West Coast LHC Jamboree

New Direct BSM Searches at the LHC

Zhen Liu
U of Maryland

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Here I attempt to complement the current efforts and provide some examples.

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2. SUSY?
3. Neutral Naturalness & Beyond?
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Top partner single and pair production searches, heavy resonance searches strong and healthy.*

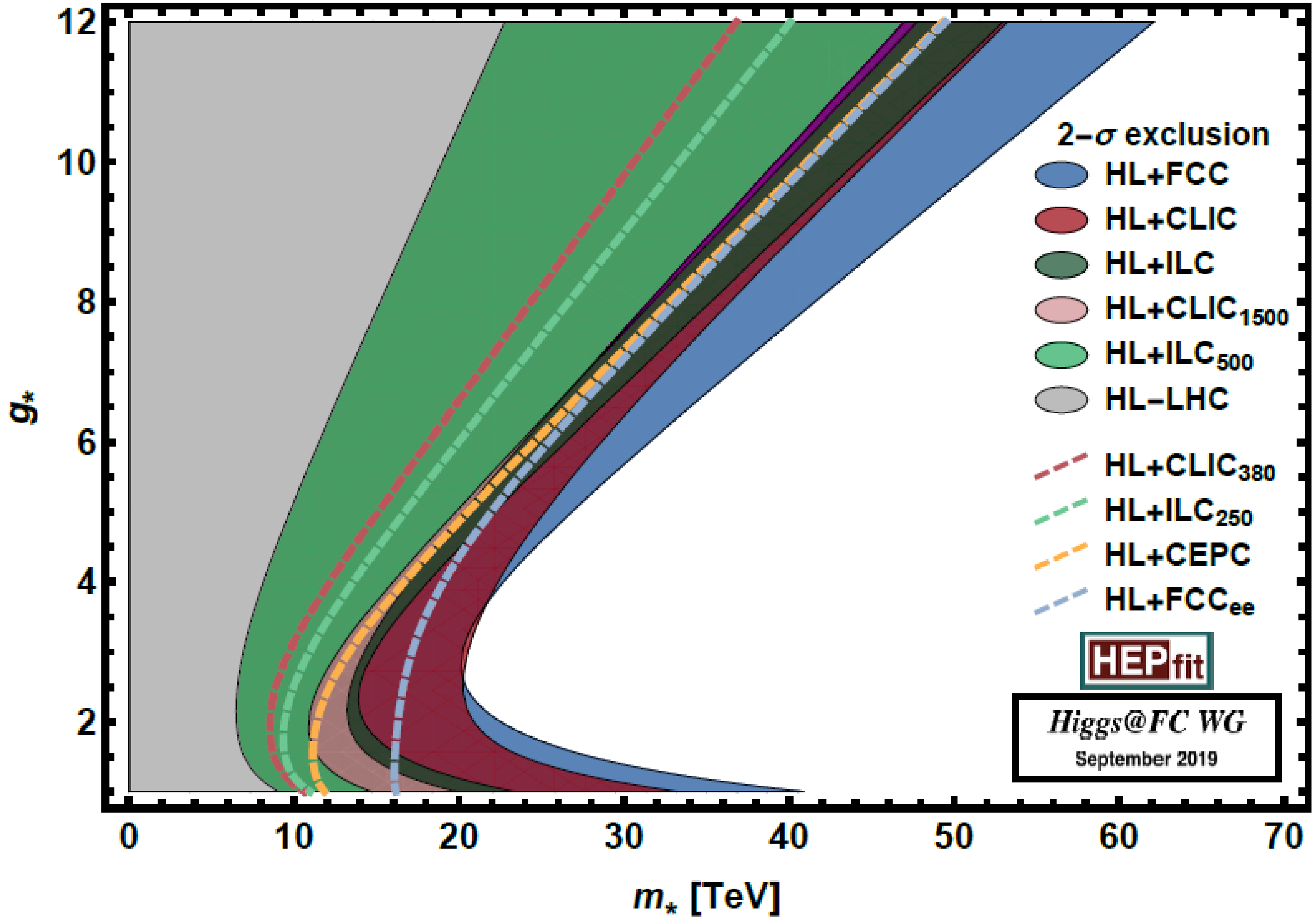
What else?

High Energy Higgs processes as probes

*theory refs:
Schmaltz, Zhong, 1810.10017
Dolan, Hewett, Kramer, Rizzo, 1601.07208
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663
Han, Lewis, Liu, 1010.4309

Composite or not?

With the heroic joint efforts from both the theorists and experimentalists, we can study the Higgs to great precision at the LHC and future colliders.



Simplified CH benchmark: 1 coupling (g_*) - 1 scale (m_*)

$$\frac{c_{\phi,6,y_f}}{\Lambda^2} = \frac{g_\star^2}{m_\star^2}, \qquad \frac{c_{W,B}}{\Lambda^2} = \frac{1}{m_\star^2}, \qquad \frac{c_{2W,2B,2G}}{\Lambda^2} = \frac{1}{g_\star^2}\frac{1}{m_\star^2},$$

$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{3W,3G}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

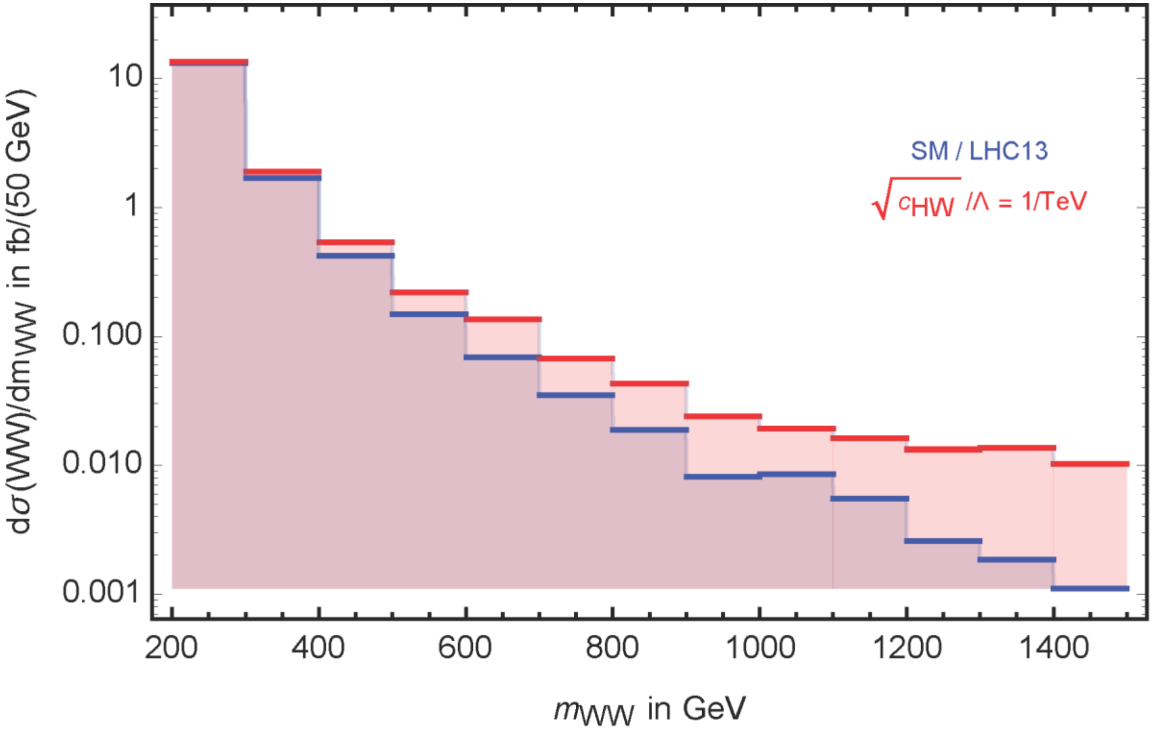
Probing EFTs with hadron colliders

- High Λ suppression ⇒ Needs precision measurements
- Typically associated with EWPO
  $$\delta \lesssim \mathcal{O}(1\%)$$
- Does hadron collider play any rule?

Doable if

$$\frac{S}{B} \propto E^n, \qquad n \geq 1$$

Example: Diboson processes



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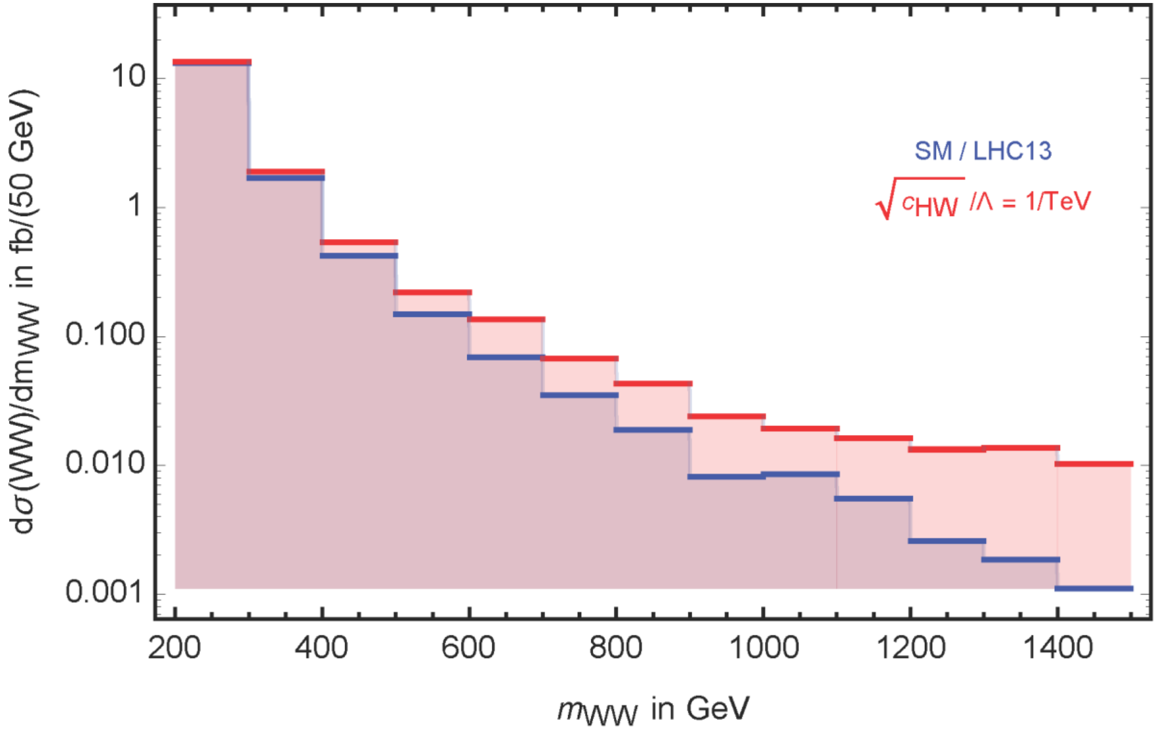

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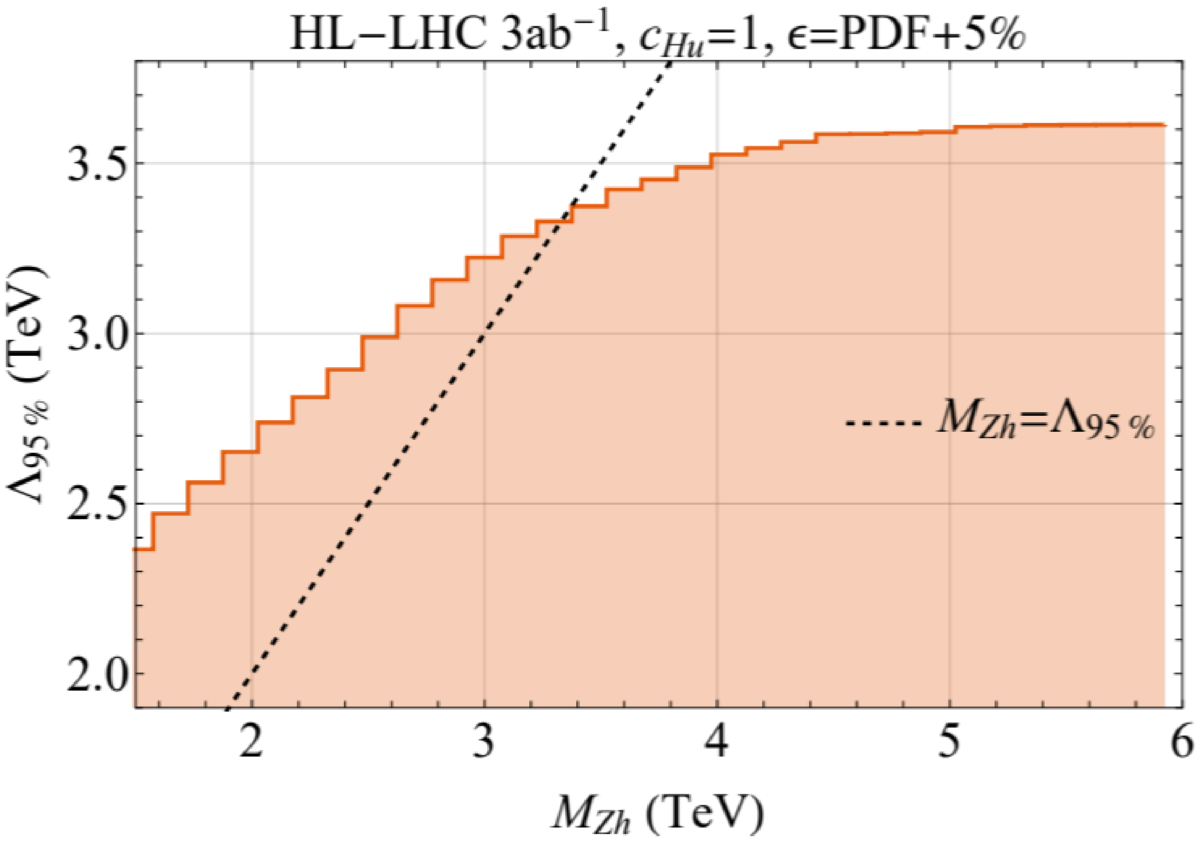
Example: Diboson processes

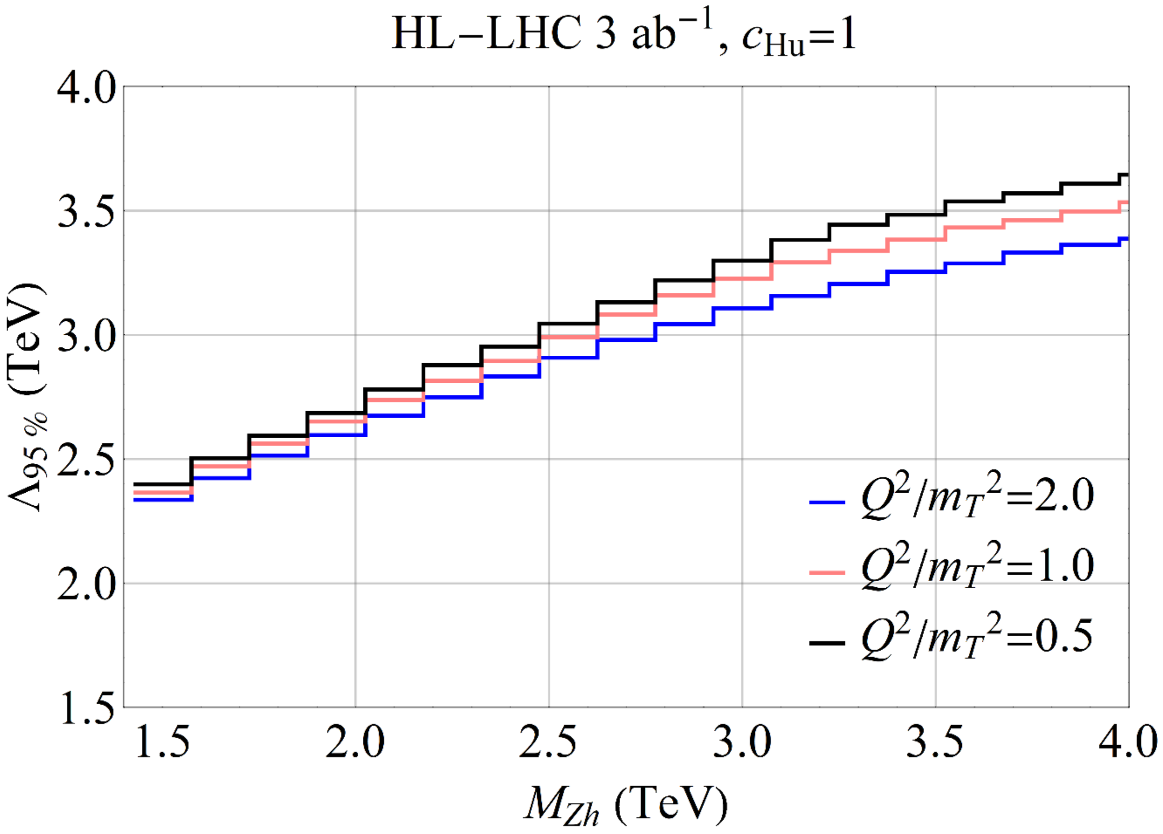
Will show an example analysis with Zh→(ll)(bb)

For more discussions on Higgs and EFT, see Ian Low’s talk this afternoon.

