UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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HEAVY HIGGS DECAYS AS A WINDOW TO THE SUPERSYMMETRIC WORLD

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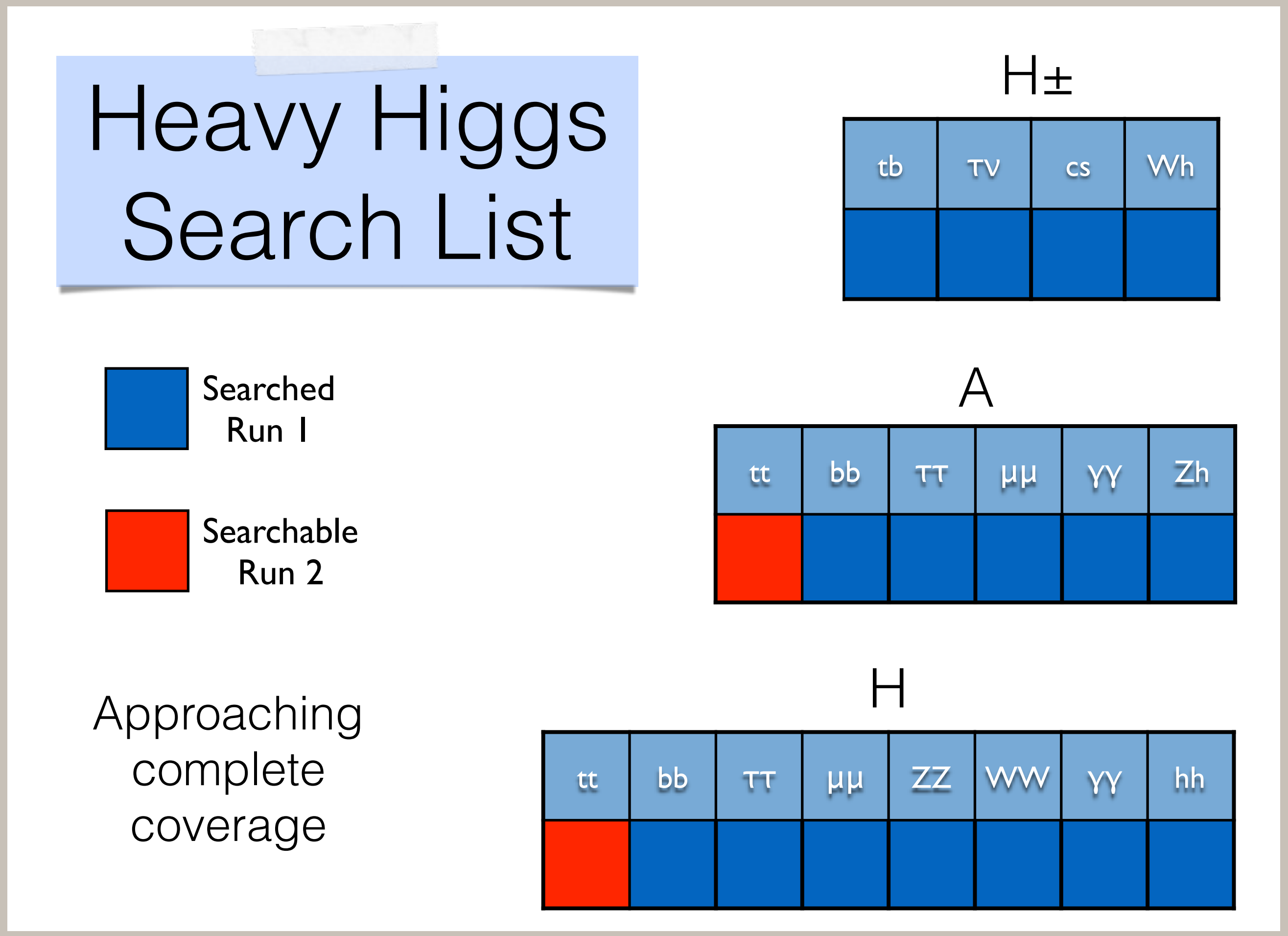
BASED ON:

HEP-PH 171X.XXXXX WITH STEFANIA GORI, ZHEN LIU

HEP-PH 1703.07800 WITH SEBASTIAN BAUM, KATHERINE FREESE, NAUSHEEN SHAH

LHC SEARCHES FOR HEAVY HIGGS BOSONS
(DECAY INTO SM FINAL STATES): A COMPREHENSIVE PROGRAM

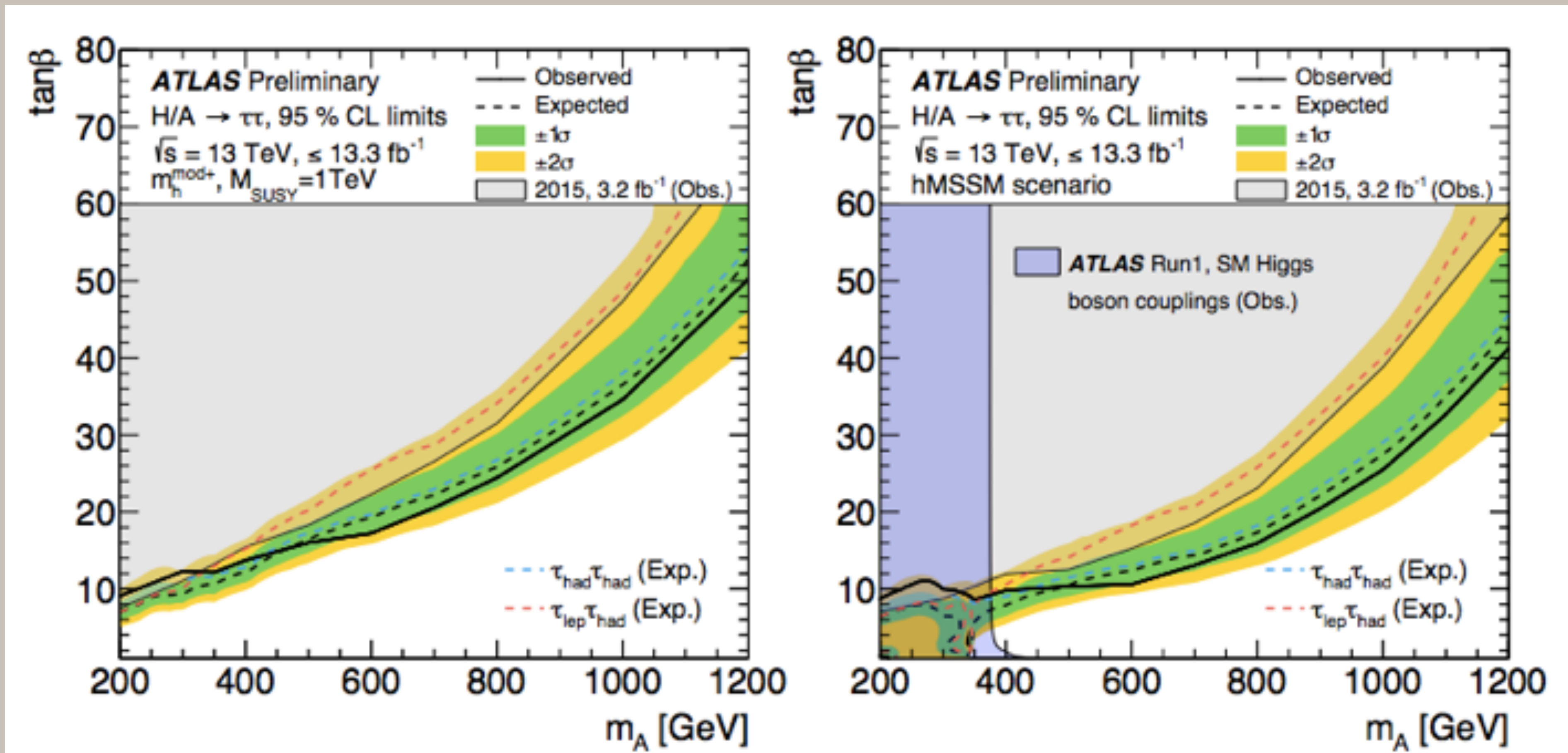
decay channel	Reference $\sqrt{s} = 8\,\text{TeV}$	Reference $\sqrt{s} = 13\,\text{TeV}$
$H \to \tau^+\tau^-$	[46–48]	[49, 50]
$H \to b\bar{b}$	–	[51]
$H \to \gamma\gamma$	[52–54]	[55–57]
$H \to ZZ$	[58]	[59–65]
$H \to WW$	[66–68]	[69–72]
$H \to h_{\text{SM}}h_{\text{SM}} \to b\bar{b}\tau^+\tau^-$	[73–75]	[76, 77]
$H \to h_{\text{SM}}h_{\text{SM}} \to b\bar{b}\ell\nu_\ell\ell\nu_\ell$	–	[78]
$H \to h_{\text{SM}}h_{\text{SM}} \to b\bar{b}b\bar{b}$	[79, 80]	[81–83]
$H \to h_{\text{SM}}h_{\text{SM}} \to b\bar{b}\gamma\gamma$	[84, 85]	[86, 87]
$A \to Zh_{\text{SM}} \to Zb\bar{b}$	[88, 89]	[90]
$A \to Zh_{\text{SM}} \to Z\tau^+\tau^-$	[73, 88]	–
$h_{\text{SM}} \to AA \to \tau^+\tau^-\tau^+\tau^-$	[91]	–
$h_{\text{SM}} \to AA \to \mu^+\mu^-b\bar{b}$	[91]	–
$h_{\text{SM}} \to AA \to \mu^+\mu^-\tau^+\tau^-$	[91]	–
$h_{\text{SM}} \to AA \to \mu^+\mu^-\mu^+\mu^-$	–	[92]
$A/H \to Zh_i/A_1$	[93]	–



