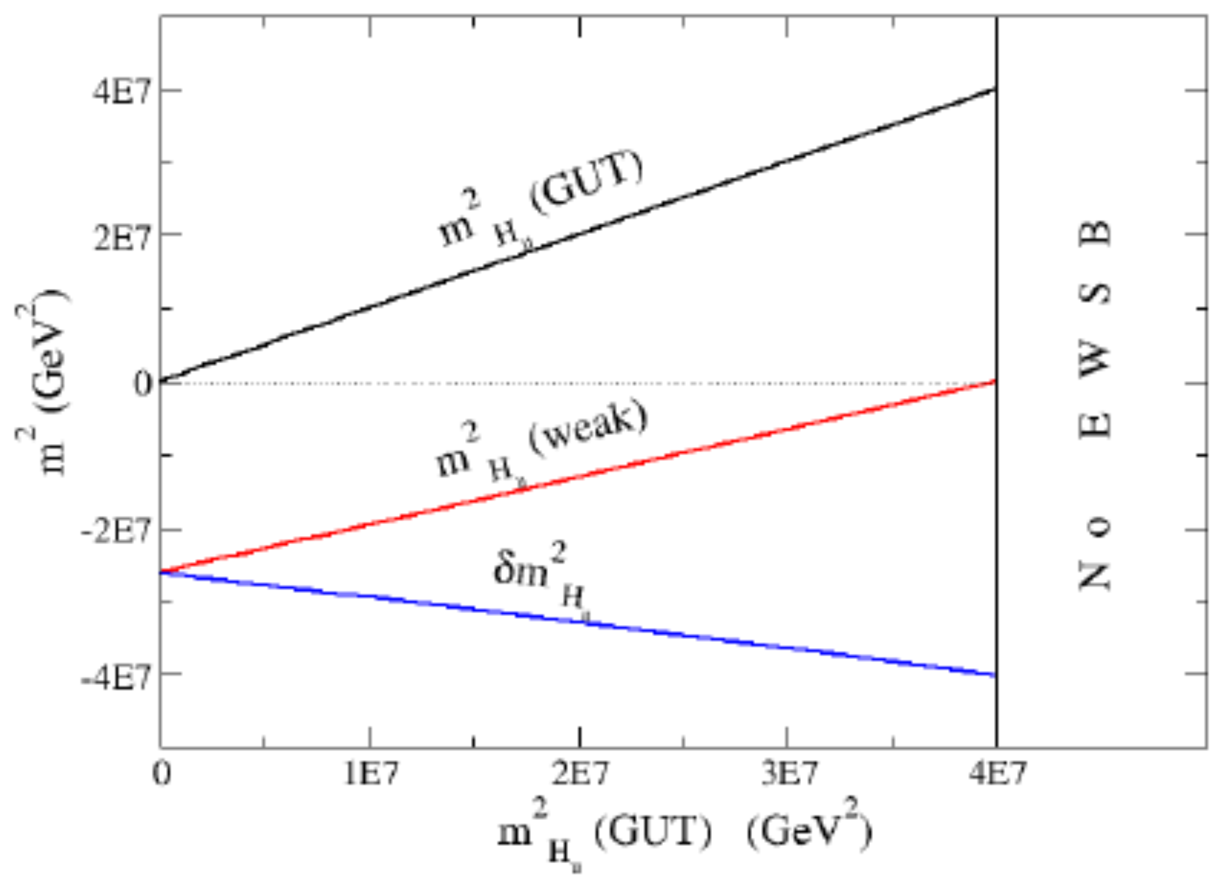
Implies 3 3rd generation squarks <500 GeV:

SUSY ruled out under $\Delta_{HS} \equiv \frac{\delta m_{H_u}^2}{m_h^2}$

BUT! too many terms ignored! NOT VALID!

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

where $t = \ln(Q^2/Q_0^2)$, $S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$ and $X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$. By neglecting gauge terms and S ($S = 0$



The bigger $m_{H_u}^2(\Lambda)$ is, the bigger is the cancelling correction- these terms are *not independent*.