High energy probes

- Data binned by M_{Zh} with bin sizes of 150 GeV
- Estimated sensitivity regions with total significance of bins with $M_{Zh} < \Lambda$ greater than 2 (for 95% exclusion)
- Assume a universal 5% systematic uncertainty
- Included scale uncertainty





W.H. Chiu, ZL, L.-T. Wang, 1909.04549

High energy probes

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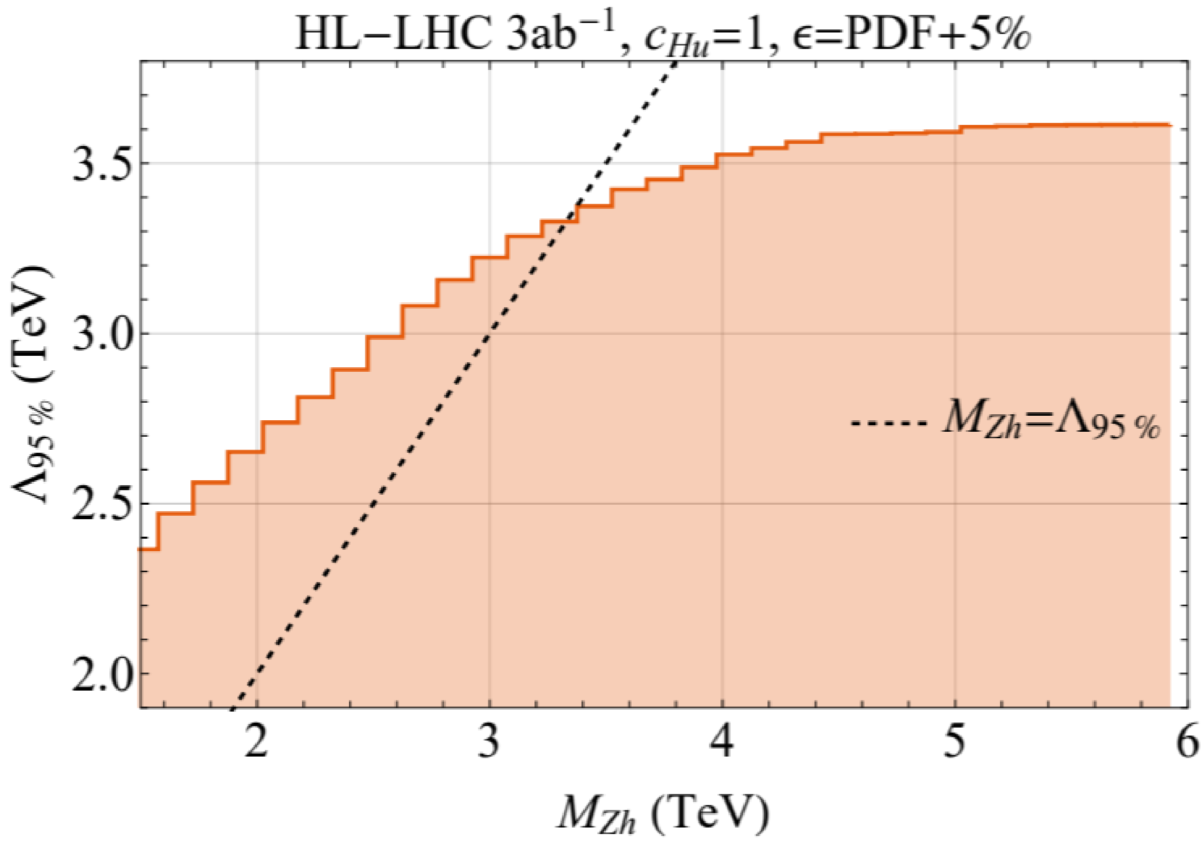
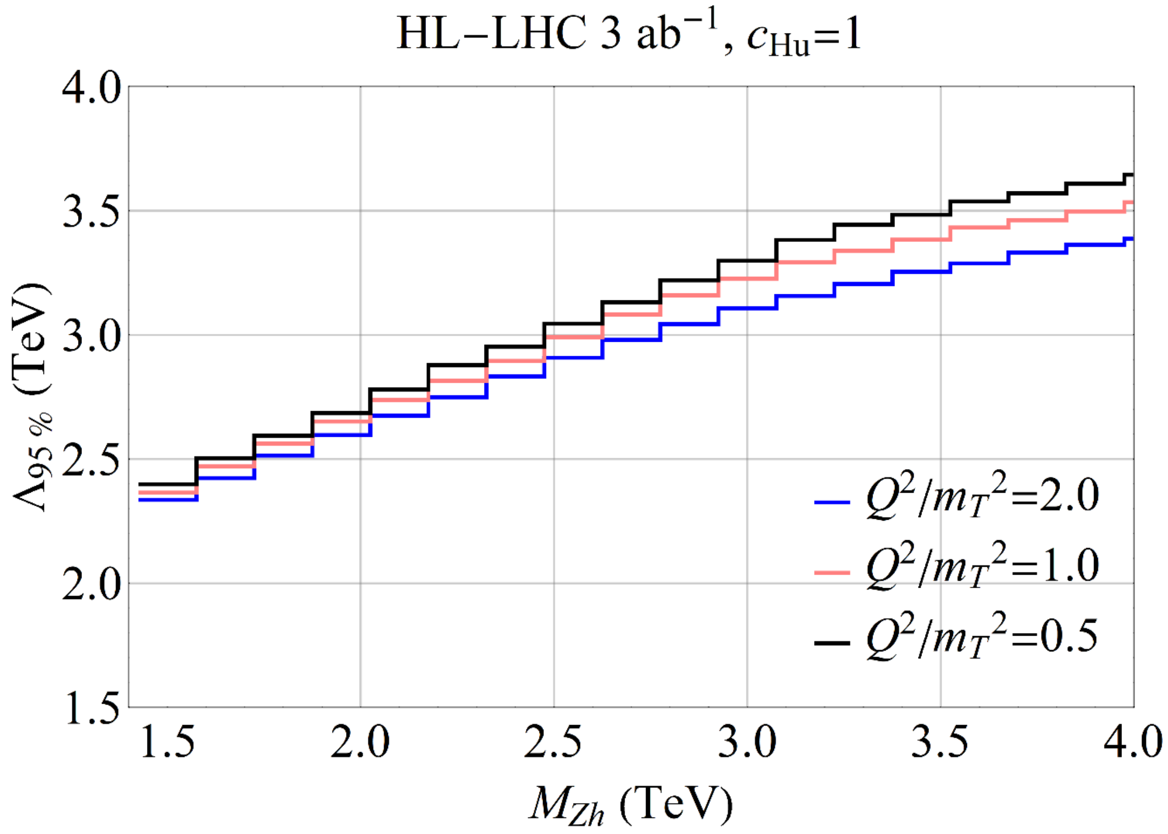
Shall be viewed as a flavor-dependent probe, as these primary processes are first generation dominated





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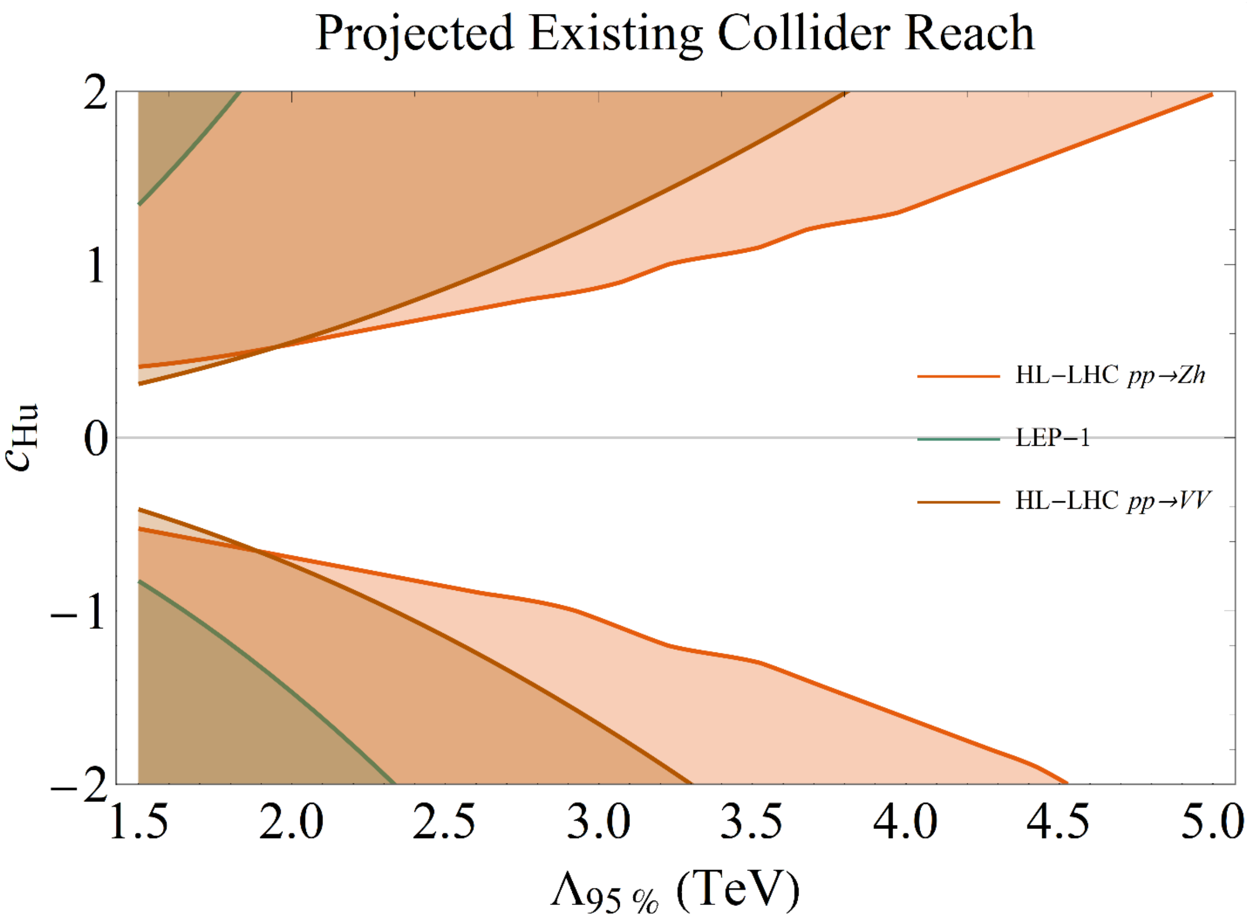
High energy probes v.s. EWPO and flavor

- For Unity Wilson Coefficient, HL-LHC ZH process can probe up to 3 TeV
- Sensitivity extend beyond 4.5 TeV for stronger interactions
- One does obtain more sensitivity when compared to LEP
- In the first two-generation partial universal theories, covers more than flavor constraints



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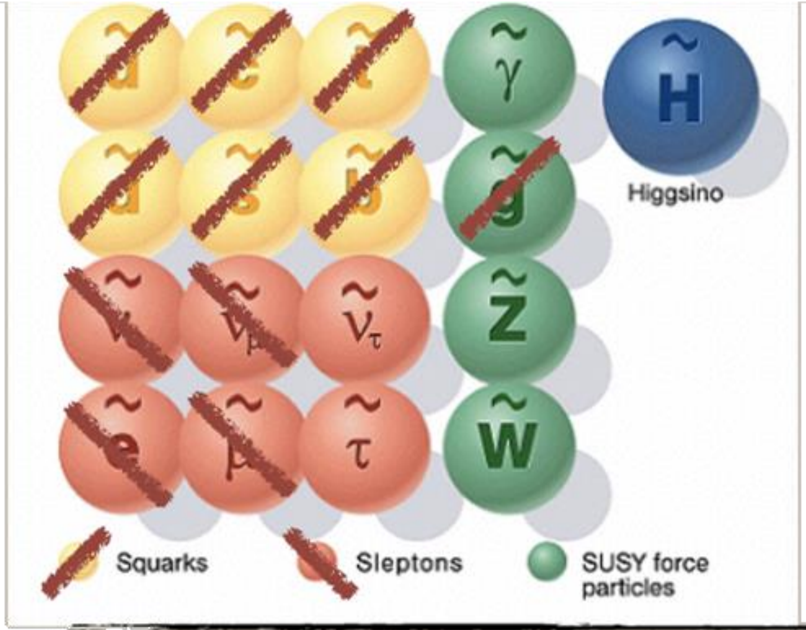
4. Electroweak Phase Transition?
5. Higgs portal?

Squark, Slepton, Ewino, etc
direct pair production
searches strong and healthy.*
What else?

Heavy Higgs as portal to SUSY sectors

*theory refs:
A series of work by: Cahill-Rowly, Gainer, Hewett, Ismail, Rizzo, et al;
J.M. Yang et al; T. Han, F. Kling, ZL, S. Su, et al; Ellis et al…

Heavy Higgs Decays beyond SM



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

lighter generation sleptons: small coupling to Higgs bosons

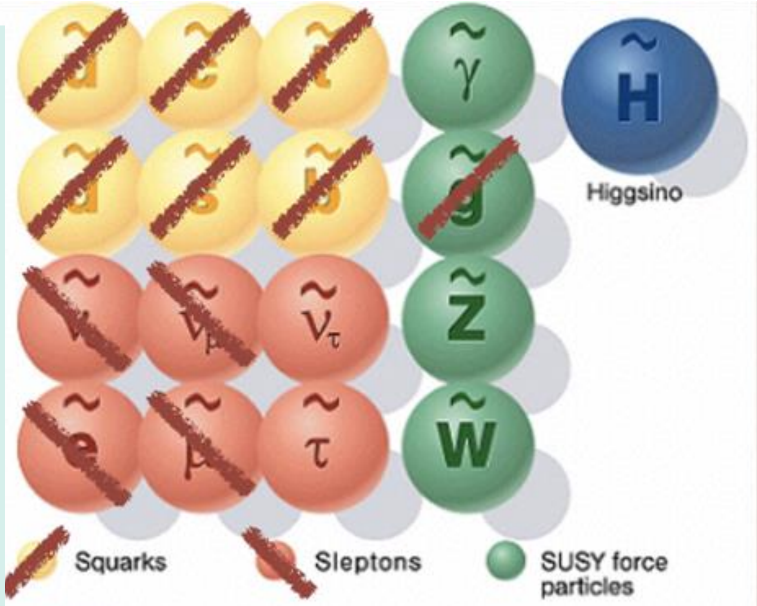
decay modes of interest :
neutralinos charginos staus

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

Heavy Higgs Decays beyond SM

Heavy Higgs bosons as Portals to Supersymmetric Electroweak Sector

- As discovery channel of heavy Higgs bosons
- As discovery channel of SUSY EW States
- As complementary coverage in heavy Higgs parameter space



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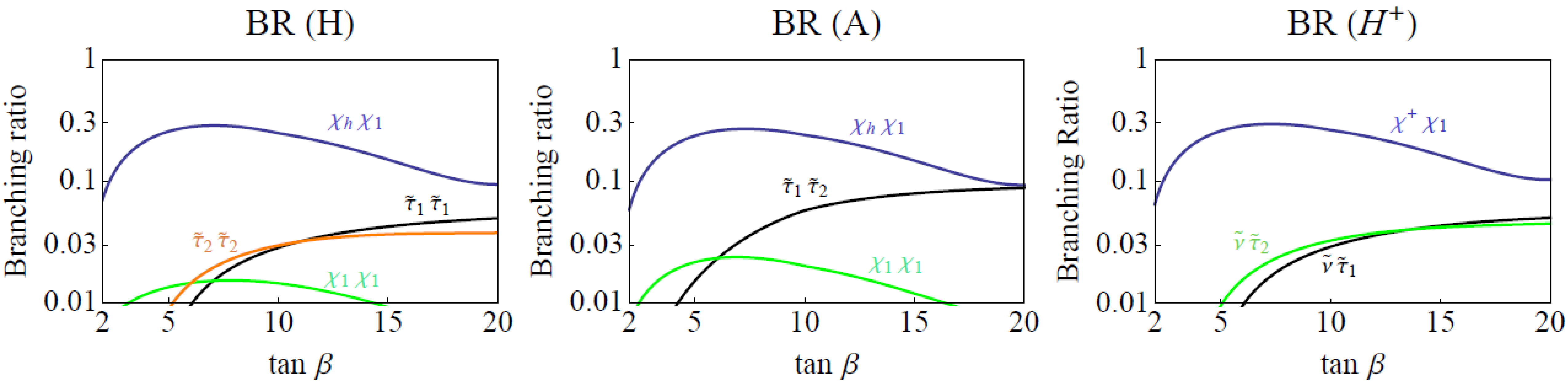
Branching fractions

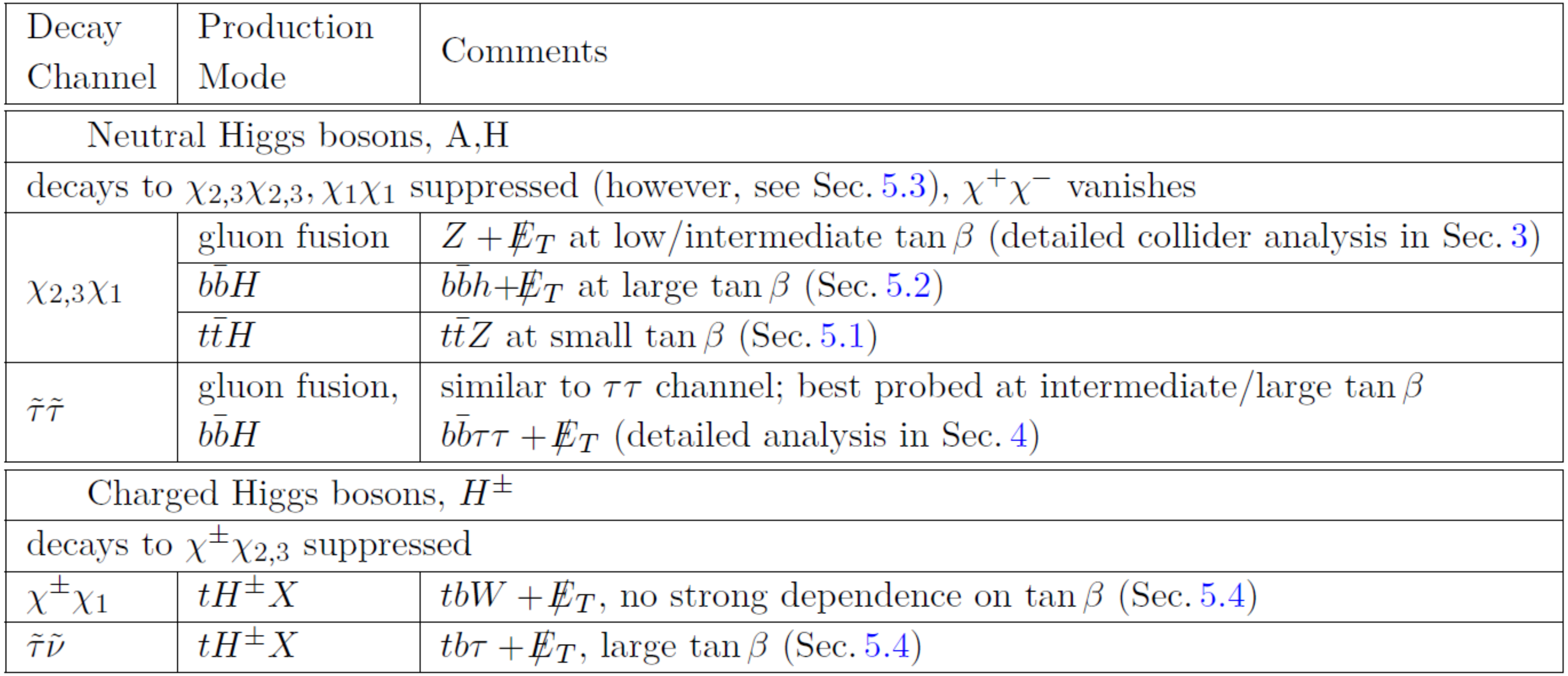


mA=800 GeV
mstau=mHiggsinos=350 GeV
mBino=150 GeV
Atau= 1 TeV

- 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 tanbeta
- same final state in signal as A/H -> tau search channel, with more MET

S. Gori, ZL, B. Shakya, 1811.11918

New Channels



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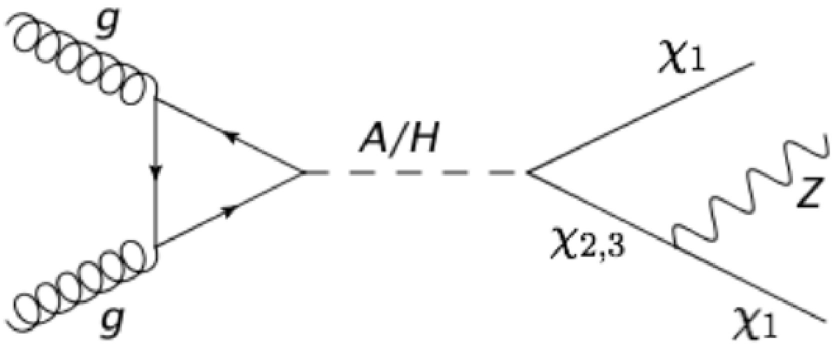
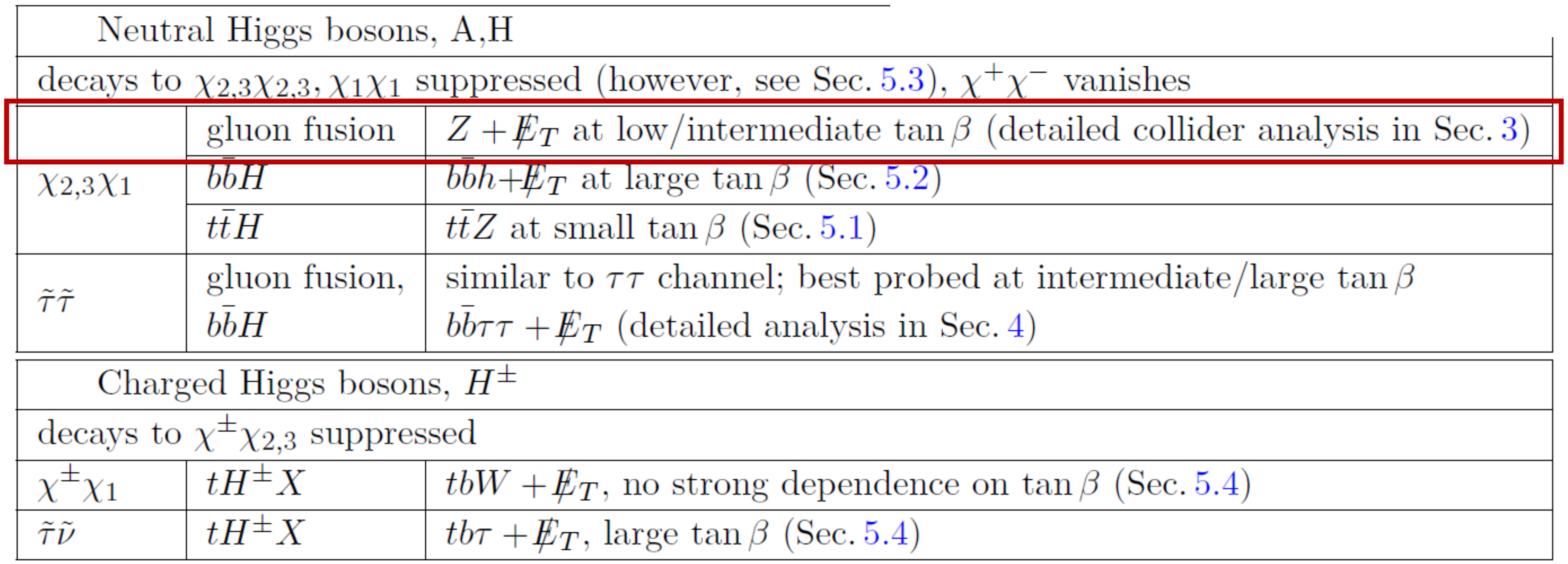
Portal to EWino





