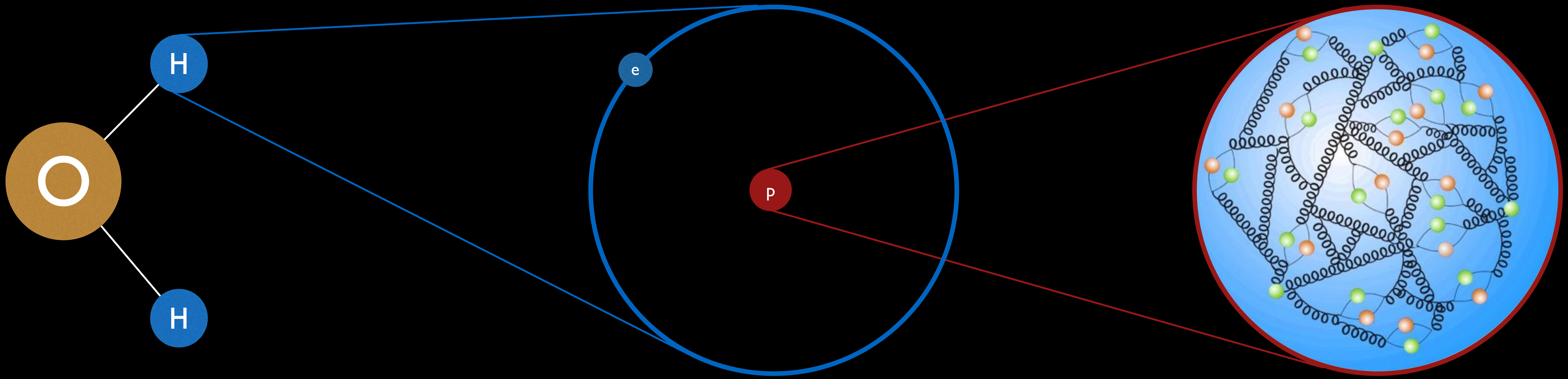
Hidden Higgses and Dark Matter
at
Current and Future Colliders

Adarsh Pyarelal

THE UNIVERSITY OF ARIZONA

What are we made of?



Water molecule
(H_2O)

Hydrogen atom

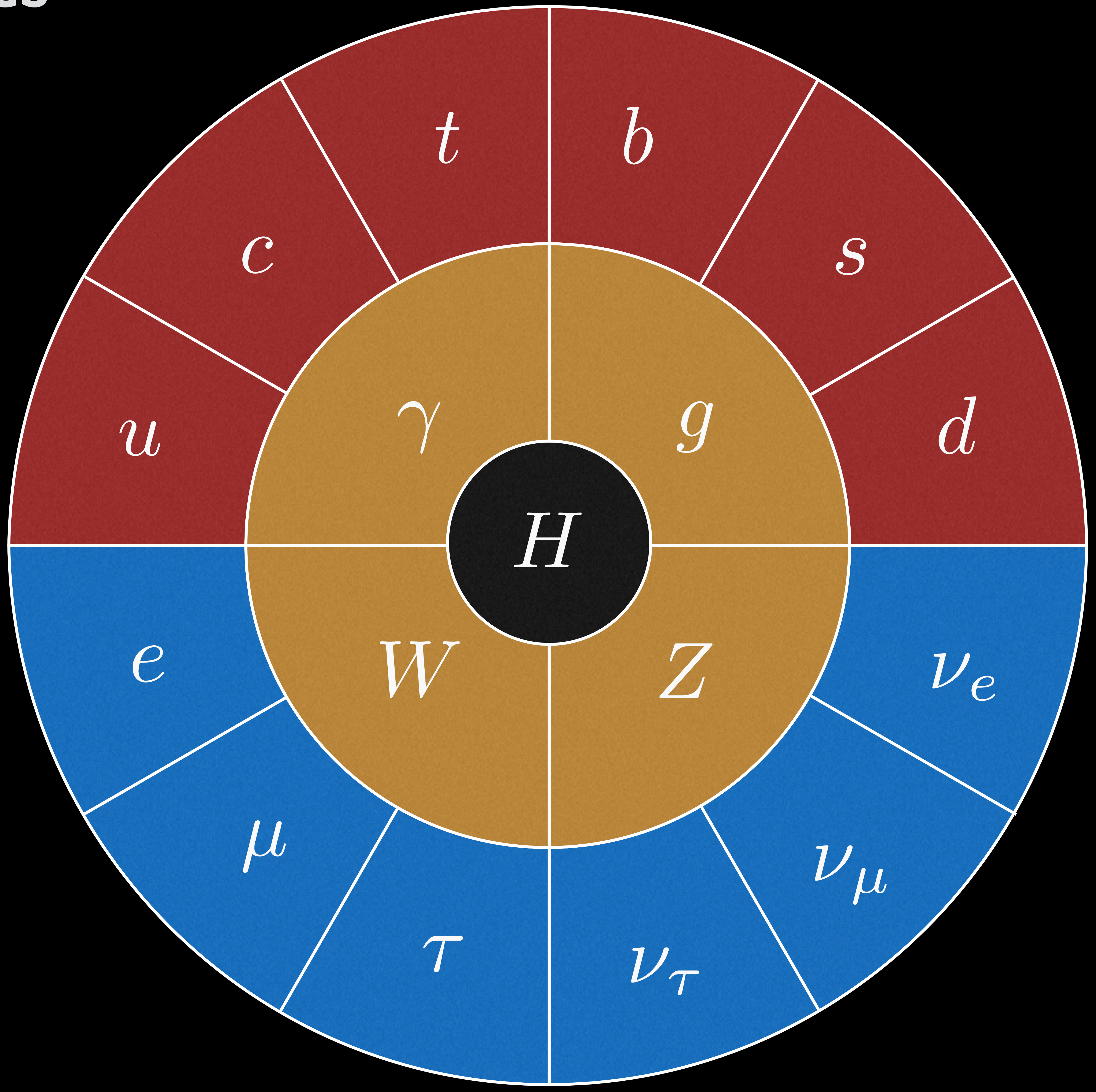
Proton

The Standard Model of Particle Physics

Matter: Quarks, Leptons

Force carriers: Gauge bosons

Gives mass to other particles: Higgs



Unanswered Questions

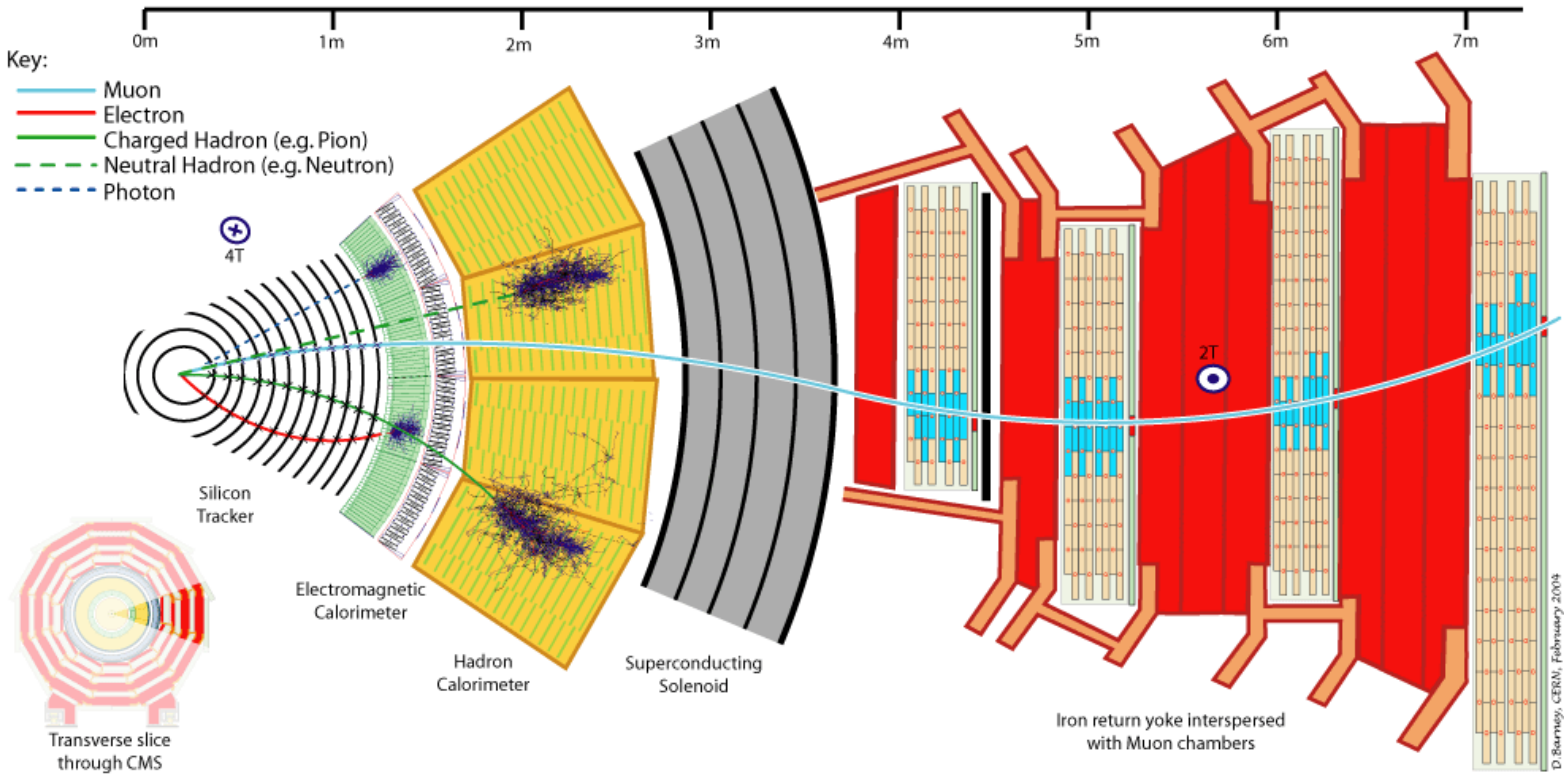
Higgs mass?

Neutrino oscillations?

?

Dark Matter?