From Nathaniel Craig's talk at Higgs Couplings '16

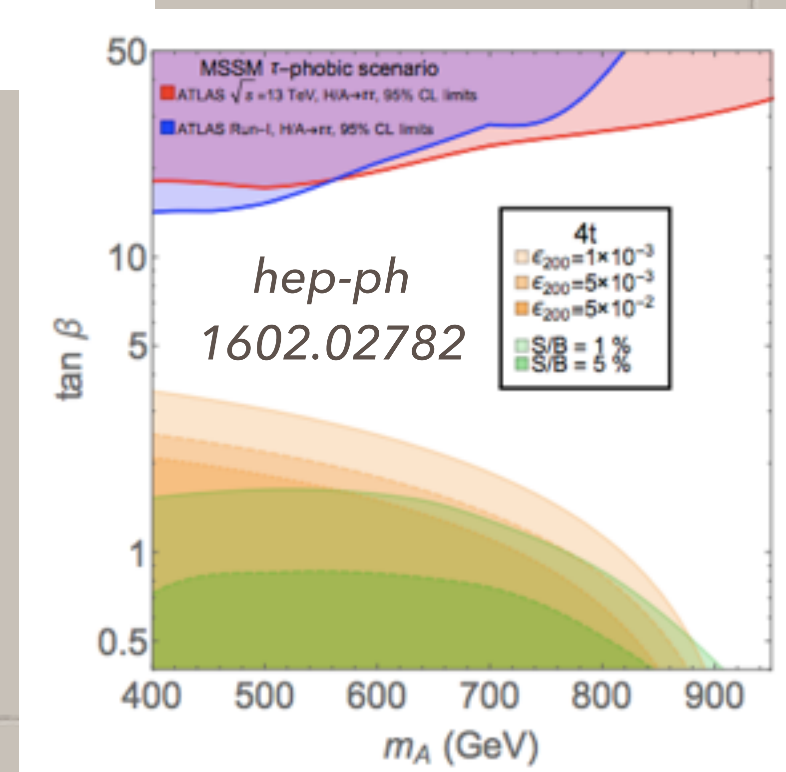
From hep-ph 1703.07800

LHC CONSTRAINTS AND PROSPECTS



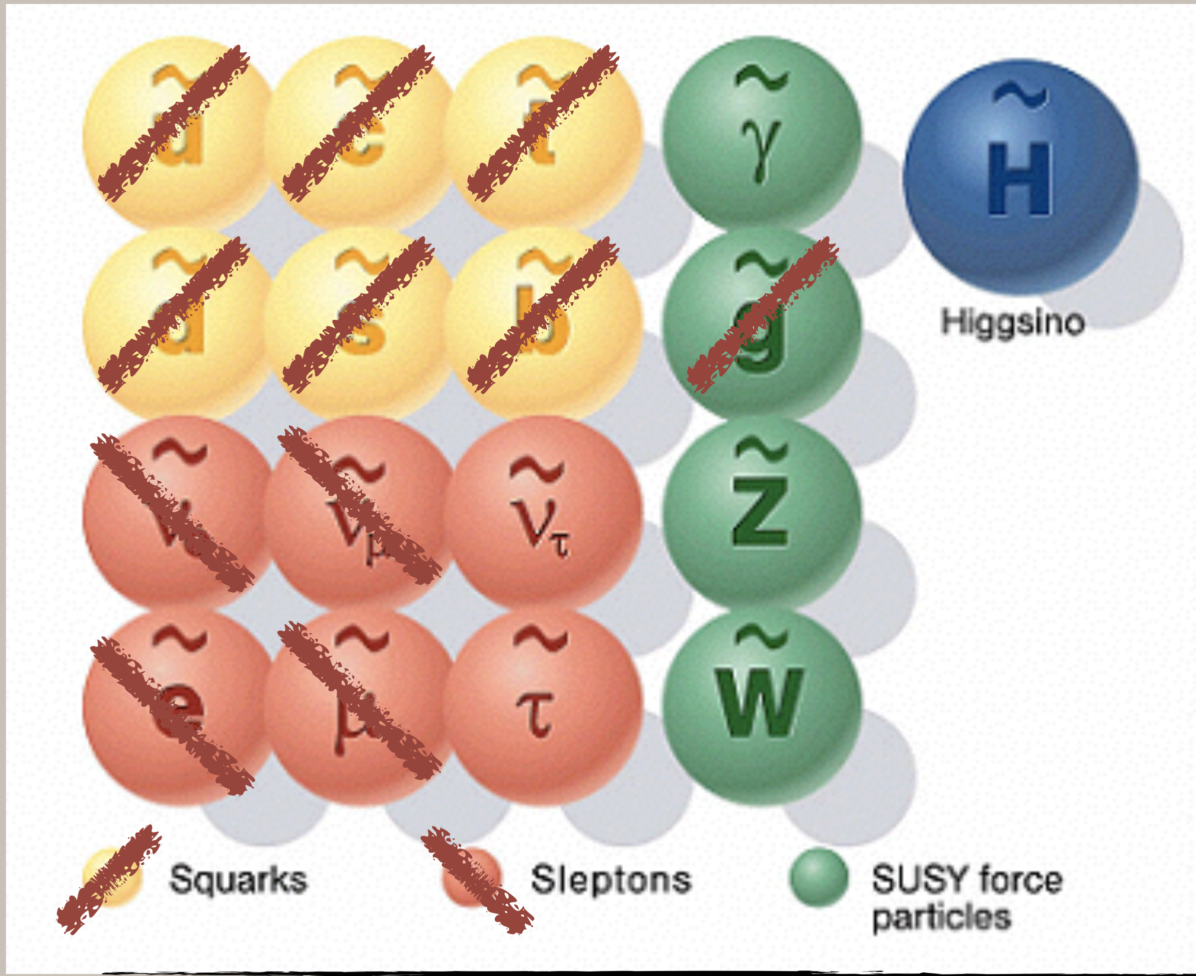
(c) m_h^{mod+} scenario

(d) hMSSM scenario



- strongest constraints from A/H -> ττ
- strongest constraints at small m_A + large tanβ
- depends somewhat on the scenario (SUSY parameters)
- difficult to probe large m_A (> 500 GeV),small tanβ (<10)
  (decays dominantly to tops, which is messy)

DECAYS BEYOND SM STATES



strongly interacting: will be discovered directly if lighter than heavy Higgs

lighter generation sleptons: small coupling to Higgs bosons

decay modes of interest :
neutralinos charginos staus

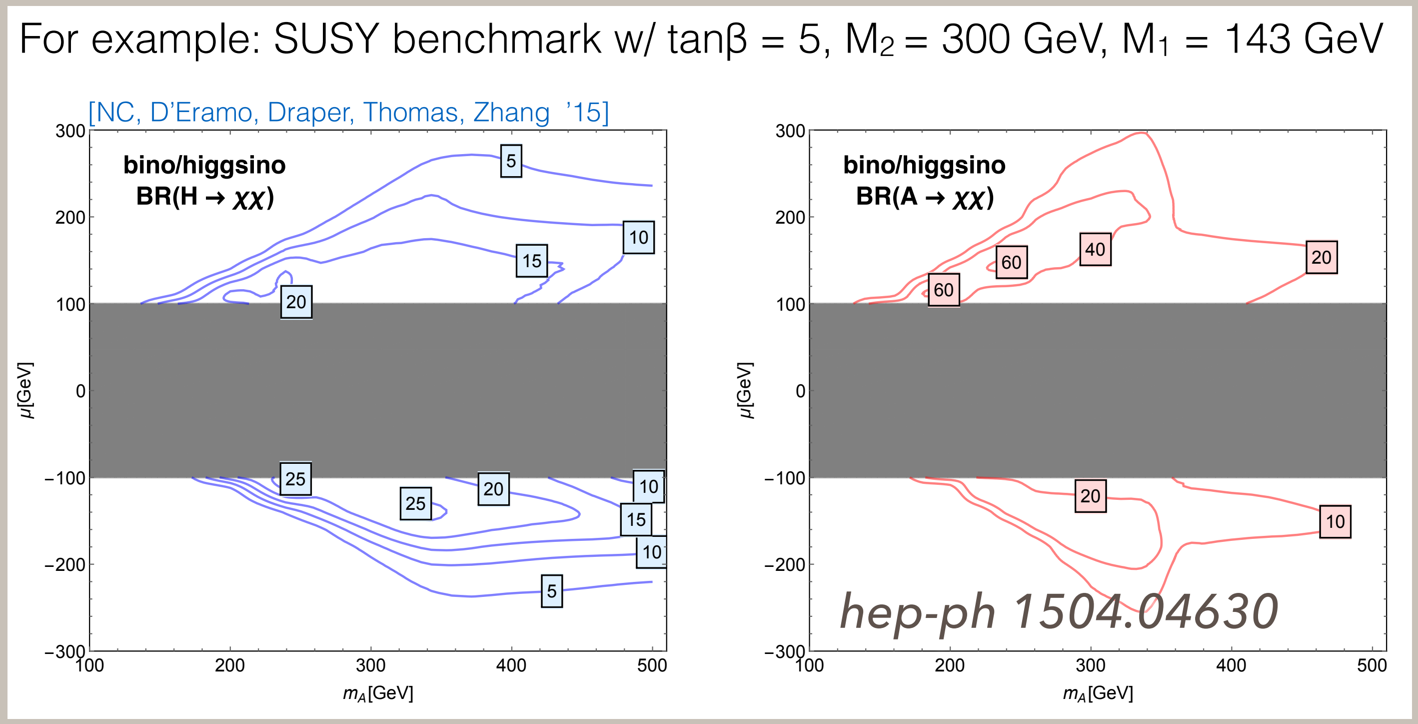
low direct production rates at the LHC,
coupling to heavy Higgs bosons can be significant

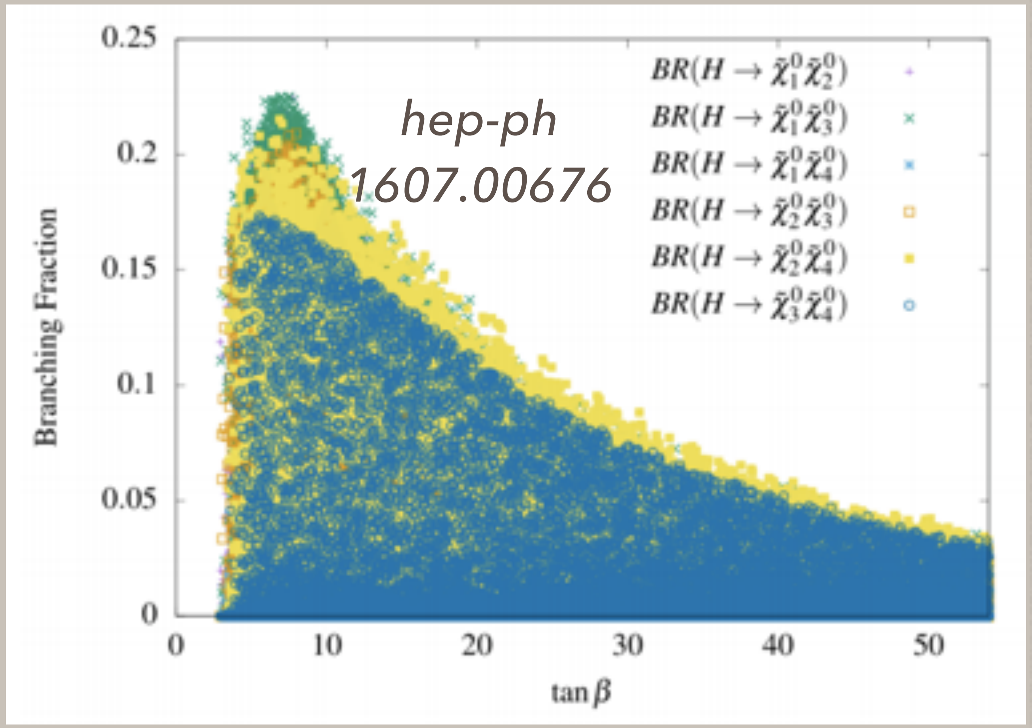
ARE HEAVY HIGGS DECAYS TO THESE STATES VIABLE SIGNALS AT THE HIGH LUMINOSITY LHC?