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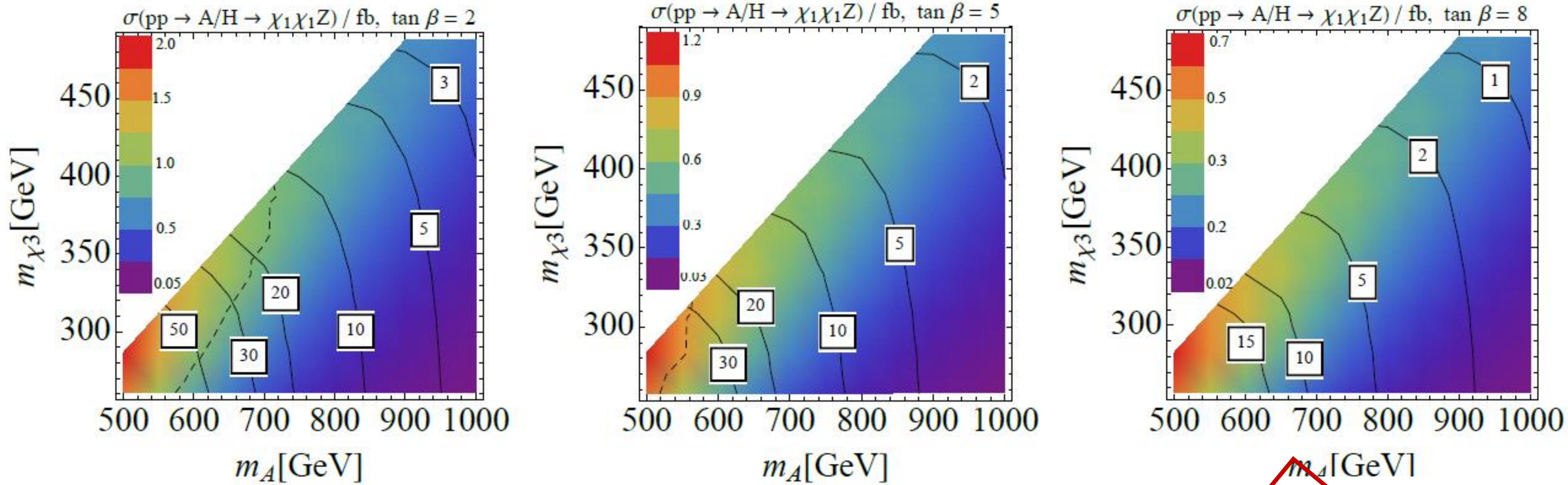
Colors: $\sigma(pp \to A, H \to \chi_1(\chi_h \to \chi_1 Z))/\sigma(pp \to \text{neutralinos} \to Z + \not{E}_T))$

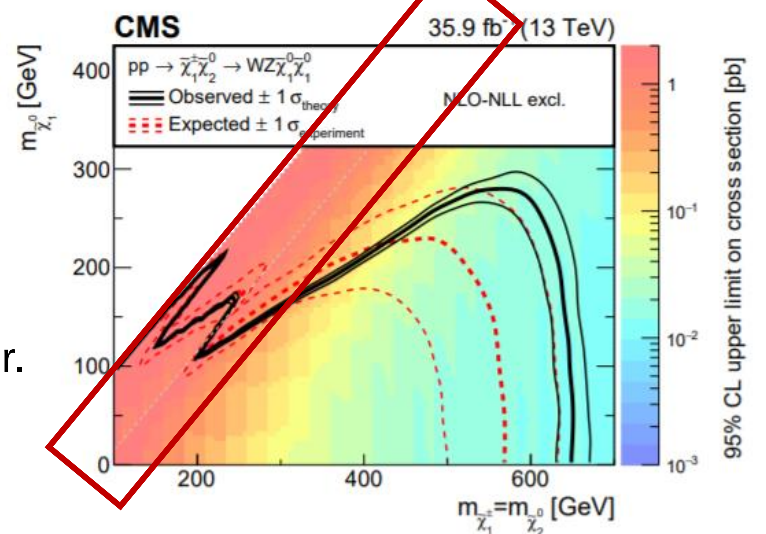
$$m_{\chi_3} \approx m_{\chi_2} \approx m_{\chi_1} + 100 \text{ GeV}$$

Portal to EWino

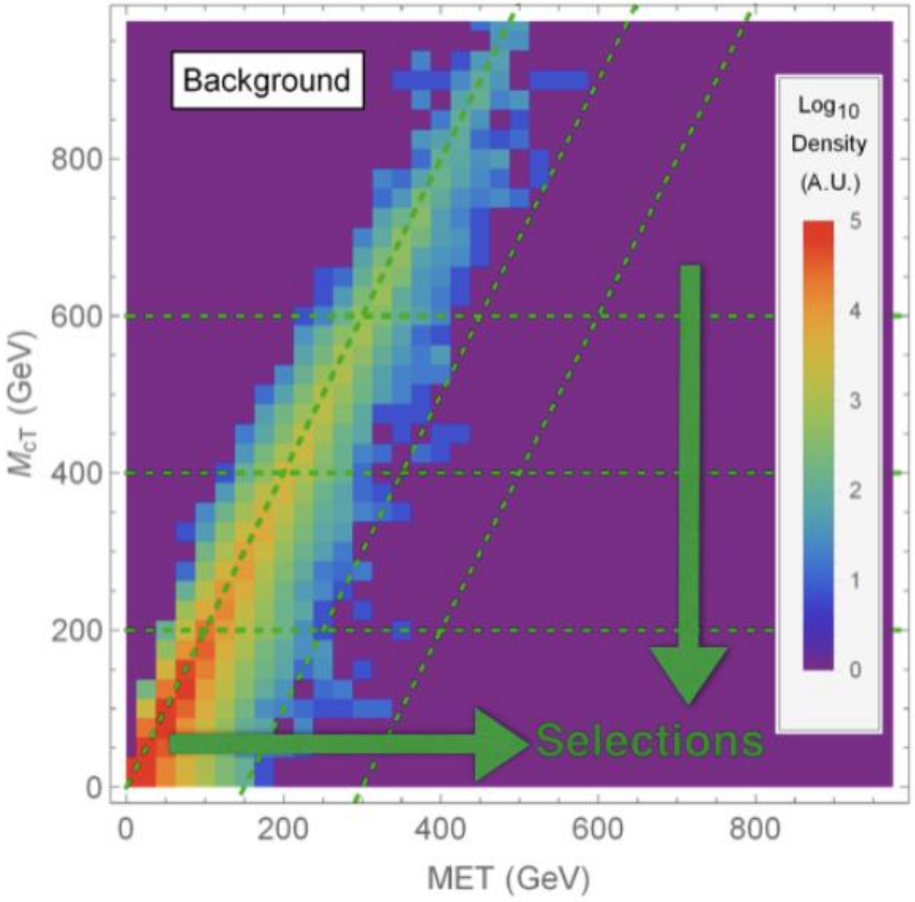


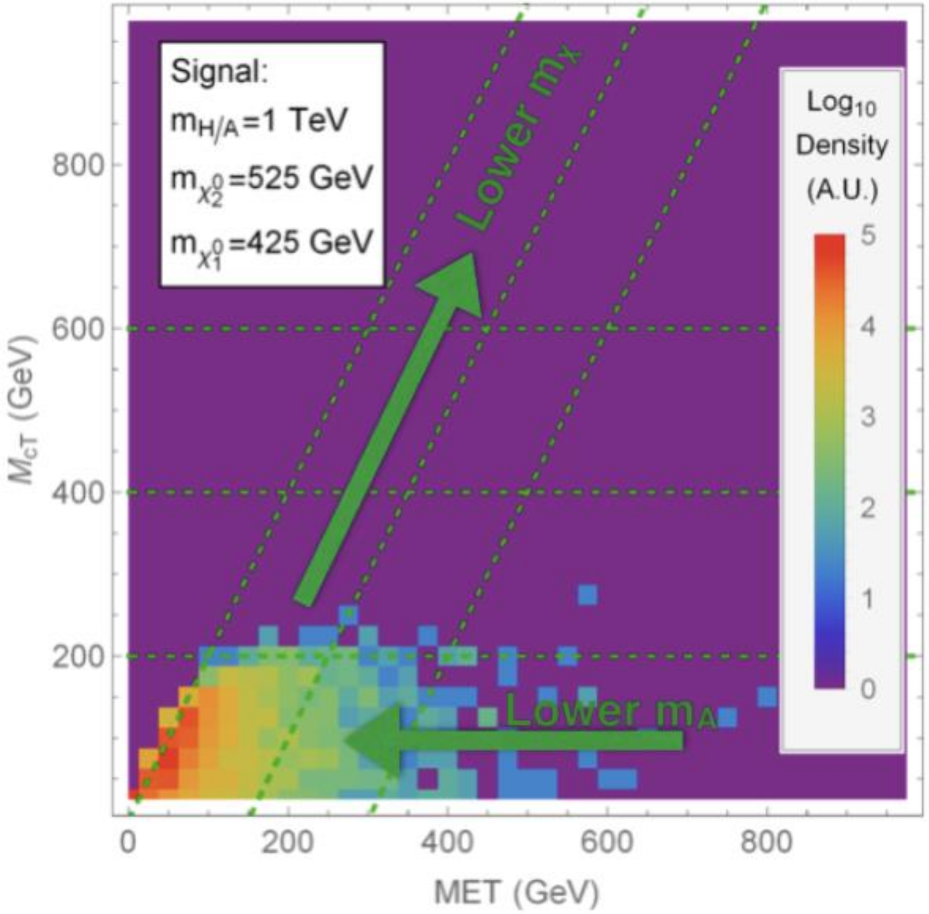
- Cross section 10s of fb;
- For low tanbeta, competitive with direct pair production
- New kinematic features from the resonance decays

Higgsino cross section lower; current limit weaker.



Kinematic features & selection





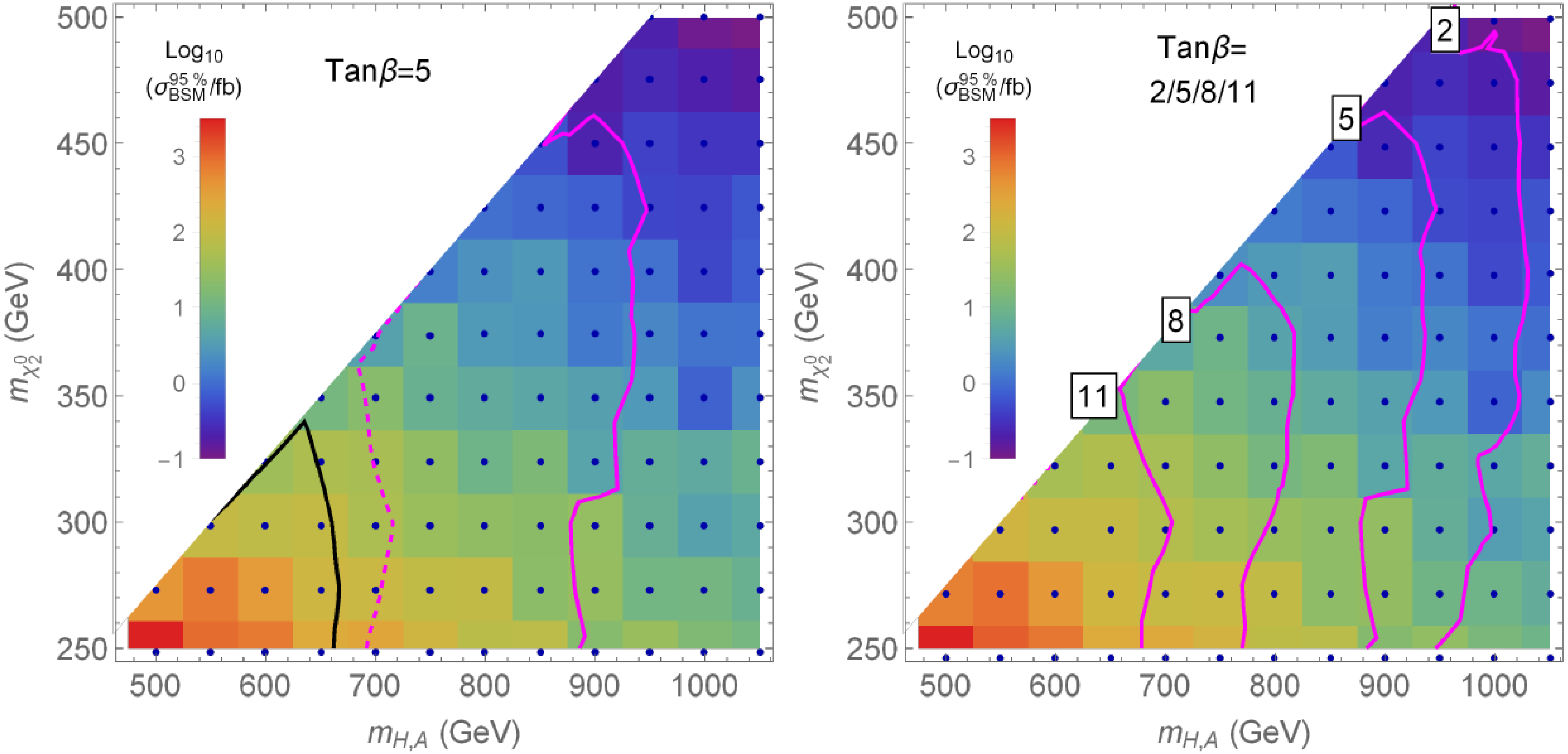
$$m_{cT}^2(\ell\ell, \not{E}_T) = 2 \times \left((|p_T^{\ell\ell}| + |\not{p}_T|)^2 - |p_T^{\ell\ell} + \not{p}_T|^2 \right)$$

Focusing on the Z->ll channel,

Dominant background, multi boson

Sensitivities

- Magenta lines: 95% exclusion at HL-LHC
- Magenta dashed: discovery at HL-LHC
- Black lines: 95% exclusion at LHC 300 fb^-1



Improving Higgsino coverages at HL-LHC through new channel;

Lower tan\beta values really strong due to the larger gg->H,A cross section

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Competitive to direct searches

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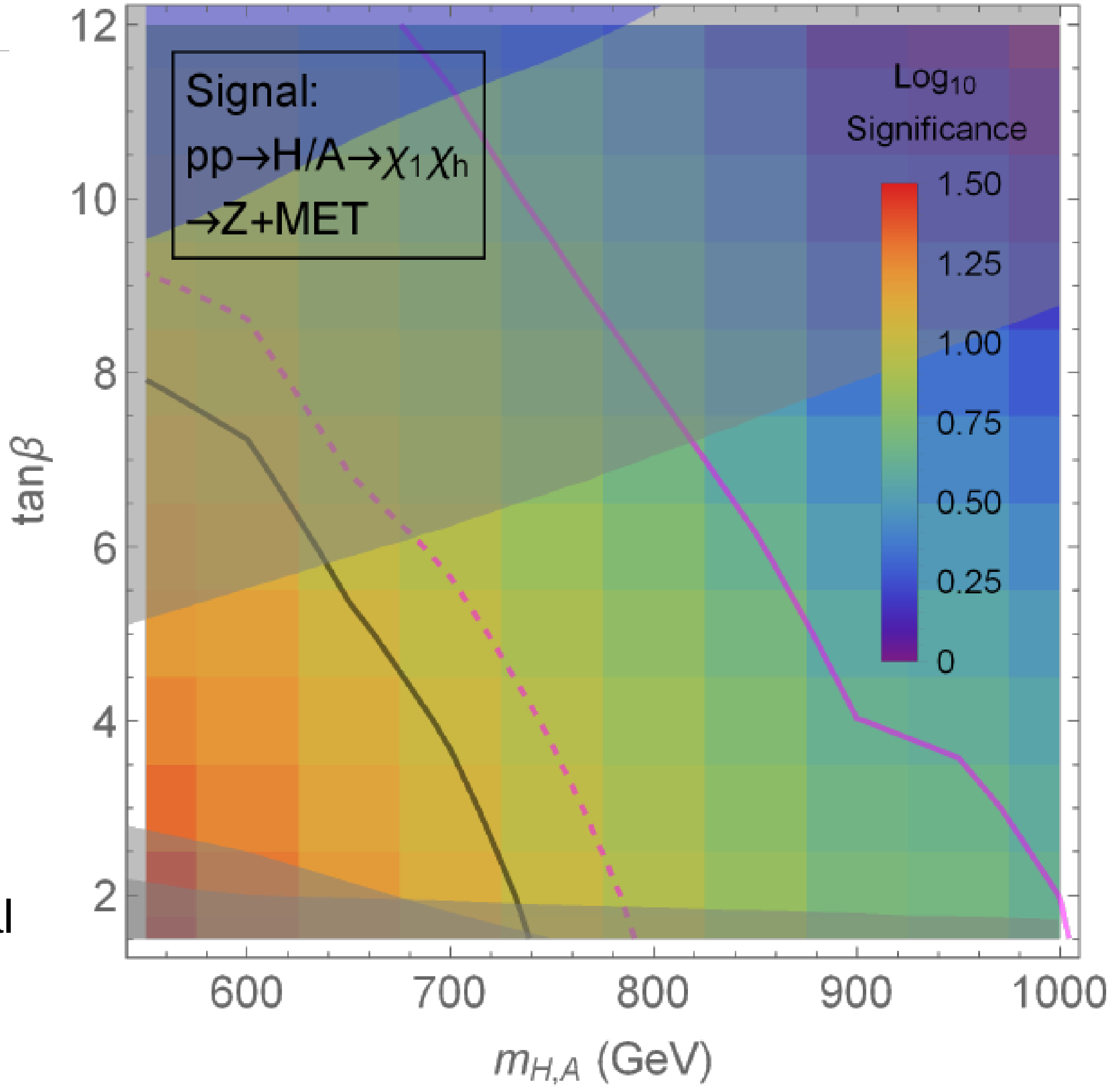
In the mA-tan\beta plane:

- Blue shades: current limits from H→$\tau\tau$
- Gray shades:
  - Upper: projections from H→$\tau\tau$
  - Lower: projections from gg→H→tt, and pp→ttH, H→tt
- Very interesting and nice coverage of the Wedge region; excellent discovery and exclusion potential