And others…


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Two Higgs Doublet Models

Minimal Supersymmetric Standard Model

Focus of this talk

Higgs bosons in Two-Higgs Doublet Model

CP-even scalars

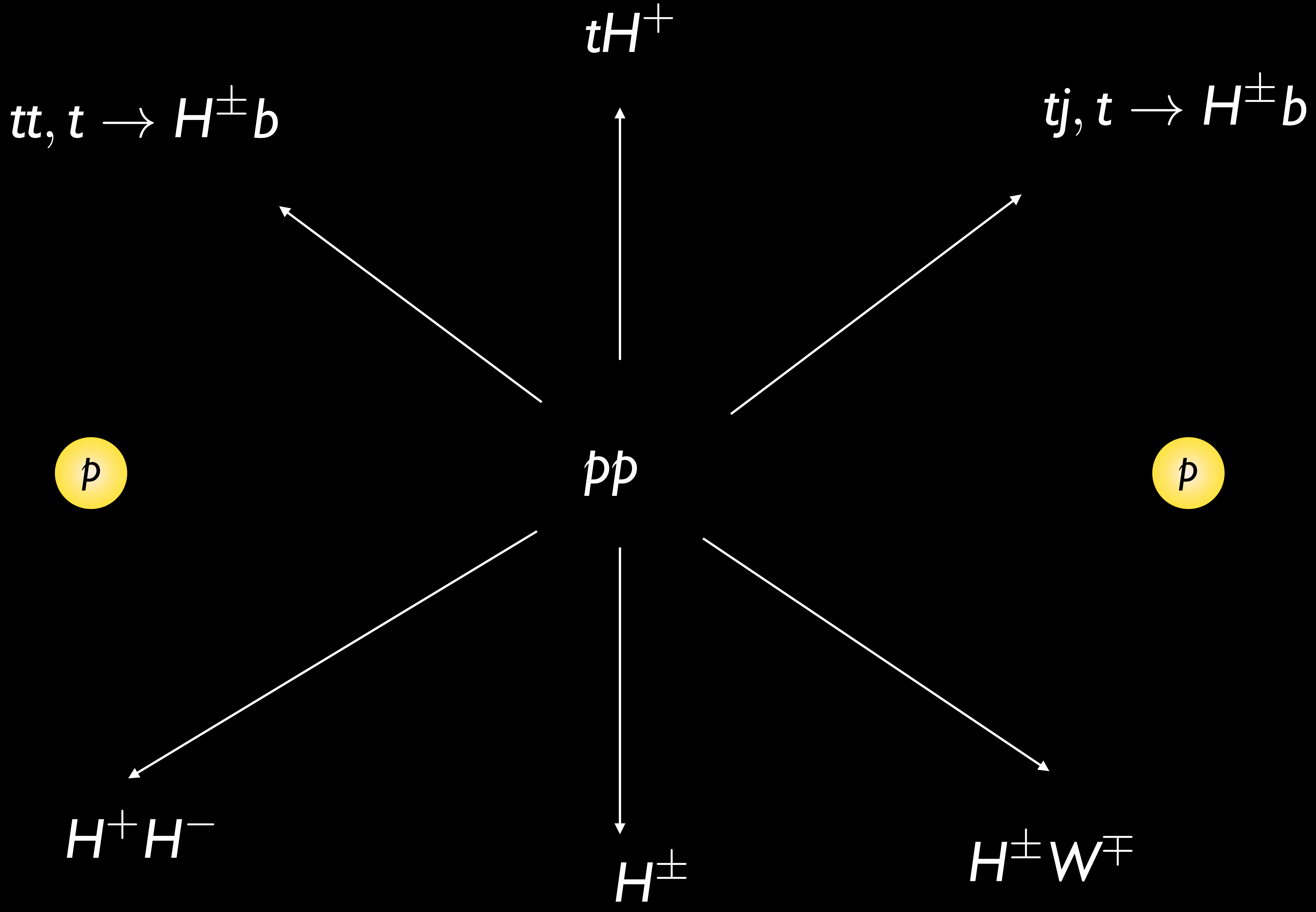
h H

CP-odd pseudoscalar

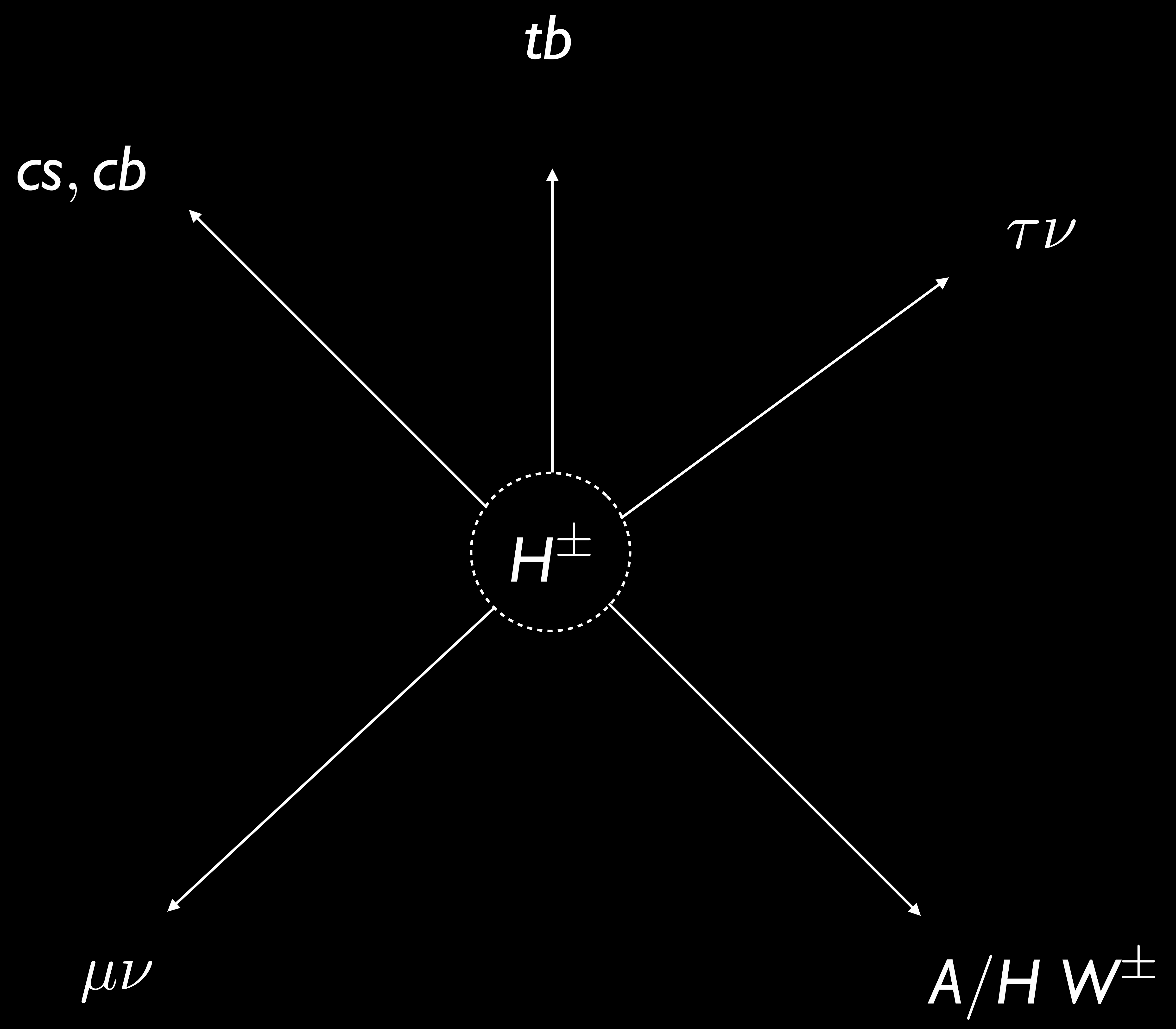
A^0

Charged Higgs Boson

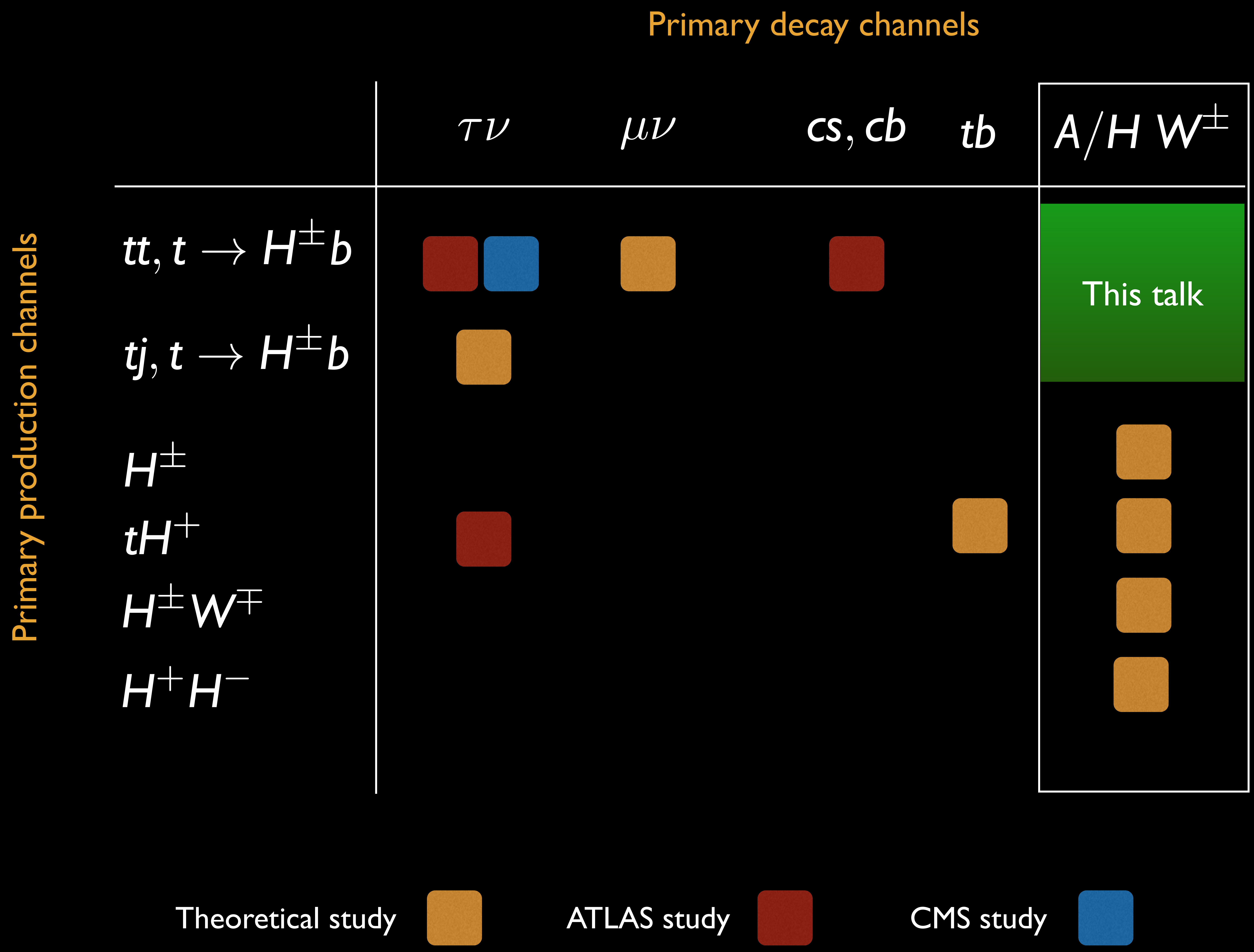
$H^{\pm}$



Primary production modes for the charged Higgs boson



Primary decay channels for the charged Higgs

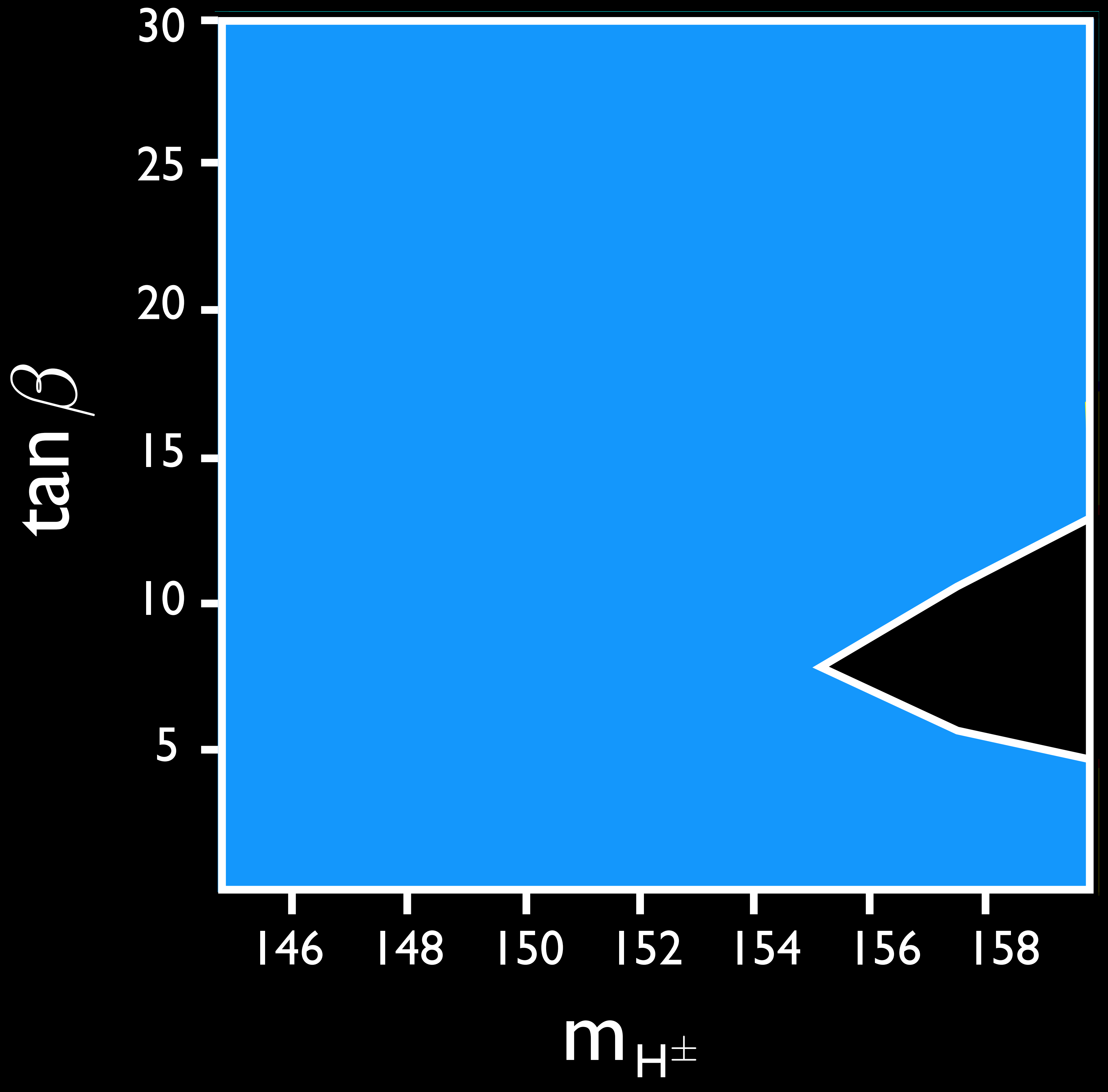


Primary decay channels
Primary production channels
$\tau\nu$
$\mu\nu$
cs, cb
tb
$A/H\ W^{\pm}$
$tt, t \to H^{\pm} b$
$tj, t \to H^{\pm} b$
$H^{\pm}$
tH^{+}
$H^{\pm} W^{\mp}$
$H^{+} H^{-}$
This talk
Theoretical study
ATLAS study
CMS study

Charged Higgs Challenges

Light (< 174 GeV)		Heavy (> 174 GeV)
✓	Soft final state particles	
	Off-shell production - rare	✓
✓	Cleaner leptonic decays suppressed	✓