* AS PROBES OF HEAVY HIGGS BOSONS
* AS DISCOVERY CHANNELS OF THESE SUSY EW STATES
* AS COMPLEMENTARY COVERAGE IN HEAVY HIGGS PARAMETER SPACE

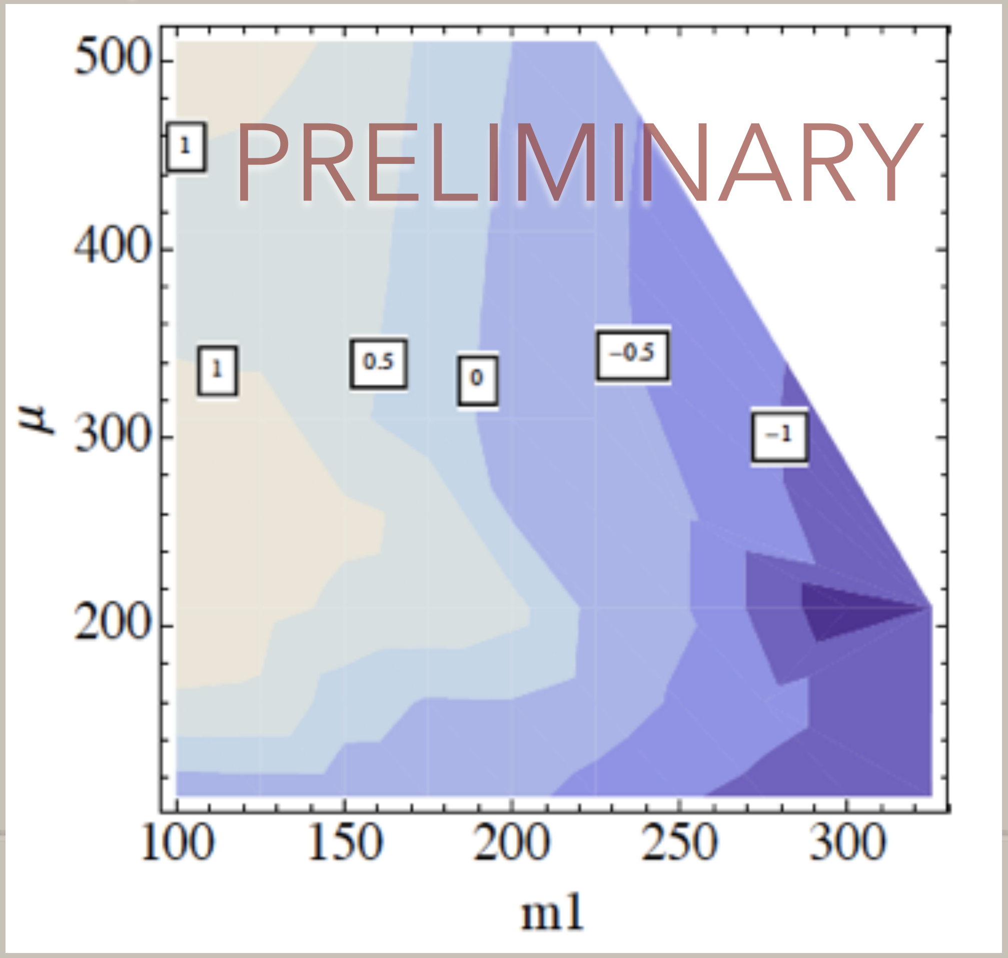
BASED ON HEP-PH 171X.XXXXX
WITH STEFANIA GORI, ZHEN LIU

DECAY INTO NEUTRALINOS





up to ~60% below ttbar threshold, O(10)% above, peaks at tan beta ~7

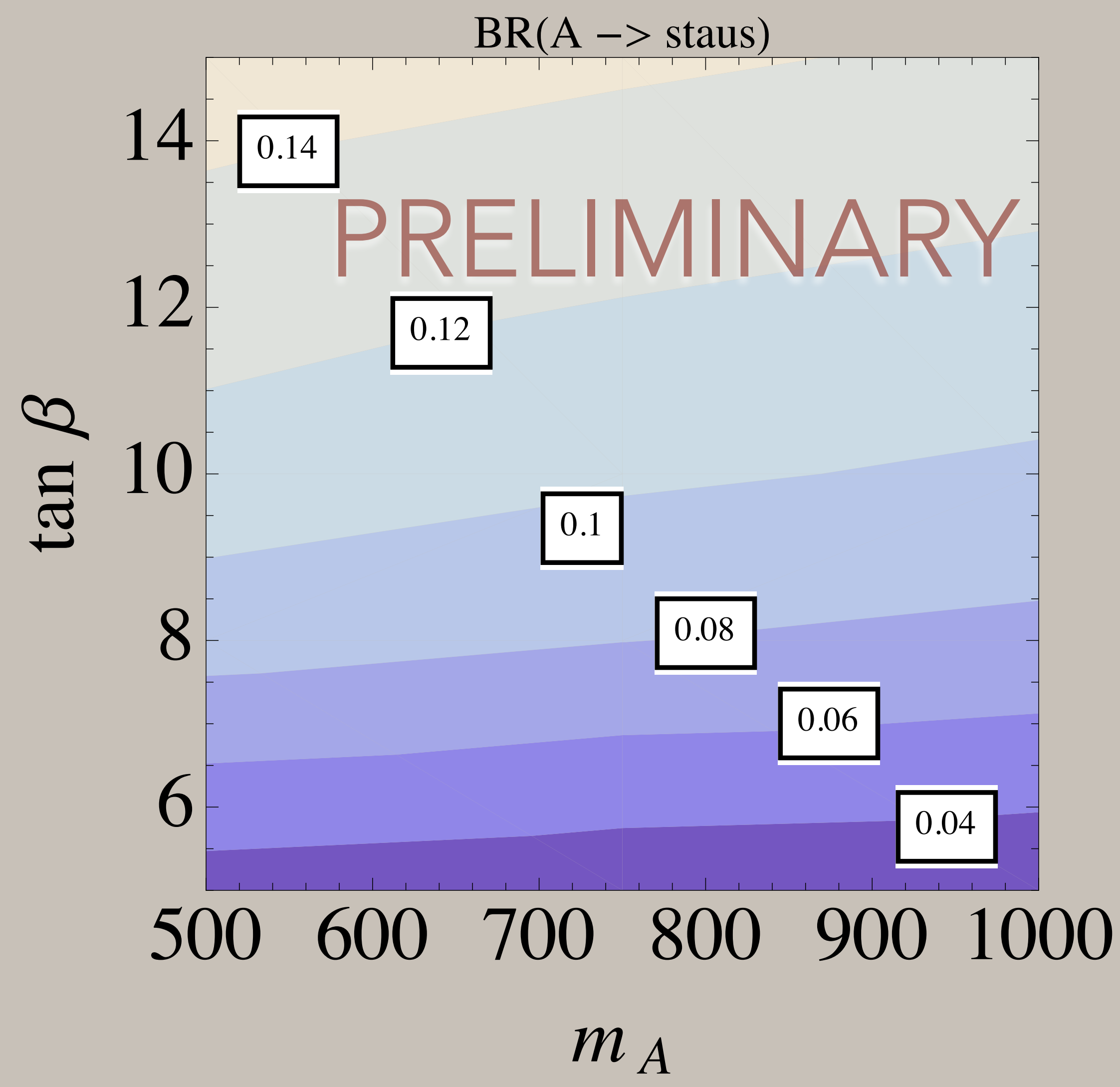


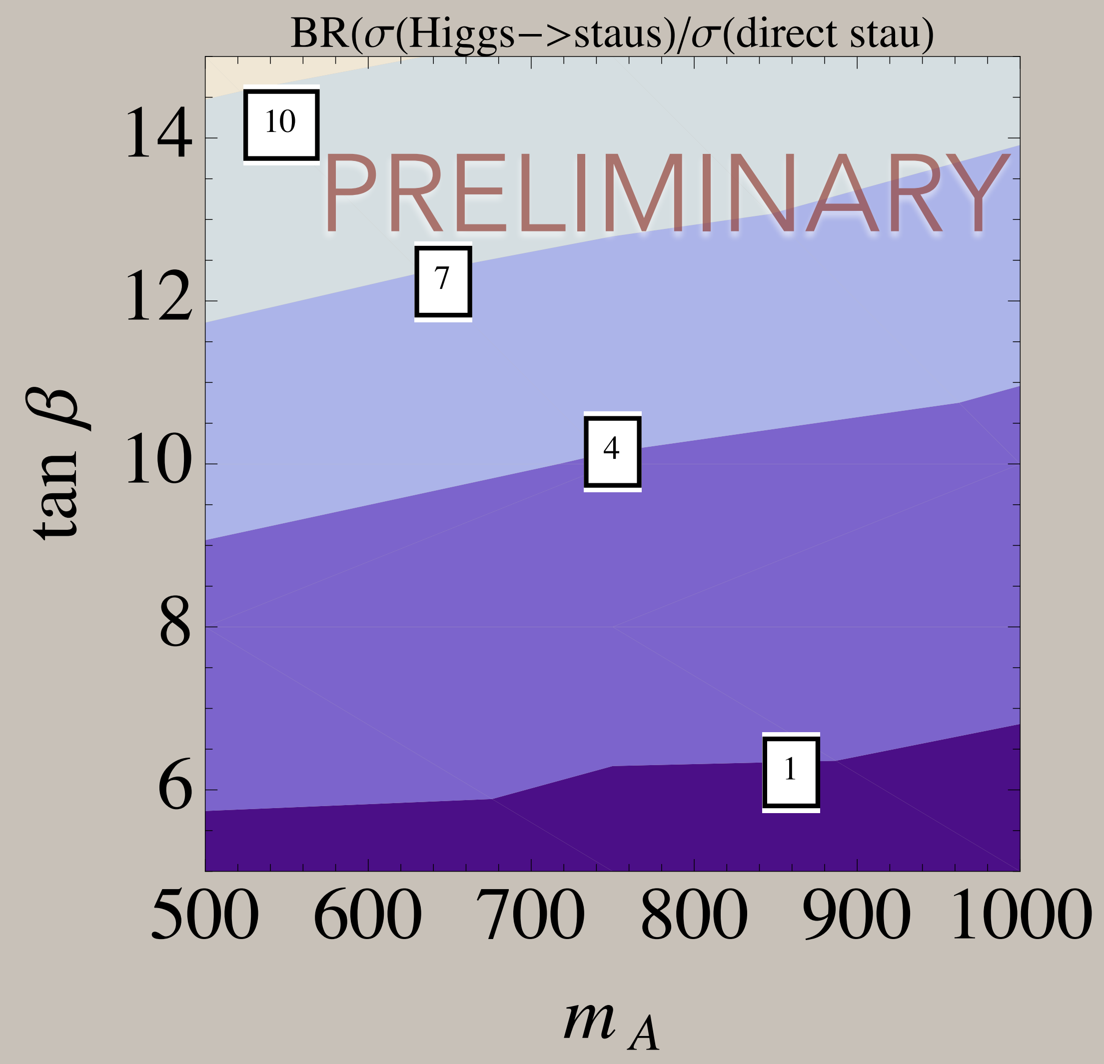
contours of $\log_{10}\left(\frac{\sigma(pp\to A\to\chi_i\chi_j)}{\sigma(pp\to\chi_i\chi_j)}\right)$

(wino decoupled, m_A, tanβ optimized)

heavy Higgs decay can be the dominant production source of neutralinos at the LHC

DECAY INTO STAUS





- coupling proportional to A_{tau}, constrained by vacuum stability
- BR(A/H->staus) can also be ~O(10)%; comparable/larger than BR(A/H->tau), scales similarly with tan beta
- same final state in signal as A/H -> tau search channel, with more MET

DIRECT PRODUCTION VS VIA HEAVY HIGGS DECAY

- tree level, but small production cross section
- off shell mediator, no kinematic information