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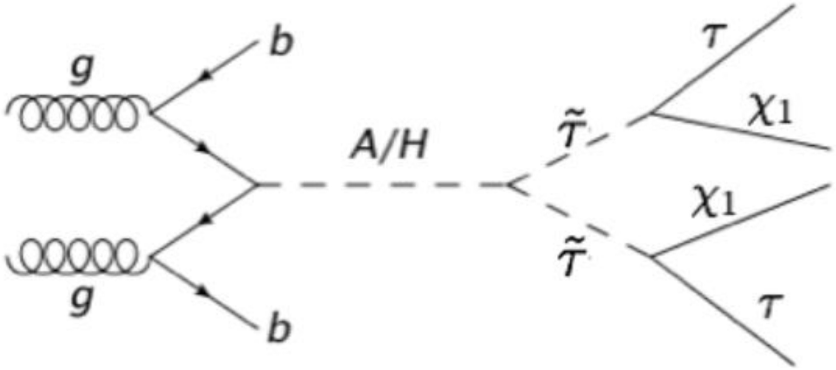

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Heavy Higgs to staus

Red lines: our new search limits

Solid:MT2>40 GeV

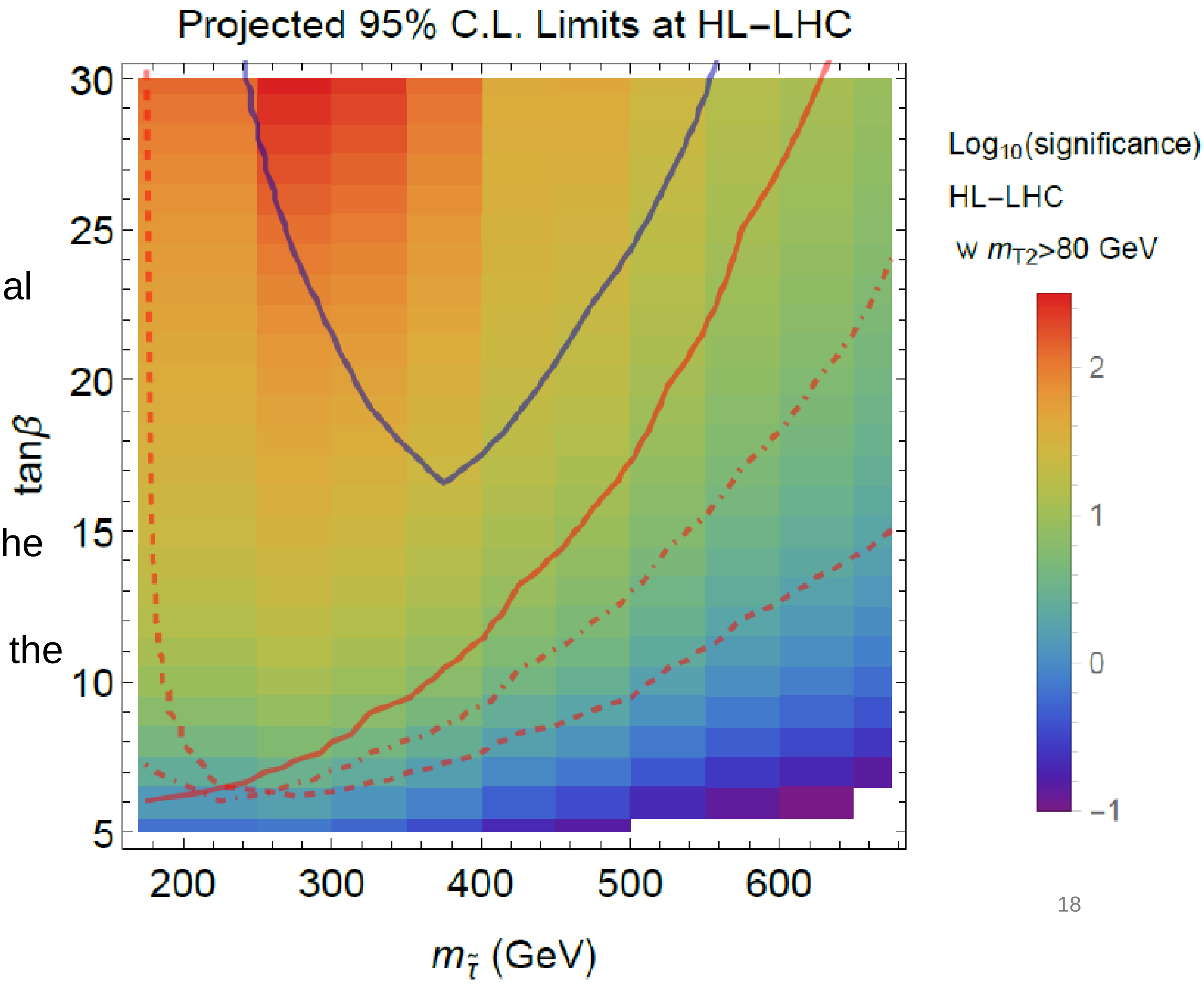
DotDashed:MT2 >80 GeV

Dashed: MT2 > 120 GeV

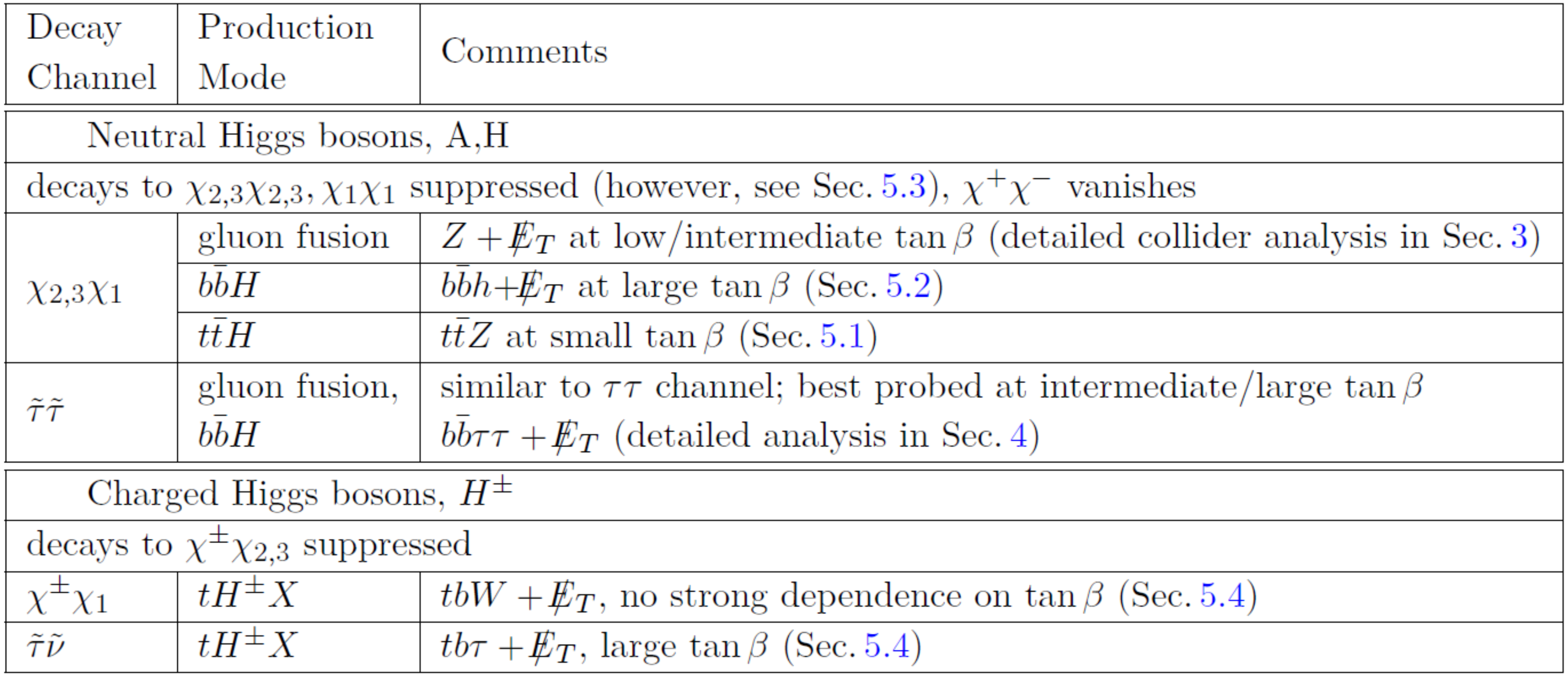
Blue: projection from H->tautau on our signal

Heavy Higgs as a portal to staus:

- Significantly improve stau coverage;
- Significant improvements comparing to the standard H->tautau analysis
- Comparable in MA-tan\beta coverage to the standard ones



Many more channels to study



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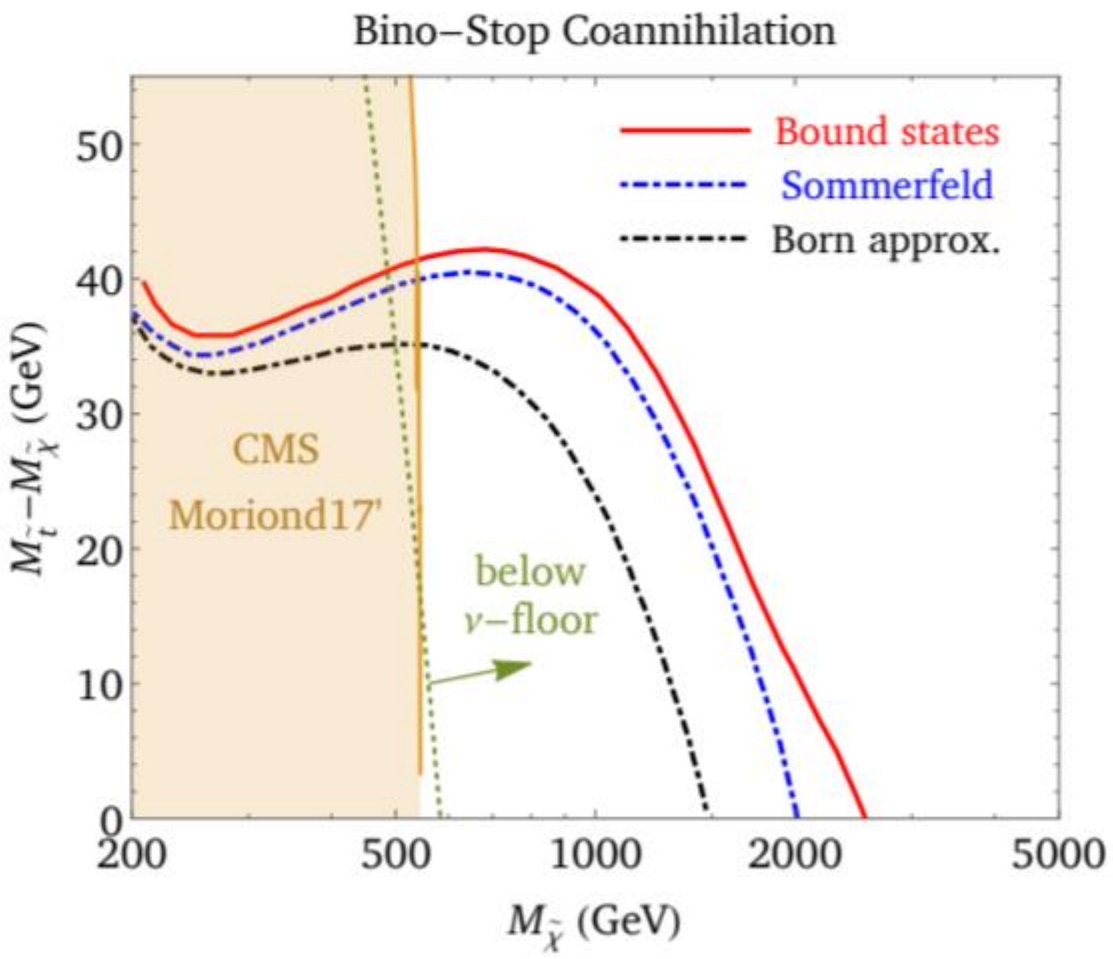
T. Han, ZL, A. Natarajan, 1303.3040

Keung, Low, Zhang 1703.02977
on DM relic

Mono-jet + (soft) displaced tracks
Work in progress, H. An, ZL, et al

Coannihilation and LLP



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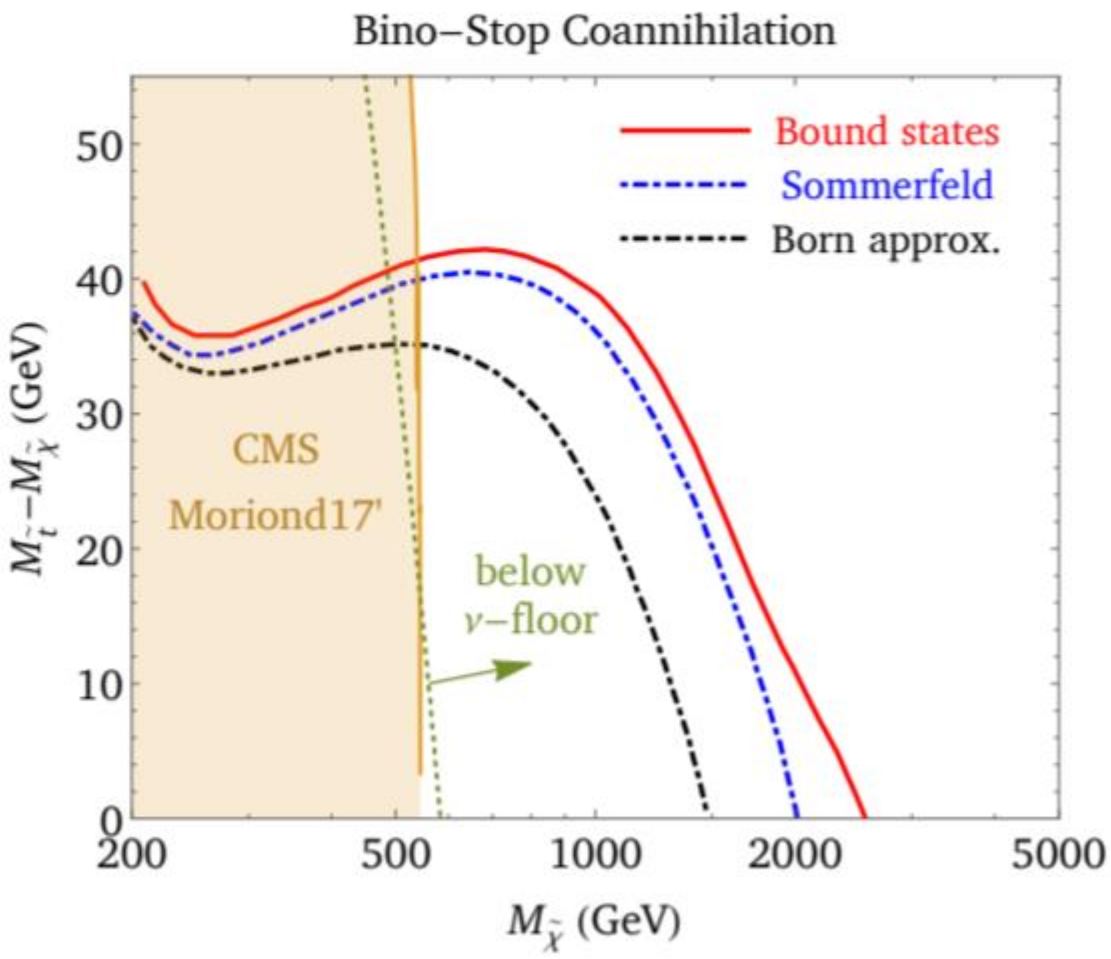

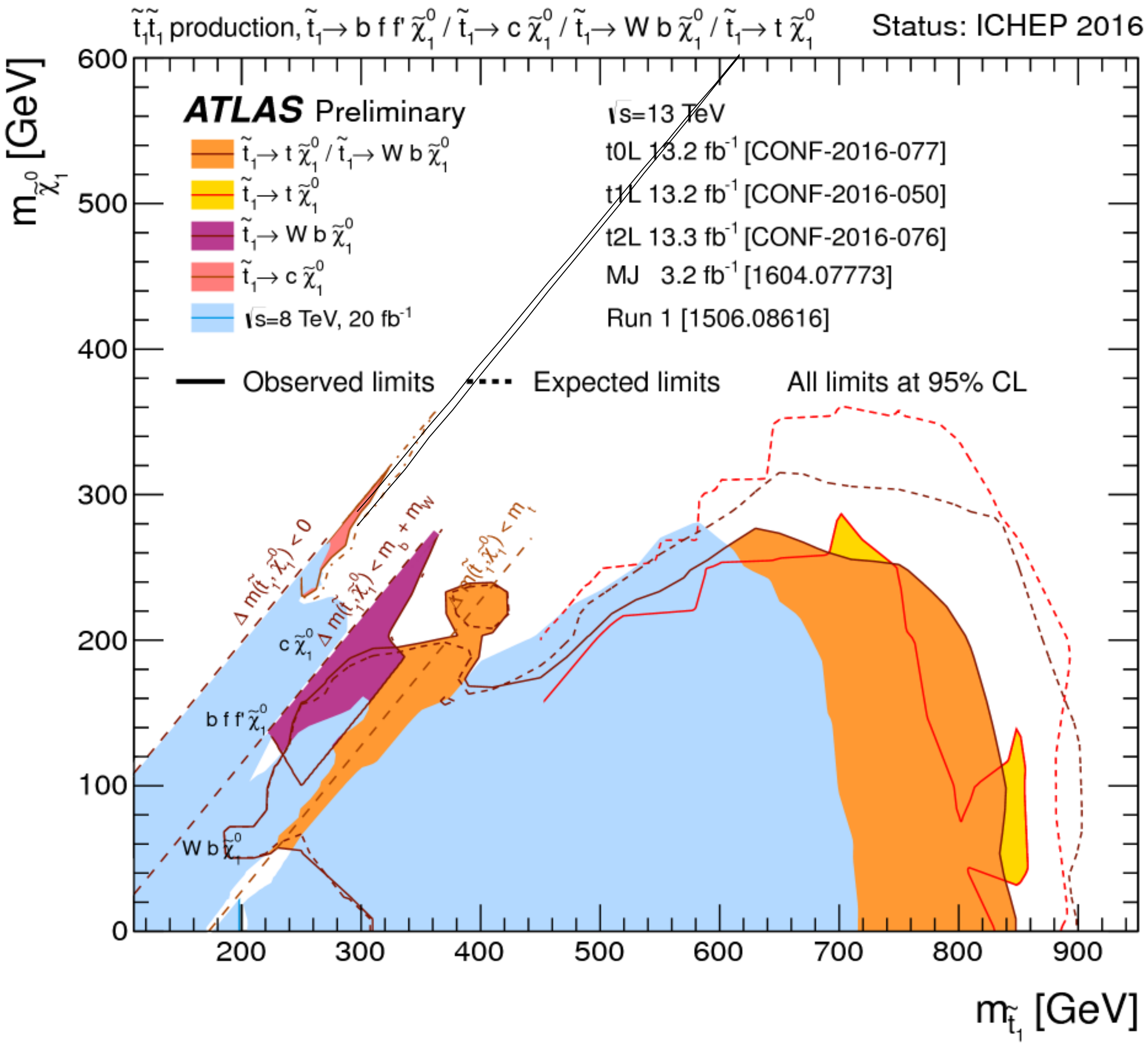

Monojet+(soft) displaced tracks will cover this well motivated region, making direct DM and coannihilator discovery