Current Limits on Light Charged Higgs

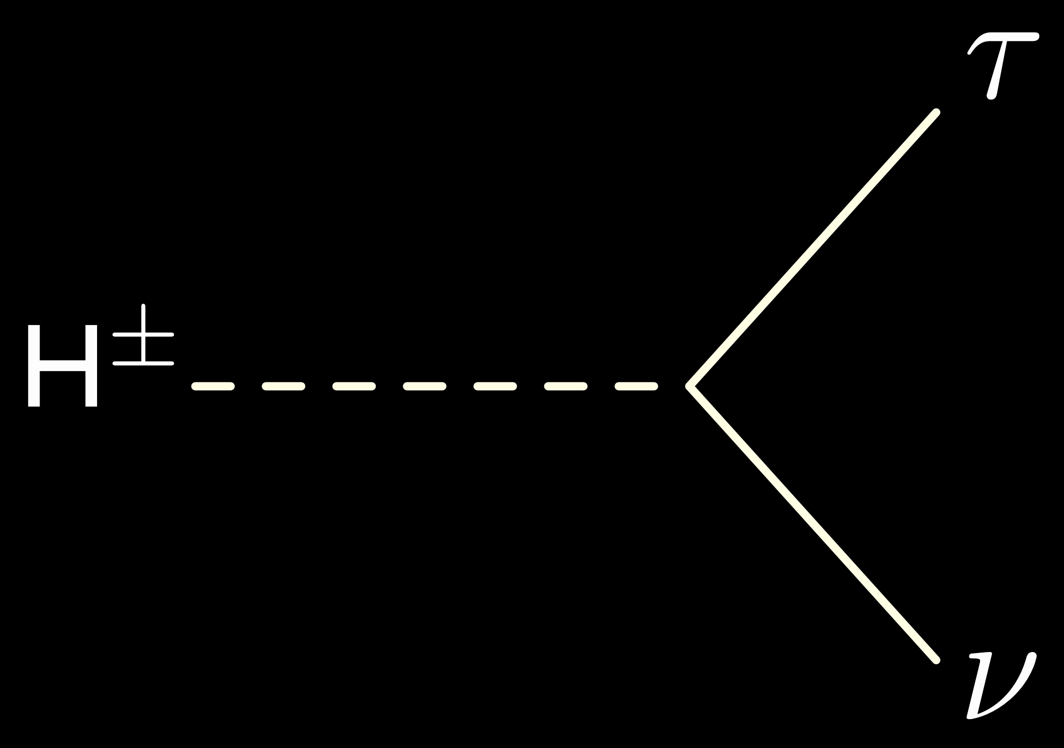


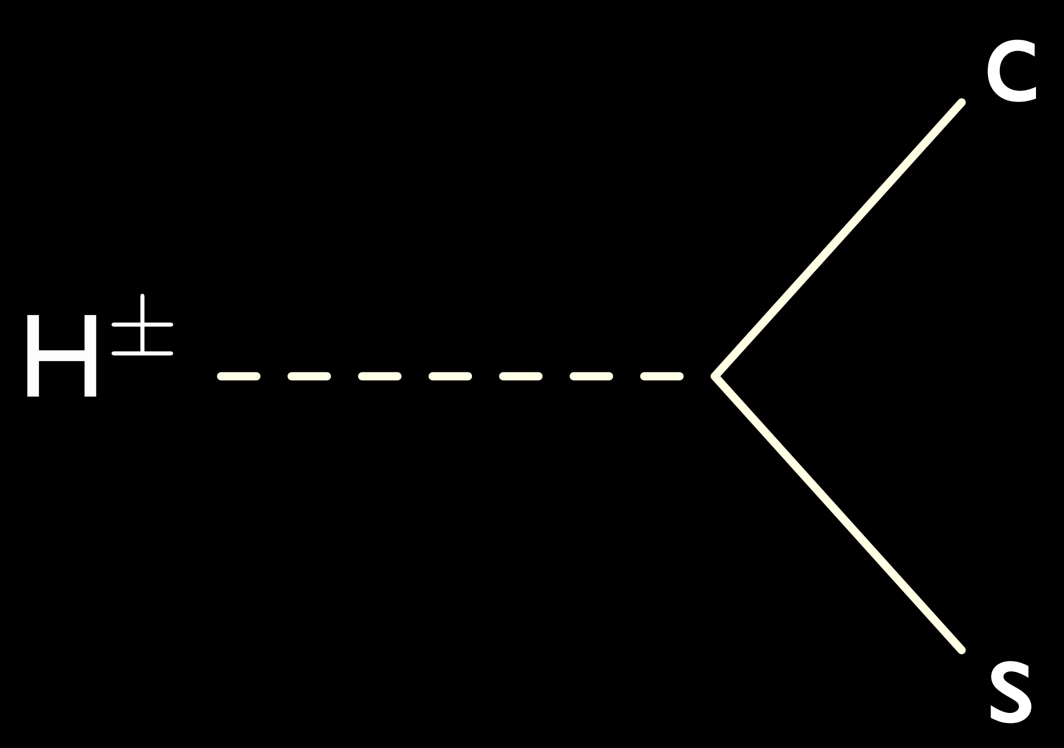
Excluded, assuming

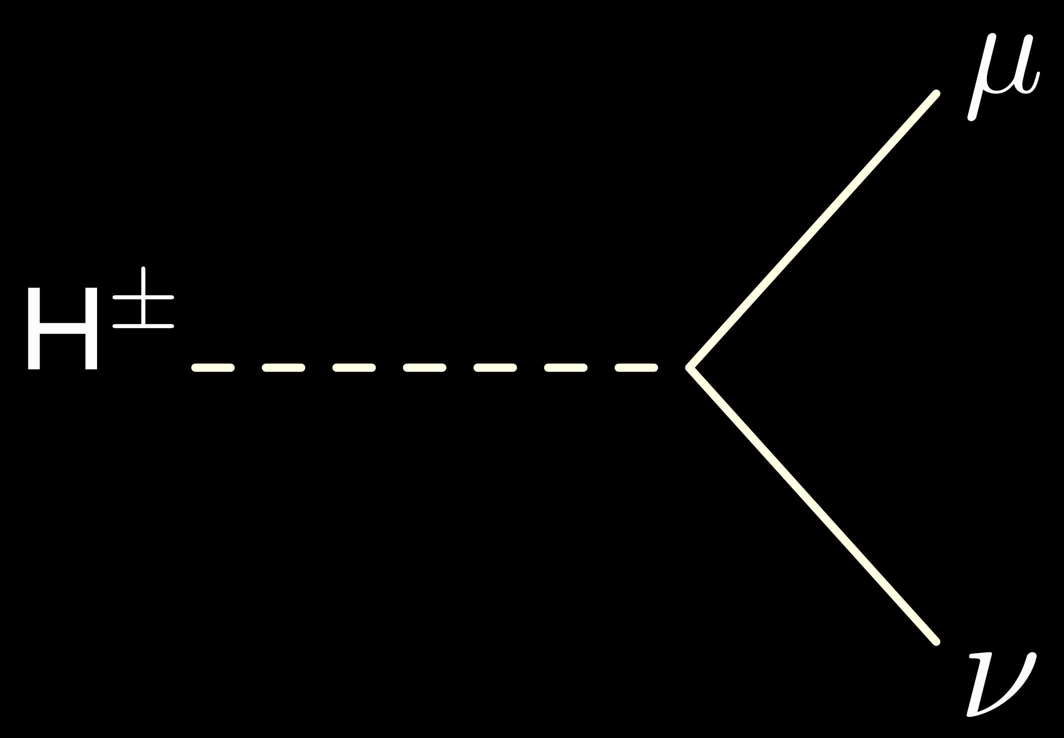
$BR(H^\pm \to \tau\nu) = 100\%$

Source:
CMS Analysis, September 2014

Primary decay modes of the Light Charged Higgs

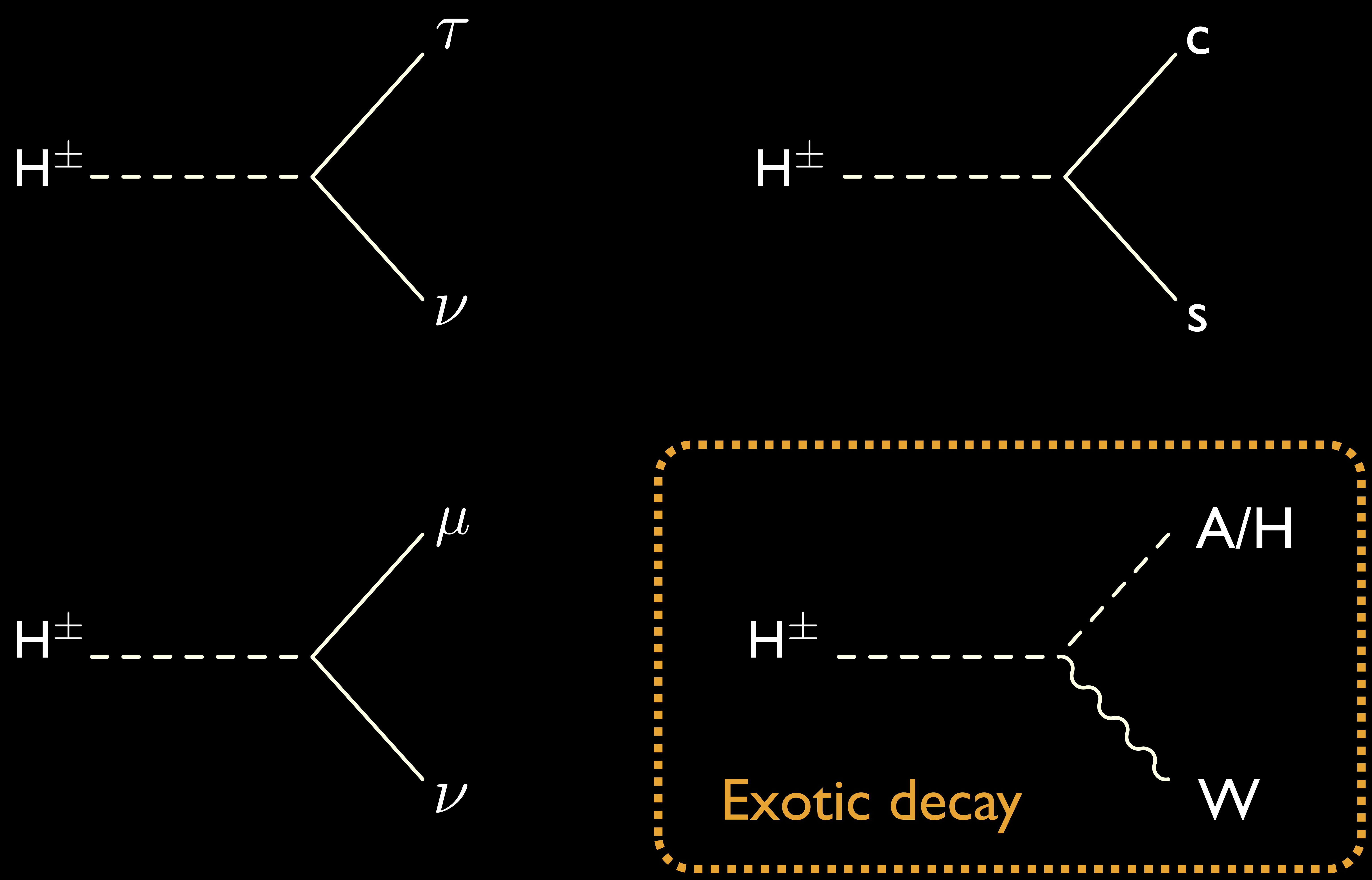






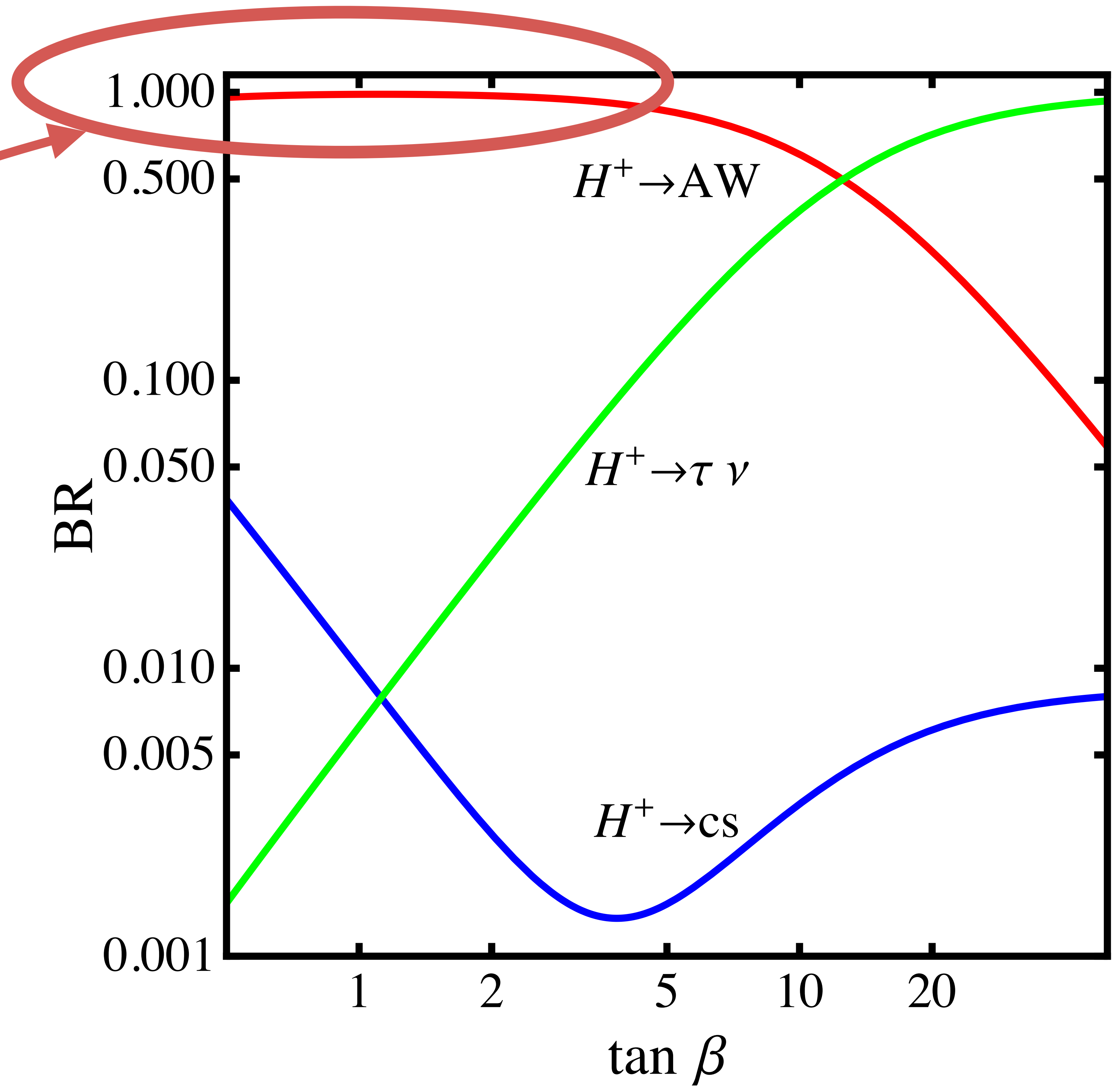
Decays to Standard Model particles

Primary decay modes of the Light Charged Higgs

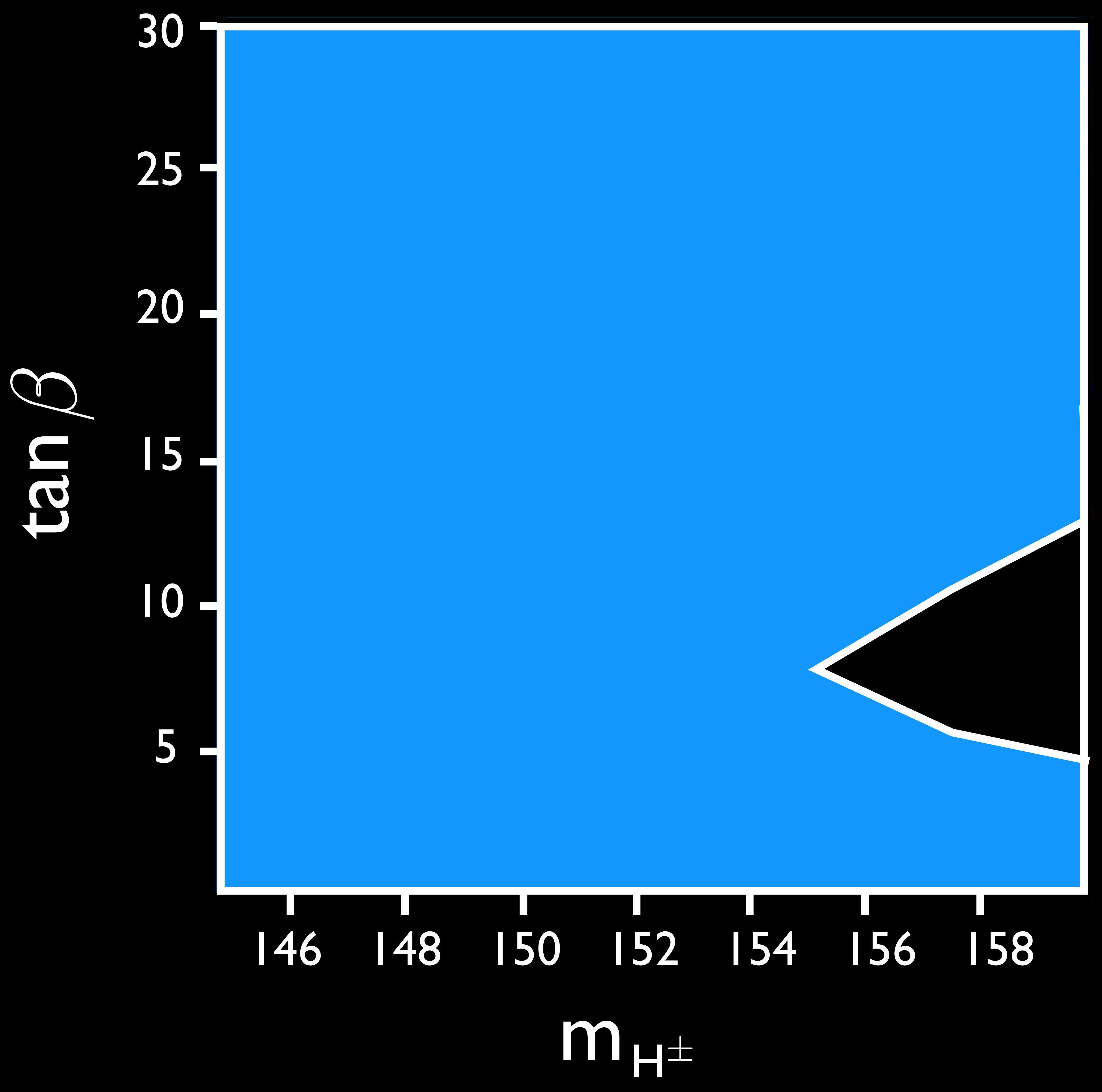


Branching Ratios

Exotic decay dominates for low tan β



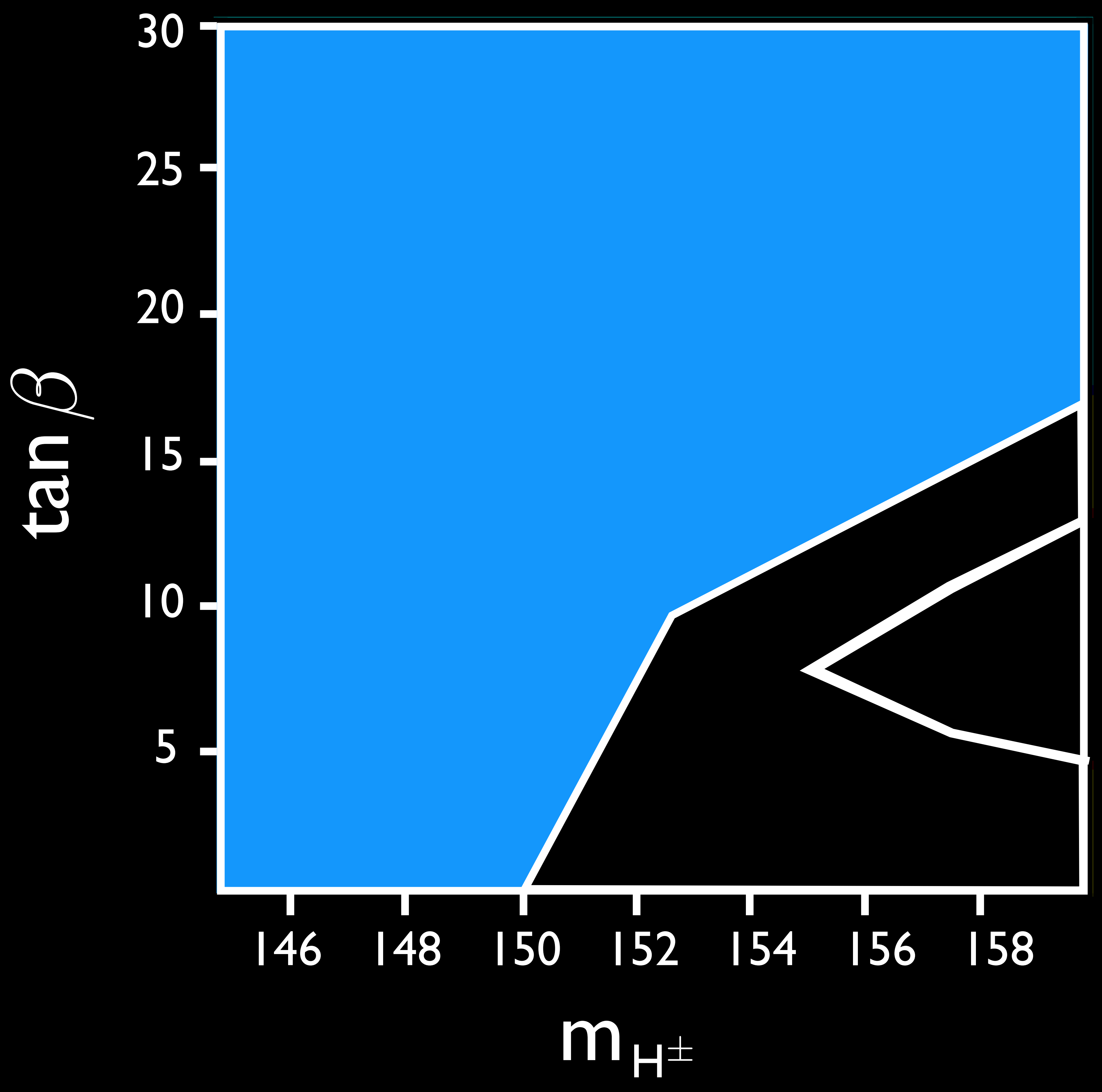
Current Limits



Excluded, assuming

$BR(H^{\pm} \to \tau\nu) = 100\%$

Weakened Limits

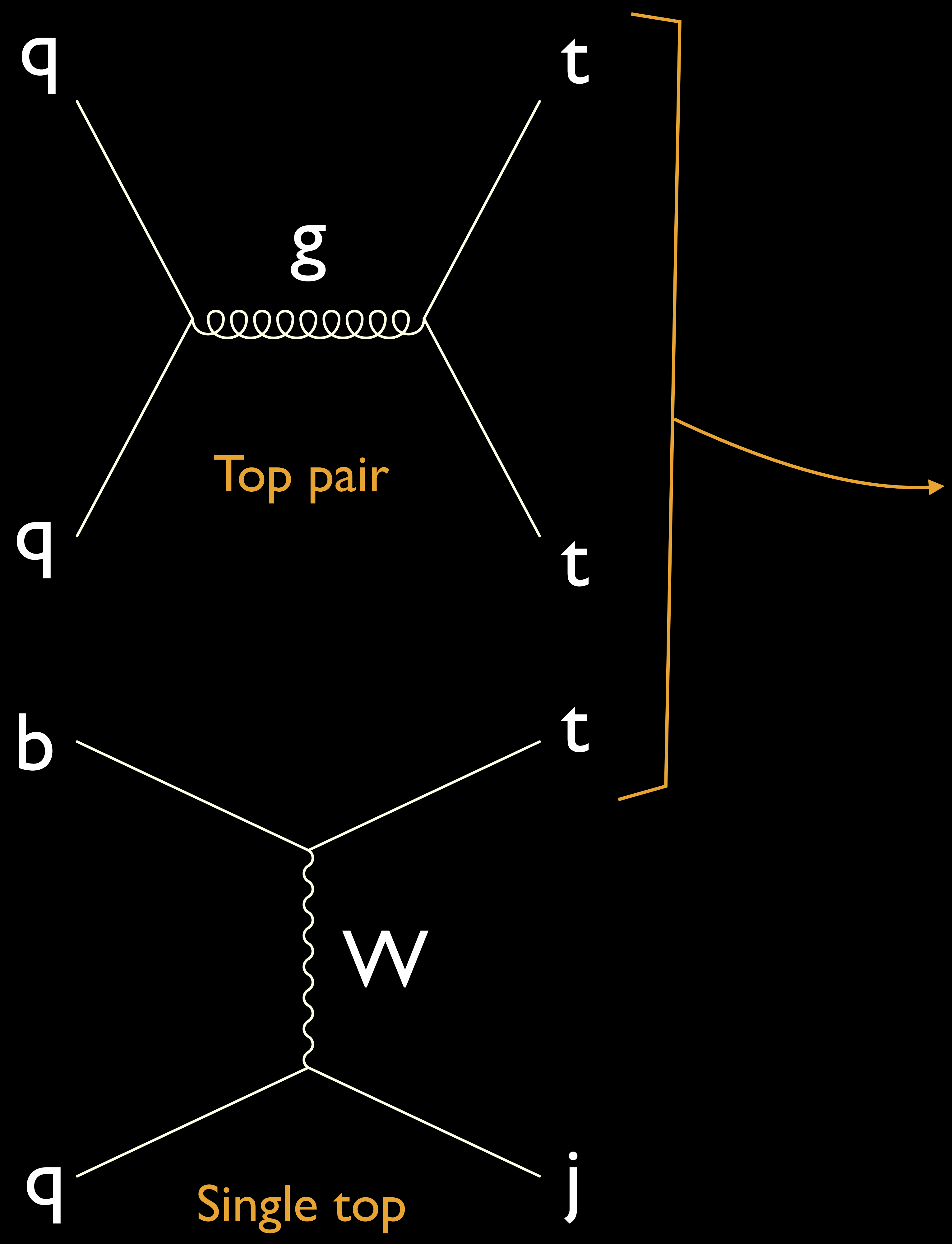


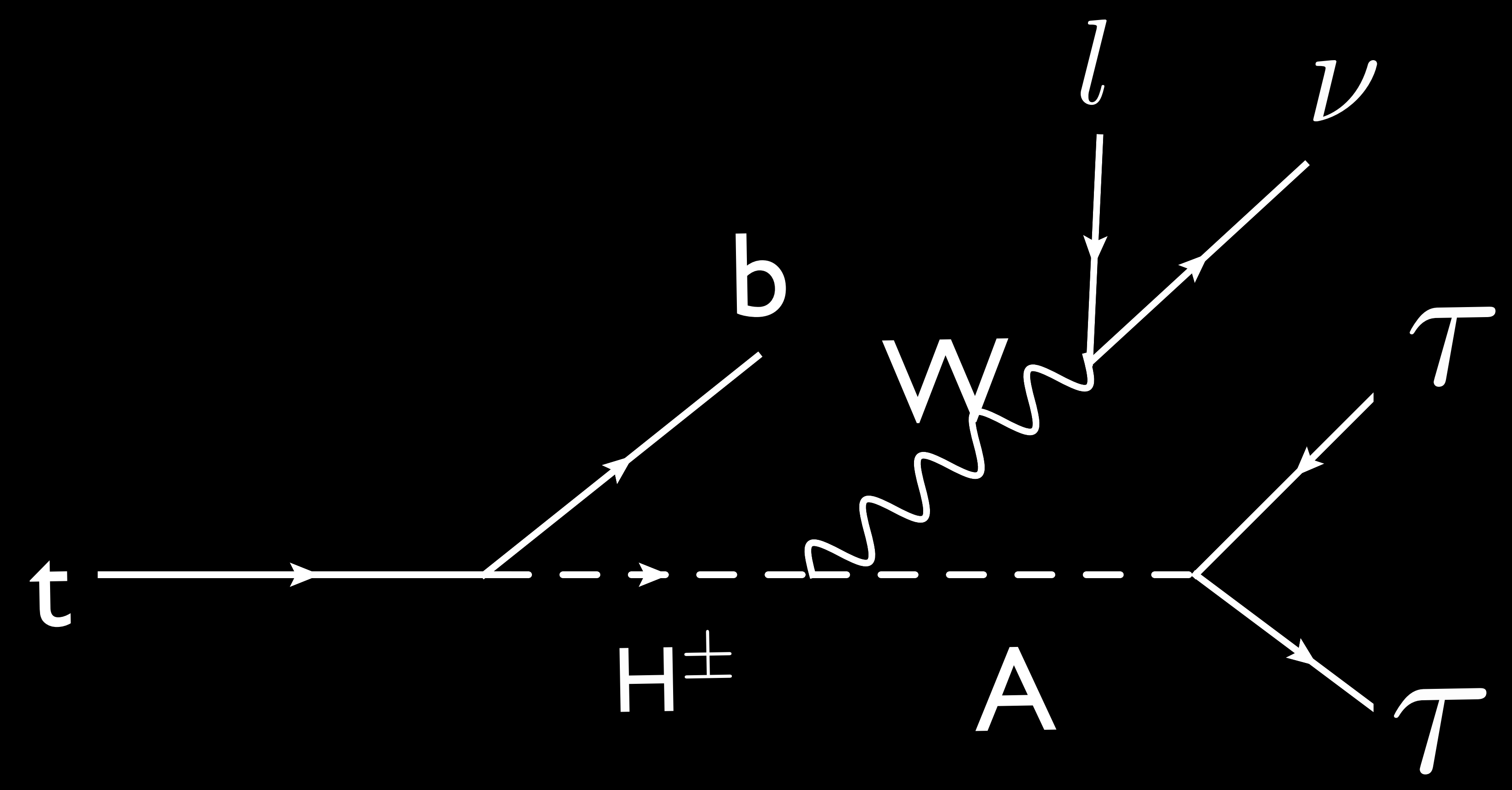
Excluded, if

$H^\pm \to AW$ is possible

(Assuming existence of
A with mass 70 GeV)

Our search channel



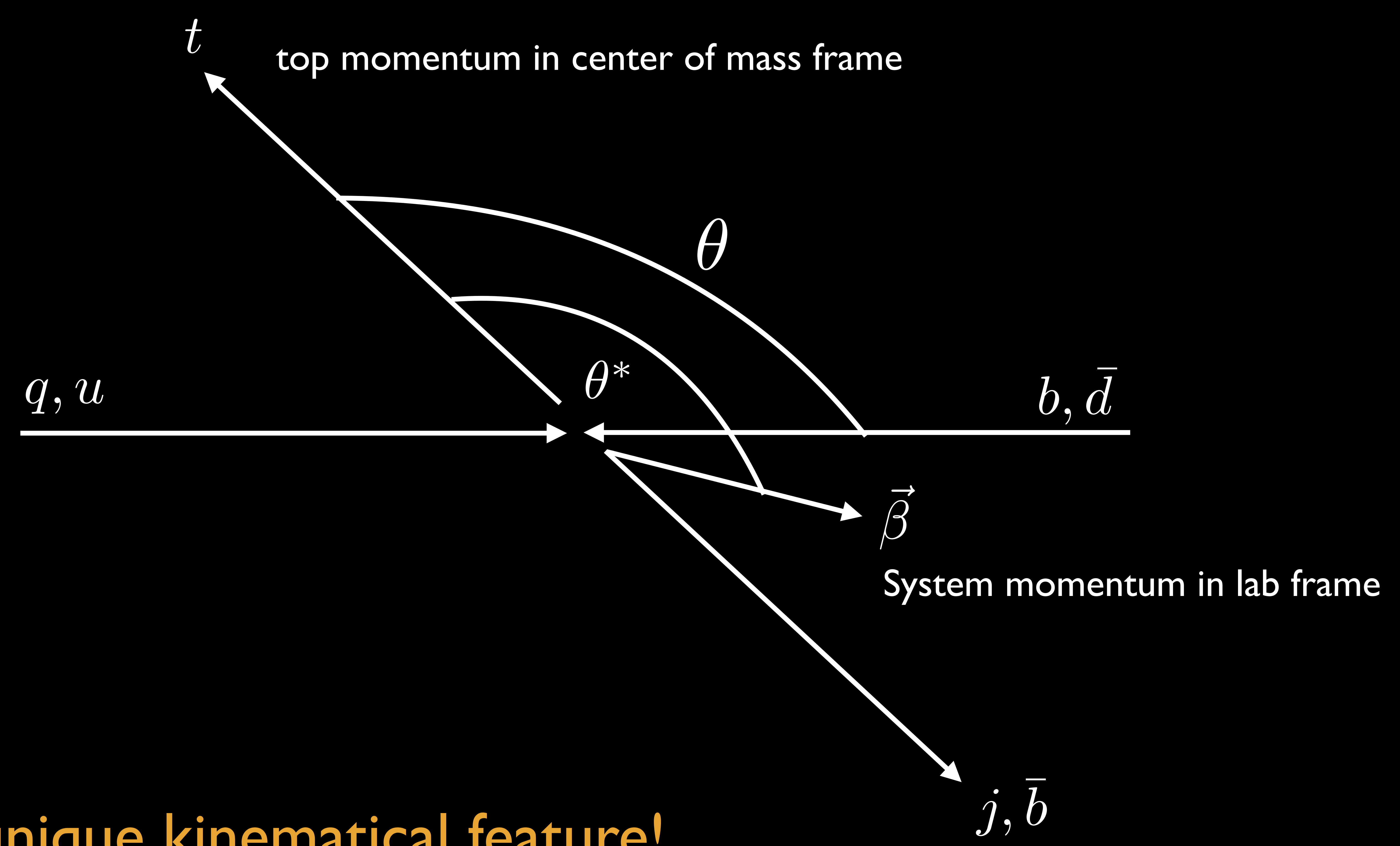


Primary backgrounds:

tt + jets

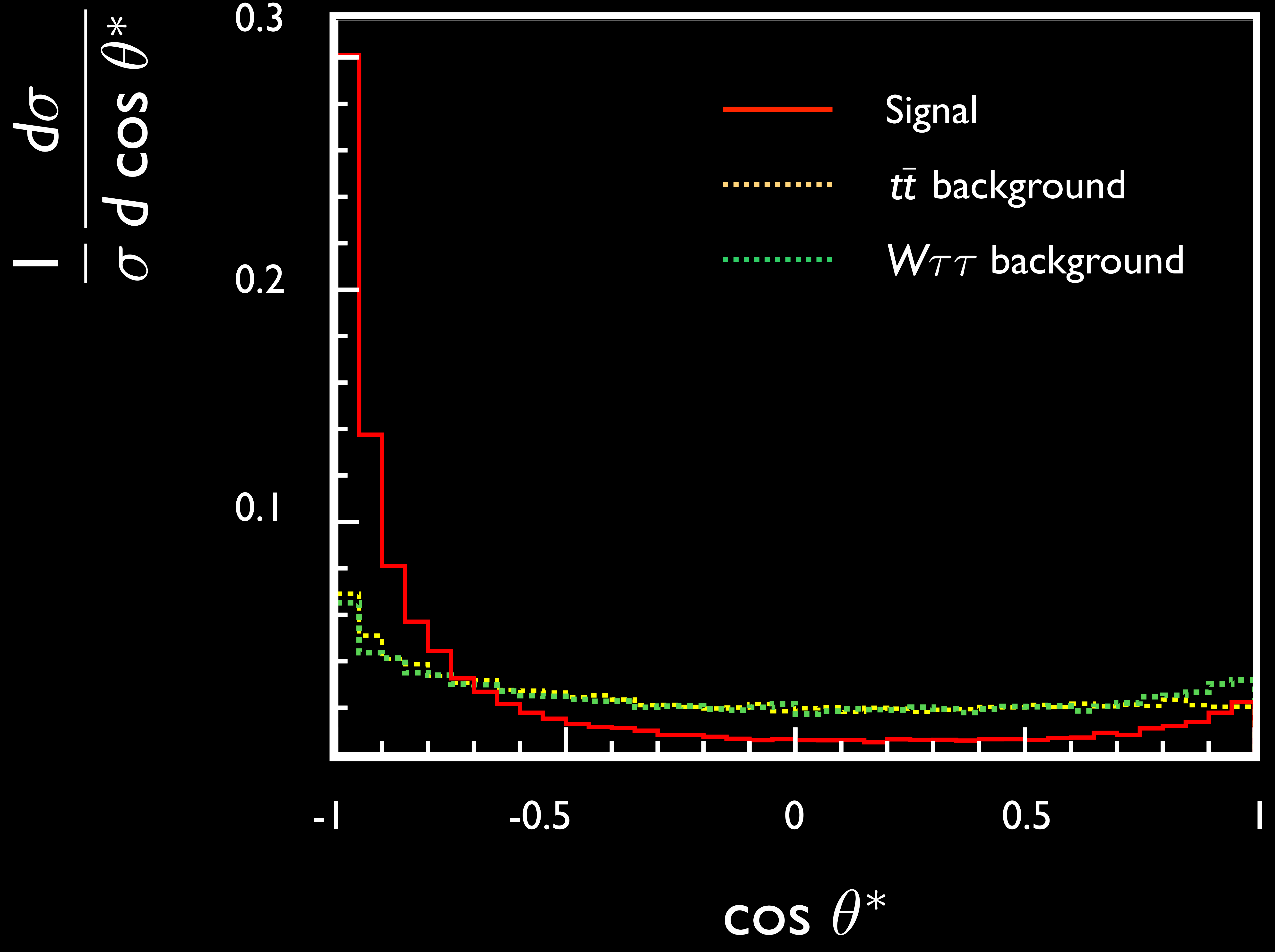
WZ + jets

Angular Correlations in Single Top Production

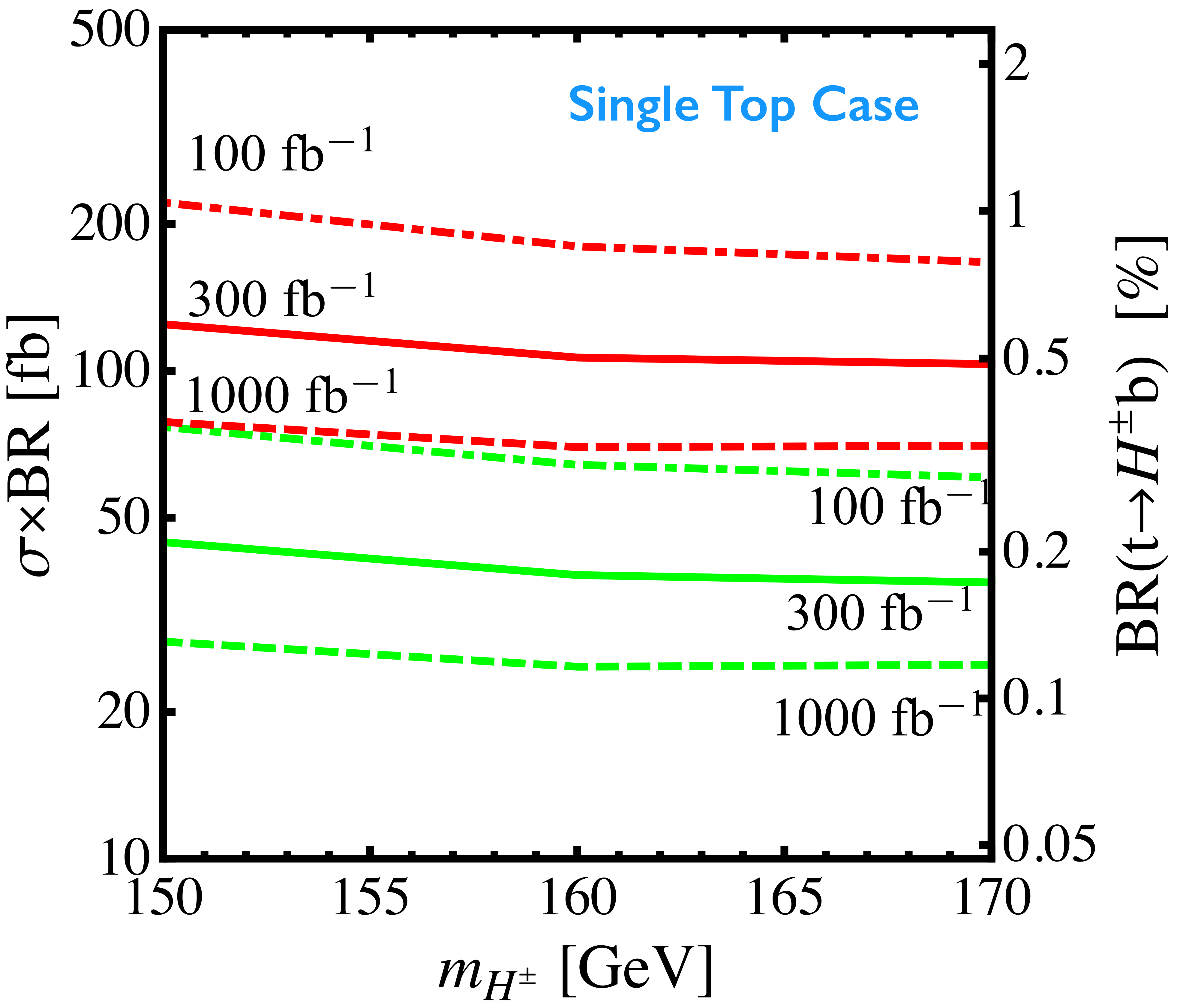


A unique kinematical feature!

Angular distribution - Signal vs. Background



Model-independent Limits



Red: Discovery

Green: Exclusion

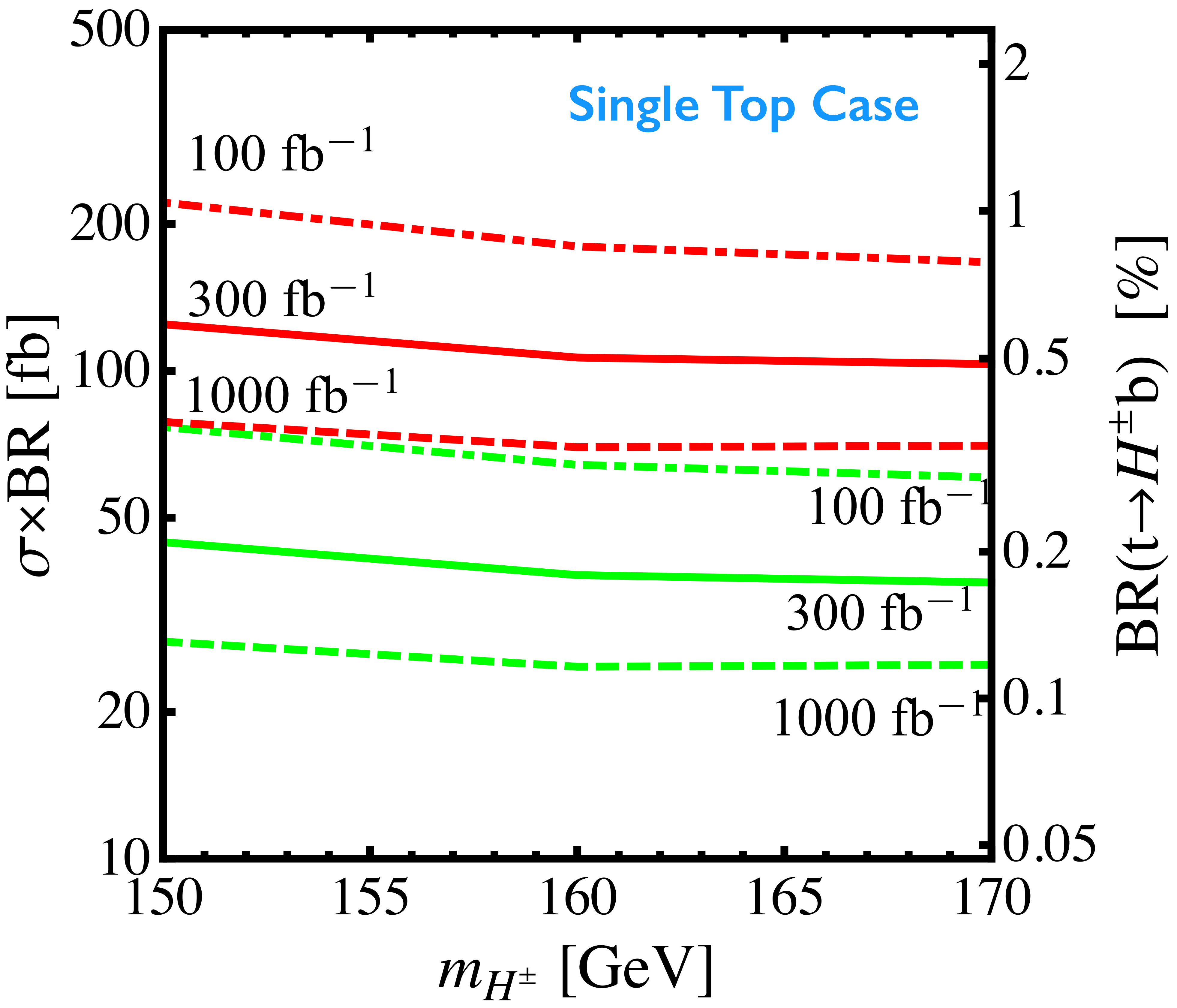
@ 14 TeV LHC

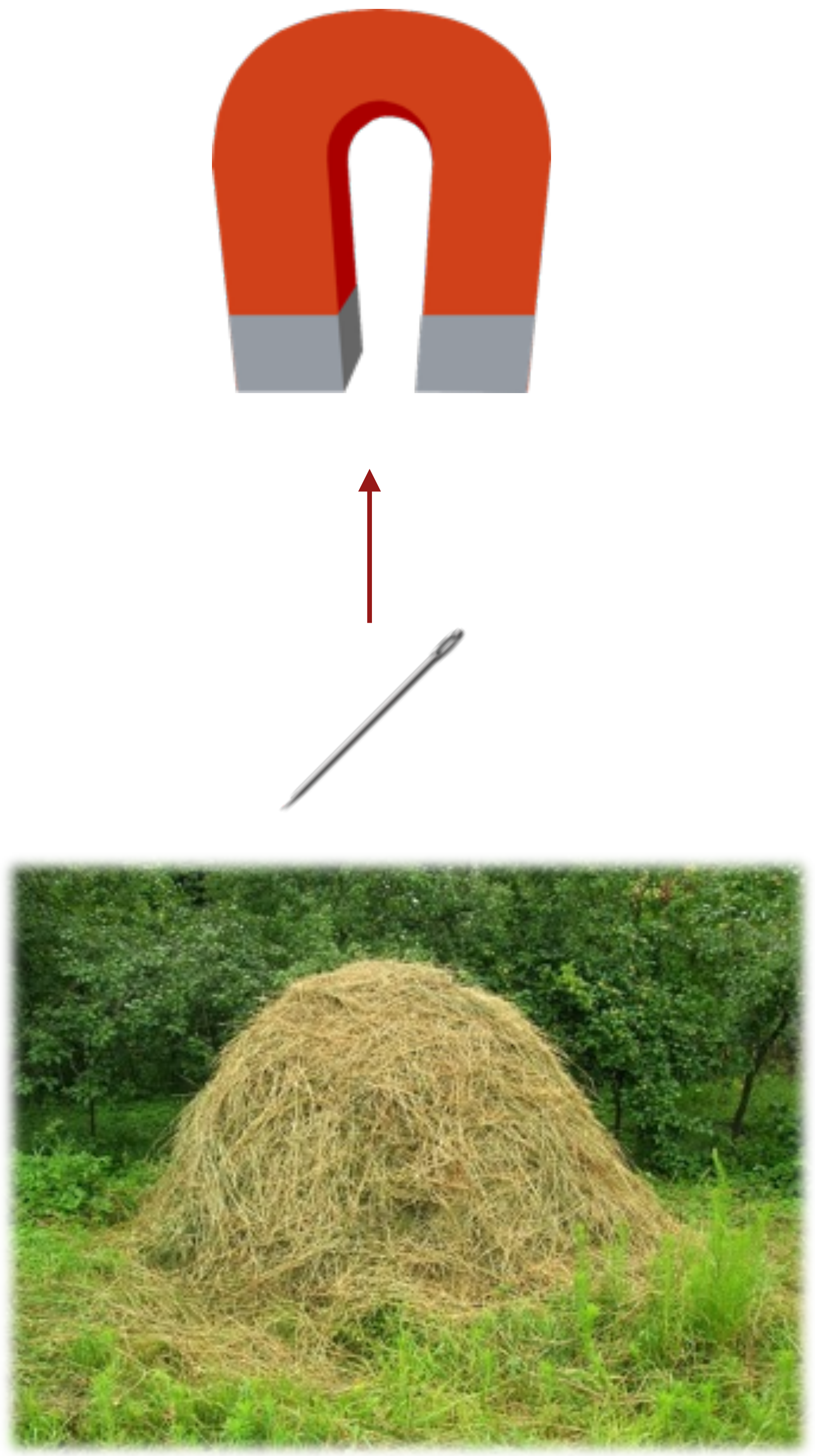
More data

↓

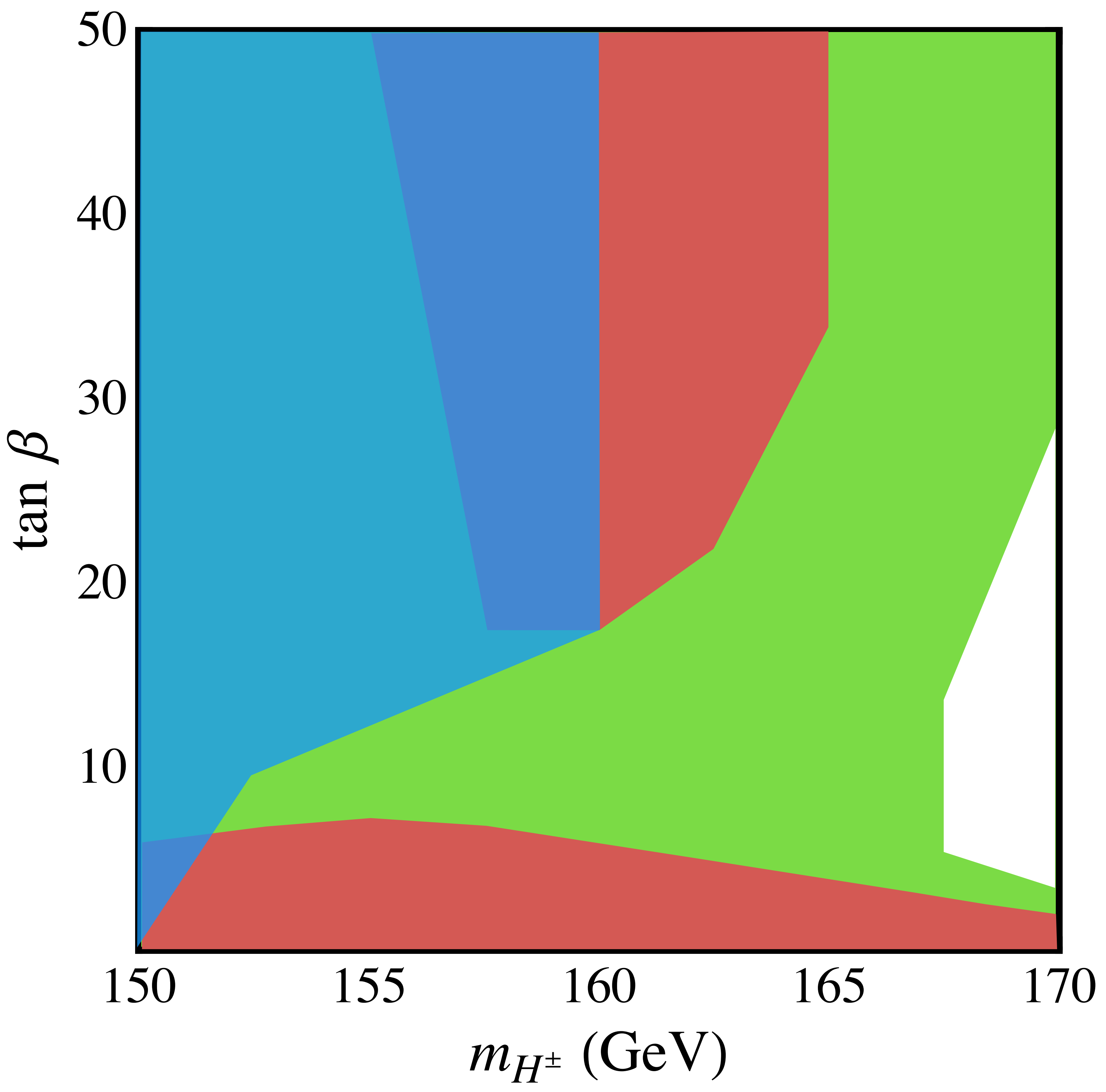
Stronger bounds!