- loop level (if gluon fusion), production cross section can still be larger
- on shell mediator: can possibly use information of the parent (Higgs)

recent work in this direction for neutralinos: hep-ph 1607.00676, 1504.04630

- neutralinos: Z couples only to Higgsino component; W to wino or Higgsino components. Higgs to gaugino-Higgsino combination
- staus: heavy Higgs couplings to staus (vs taus) enhanced by trilinear A_{tau} term

MANY POSSIBLE FINAL STATES, SOME BETTER THAN OTHERS…

$bbA/H,\ A/H \to \textbf{invisible}$

$pp \to H/A \to \chi_{2,3} + \chi_1 \to \chi_1\chi_1 Z$

$bbA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 h$

$ttA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 Z$

$tbH^\pm,\ H^\pm \to \chi^\pm\chi_1,\ \chi^\pm \to \chi_1 W^\pm$

$bbA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 Z$

$H \to \chi_3, \chi_1 \quad \chi_3 \to \chi_2 Z^* \quad \chi_2 \to \chi_1 Z^*$

$H \to \chi_2, \chi_3$

etc…

- invisible
- mono Z
- bbh
- ttZ
- final states suffer from ttbar background
- ZZ, Zh from multiple/cascade decays

see also 1711.00056

MANY POSSIBLE FINAL STATES, SOME BETTER THAN OTHERS…

$bbA/H,\ A/H \to \textbf{invisible}$

- invisible

$pp \to H/A \to \chi_{2,3} + \chi_1 \to \chi_1\chi_1 Z$

- mono Z

$bbA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 h$

- bbh

$ttA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 Z$

- ttZ

$tbH^\pm,\ H^\pm \to \chi^\pm\chi_1,\ \chi^\pm \to \chi_1 W^\pm$

$bbA/H,\ A/H \to \chi_1\chi_3,\ \chi_3 \to \chi_1 Z$

- final states suffer from ttbar background

$H \to \chi_3, \chi_1 \quad \chi_3 \to \chi_2 Z^* \quad \chi_2 \to \chi_1 Z^*$

$H \to \chi_2, \chi_3$

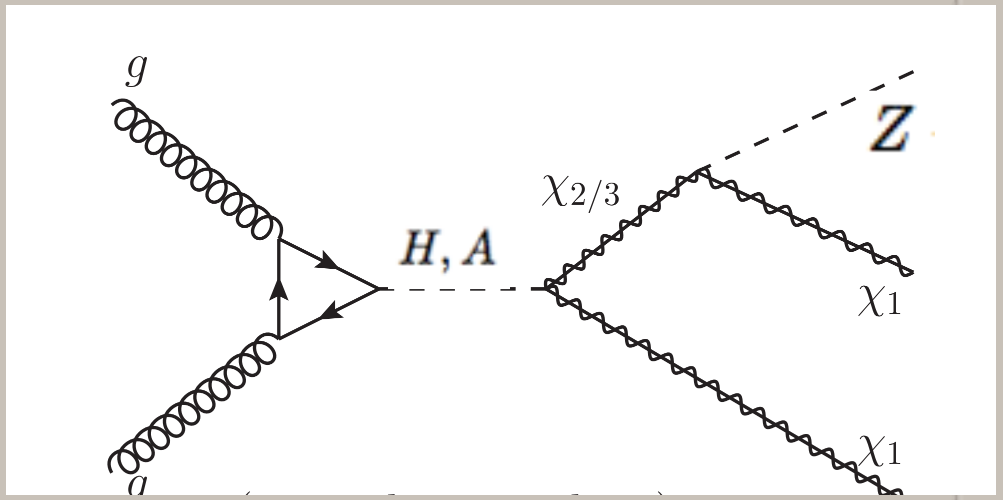
- ZZ, Zh from multiple/cascade decays

etc…

see also 1711.00056

DECAY TO NEUTRALINOS

setup: bino LSP, Higgsino NLSP, splitting ~100 GeV
(winos decoupled)



$$pp \to H/A \to \chi_{2,3} + \chi_1 \to \chi_1 \chi_1 Z$$

- require dilepton pair to reconstruct Z mass (85-95 GeV)
- optimize: lower cut on missing transverse energy, and upper cut on

the clustered transverse mass of the whole $\ell^+\ell^- + \not{E}_T$ system $m_{cT}(\ell\ell, \not{p}_T)$, defined as,

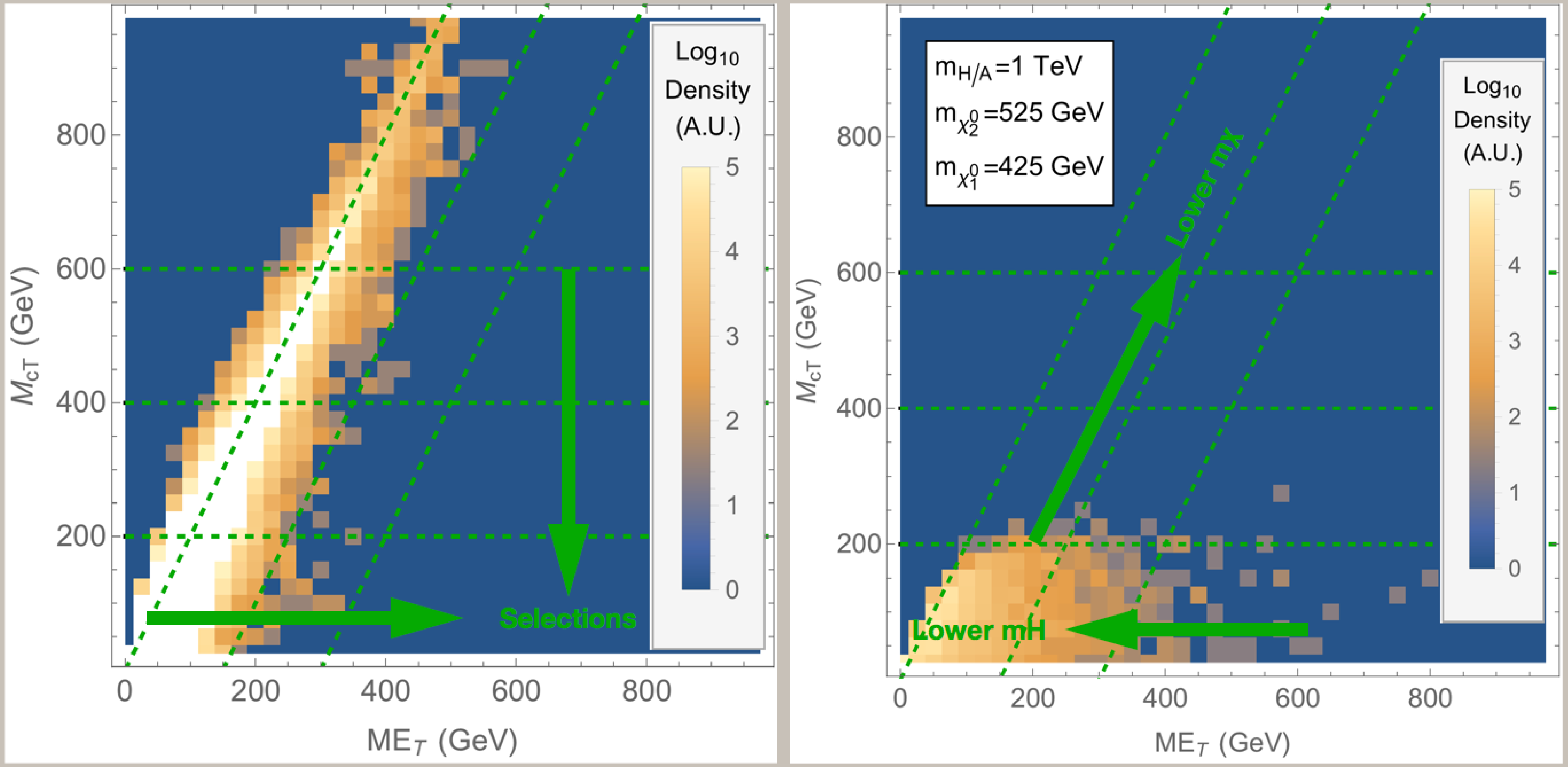
$$m_{cT}^2(\ell\ell, \not{E}_T) = (\sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2} + |\not{p}_T|)^2 - (p_T^{\ell\ell} + \not{p}_T)^2,$$

where $\not{p}_T$ is the three vector of the missing energy.