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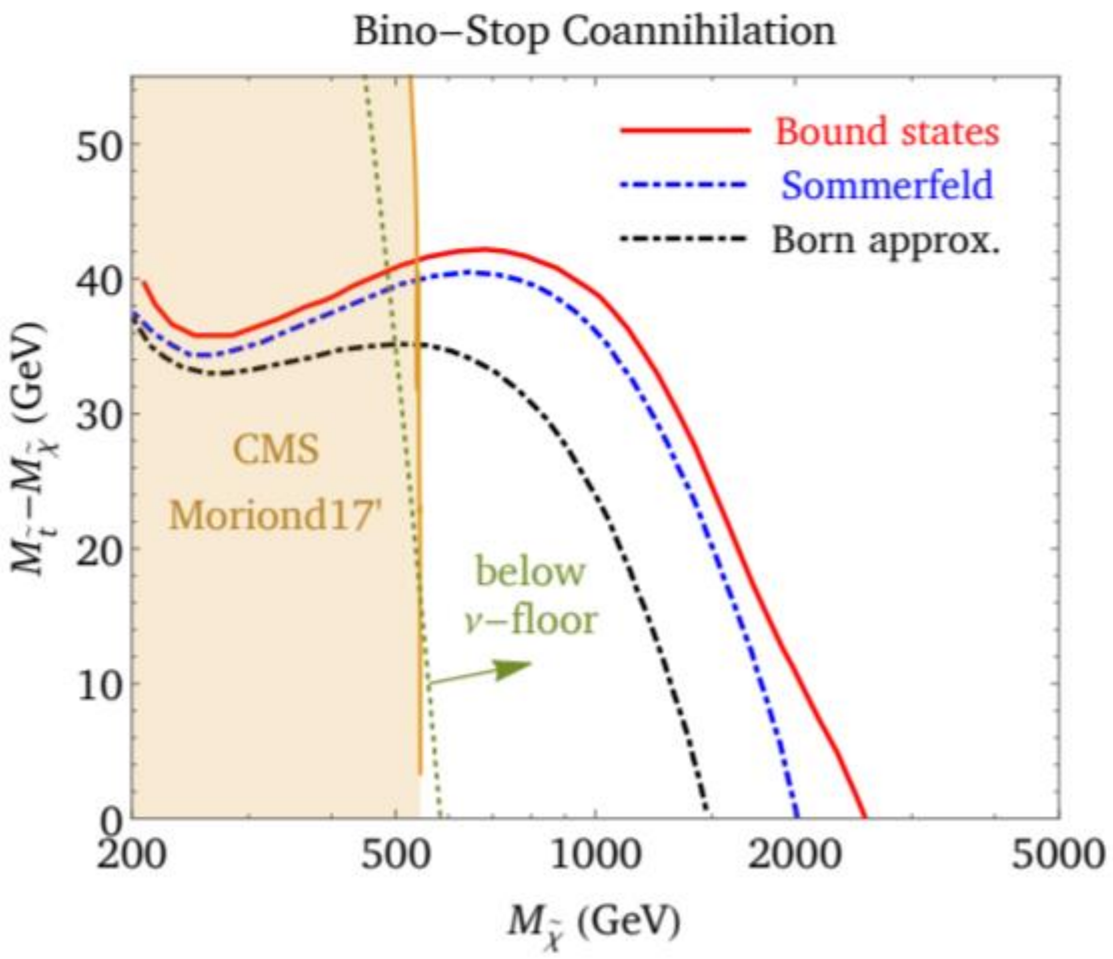

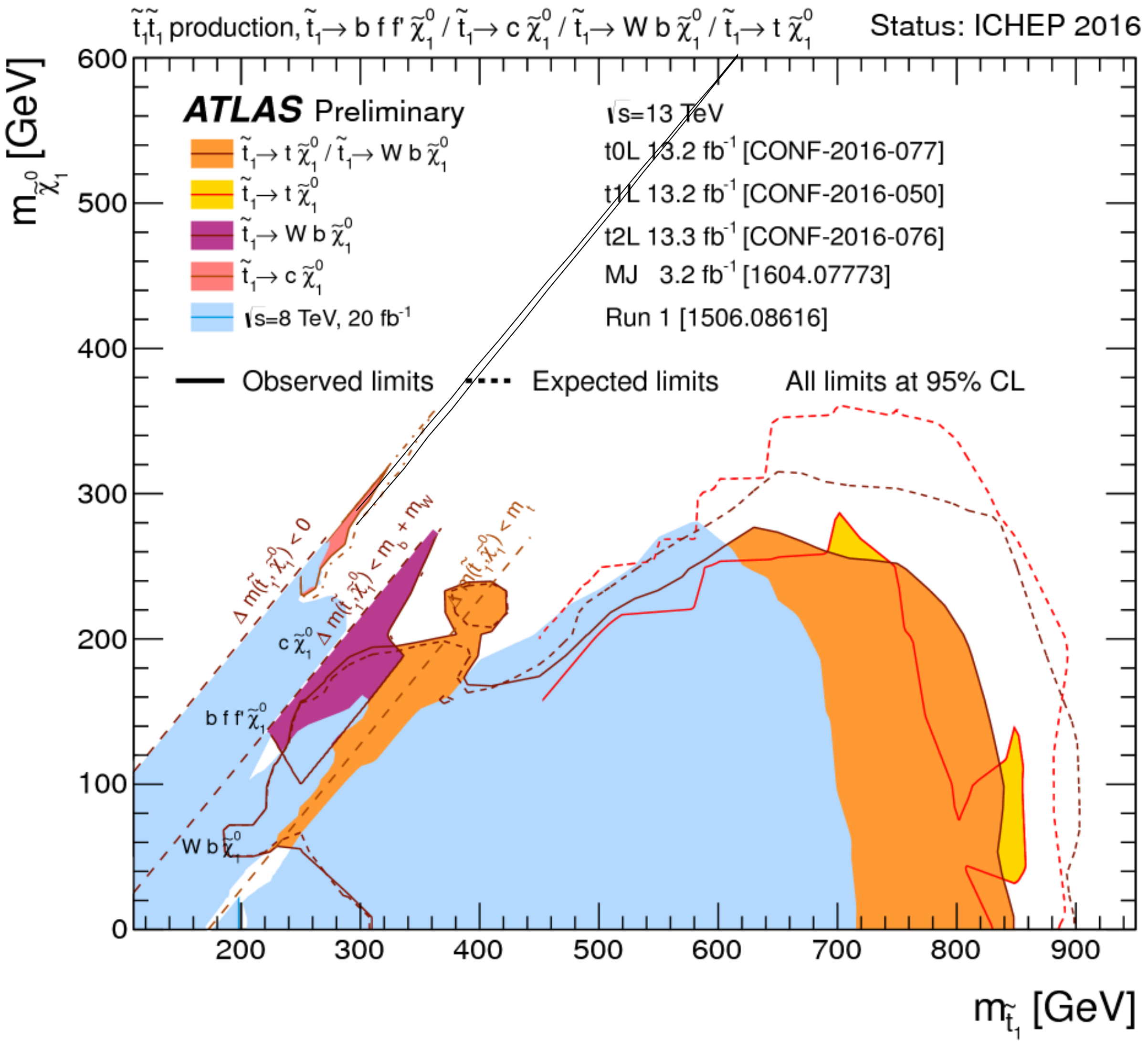

Stau coannhiliation predicts soft (but prompt) tau leptons, needs to go after soft leptons

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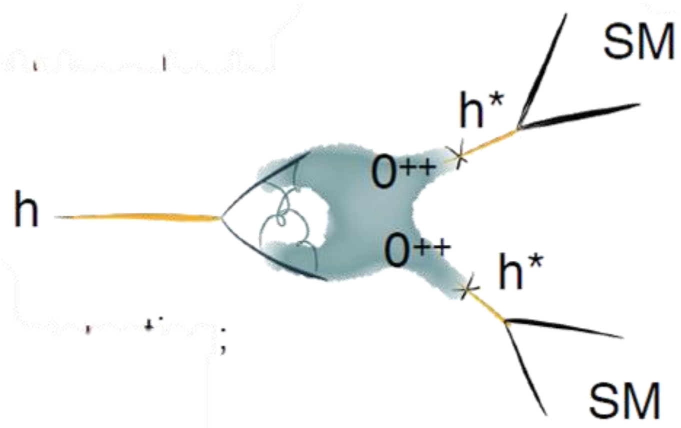
Higgs decays to Long-lived particles & beyond

Model building: Chacko, Goh, Harnik, hep-ph/0506256, hep-ph/0512088, +Burdman hep-ph/0609152+many… **Pheno:** Craig, Katz, Strassler, Sundrum 1501.05310 +many…

Higgs to LLPs: LLP triggers greatly boost the reach



J. Liu, ZL, LT Wang, 1805.05957

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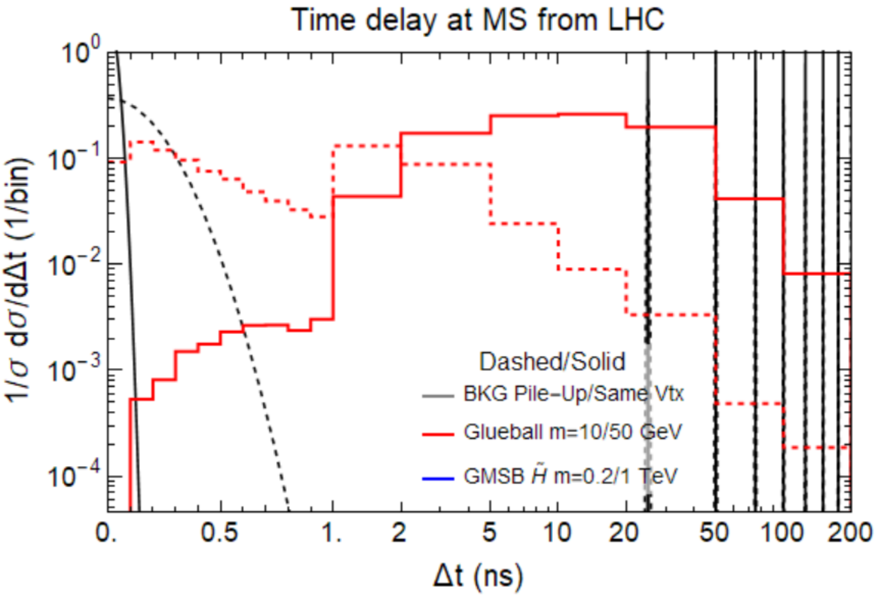

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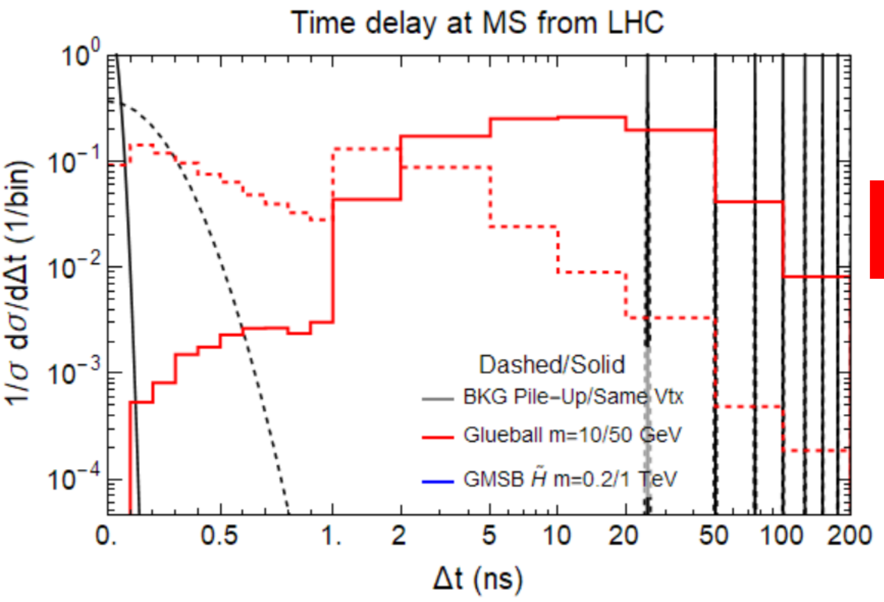

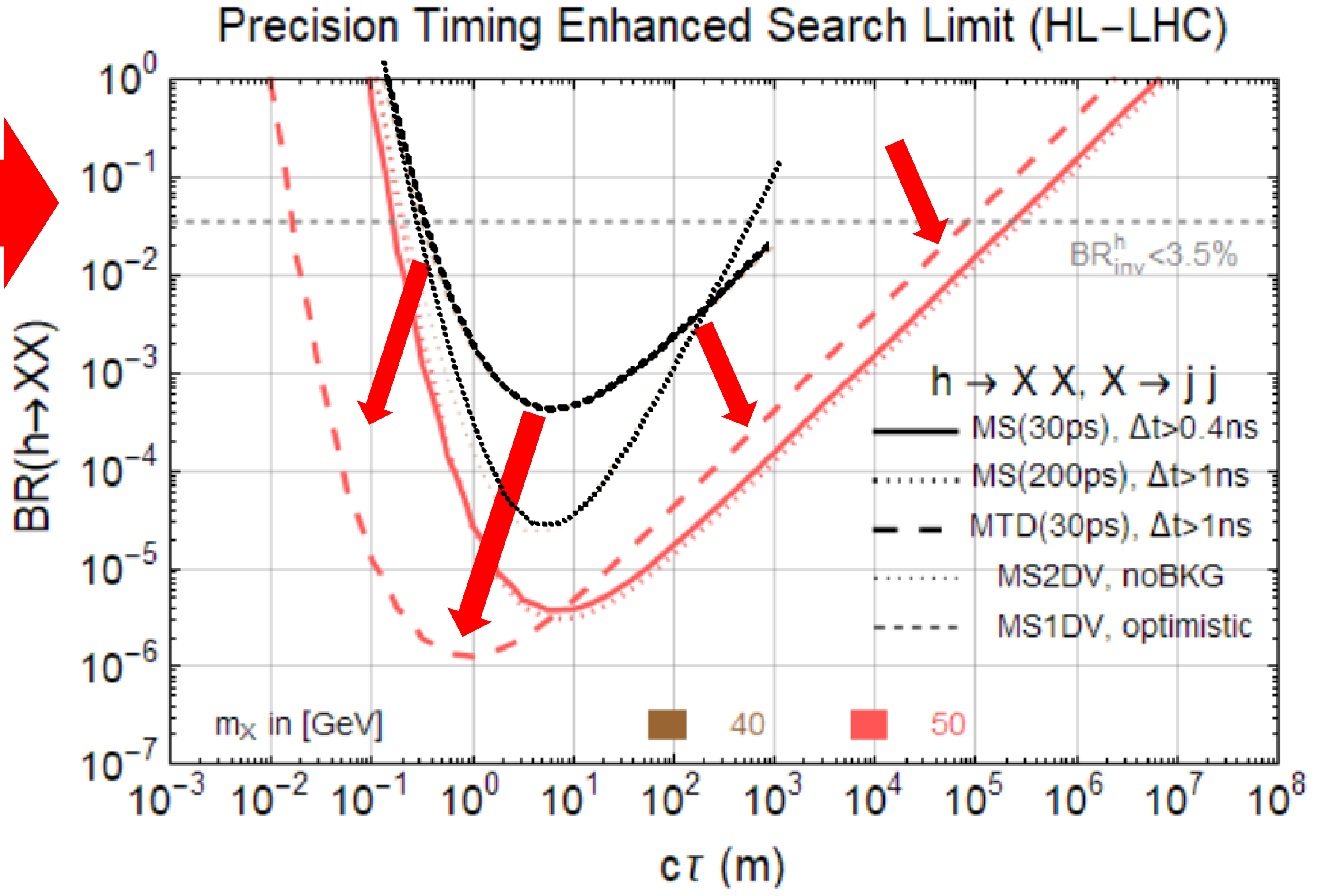

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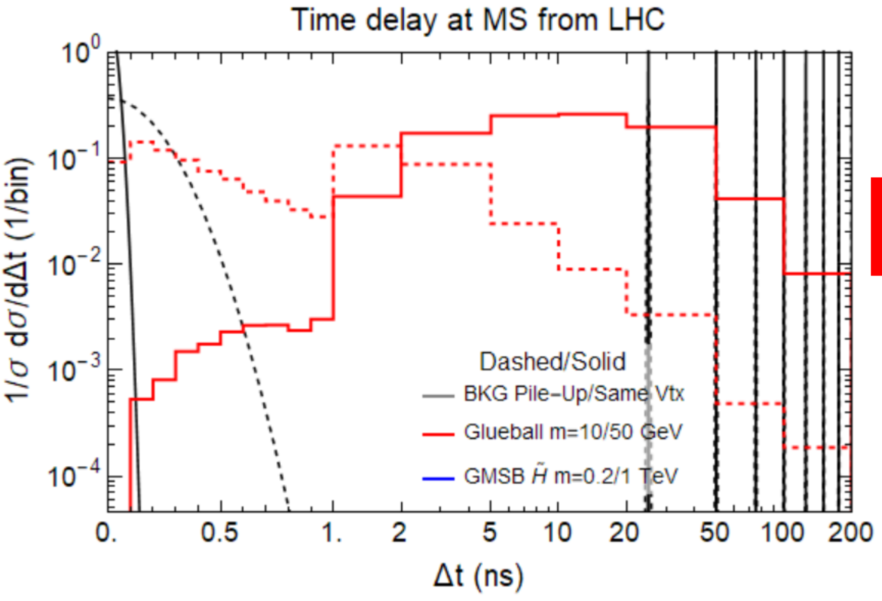

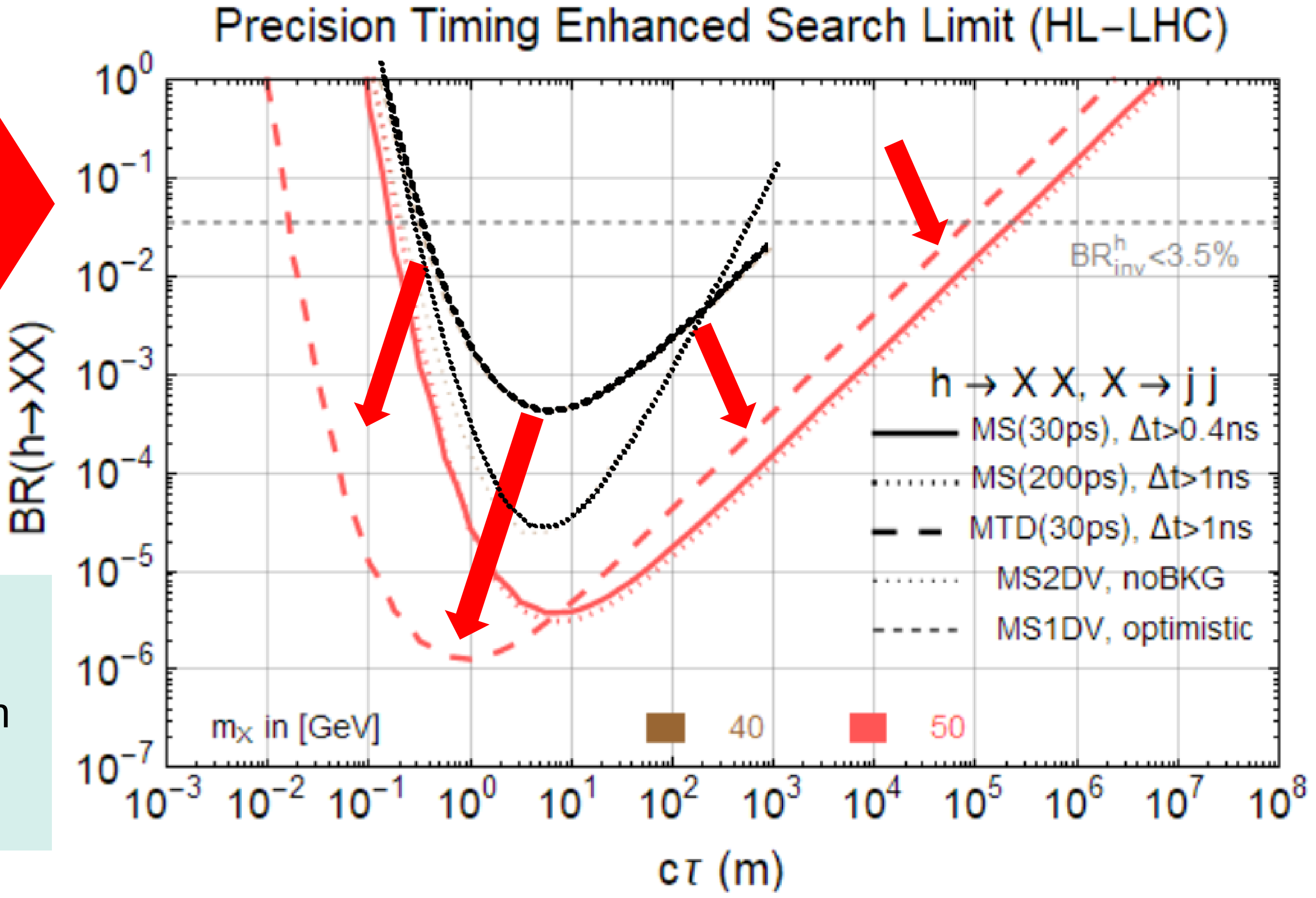

A lot new ideas and possibilities to improve the Higgs to long-lived particles searches; (See LLP talks and discussion today and tomorrow, e.g, by F. Kling, S. Pagan Griso)