Model-independent Limits





2HDM Implications



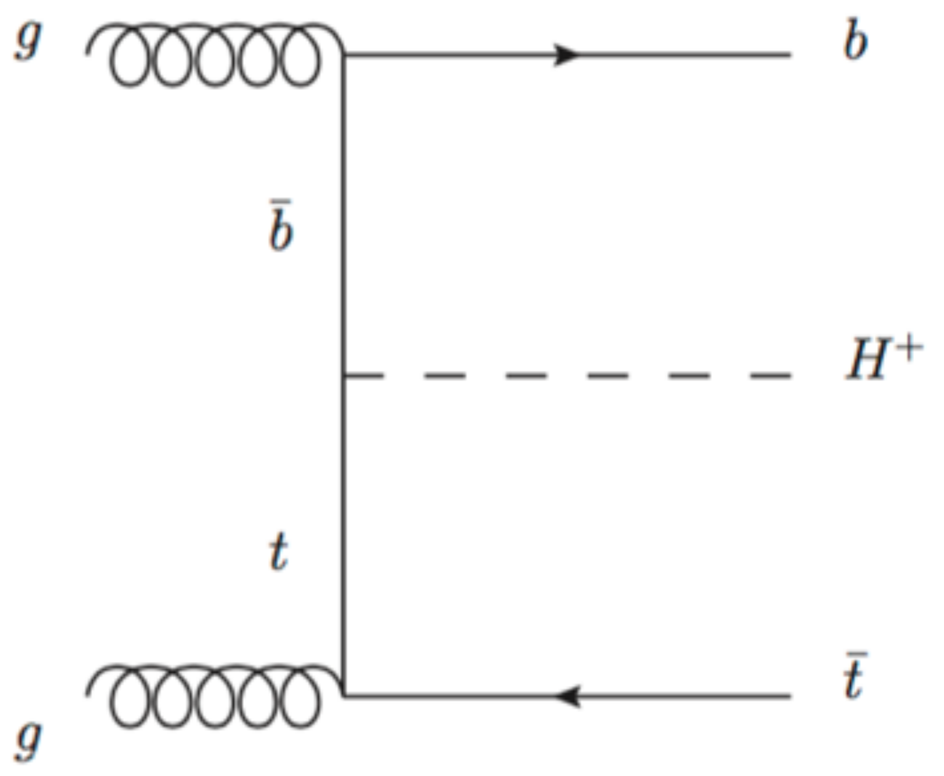
Excluded by CMS @ 20 fb^{-1}

Can be excluded using our search strategy at 300 fb^{-1}

Can be discovered using our search strategy @ 300 fb^{-1}

Heavy Charged Higgses

Production in association with a top quark



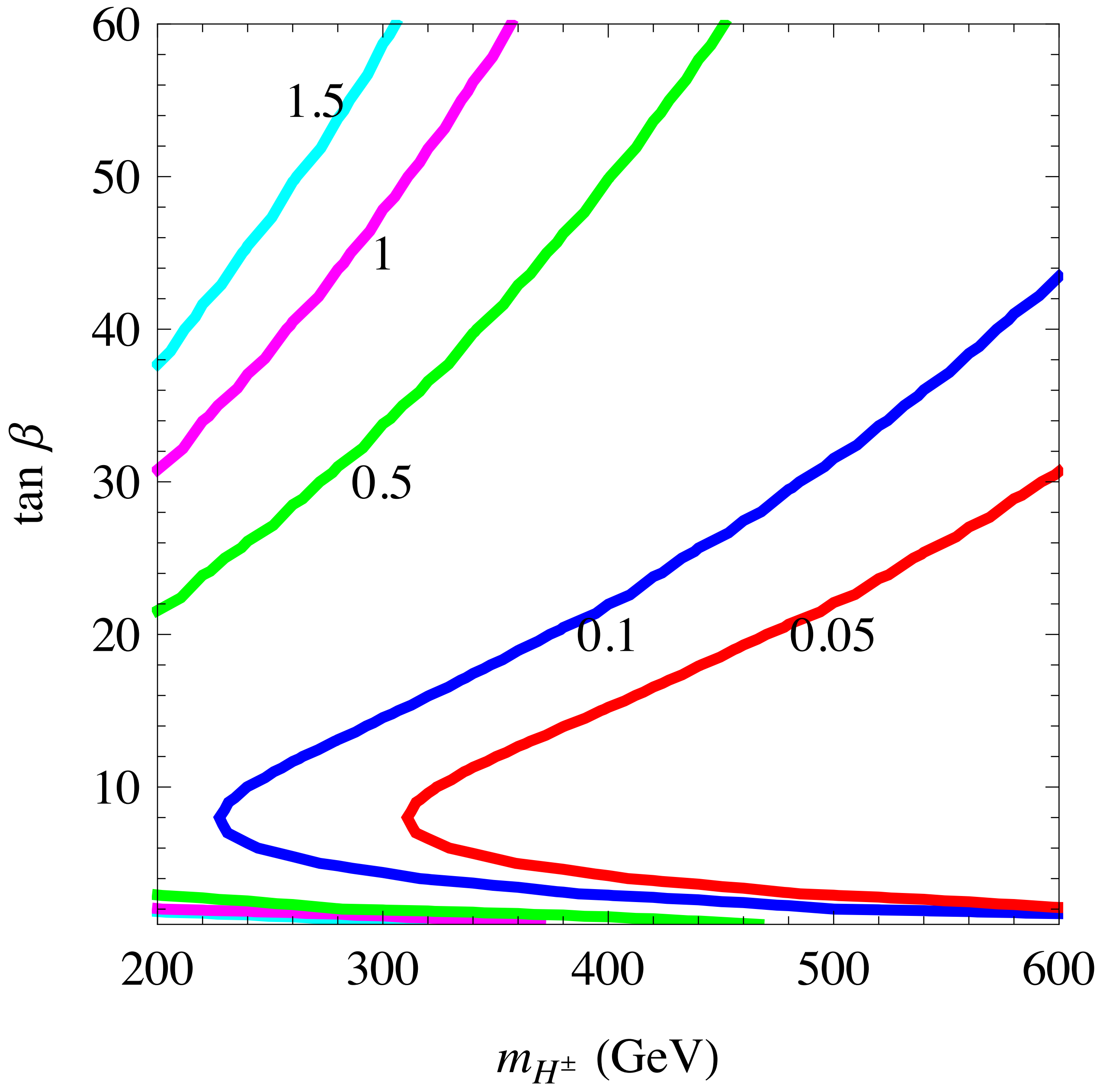
$H^\pm \rightarrow tb$, large BG

$H^\pm \rightarrow \tau\nu$ or cs,

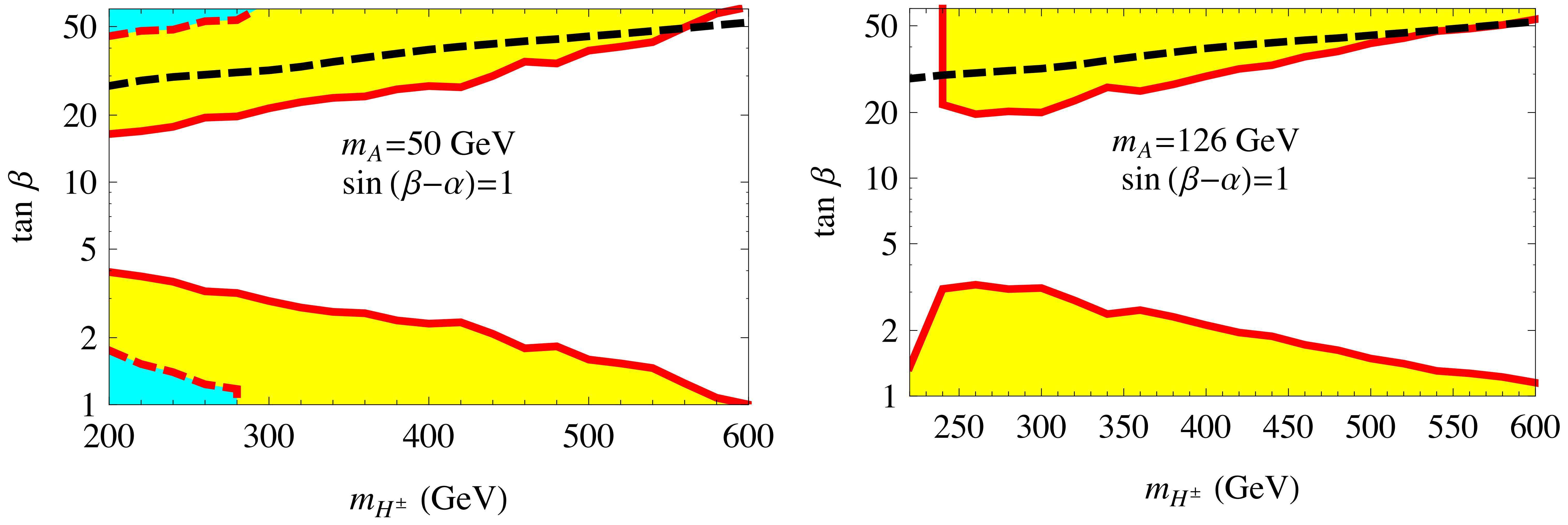
suppressed Br.

B. Coleppa, F. Kling, and S. Su,
Charged Higgs search via AW/HW channel,
JHEP 12 (2014) 148, [arXiv:1408.4119].

Production cross section (pb) @ 14 TeV



Reach in parameter space



Exotic Higgs Decays - Big picture

- Consistent with theories that explain matter-antimatter imbalance in the universe.
- Can dominate over SM final states in regions of parameter space.

In the near future…

Table 5.1: Summary of all the possible exotic decay modes and the dominant final states for non-SM Higgs bosons

Parent Higgs	Decay type	Channels in 2HDM	Main Final States
Neutral Higgs H,A	HH	$H \to AA, hh$	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$
	HZ	$H \to AZ, A \to HZ, hZ$	$(ll/qq/\nu\nu)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$
	H^+H^-	$H \to H^+H^-$	$(tb/\tau\nu/cs)(tb/\tau\nu/cs)$
	$H^\pm W^\mp$	$H/A \to H^\pm W^\mp$	$(l\nu/qq')(tb/\tau\nu/cs)$
Charged Higgs	$HW^\pm$	$H^\pm \to hW^\pm/HW^\pm/AW^\pm$	$(l\nu/qq')(bb/\tau\tau/WW/ZZ/\gamma\gamma)$

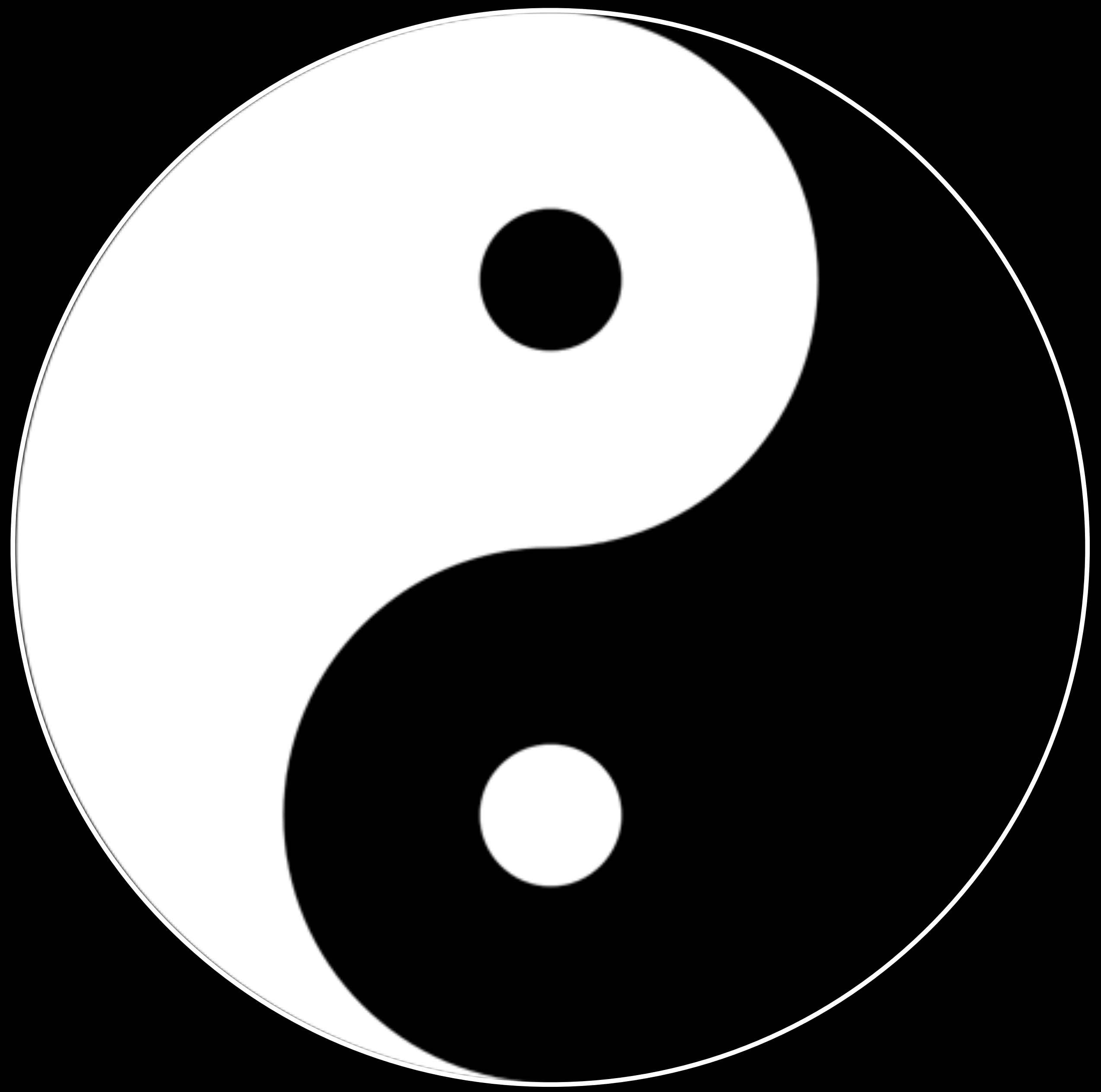
Name	Plane	Decays	m_{12}^2
IA	$m_A > m_H = m_{H^\pm}$	$A \to H^\pm W^\mp$ $A \to HZ$	$m_H^2 s_\beta c_\beta$ 0
IB	$m_A < m_H = m_{H^\pm}$	$H \to AZ/AA$ $H^\pm \to AW^\pm$	0
IIA	$m_H > m_A = m_{H^\pm}$	$H \to AZ/AA$ $H \to H^+H^-/H^\pm W^\pm$	0
IIB	$m_H < m_A = m_{H^\pm}$	$A \to HZ$ $H^\pm \to HW^\pm$	$m_H^2 s_\beta c_\beta$ 0
III	$m_A = m_H = m_{H^\pm}$ vs $c_{\beta-\alpha}$	$A \to hZ, H^\pm \to hW^\pm$ $H \to hh$	$m_H^2 s_\beta c_\beta$ 0

Table 5.2: Summary of benchmark planes for exploring exotic Higgs decays in 2HDMs that survive theoretical and experimental constraints. Source: [4].

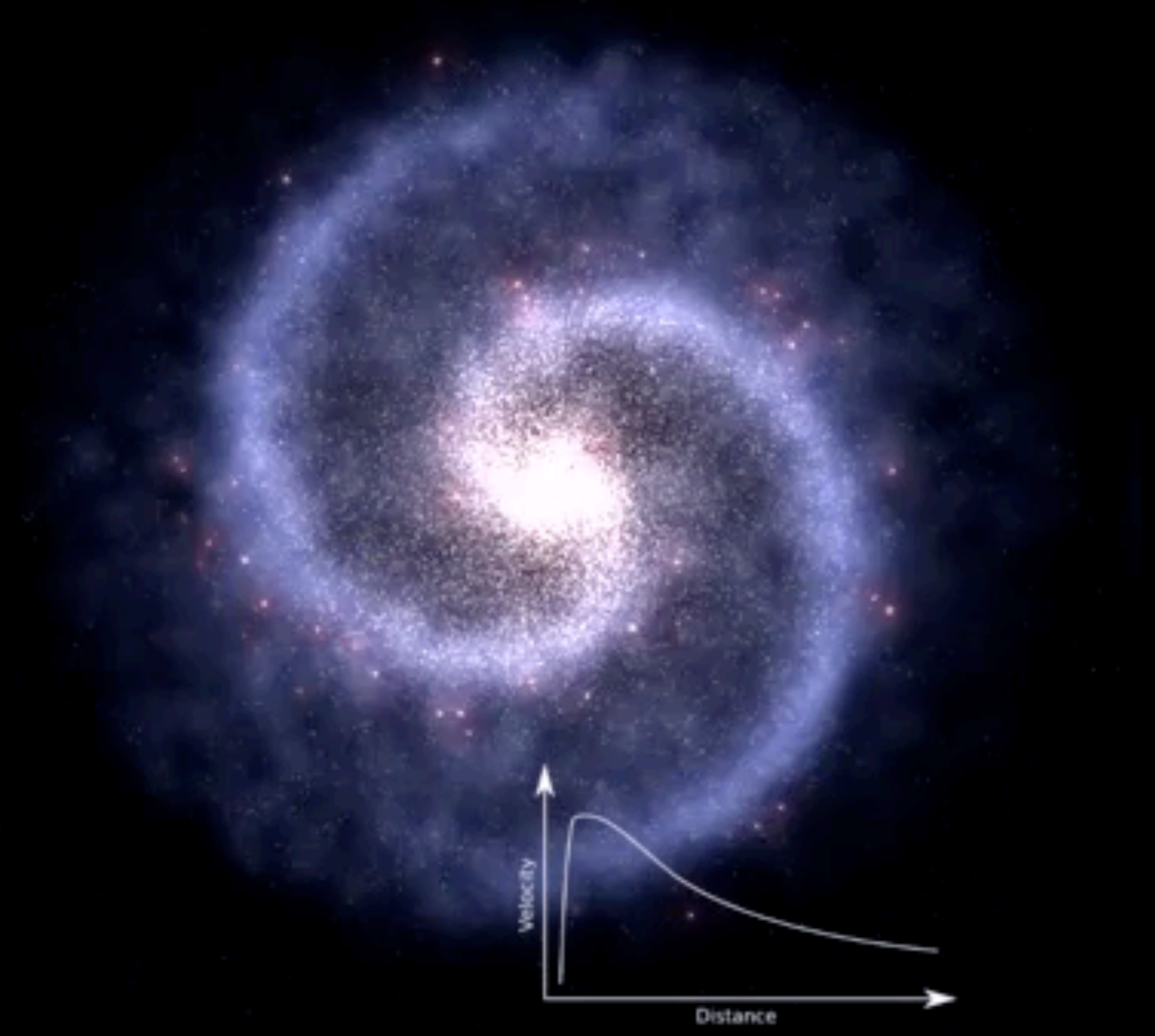
F Kling, J M No, and S Su.
"*Anatomy of Exotic Higgs Decays in 2HDM*".
arXiv: 1604.01406