Background: dominant: ZZ, subdominant: WW

DECAY TO NEUTRALINOS

BACKGROUND VS SIGNAL

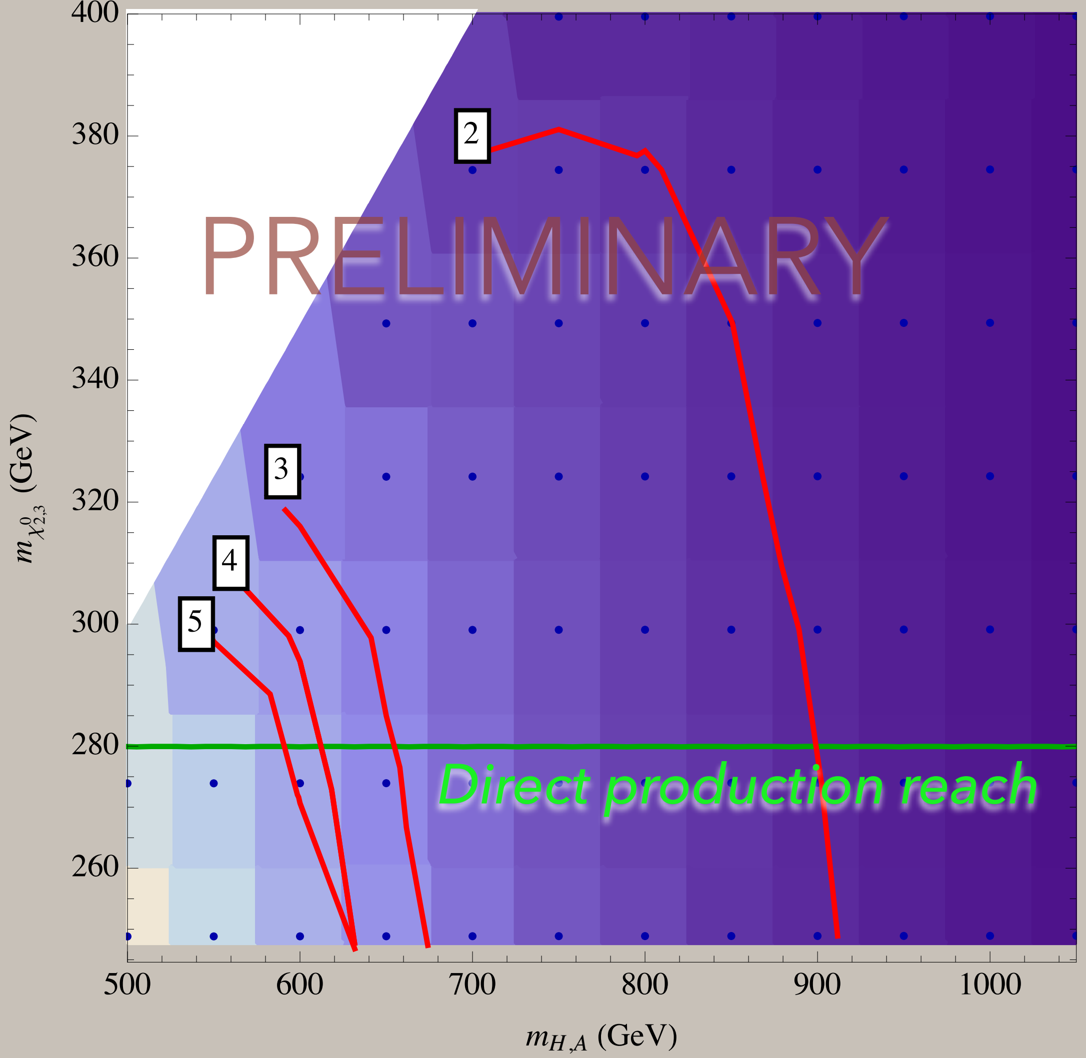


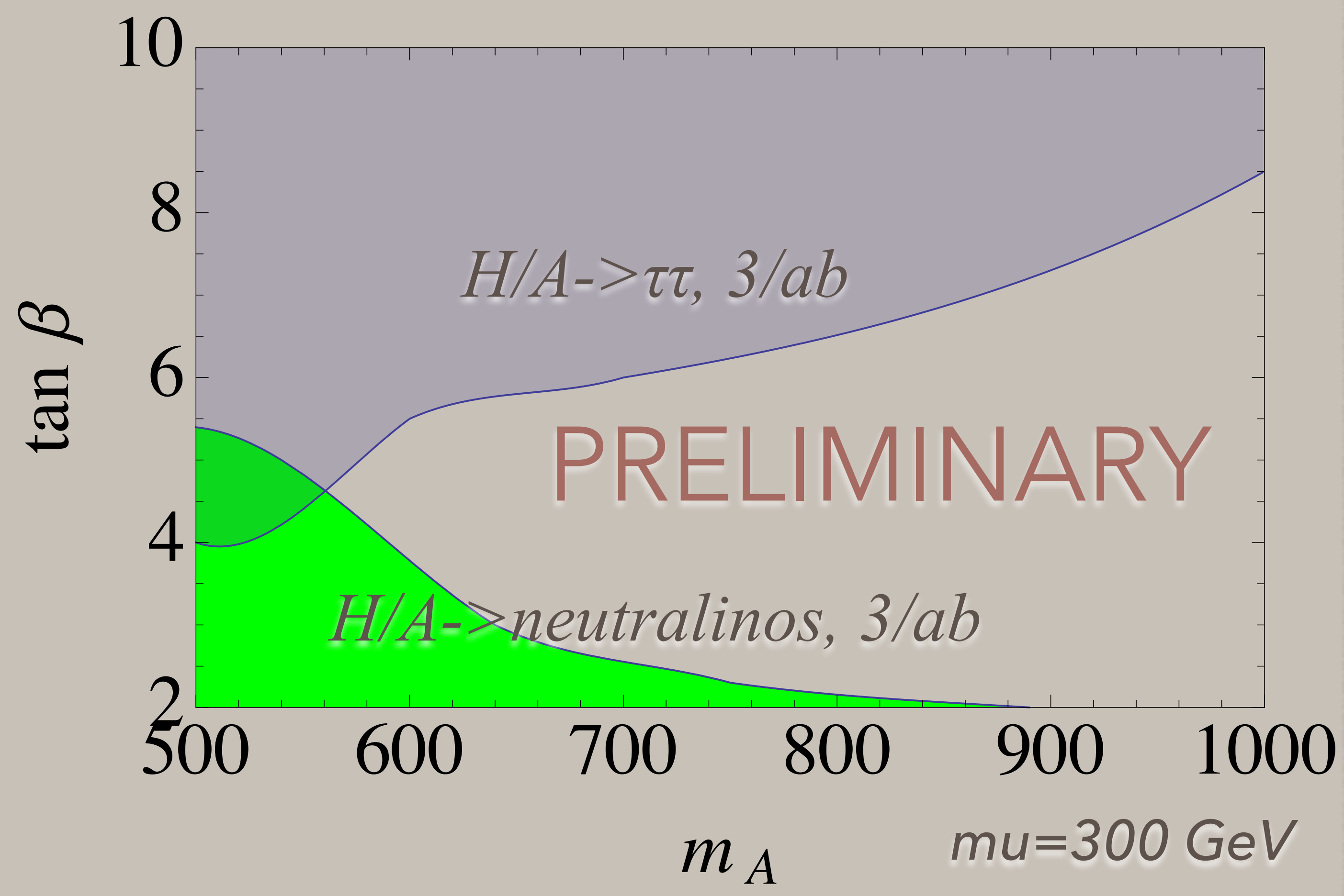
Background: MET and clustered transverse mass correlated

DECAY TO NEUTRALINOS

REACH IN PARAMETER SPACE

2σ exclusion contours for various values of tan beta





- can probe the high m_A, low tan beta regime
- can probe neutralinos beyond what is in reach of direct production

BEYOND THE MSSM: CAN OTHER DECAY MODES DOMINATE HEAVY HIGGS PHENOMENOLOGY?

BASED ON HEP-PH 1703.07800

WITH SEBASTIAN BAUM, KATHERINE FREESE, NAUSHEEN SHAH

NMSSM: MOTIVATION

- extend MSSM by a SM-singlet chiral superfield

$$W \supset \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta$$

- 125 GeV mass at tree level for λ~0.65, tanβ~O(1)

- In NMSSM, λ < 0.75 to avoid Landau pole below GUT scale. For 0.75 < λ < 2 ("λ-SUSY"), Landau pole below GUT scale but above 10 TeV (consistent with all measurements)

(Agashe, Cui, Franceschini, 1209.2115
Gherghetta, von Harling, Medina, Schmidt, 1212.5243)
Farina, Perelstein, Shakya, 1310.0459

Higgs mass and fine-tuning considerations favor
large λ (>0.6) and **tanβ~O(1)**

ADDITIONAL STATES+INTERACTIONS

additional fields: singlet scalar, pseudoscalar, fermion (singlino)

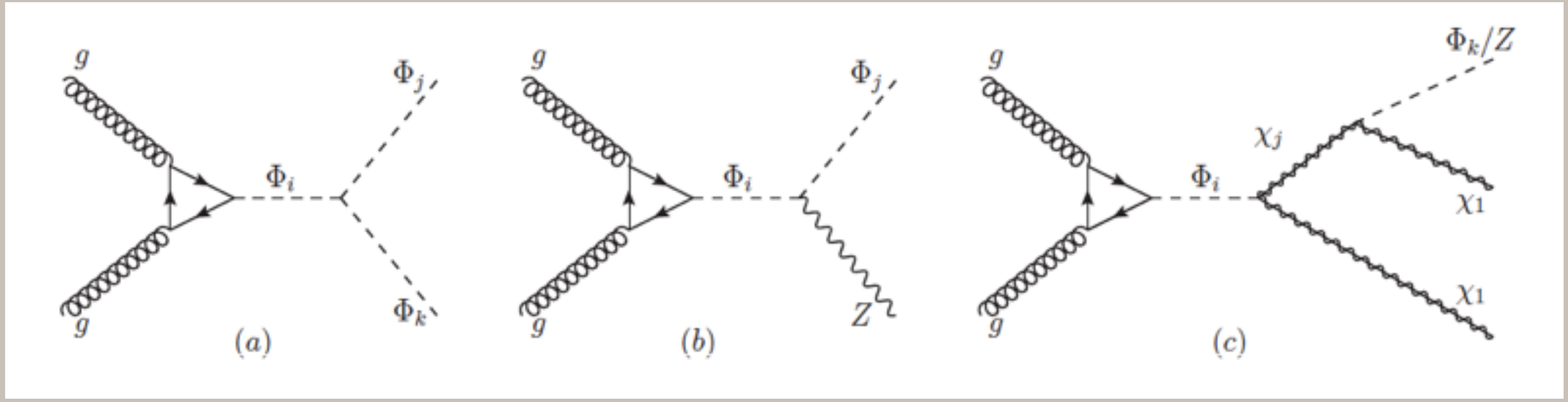
$$W \supset \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

gives rise to triple Higgs and Higgs-neutralino-neutralino couplings

decays of the form

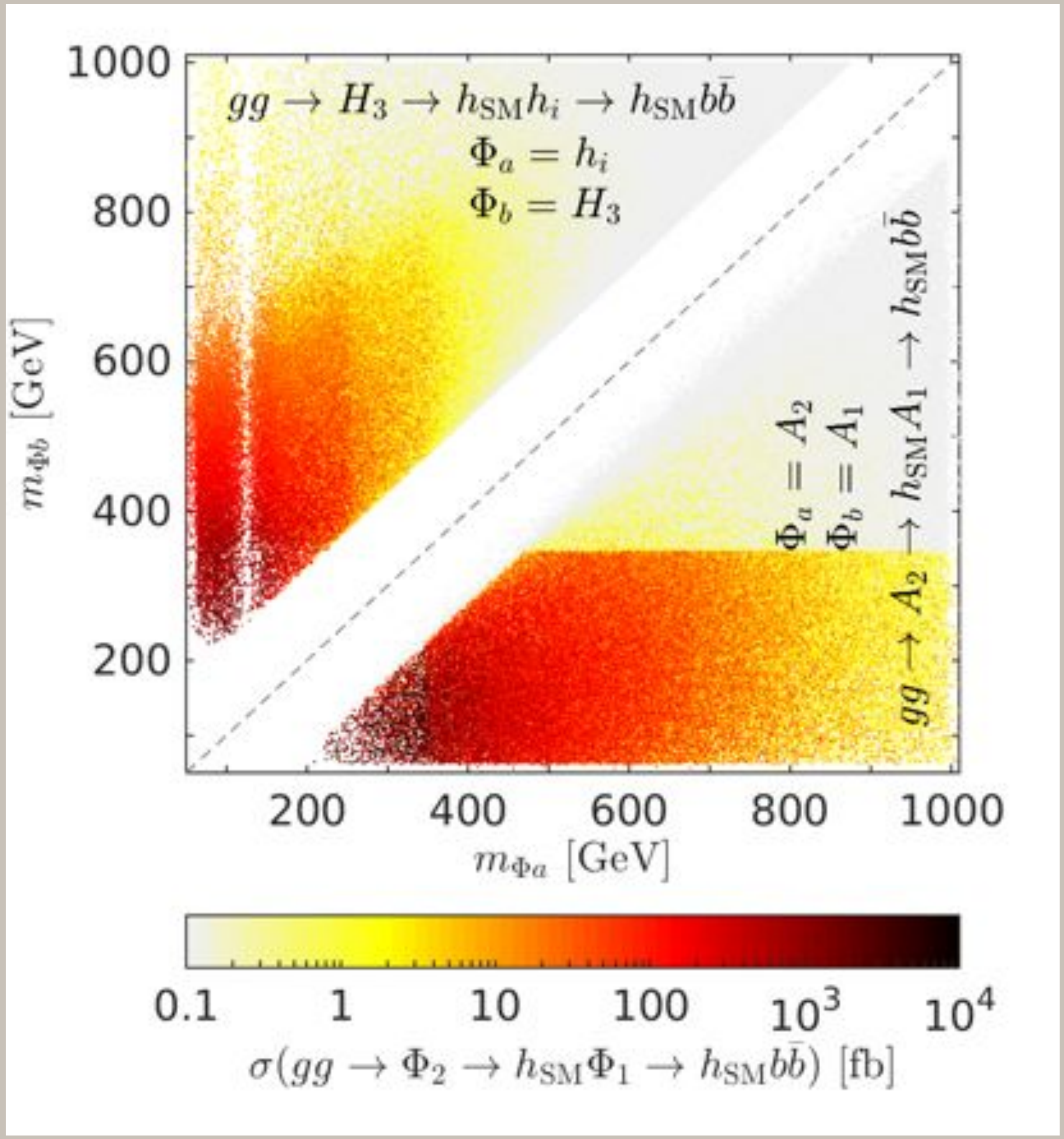
not present in the MSSM!