J. Liu, ZL, LT Wang, 1805.05957

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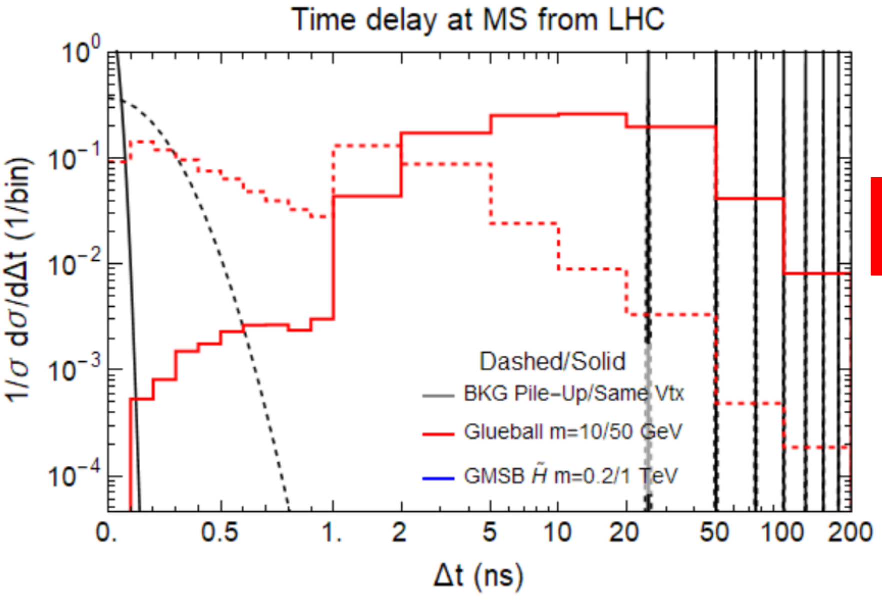
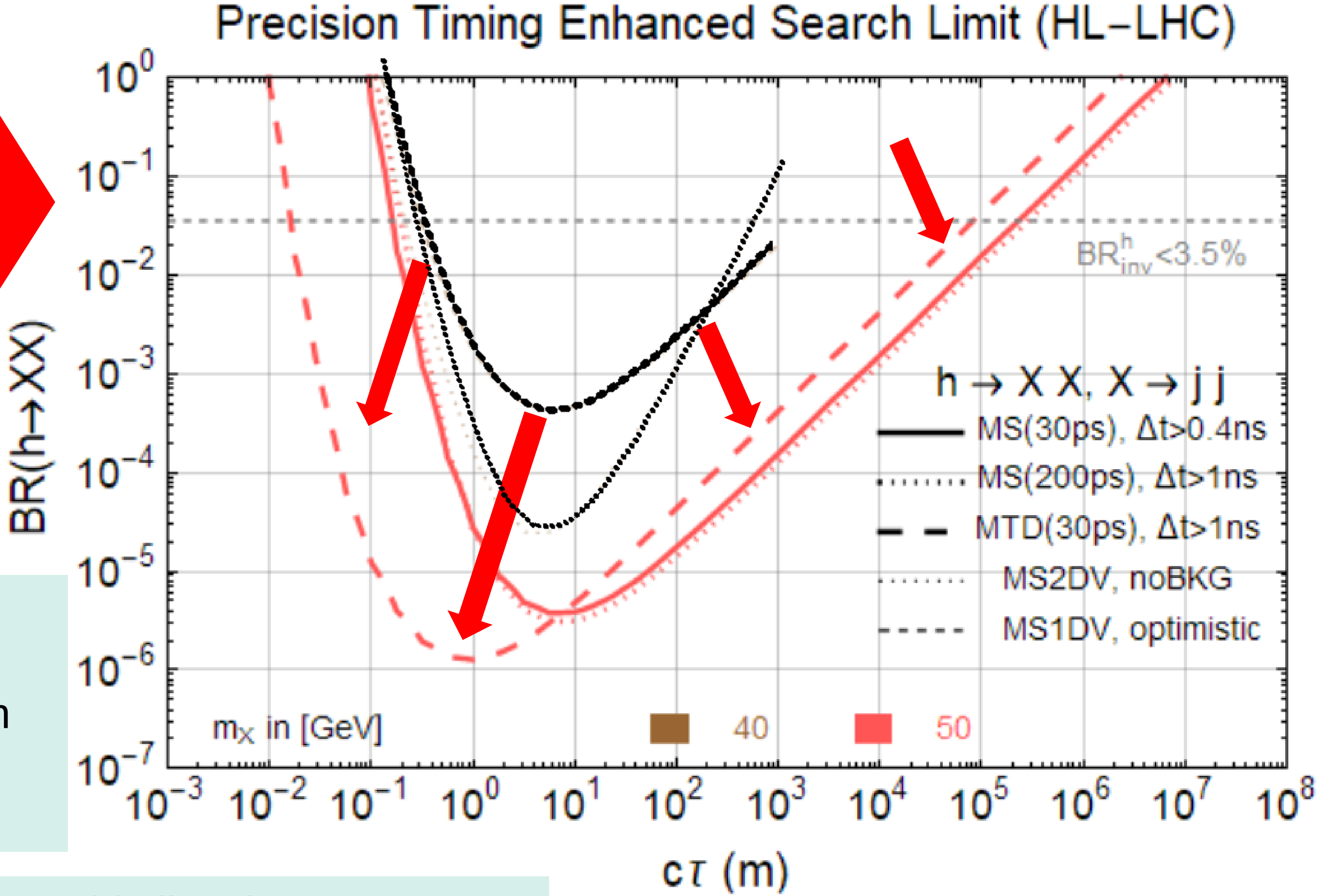




A lot new ideas and possibilities to improve the Higgs to long-lived particles searches; (See LLP talks and discussion today and tomorrow, e.g, by F. Kling, S. Pagan Griso)

Beyond Neutral Naturalness also predicts quirk like signatures for top partners: M. Luty, 0805.4642 + J. Evans, 1811.08903

J. Liu, ZL, LT Wang, 1805.05957

Big Questions→ Big Opportunities

1. Fundamental or composite?
2. SUSY?
3. Neutral Naturalness & Beyond?
4. Electroweak Phase Transition?
5. Higgs portal?

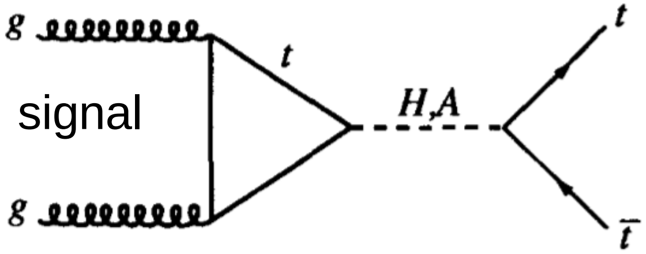
Trilinear Higgs measurements program strong and healthy. What else?

HH resonance

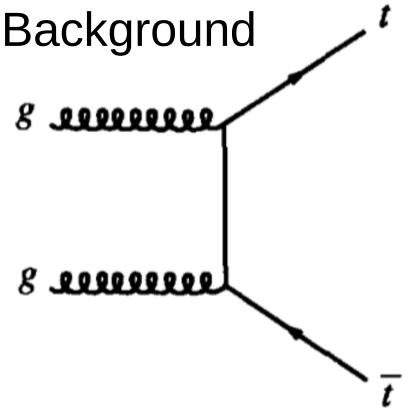
Higgs exotic decays

Unfamiliar look of heavy Scalars

signal

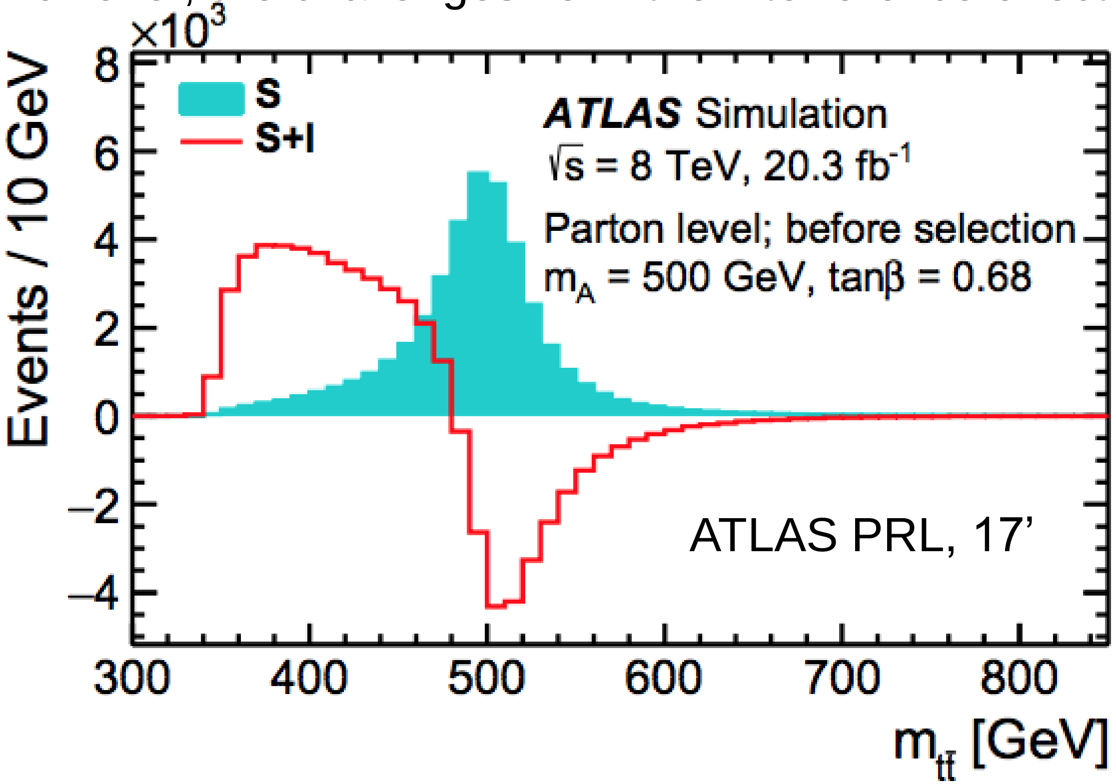


Background



Plus s- and u- channel
Plus s-channel $q\bar{q} \rightarrow t\bar{t}$

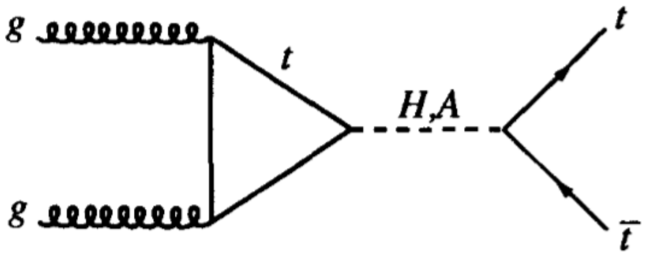
LHC being top factory, the $t\bar{t}$ statistics is very good. $S/\sqrt{B}$ is quite reasonable.
However, the challenges lie in the interference effect.

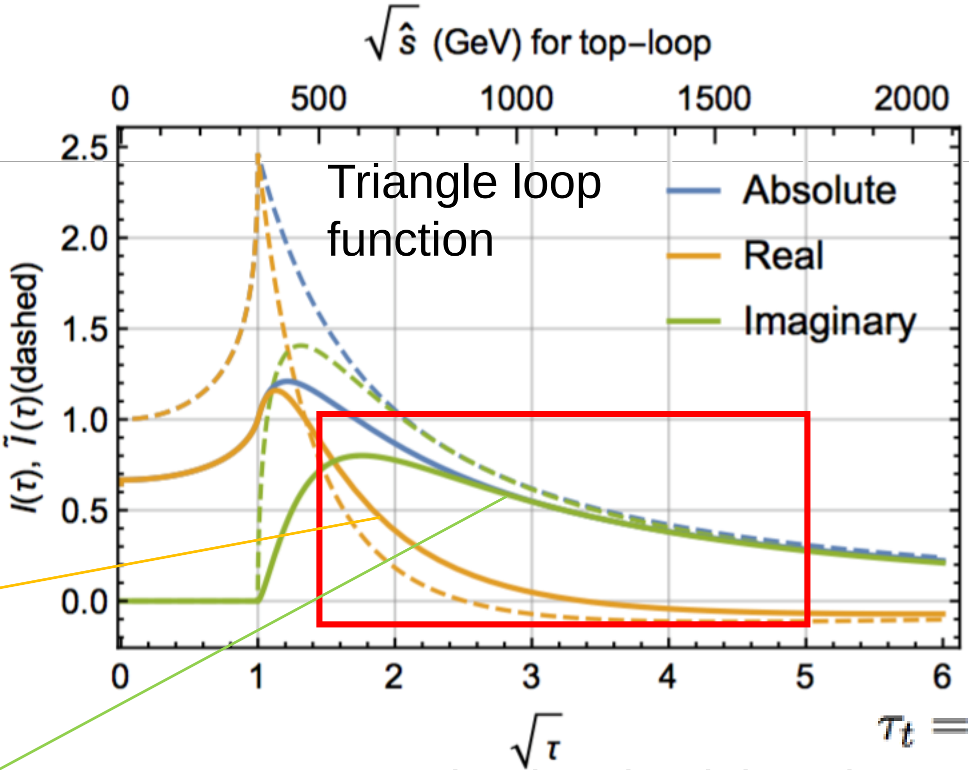


ATLAS PRL, 17'

D. Dicus, A. Stange, S. Willenbrock, 1991; See also recent work by M. Carena, ZL, 1608.07282 N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and also Jung, Sung, Yoon arXiv:1505.00291, S. Gori, I.-W. Kim, N. Shah, K. Zurek arXiv:1602.02782

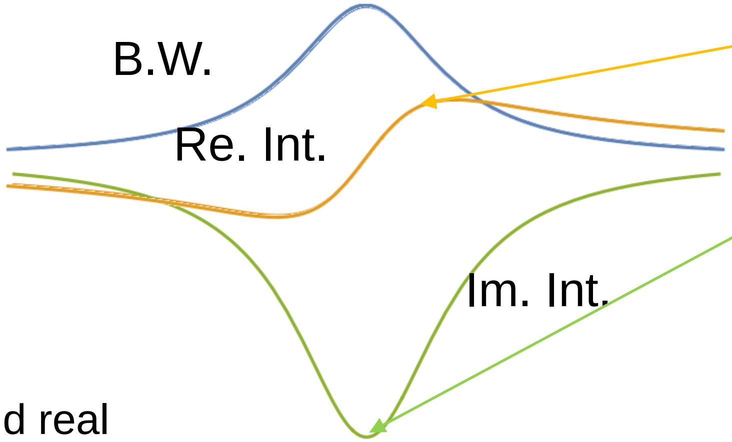
Challenges (interferences)





$$\tau_t = \frac{\hat{s}}{4m_t^2}$$

Once across the threshold, imaginary piece arises drastically and the real piece decreases.

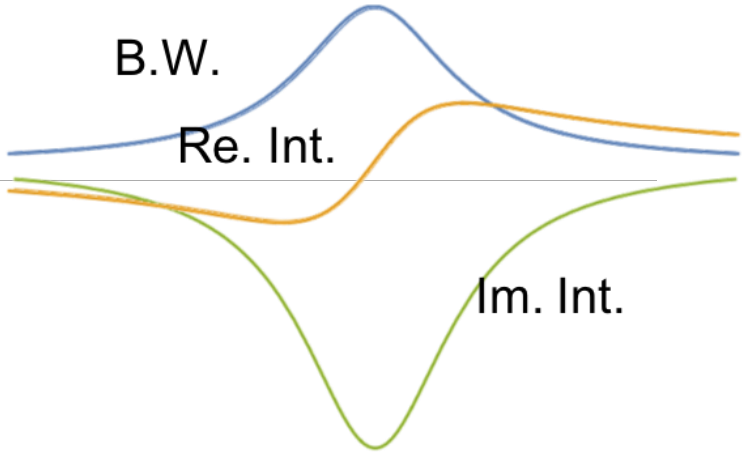


Background real
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

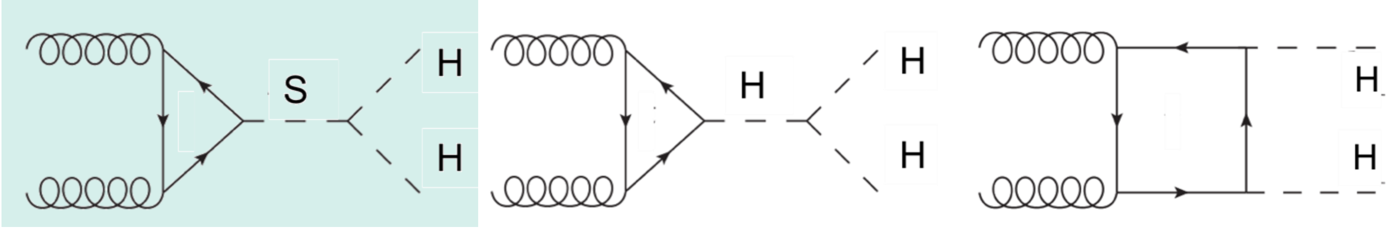
A strong phase
``insensitive”* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.

*subject to difference in loop functions

HH resonances with nontrivial interference



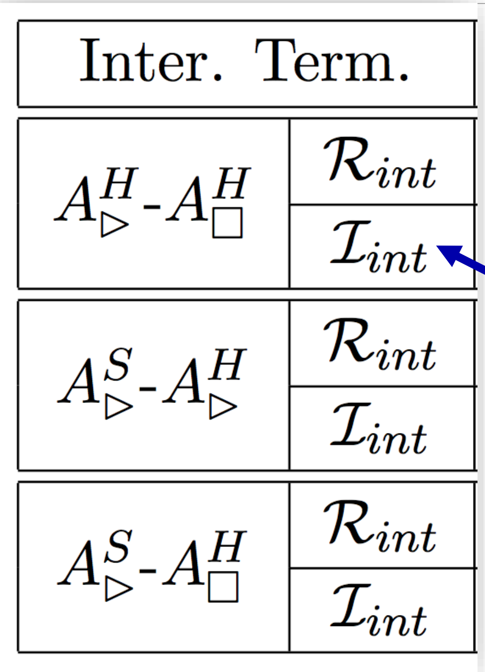
Singlet extension of the SM helps strengthen the electroweak phase transition.