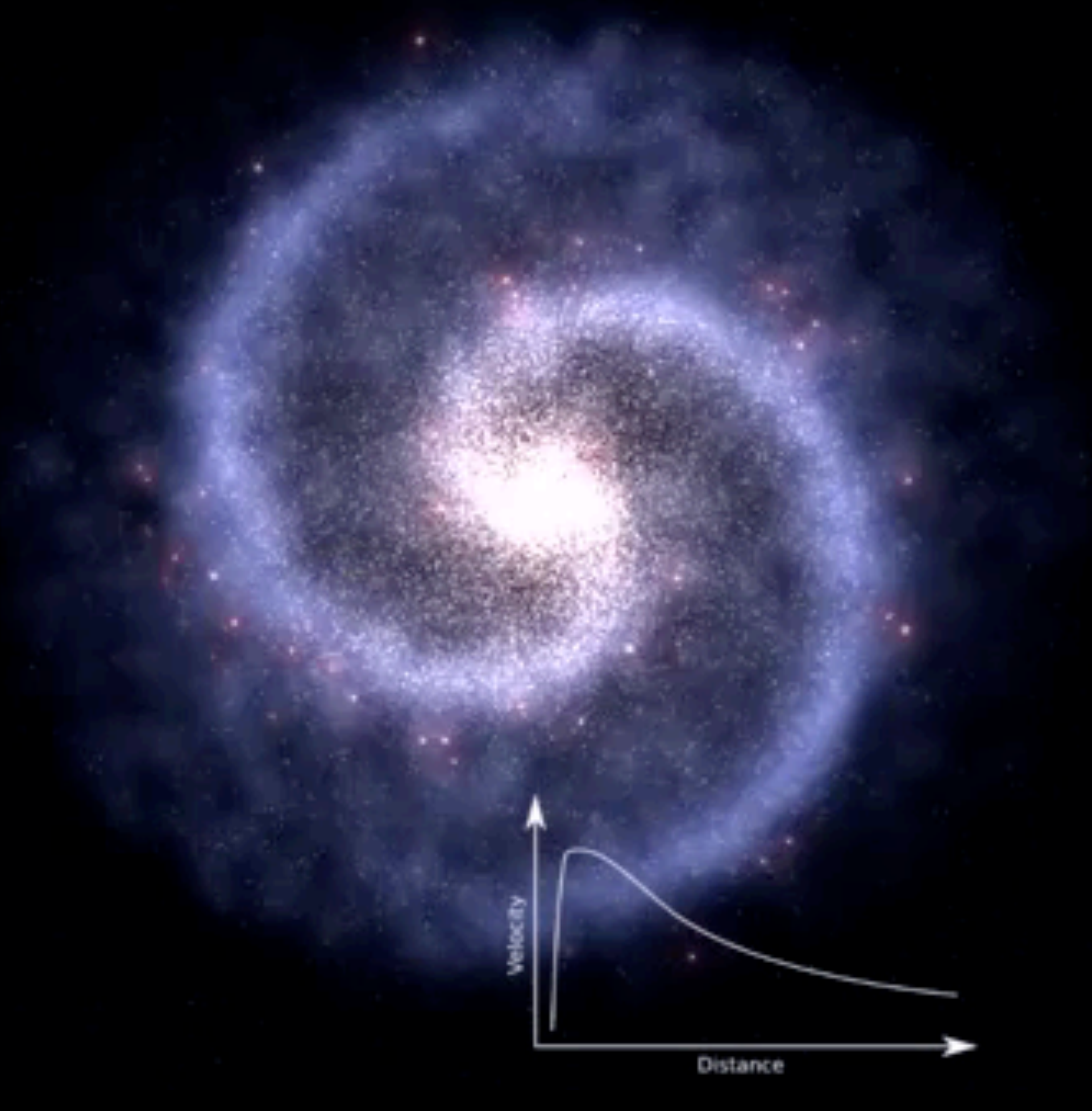
Conclusion

Conventional decay channels

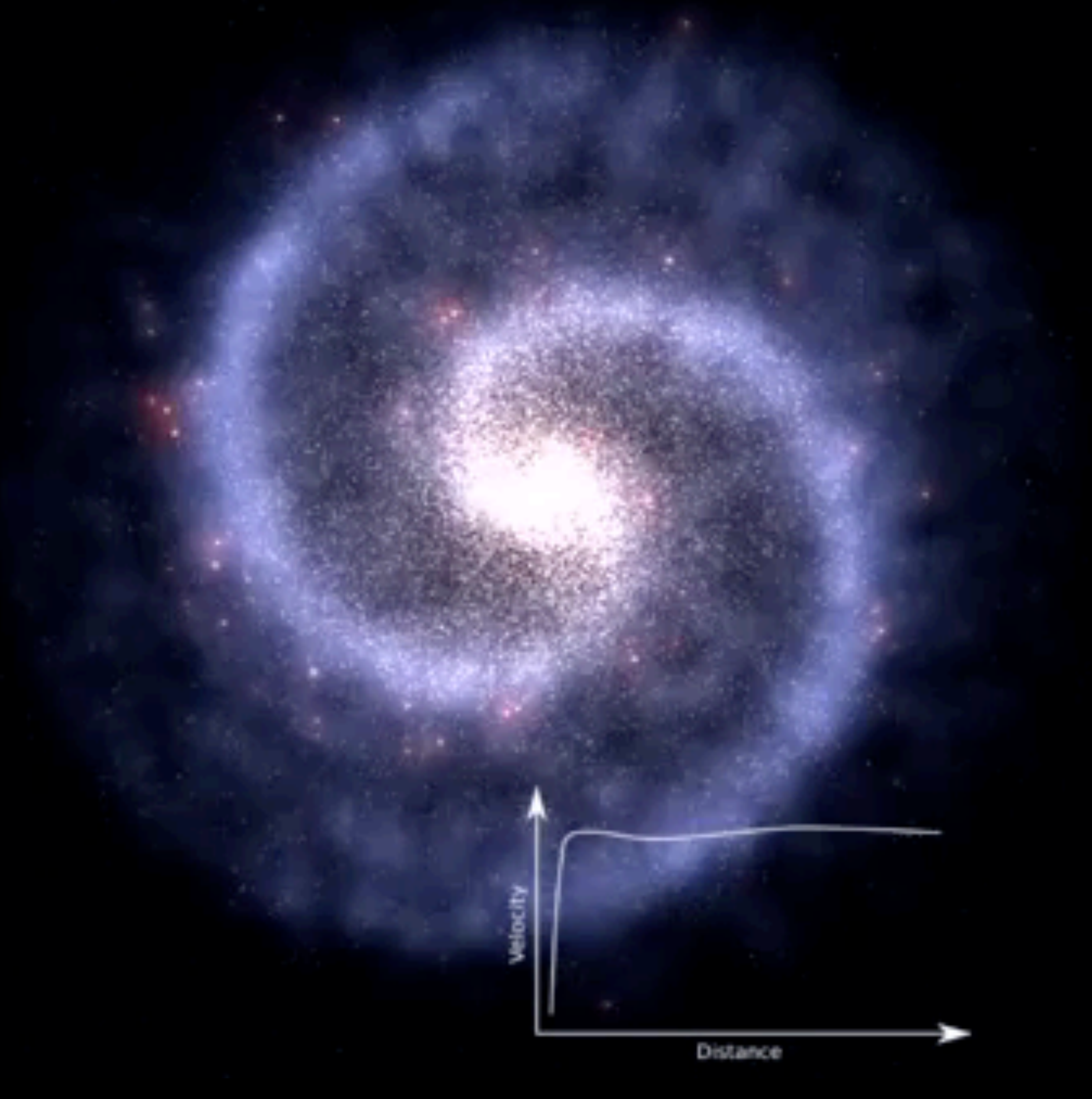


Exotic decay channels


Velocity
Distance



Without dark matter



With dark matter
(edges rotate faster)

Dark Matter = Weakly Interacting Massive Particles (WIMPs)?

WIMPs from Supersymmetry (SUSY)


Boson
Supersymmetry transformation
Fermion

Neutralino Dark Matter

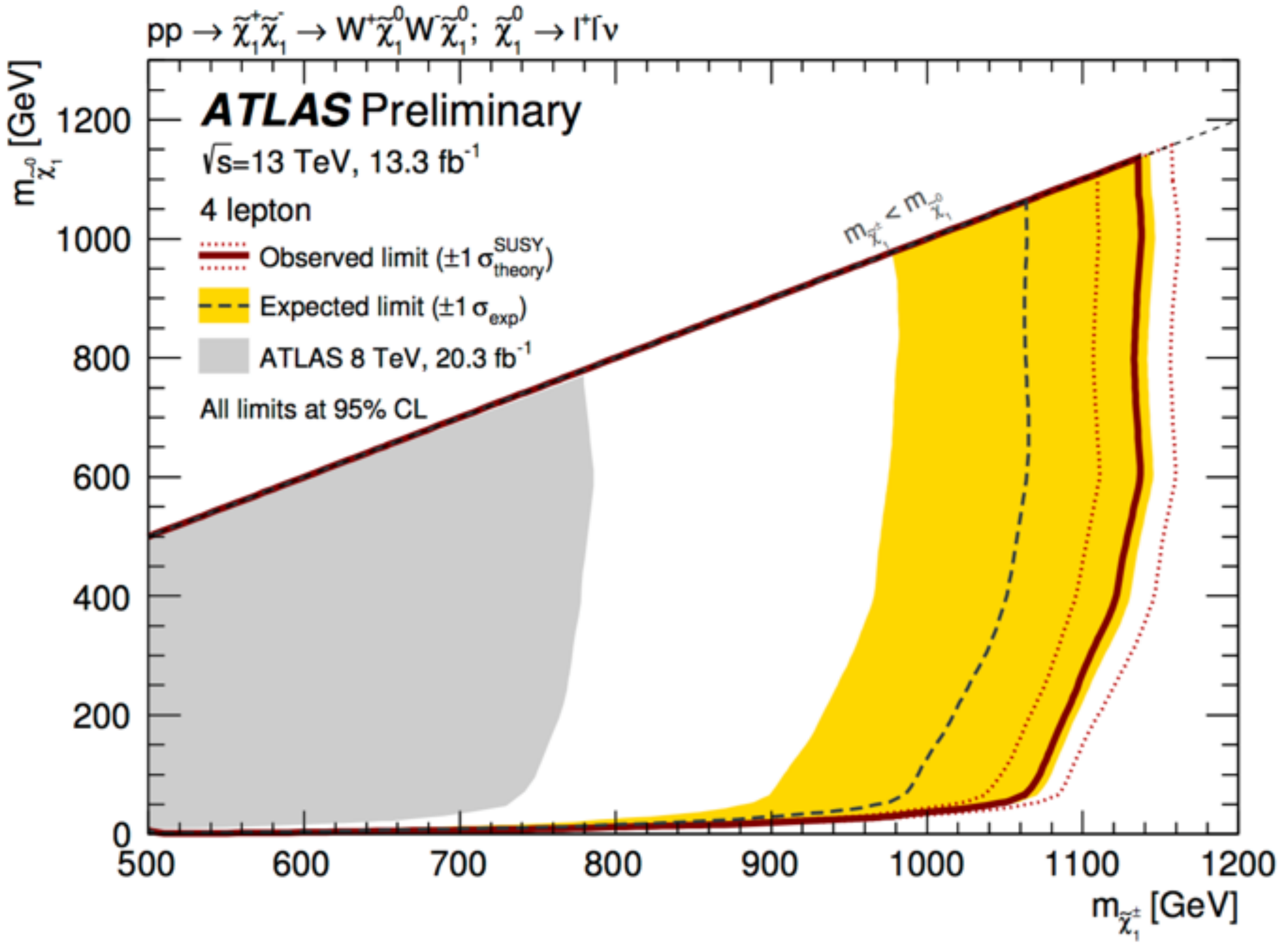
$\tilde{B}^0$ $\tilde{H}_1^0$ $\tilde{H}_2^0$ $\tilde{W}^0$