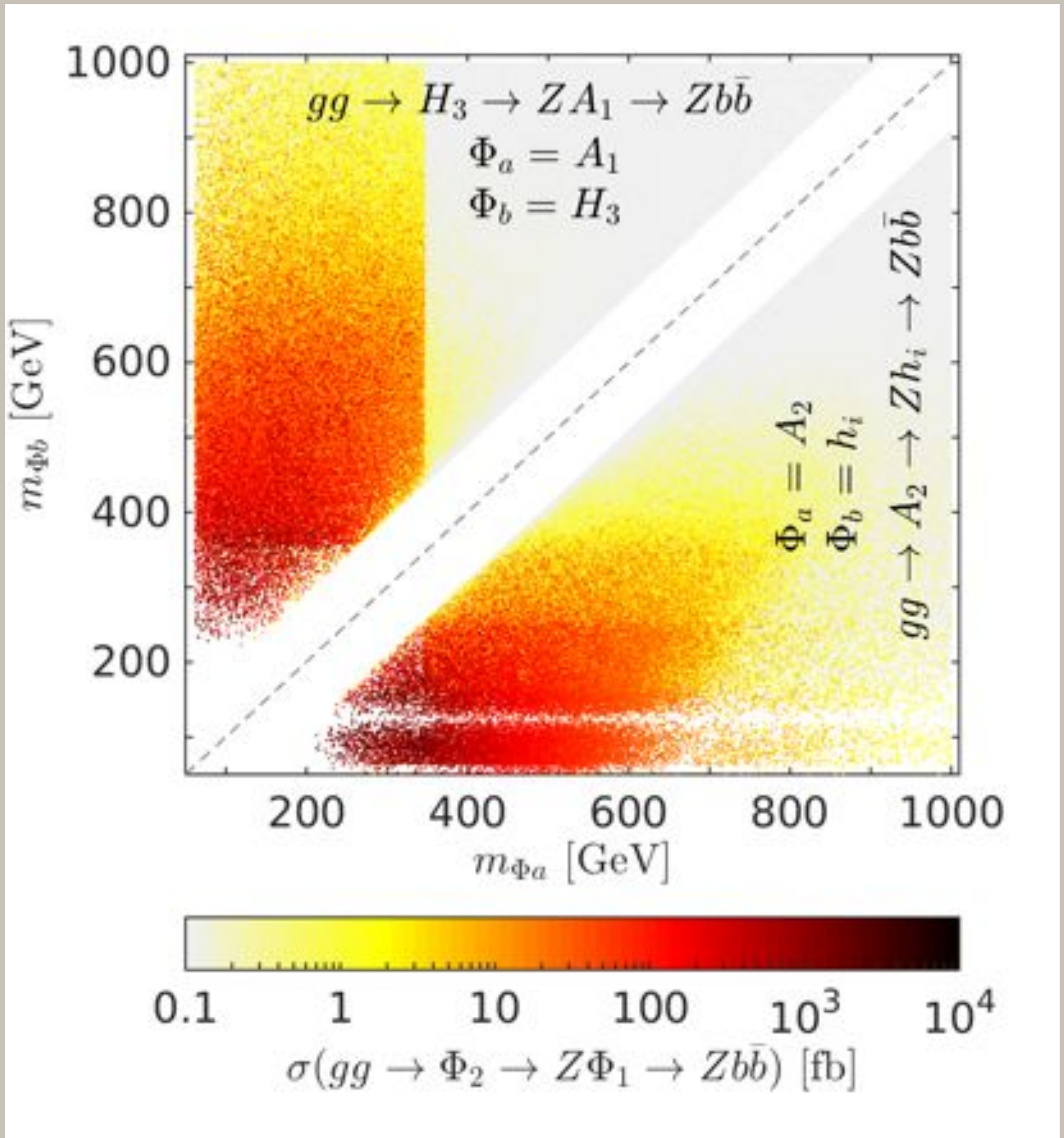
$$(H_i \to H_j H_k / A_j A_k), \ (A_i \to A_j H_k), \ (H_i / A_i \to \chi_j \chi_k)$$



can dominate heavy Higgs phenomenology !