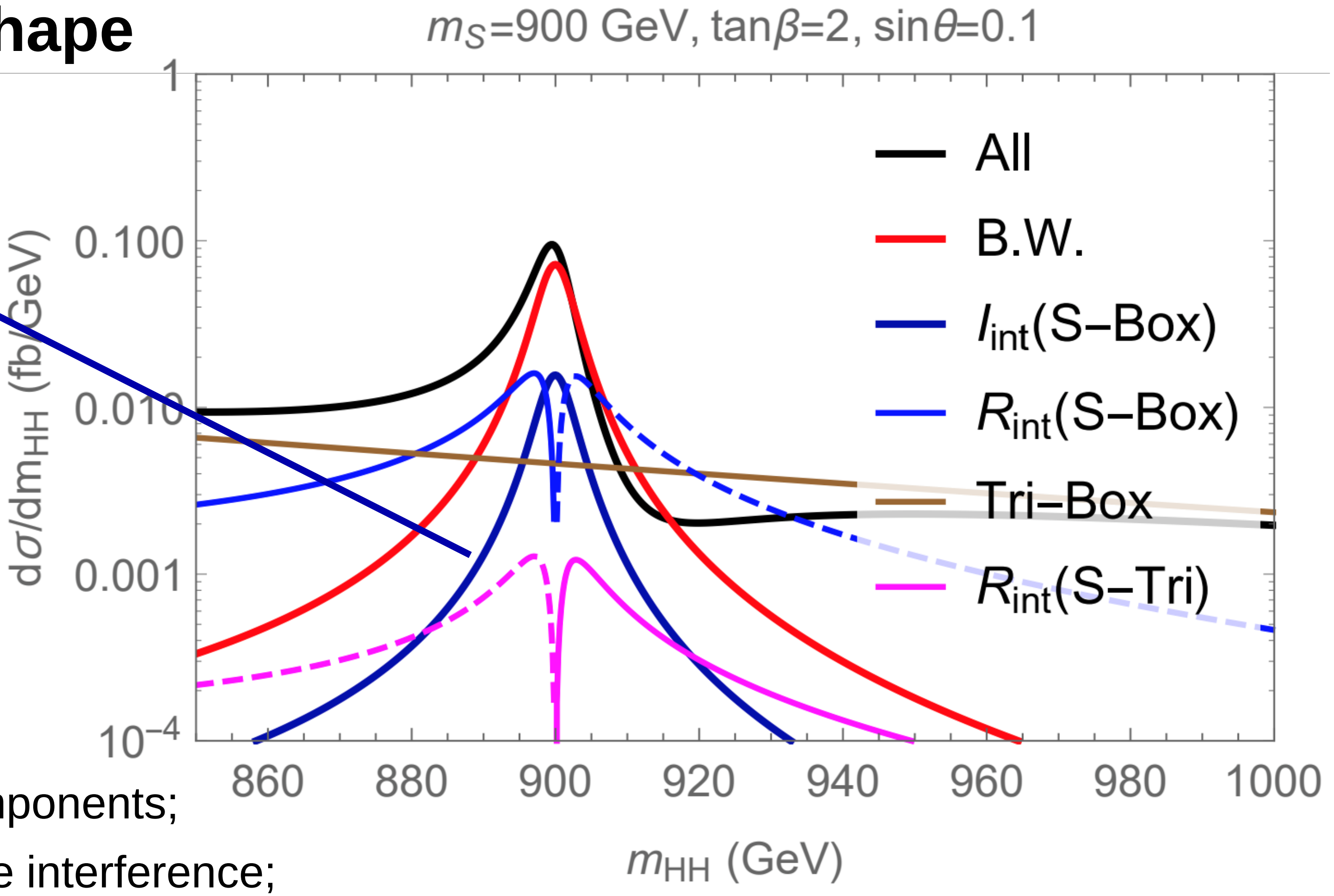
Inter. Term.		rel. phase	proportionality	Inter. Sign
$A^H_{\triangleright}$-$A^H_{\square}$	$\mathcal{R}_{int}$	$\cos(\delta_{\triangleright} - \delta_{\square})$	$\cos^3\theta\lambda_{HHH}$	$-$
	$\mathcal{I}_{int}$	$\sin(\delta_{\triangleright} - \delta_{\square})$	0^*	0
$A^S_{\triangleright}$-$A^H_{\triangleright}$	$\mathcal{R}_{int}$	1	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	$-/+$
	$\mathcal{I}_{int}$	0	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	0
$A^S_{\triangleright}$-$A^H_{\square}$	$\mathcal{R}_{int}$	$\cos(\delta_{\triangleright} - \delta_{\square})$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+/-$
	$\mathcal{I}_{int}$	$\sin(\delta_{\triangleright} - \delta_{\square})$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+$

M. Carena, ZL, M. Riembau, 1801.00794

Interference Line shape



Inter. Term.	
$A^{H}_{\triangleright}$-$A^{H}_{\square}$	$\mathcal{R}_{int}$
	$\mathcal{I}_{int}$
$A^{S}_{\triangleright}$-$A^{H}_{\triangleright}$	$\mathcal{R}_{int}$
	$\mathcal{I}_{int}$
$A^{S}_{\triangleright}$-$A^{H}_{\square}$	$\mathcal{R}_{int}$
	$\mathcal{I}_{int}$



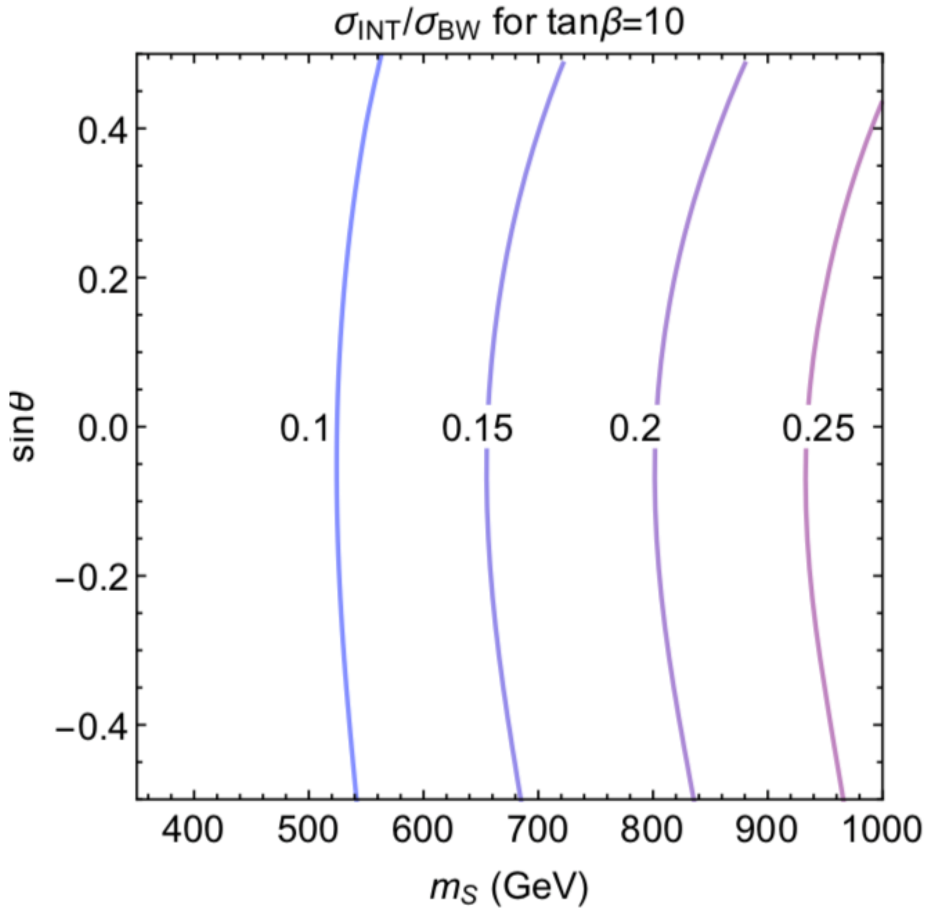
Logarithmic to see other components;

Dashed represent destructive interference;

Dark blue, unique on-shell constructive interference

M. Carena, ZL, M. Riembau, 1801.00794

Size of the on-shell interference



The size of the on-shell interference effect w.r.t. the resonant signal.

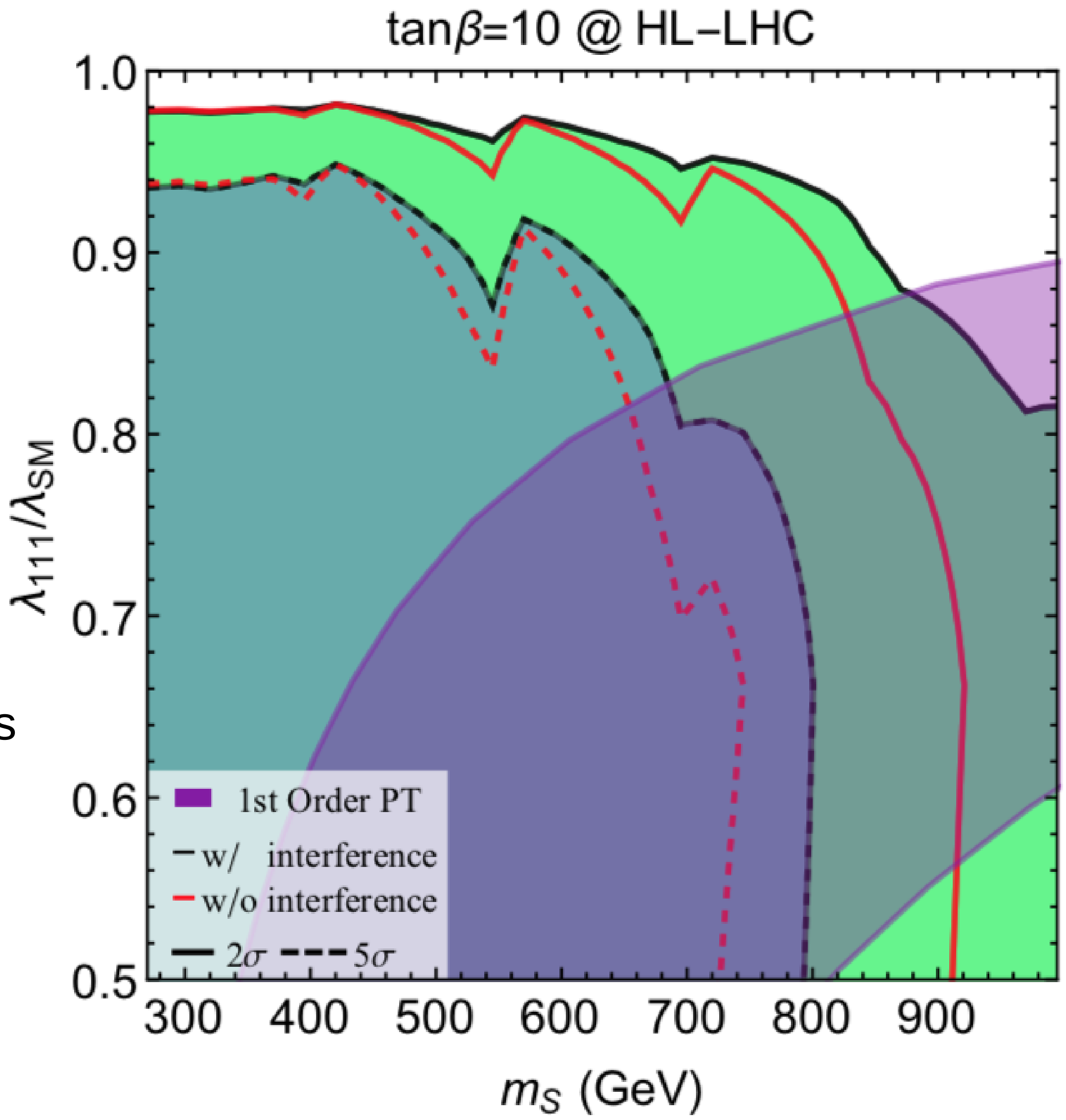
For different parameters, it could be up to 40% below 1 TeV or increase even further for heavier singlet masses.

Interference Line shape

Using the bb$\gamma\gamma$ analysis done by Azatov, Contino, Panico and Son 15', we perform a differential analysis of the lineshapes:

- Black/red lines, w/wo interference effect;
- Purple shaded region, 1st Order Phase transition through an EFT analysis;
- The correct inclusion of the interference effect extend our sensitivity in the 1st order PT

- Correctly taking into account this effect can enhance the signal strength sizably and differential lines hape analysis shows that the inclusion of interference effect will enhance the sensitivity to this model.
- The interference effect is relevant where a first order electroweak phase transition is enabled in this model through a simplified EFT analysis.



M. Carena, ZL, M. Riembau, 1801.00794

M. Carena, ZL, Y.K. Wang, **to appear**

Blind spot: spontaneous Z2 breaking

Spontaneous Z2 breaking singlet extension of the SM well motivated. It can also be viewed as a proxy (simplified discussion) to evaluate:
Dark sector gauge theories needs to be Higgsed;
Dark Higgs talks to our sector through the H^2 H_d^2 mixing quartic;

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

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However, answer not clear:

- No explicit studies in the literature (they are either Z2 preserving or explicit Z2 breaking);
- Large mixing quartic disallowed (not like the Z2 preserving case)
- No H^6 operator generated at tree level (not like the explicit Z2 breaking case).

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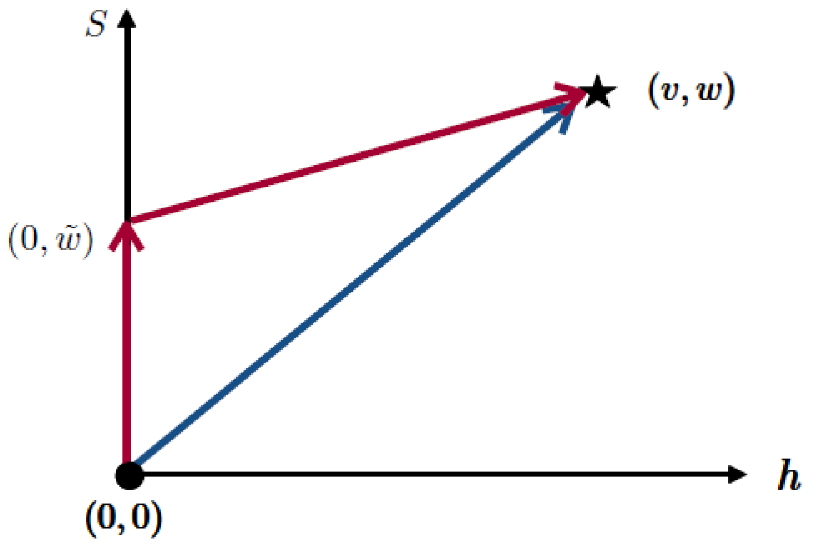

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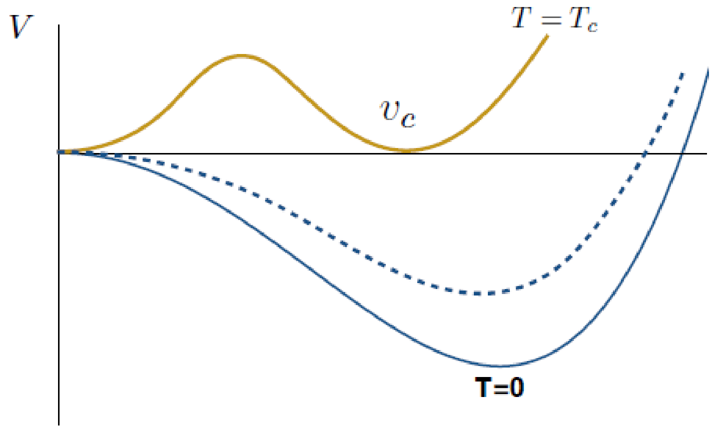
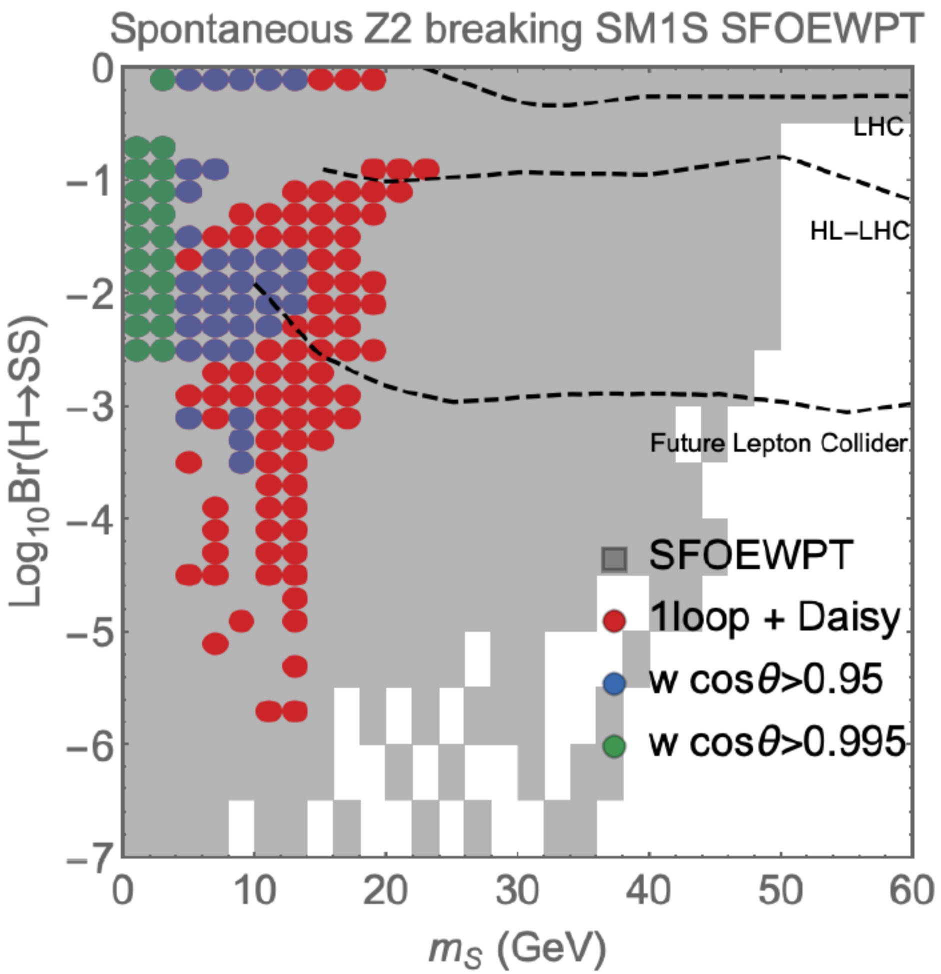
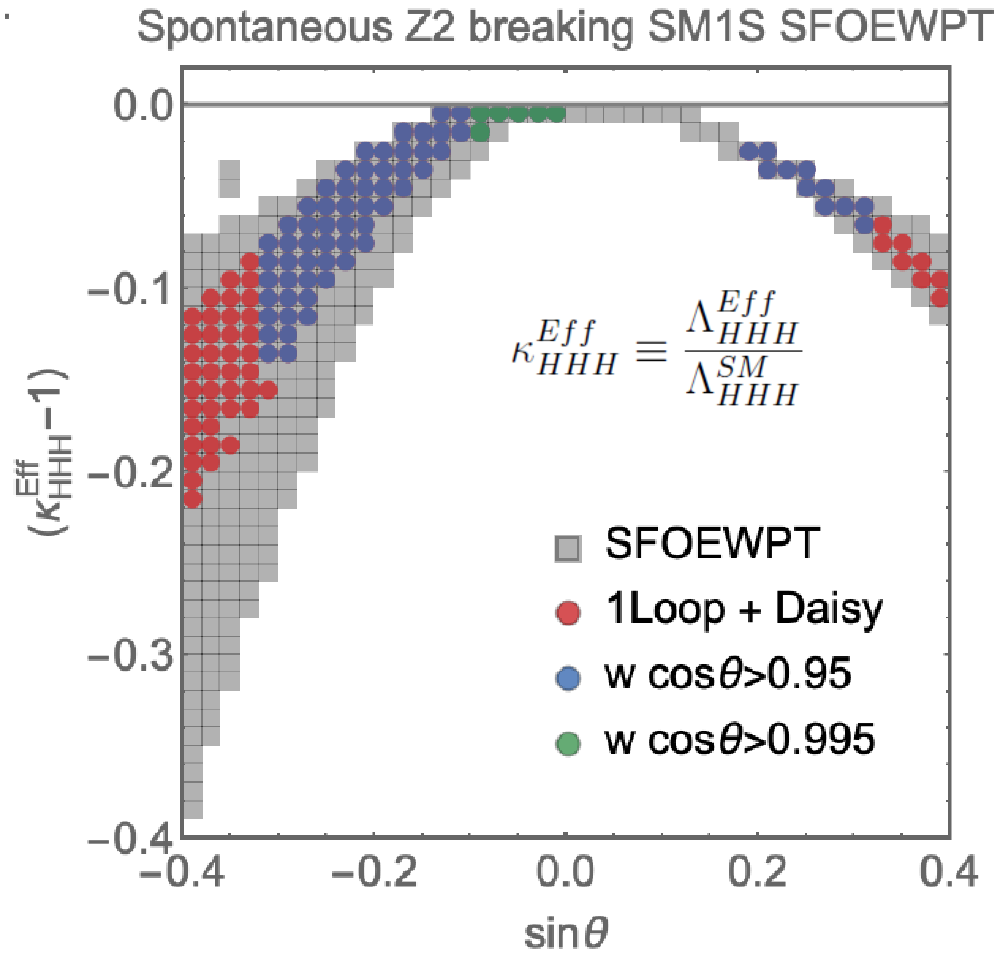