For big enough $m_{H_u}^2(\Lambda)$, then $m_{H_u}^2$ driven to natural value at weak scale: *radiatively driven naturalness (RNS)*

HB, Barger, Mickelson, Padeffke, Savoy
arXiv:1309.2984 and 1404.2277

EENZ/BG naturalness

$$\Delta_{EENZ/BG} \equiv max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right|$$

- depends on input parameters of model
- different answers for same inputs assuming different models

model	c_{m_0}	$c_{m_{1/2}}$	c_{A_0}	c_μ	c_{H_u}	c_{H_d}	Δ_{BG}
mSUGRA	156	762	1540	-25.1	$--$	$--$	1540
NUHM2	16041	762	1540	-25.1	-15208	-643.6	16041

parameters introduced to parametrize our ignorance of SUSY breaking;
not expected to be fundamental

e.g. SUSY with dilaton-dominated breaking: $m_0^2 = m_{3/2}^2$ with $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

(doesn't make sense to use independent m0, mhf, A0)

while Δ_{BG} tells us about fine-tuning in our computer codes,
what we really want to know is: is nature fine-tuned or natural?

For correlated soft terms, then $\Delta_{BG} \rightarrow \Delta_{EW}$

Alternatively, only place independent soft terms makes sense
is in multiverse: but then selection effects in action

In fertile patch of vacua with MSSM as weak scale effective theory
but with no preferred SUSY breaking scale...

$$dP/d\mathcal{O} \sim f_{prior} \cdot f_{selection}$$

What is f(prior) for SUSY breaking scale?

In string theory, usually multiple (~10) hidden sectors
containing a variety of F- and D- breaking fields

For comparable <Fi> and <Dj> values, then expect

$$f_{prior} \sim m_{soft}^{2n_F+n_D-1}$$

Douglas ansatz

arXiv:0405279

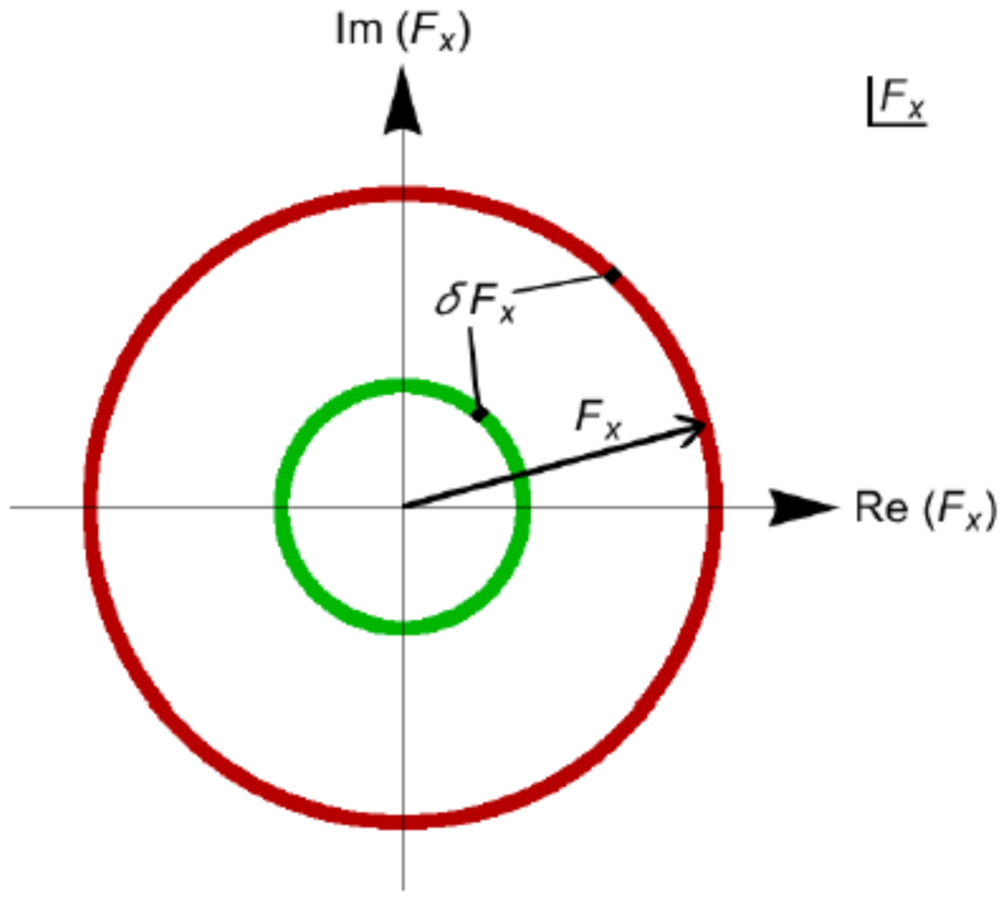


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

Under single F-term
SUSY breaking,
expect linear increasing
statistical selection
of soft terms