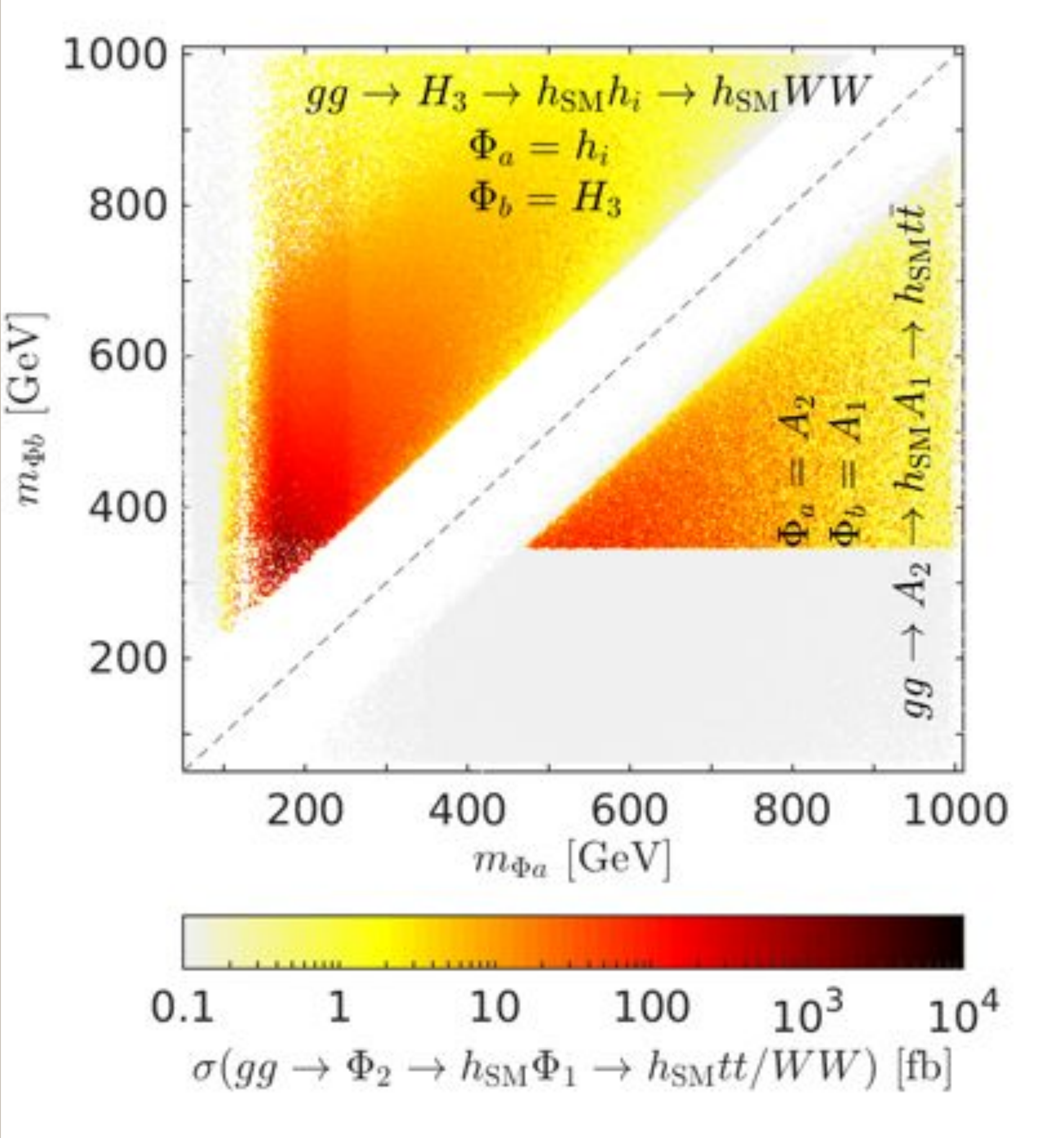
CROSS SECTIONS: FULLY VISIBLE FINAL STATES

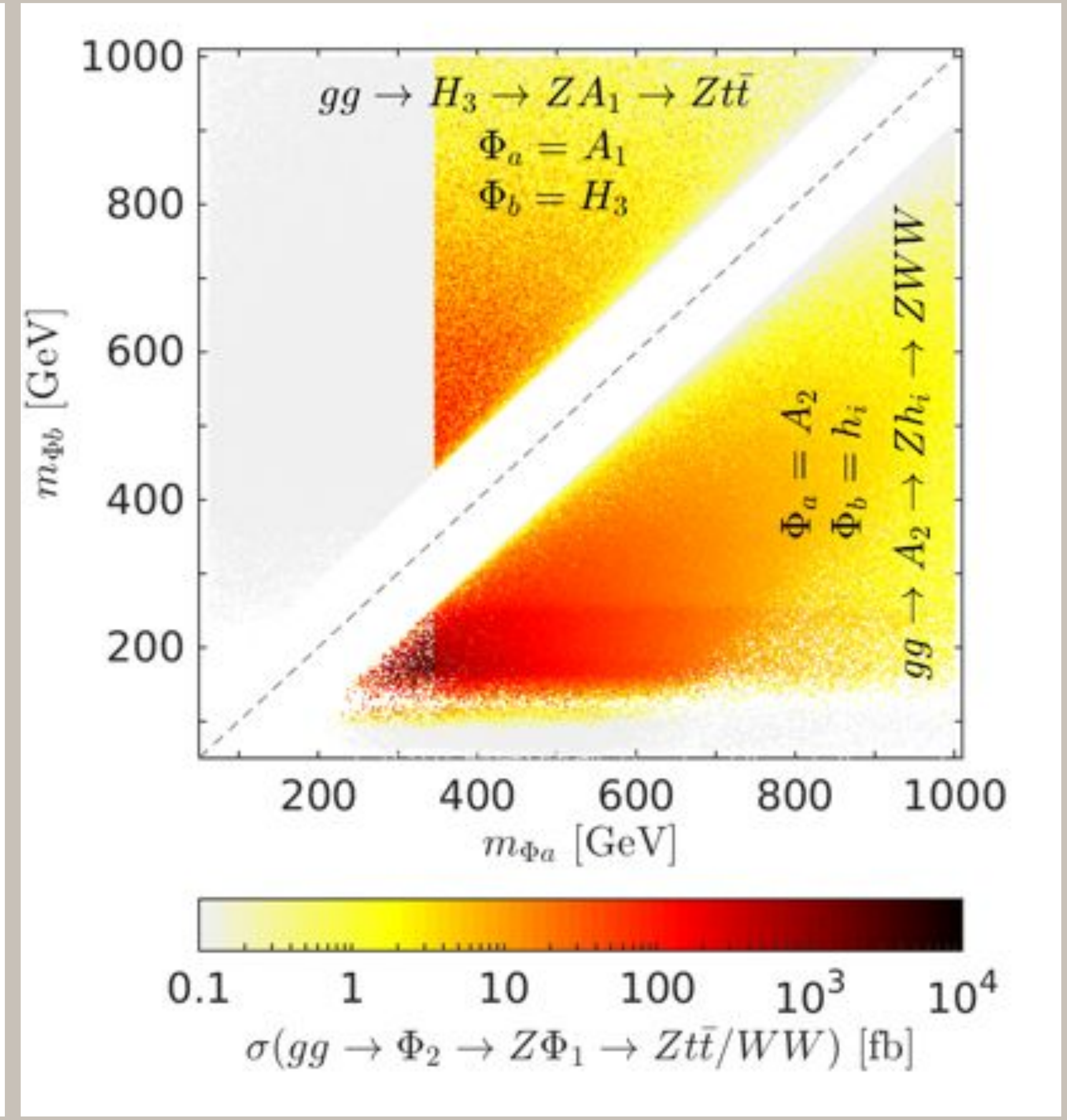




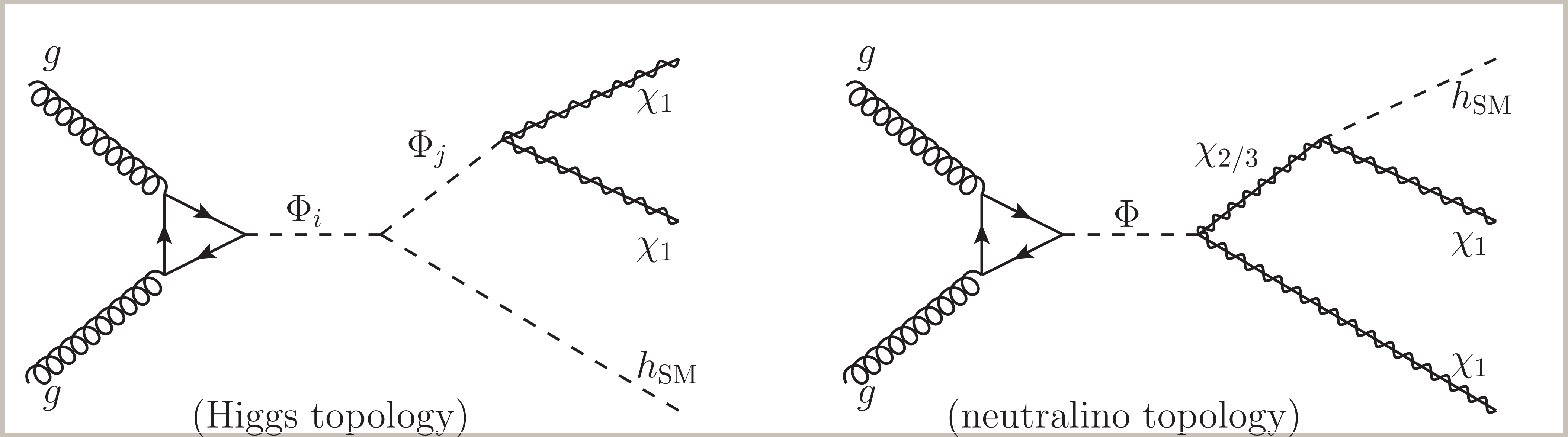
@ 13 TeV LHC

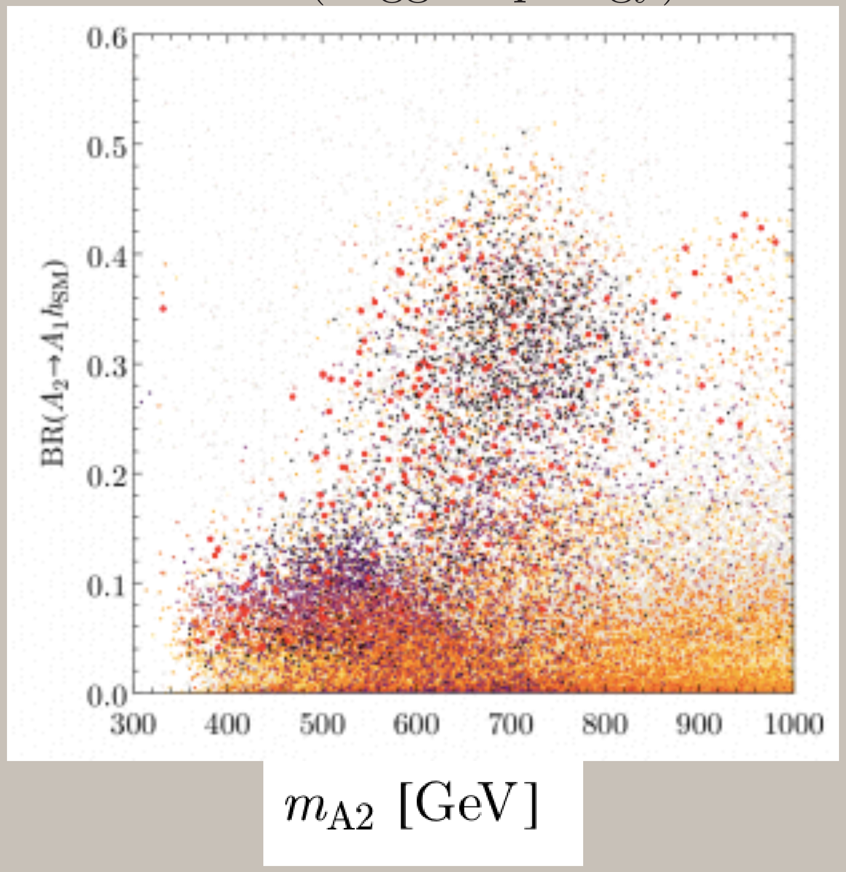
CROSS SECTIONS:
HEAVY FINAL STATES





MONO-HIGGS + MET TOPOLOGY





note: all vertices proportional to λ

focus on higgs -> diphoton (mono-Higgs studies find it to be the best channel)