Bino

Neutral Higgsinos

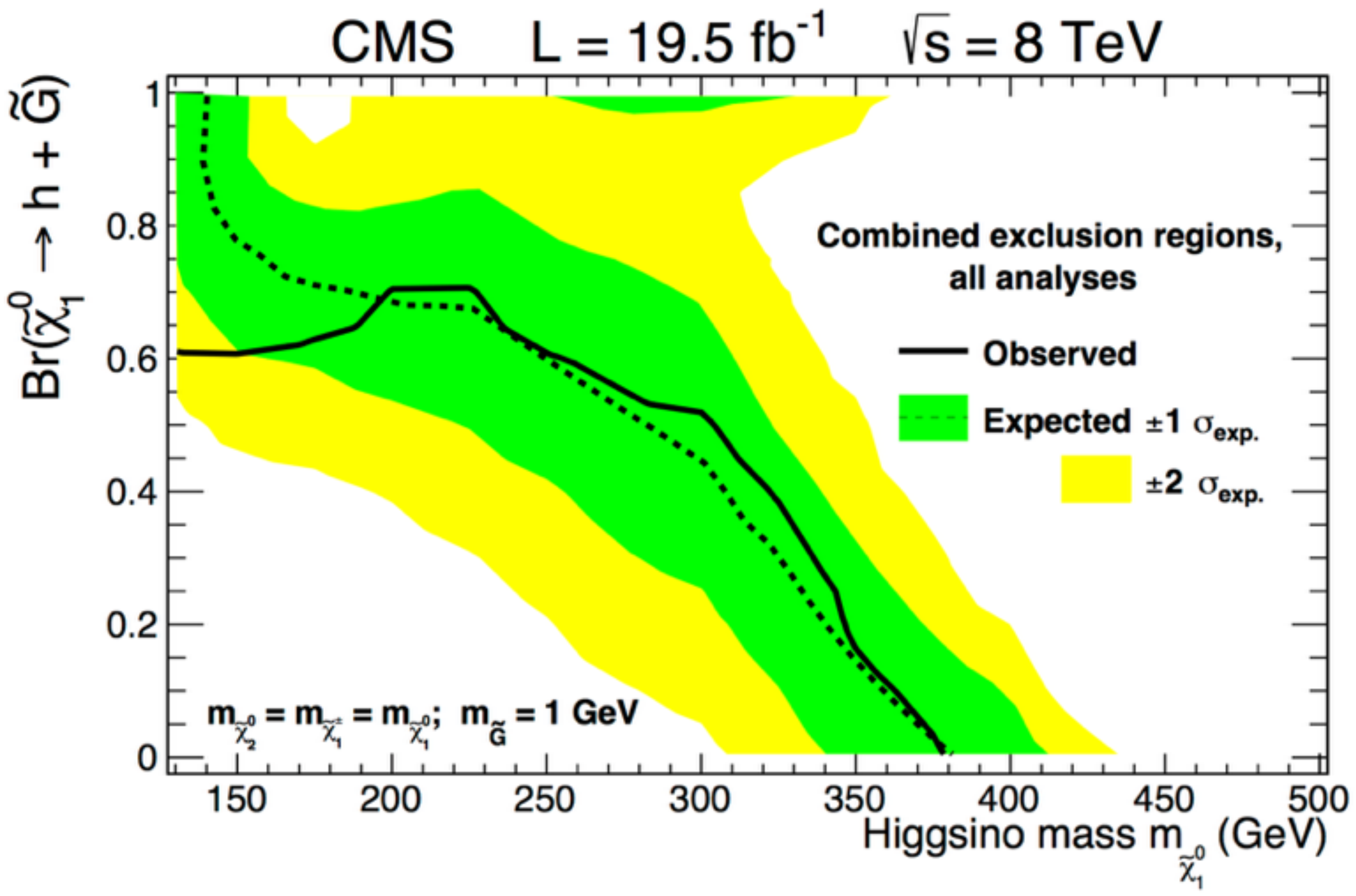
Neutral Wino

Limits on winos



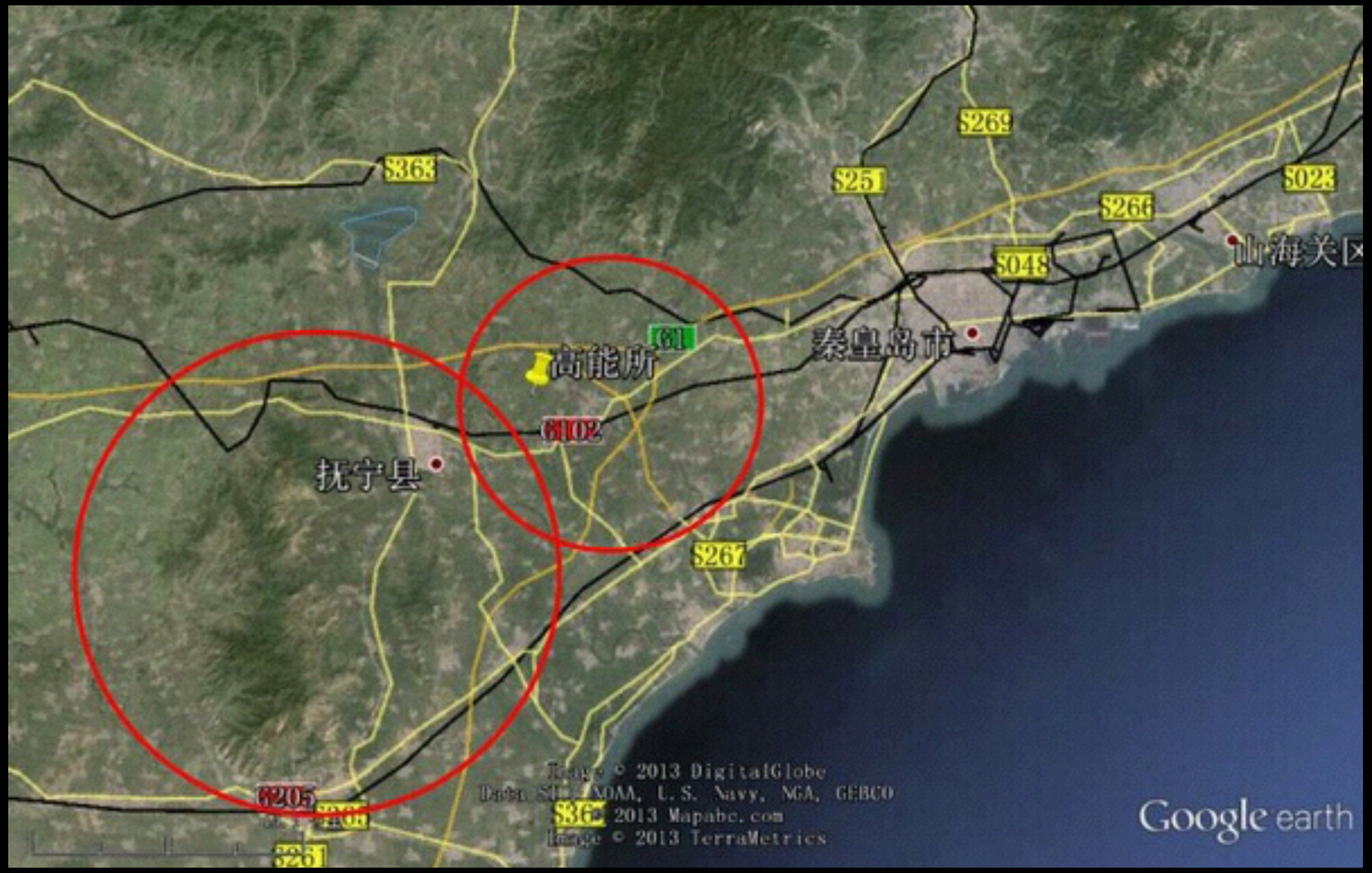
ATLAS-CONF-2016-075

Limits on higgsinos

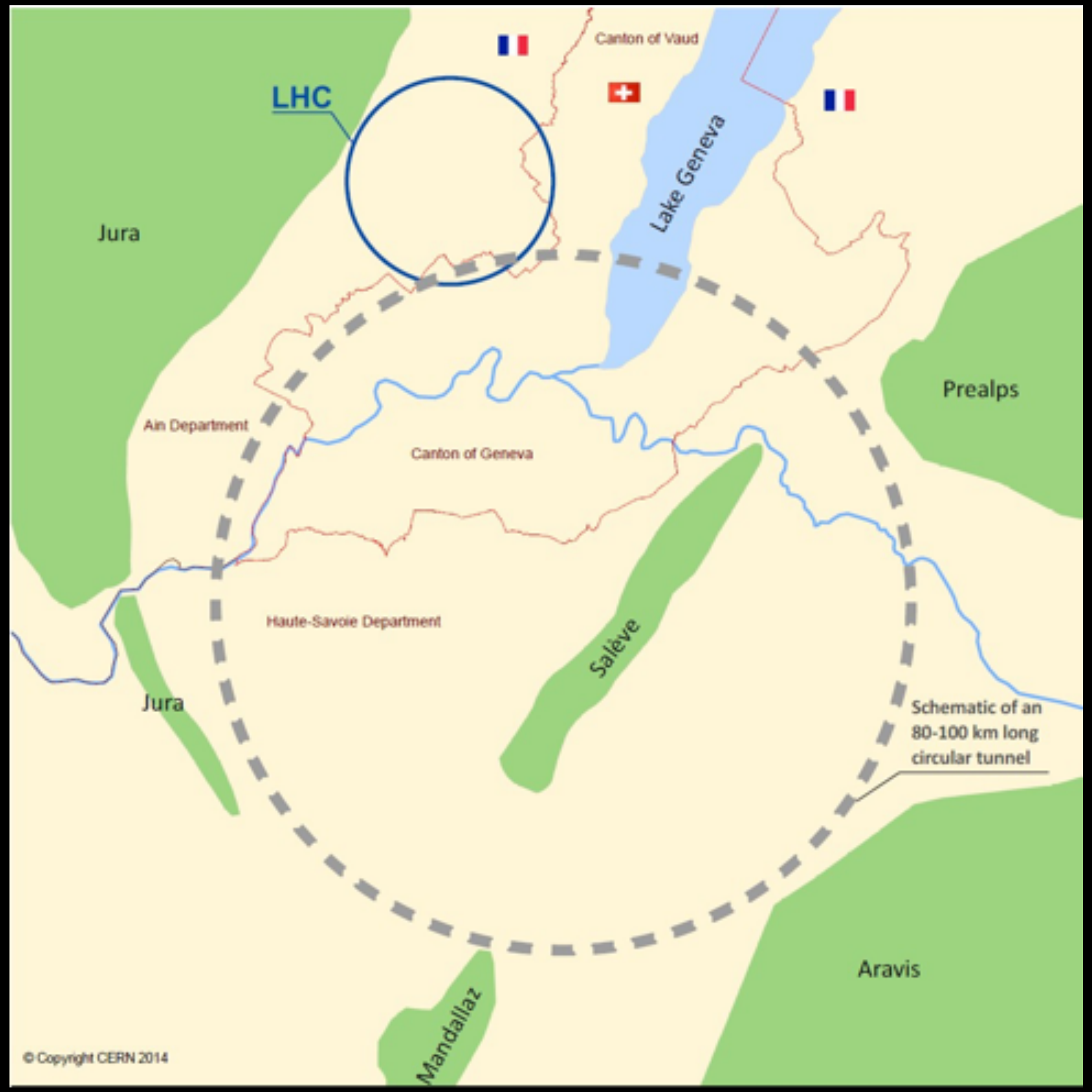


CMS-SUS-14-002

Future Colliders

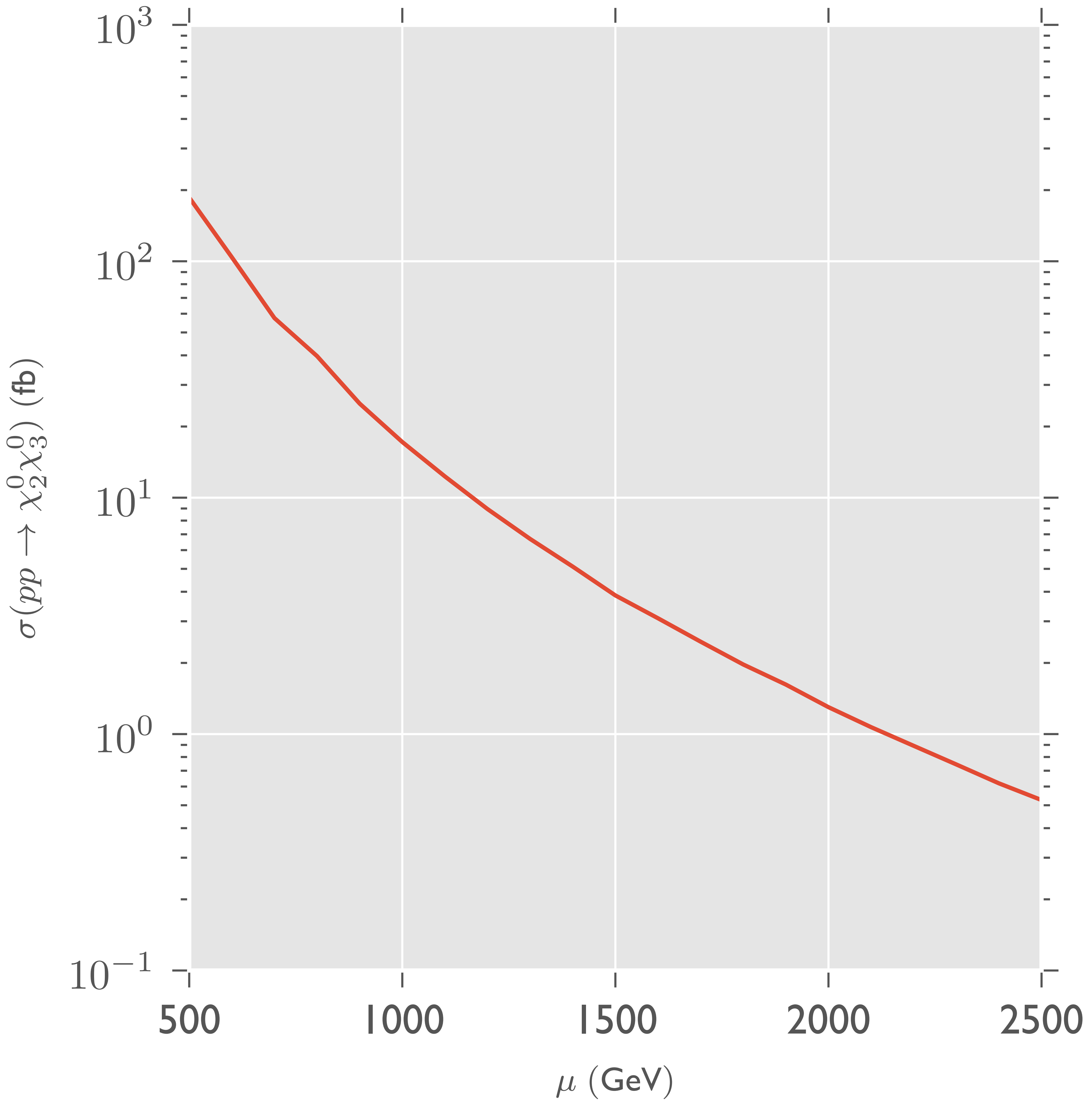


CEPC-SppC (China)

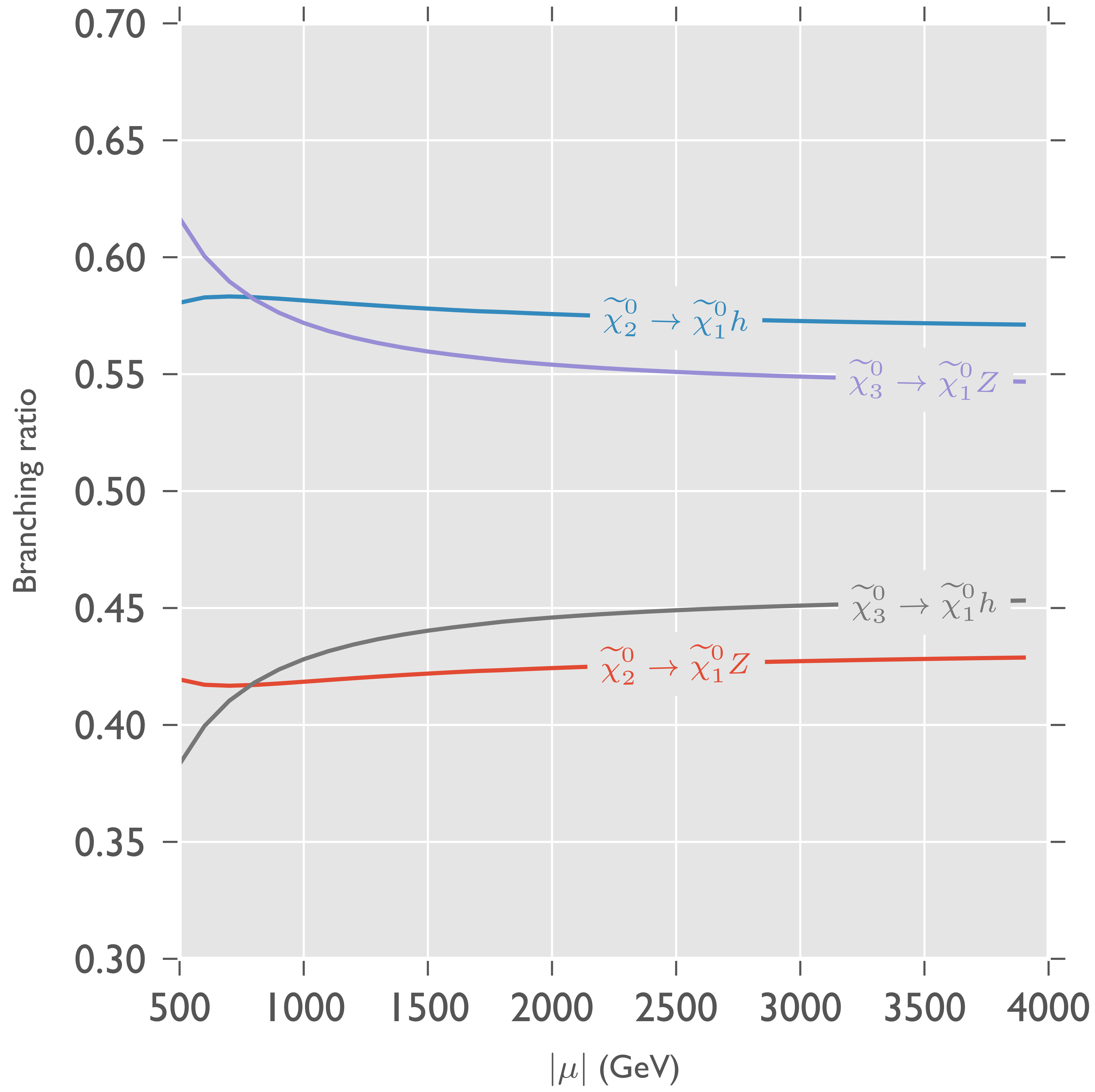


FCC-hh (CERN)

Higgsino pair production cross-section @ 100 TeV

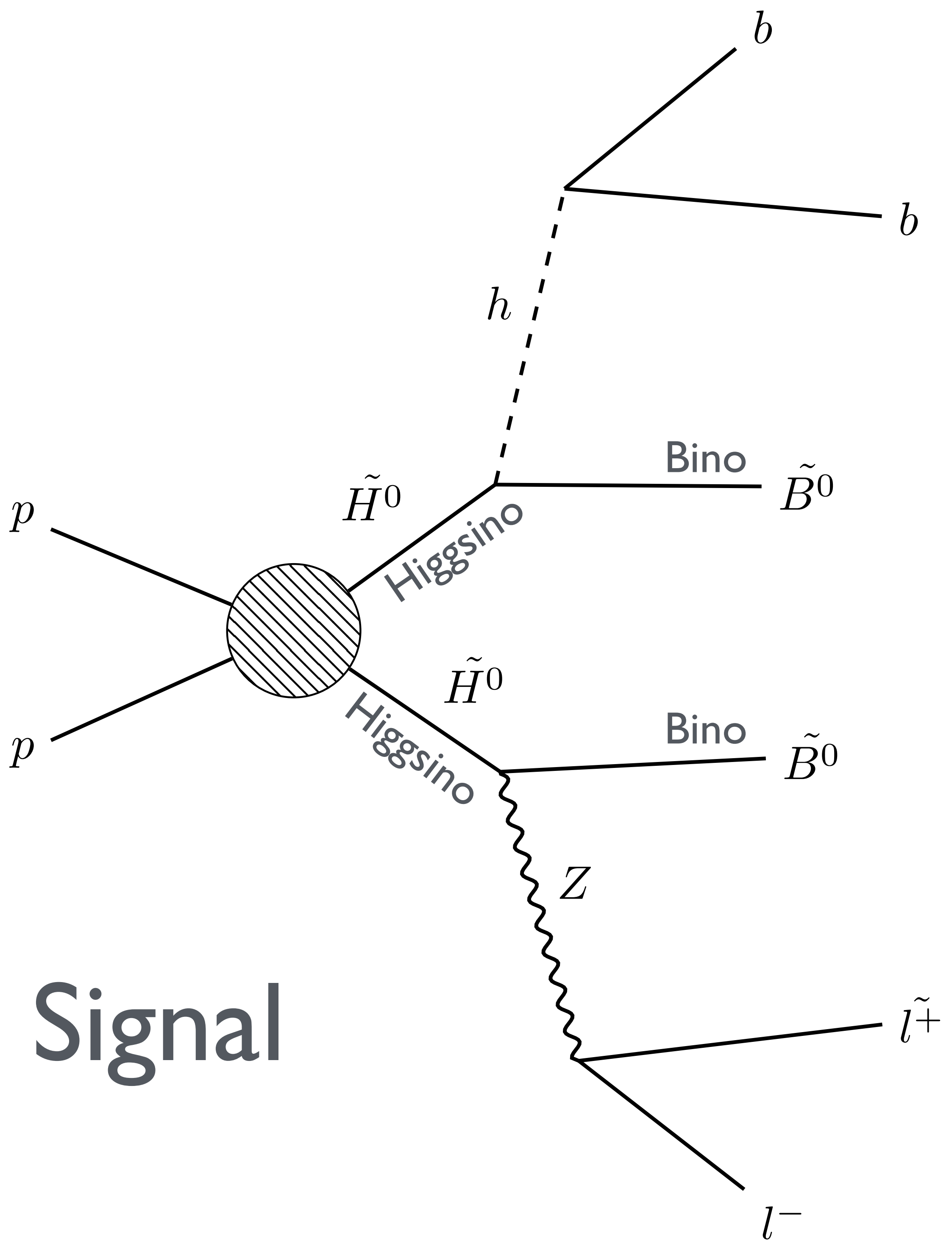


Higgsino branching ratios



Bino mass = 25 GeV

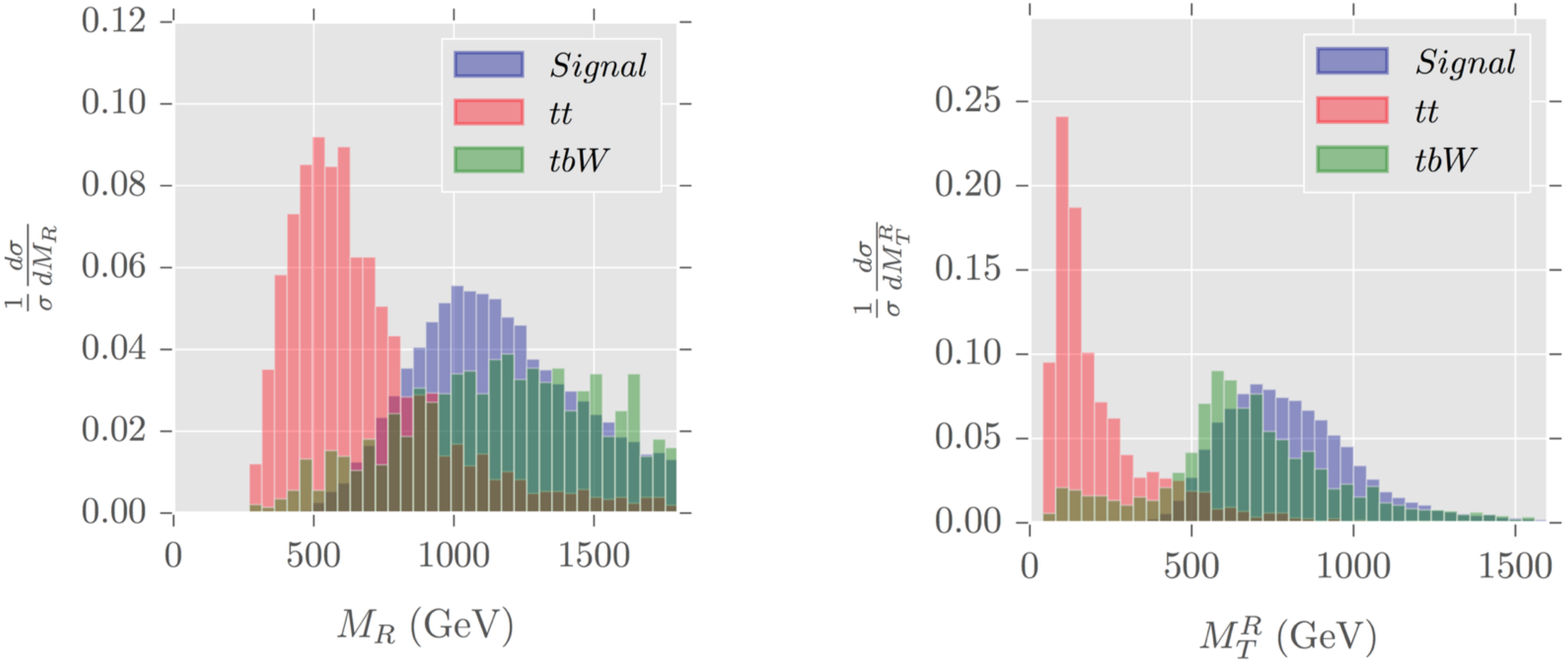
Our search channel

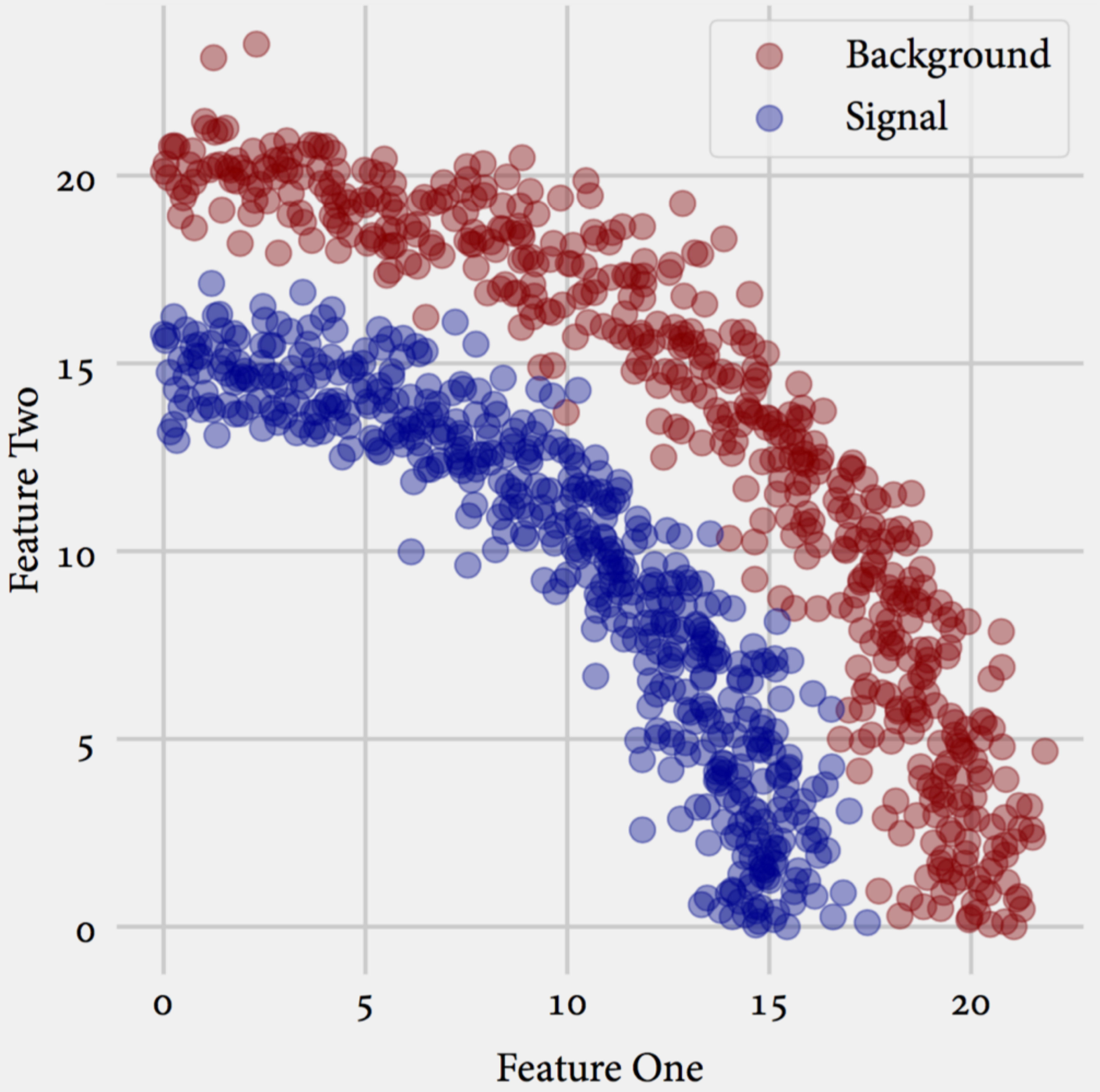


Signal

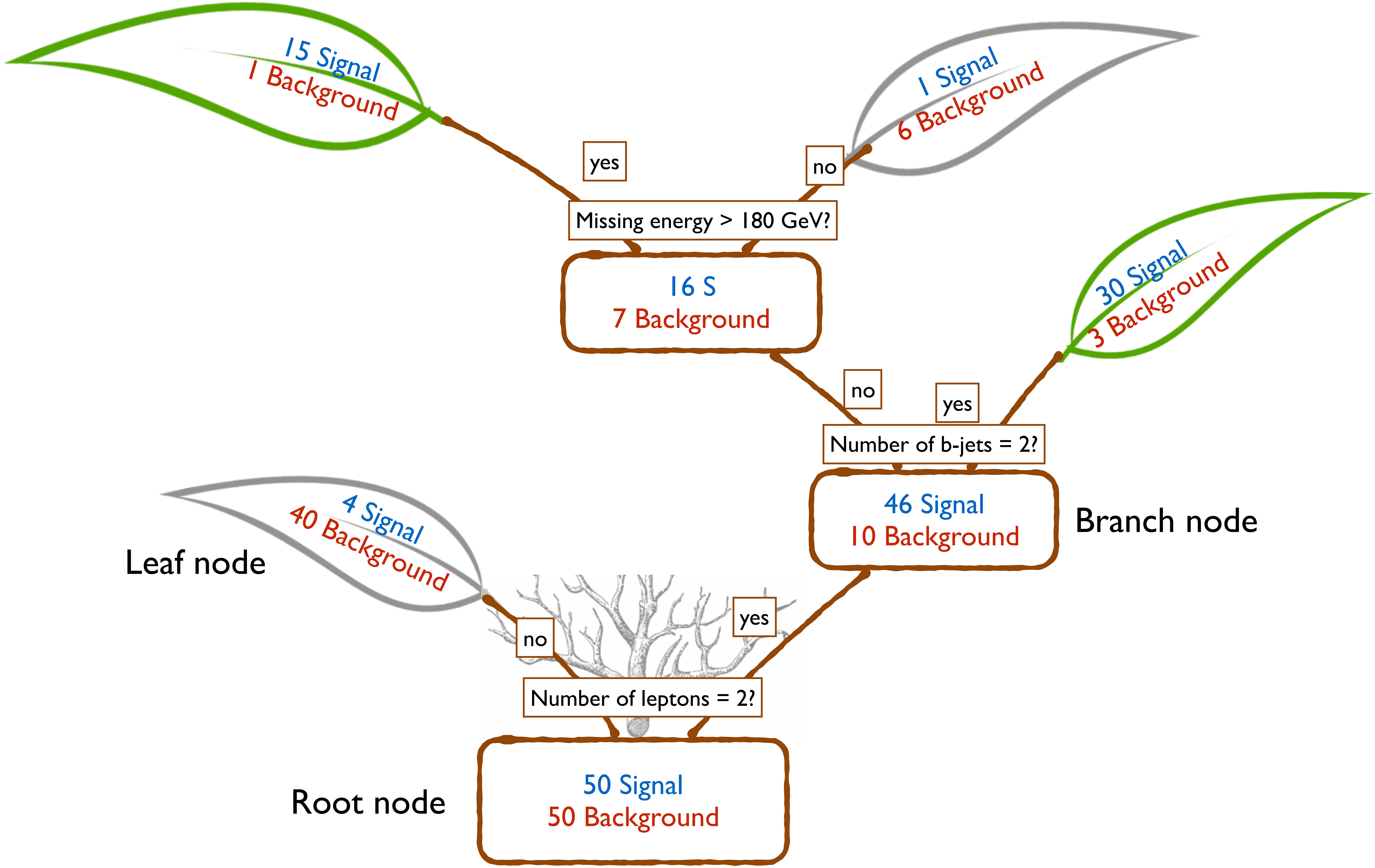
- Final state:
  - ✦ 2 b jets,
  - ✦ two same flavor, opposite charge leptons
  - ✦ missing energy
- Backgrounds:
  - ✴ tt
  - ✴ tbW
  - ✴ bbWW