search for mono-Higgs+MET by both ATLAS and CMS

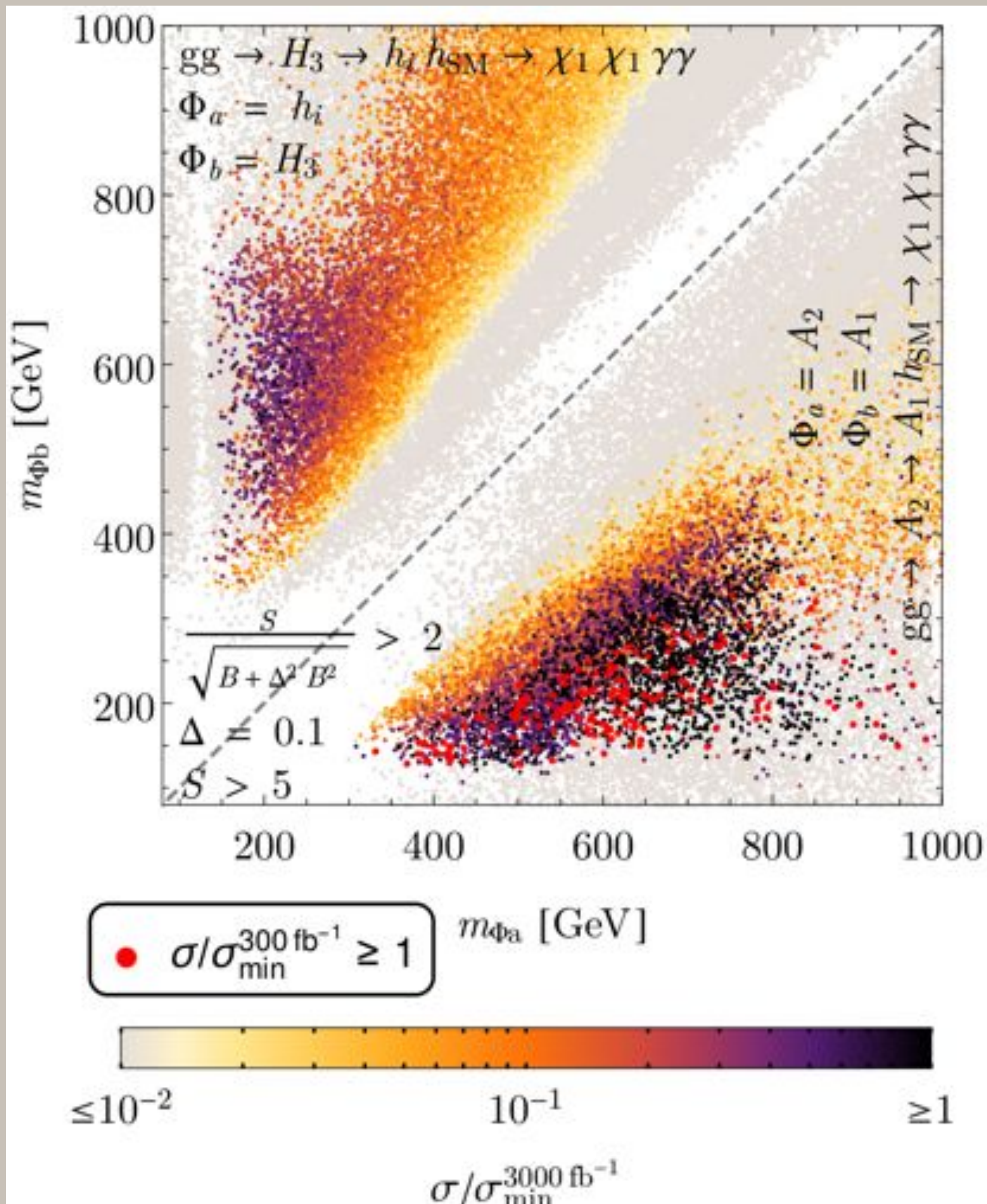
ATLAS-CONF-2016-011

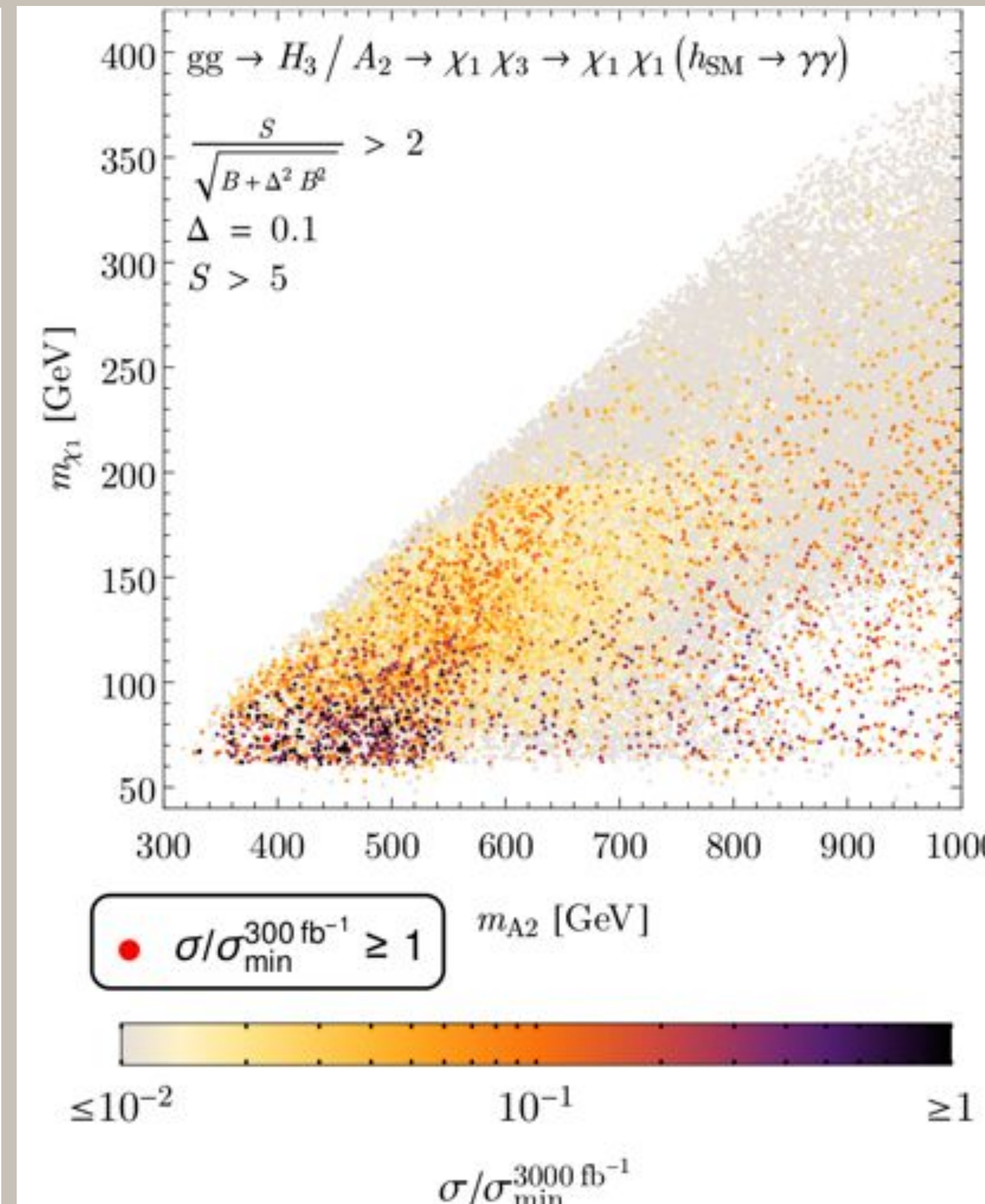
ATLAS-CONF-2016-087

CMS-PAS-EXO-16-011

repeat the analysis from ATLAS

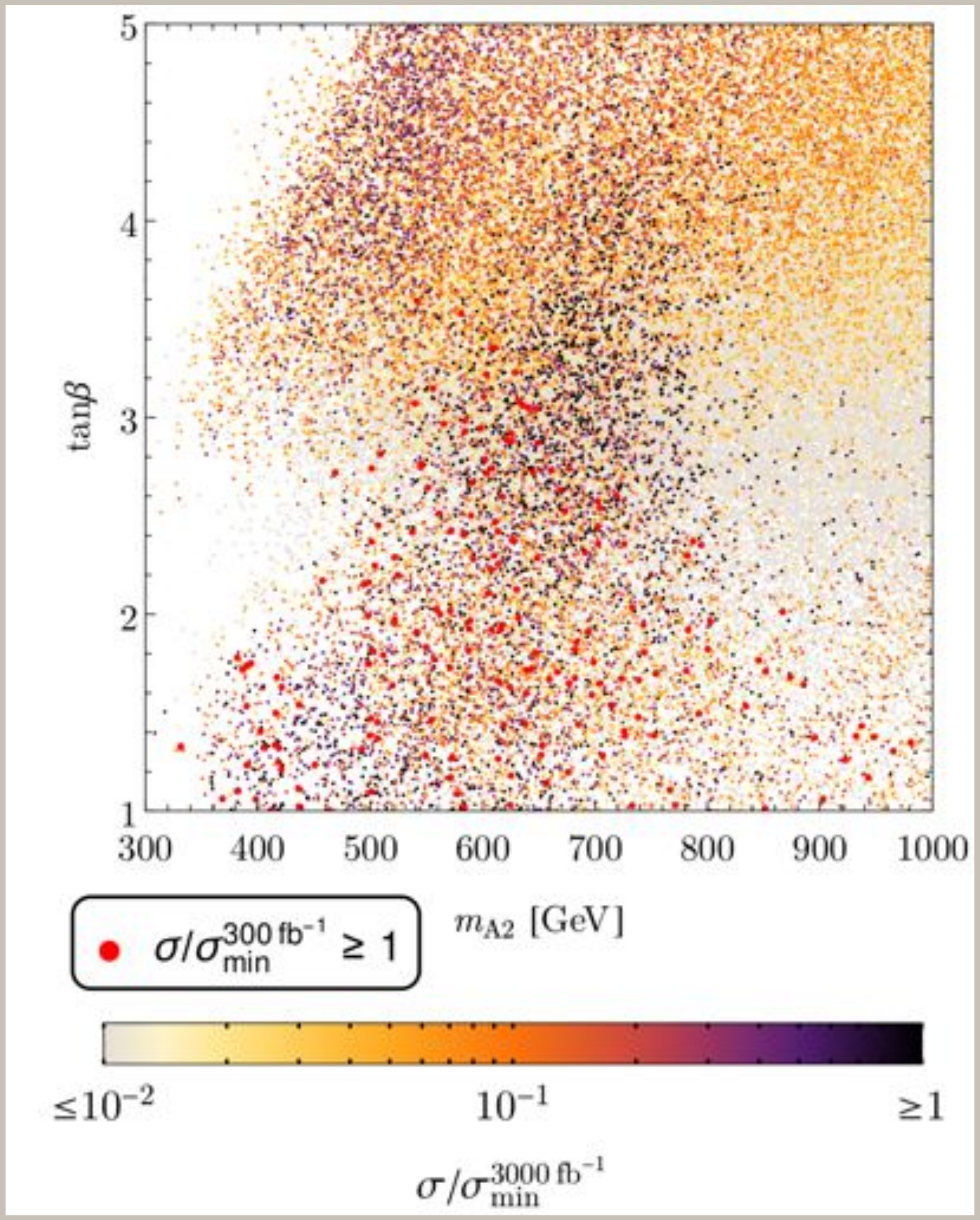
REACH (IN MASSES)



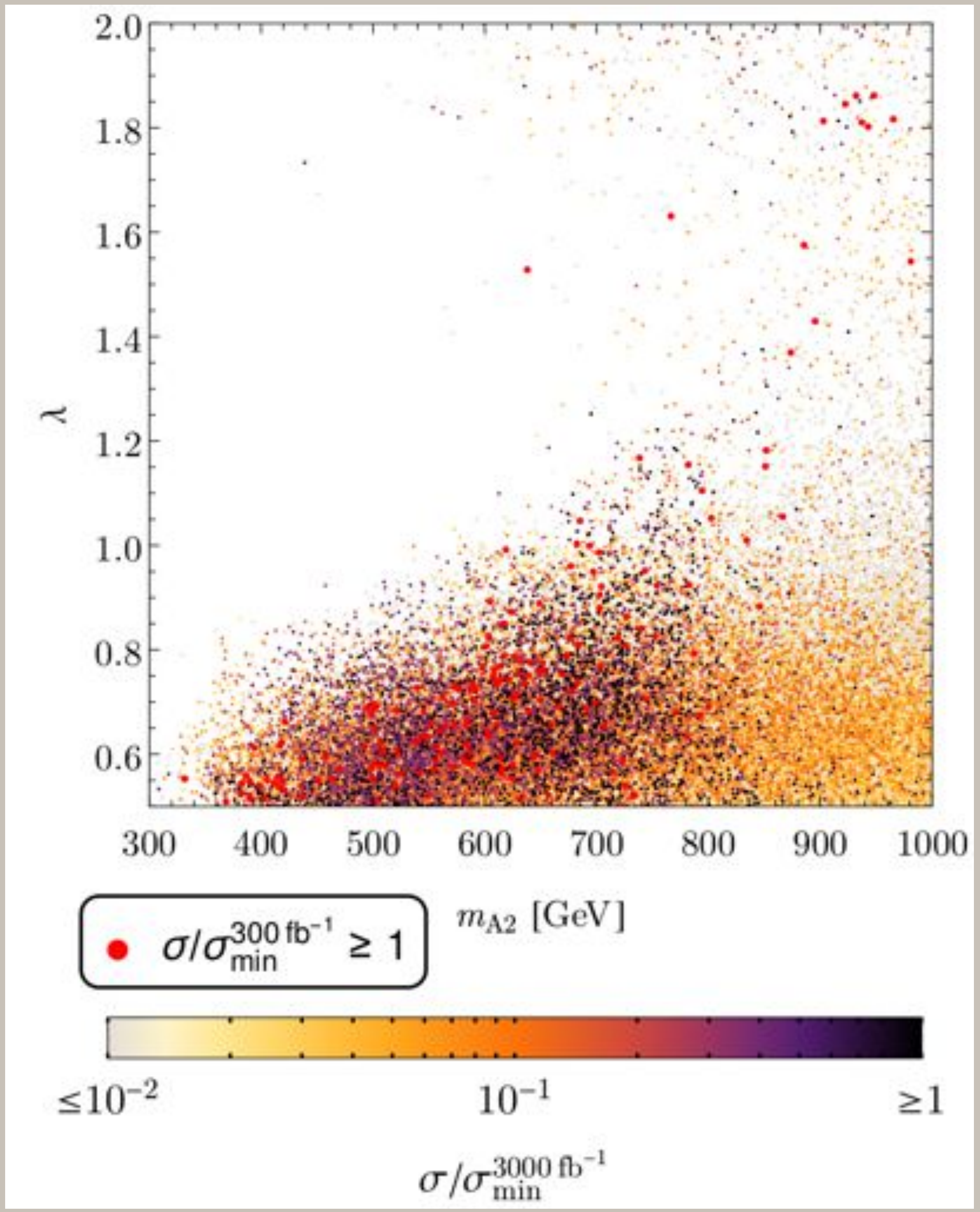


Higgs topology provides better reach: Higgs comes out of the primary vertex and is back to back with missing energy

REACH (IN PARAMETER SPACE)



good reach at low tan beta,
can probe heavy Higgs bosons up to the TeV scale
even in the regime traditionally plagued by ttbar



heavier masses can be probed for
larger lambda

SUMMARY

Heavy Higgs bosons can have **large branching ratios to supersymmetric electroweak particles (neutralinos, staus) - promising new decay modes** to look for

neutralino, stau production via Higgs decay can be **larger** than direct production; additionally, can **use the information that they come from Higgs decays** to aid in searches (MSSM)

decays to lighter higgs or neutralinos can be **enhanced with new large couplings** (NMSSM); can give **new channels** that **dominate heavy Higgs phenomenology**

possible to probe **TeV scale Higgs bosons** in the **problematic low tanβ, heavy mA regime**