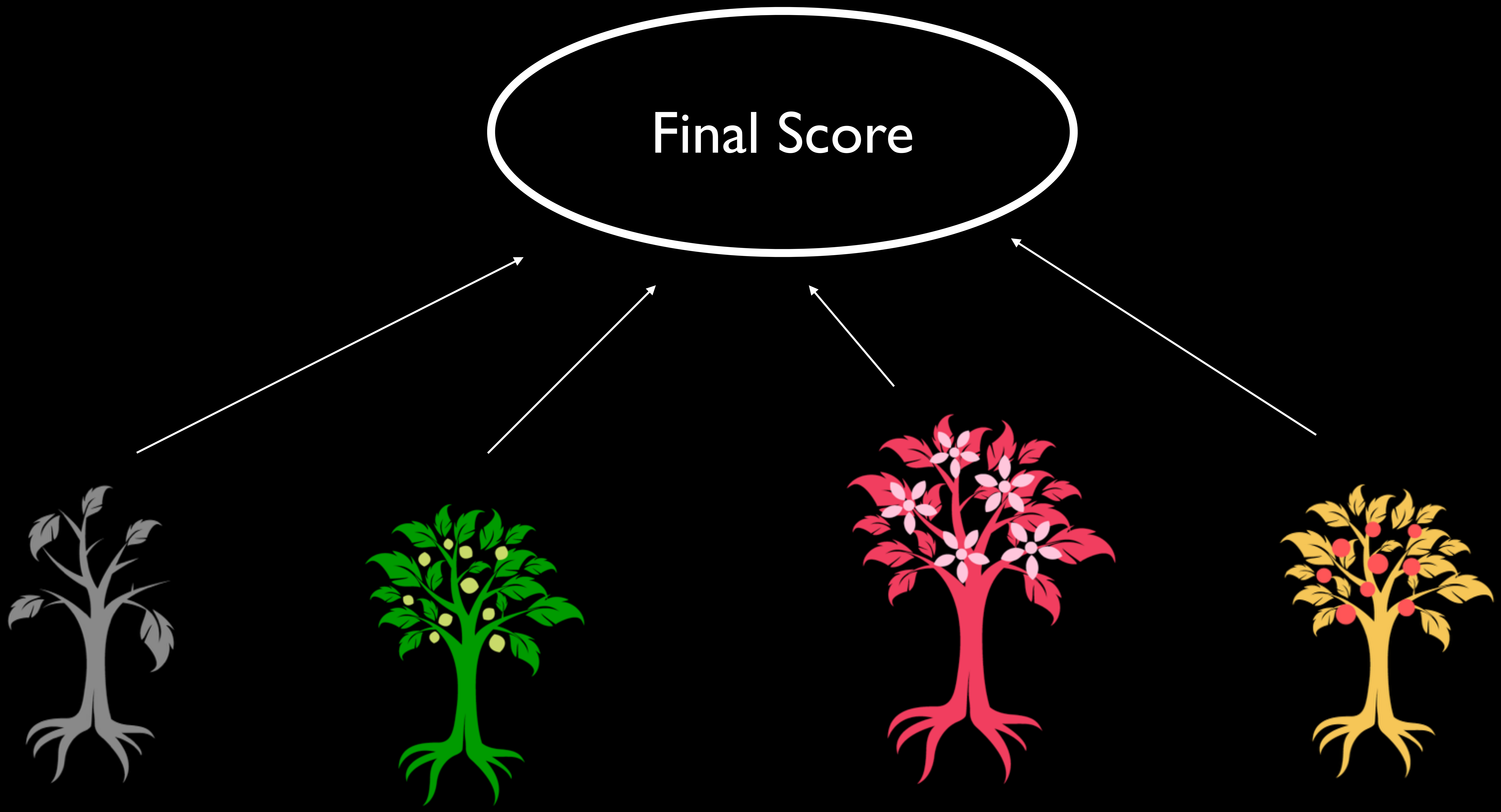
Razor variable kinematic distributions

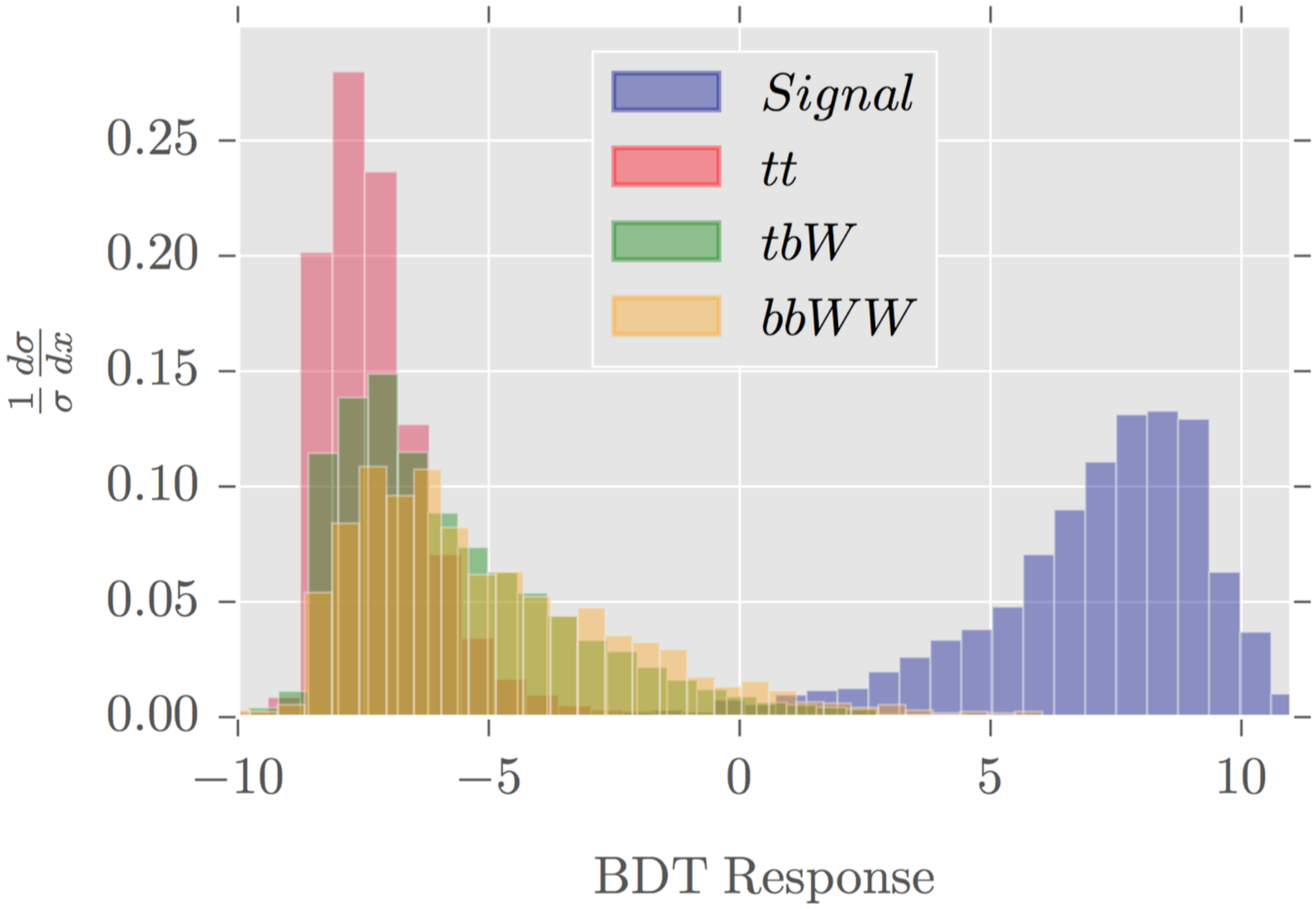




Example of nonlinear decision boundary in 2D feature space

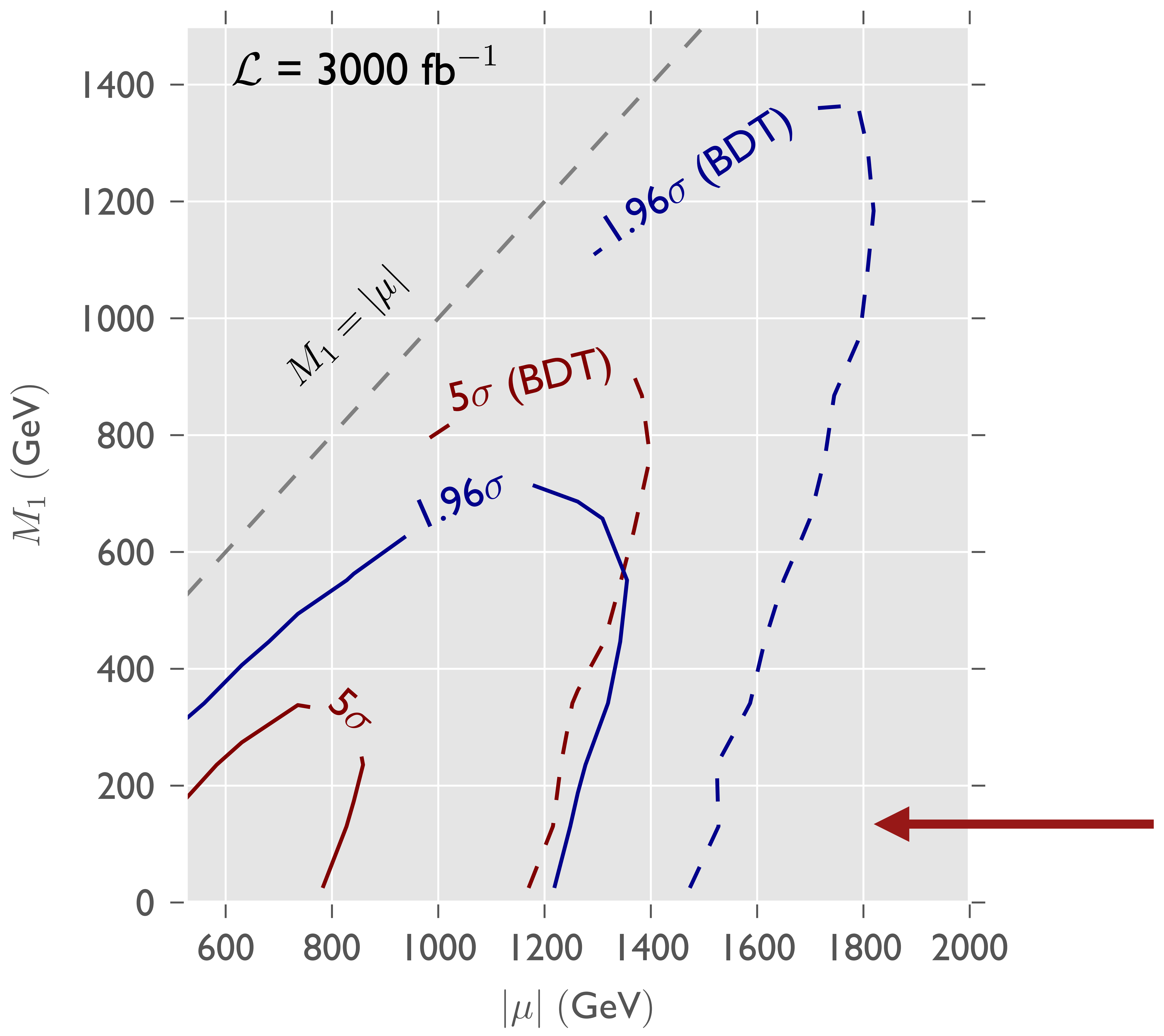

15 Signal
1 Background
yes
1 Signal
6 Background
no
Missing energy > 180 GeV?
16 S
7 Background
no
yes
30 Signal
3 Background
Number of b-jets = 2?
46 Signal
10 Background
Branch node
4 Signal
40 Background
Leaf node
no
yes
Number of leptons = 2?
50 Signal
50 Background
Root node


Final Score



Signal
tt
tbW
bbWW
0.25
0.20
0.15
0.10
0.05
0.00
$\frac{1}{\sigma}\frac{d\sigma}{dx}$
−10
−5
0
5
10
BDT Response

Reach in parameter space



Collimated b-jets reduce reach in this area

Conclusions

- Exotic Higgs decays are a good complementary avenue for discovery at current and future colliders

- A 100 TeV collider will open up many new physics opportunities, including finding a dark matter candidate particle.

- Machine learning will likely play an increasing role in particle physics in the future.

Thank you!

(Questions?)

The Hierarchy Problem

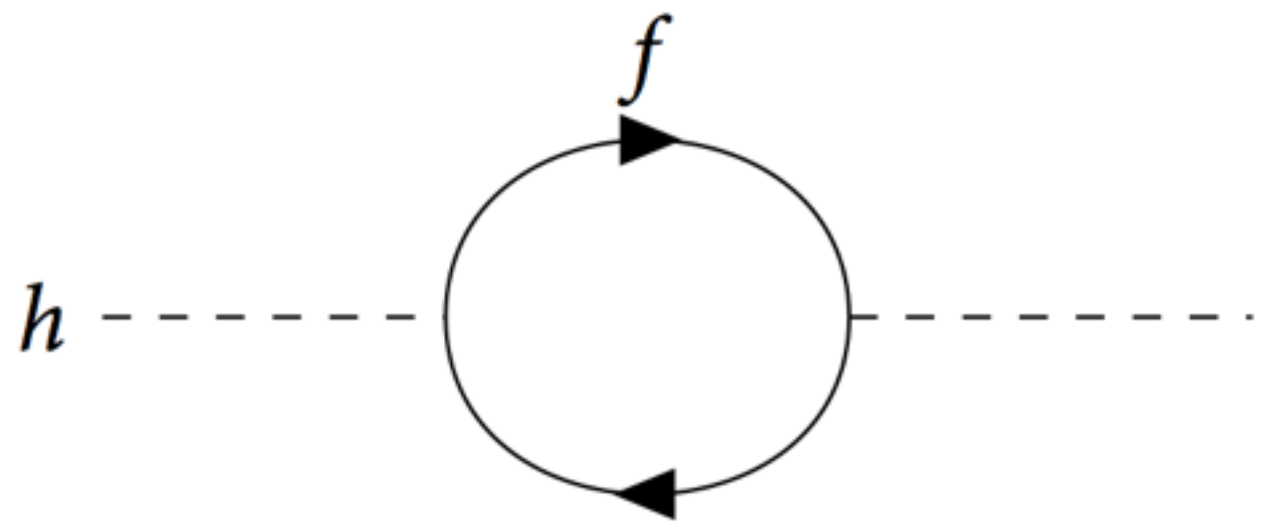


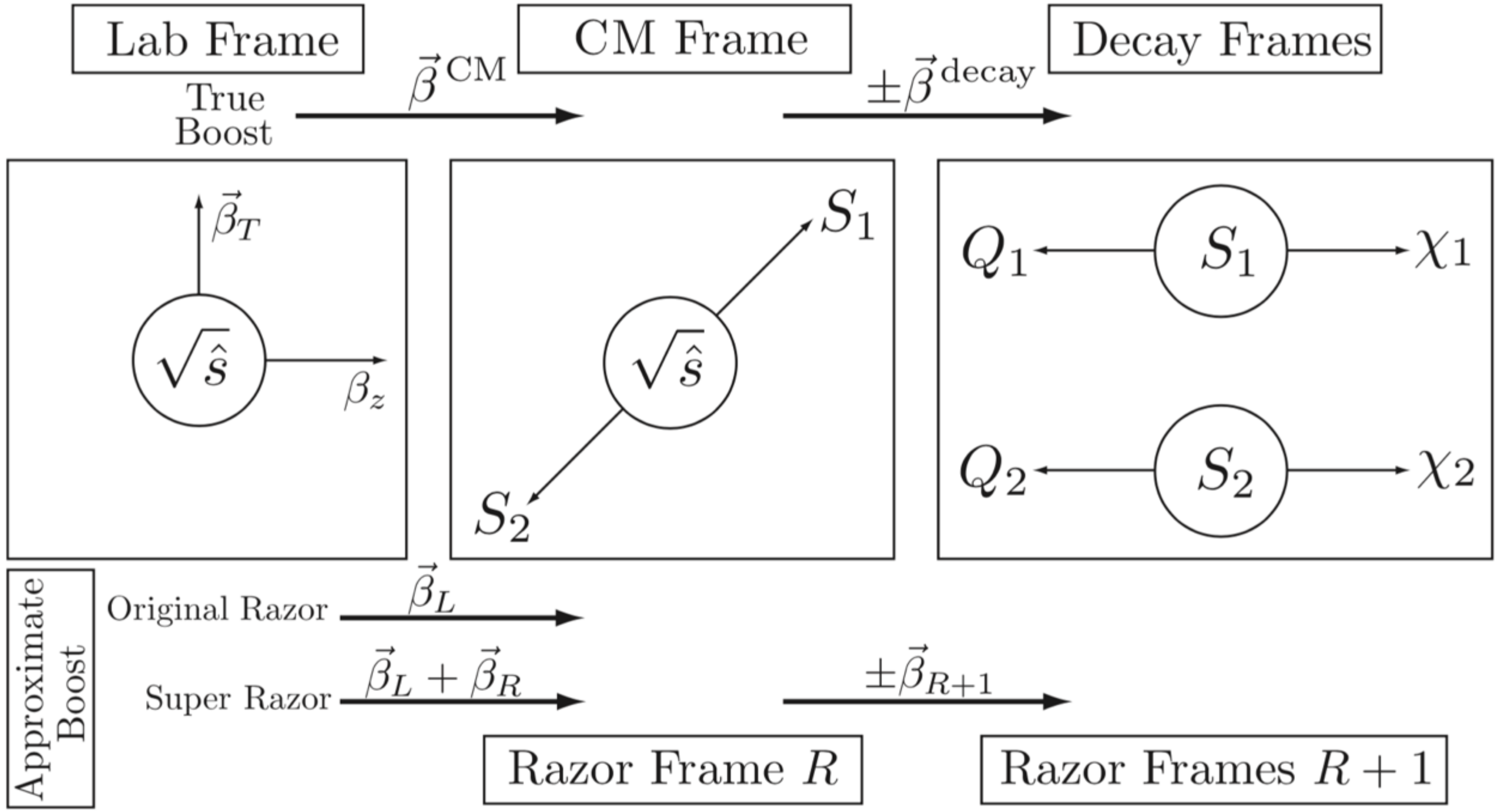
Figure 2.2: Feynman diagram for the one-loop fermionic correction to the SM Higgs mass

Figure 2.3: Feynman diagram for the one-loop scalar correction to the SM Higgs mass

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 + \ldots\right]$$

Razor variables arXiv:1006.2727



Razor variables arXiv:1006.2727

$$M_R = \sqrt{(E_1 + E_2)^2 - (q_1^z + q_2^z)^2}$$

$$M_T^R = \sqrt{\frac{1}{2}\left[\not{E}_T(|\vec{q}_{1T}| + |\vec{q}_{2T}|)^2 - \vec{\not{E}}_T \cdot (\vec{q}_{1T} + \vec{q}_{2T})\right]}$$