$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

M. Carena, ZL, Y.K. Wang, **to appear**

Predicts H→ss exotic decays and modified HH production



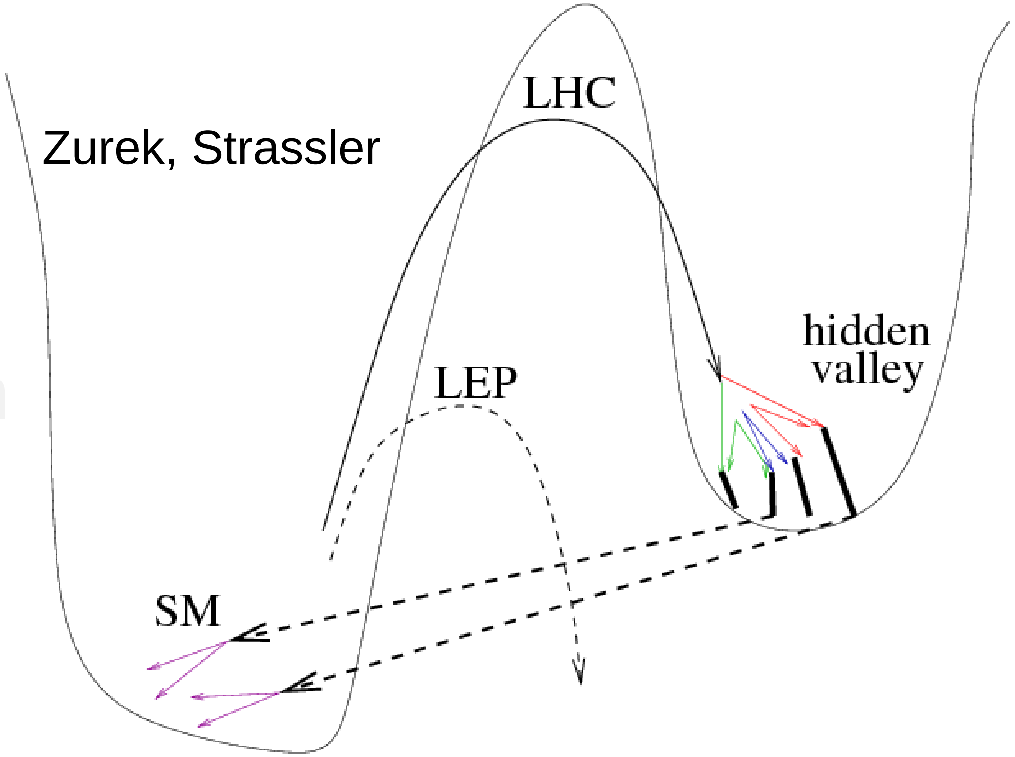


$$\Lambda^{\rm Eff}_{HHH} = \frac{2}{3}\sin\theta\frac{\hat{s}^2}{(\hat{s}-m_S^2)^2+i\Gamma_S m_S}\Lambda_{SHH}+\cos\theta\frac{\hat{s}^2}{(\hat{s}-m_H^2)^2+i\Gamma_H m_H}\Lambda_{HHH}$$
$$\simeq \frac{2}{3}\sin\theta\Lambda_{SHH}+\cos\theta\Lambda_{HHH}.$$

Big Questions➔ Big Opportunities

1. Fundamental or com
2. SUSY?
3. Neutral Naturalness

5. Higgs portal?



Zurek, Strassler

Higgs exotic decays

Higgs portal & exotic decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most searches focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.

(theoretical interests)

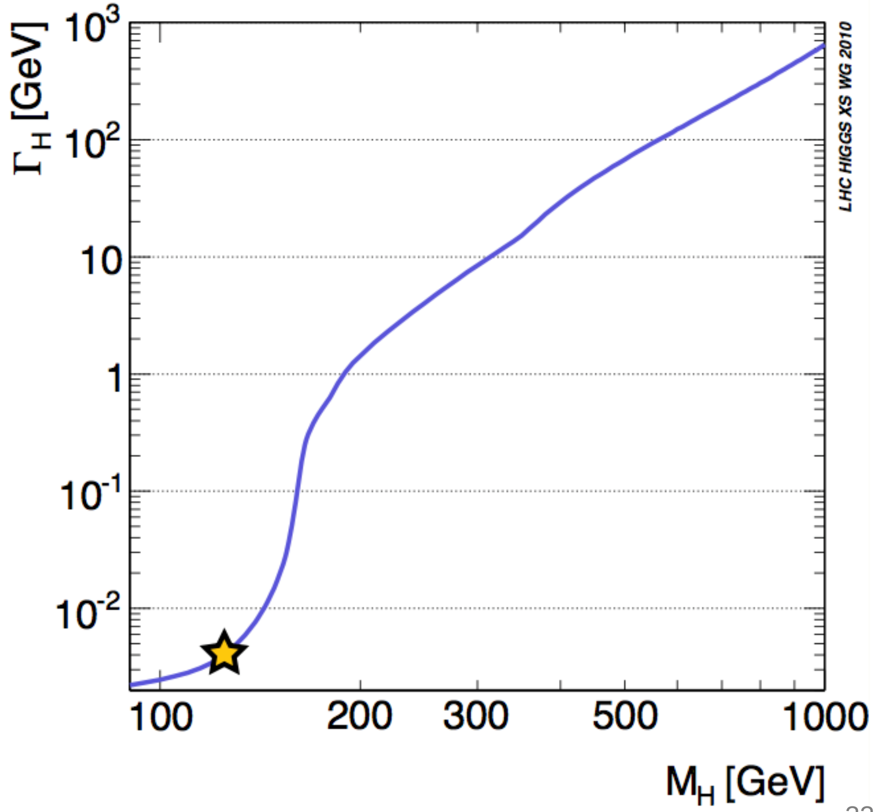
- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

(complementarity)

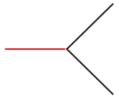
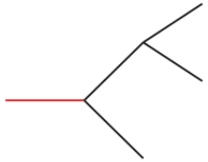
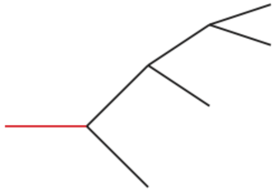
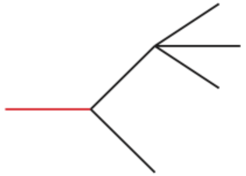
- Higgs has tiny width ~4 MeV

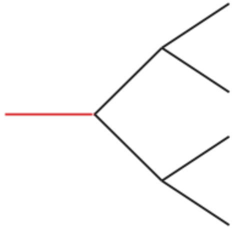
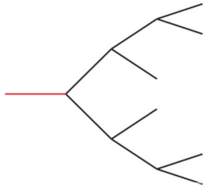
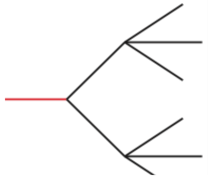
$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.
Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$



Organizing the exotic decays

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_{\mathrm{T}}$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_{\mathrm{T}}$
	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
	$h \to (\mu^+\mu^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$
	$h \to jj + \not{E}_{\mathrm{T}}$
	$h \to \tau^+\tau^- + \not{E}_{\mathrm{T}}$
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}} + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}} + X$

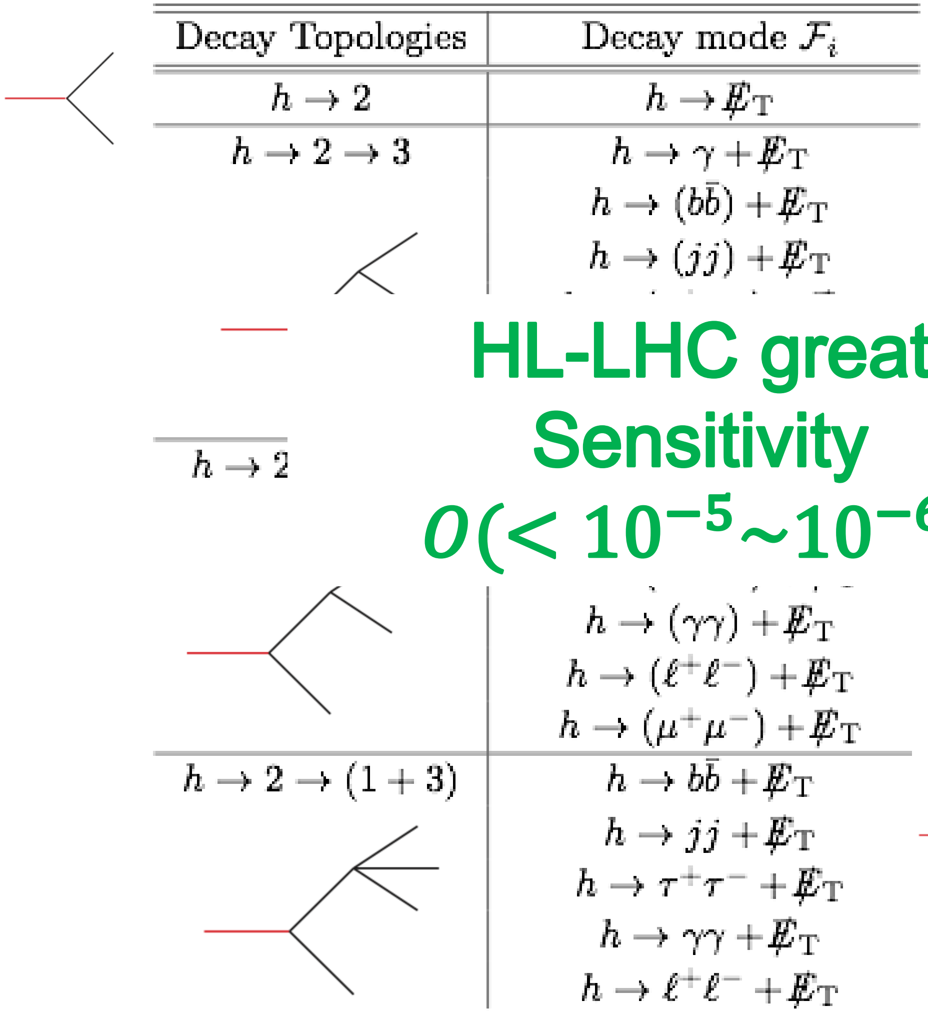
Exotic decays of the 125 GeV Higgs boson

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

1312.4992

Coverage & Potential

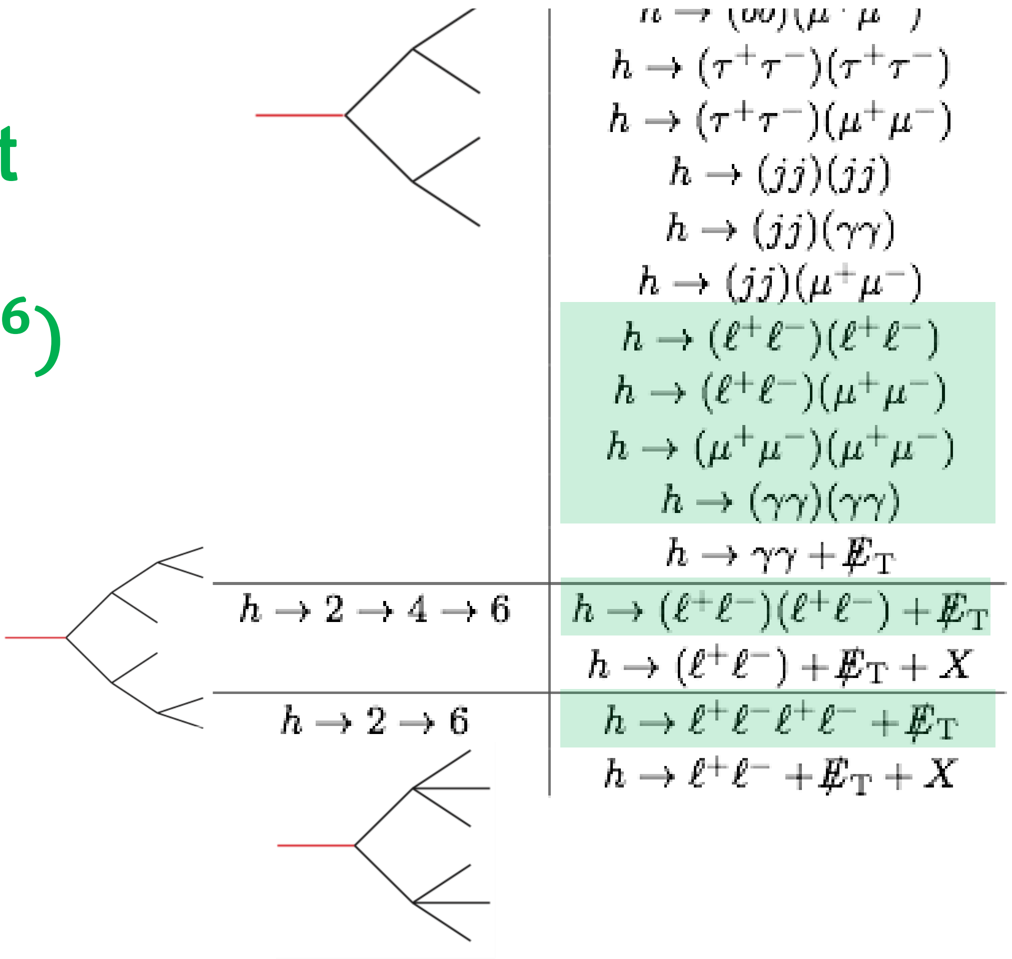
- ~0.5 Billions Higgs produced at HL-LHC;
- 2-3 orders of magnitude more than future Higgs factories;
- Unique Higgs properties can be learned and great discovery potential for certain channels;



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not\!\!E_{\mathrm{T}}$
$h \to 2 \to 3$	$h \to \gamma + \not\!\!E_{\mathrm{T}}$ $h \to (b\bar{b}) + \not\!\!E_{\mathrm{T}}$ $h \to (jj) + \not\!\!E_{\mathrm{T}}$
$h \to 2$	$h \to (\gamma\gamma) + \not\!\!E_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not\!\!E_{\mathrm{T}}$ $h \to (\mu^+\mu^-) + \not\!\!E_{\mathrm{T}}$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not\!\!E_{\mathrm{T}}$ $h \to jj + \not\!\!E_{\mathrm{T}}$ $h \to \tau^+\tau^- + \not\!\!E_{\mathrm{T}}$ $h \to \gamma\gamma + \not\!\!E_{\mathrm{T}}$ $h \to \ell^+\ell^- + \not\!\!E_{\mathrm{T}}$

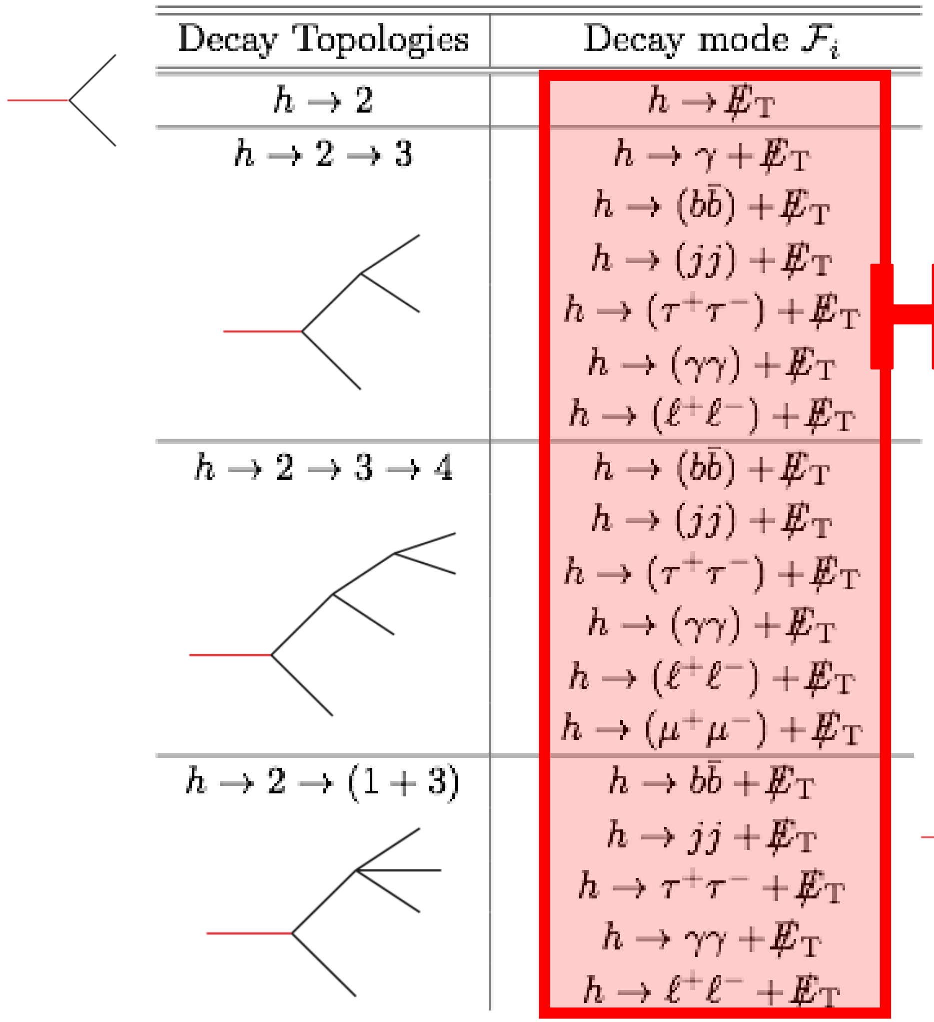
HL-LHC great Sensitivity

$O(< 10^{-5} \sim 10^{-6})$



	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not\!\!E_{\mathrm{T}}$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not\!\!E_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not\!\!E_{\mathrm{T}} + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_{\mathrm{T}}$ $h \to \ell^+\ell^- + \not\!\!E_{\mathrm{T}} + X$

Coverage & Potential



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_{\mathrm{T}}$
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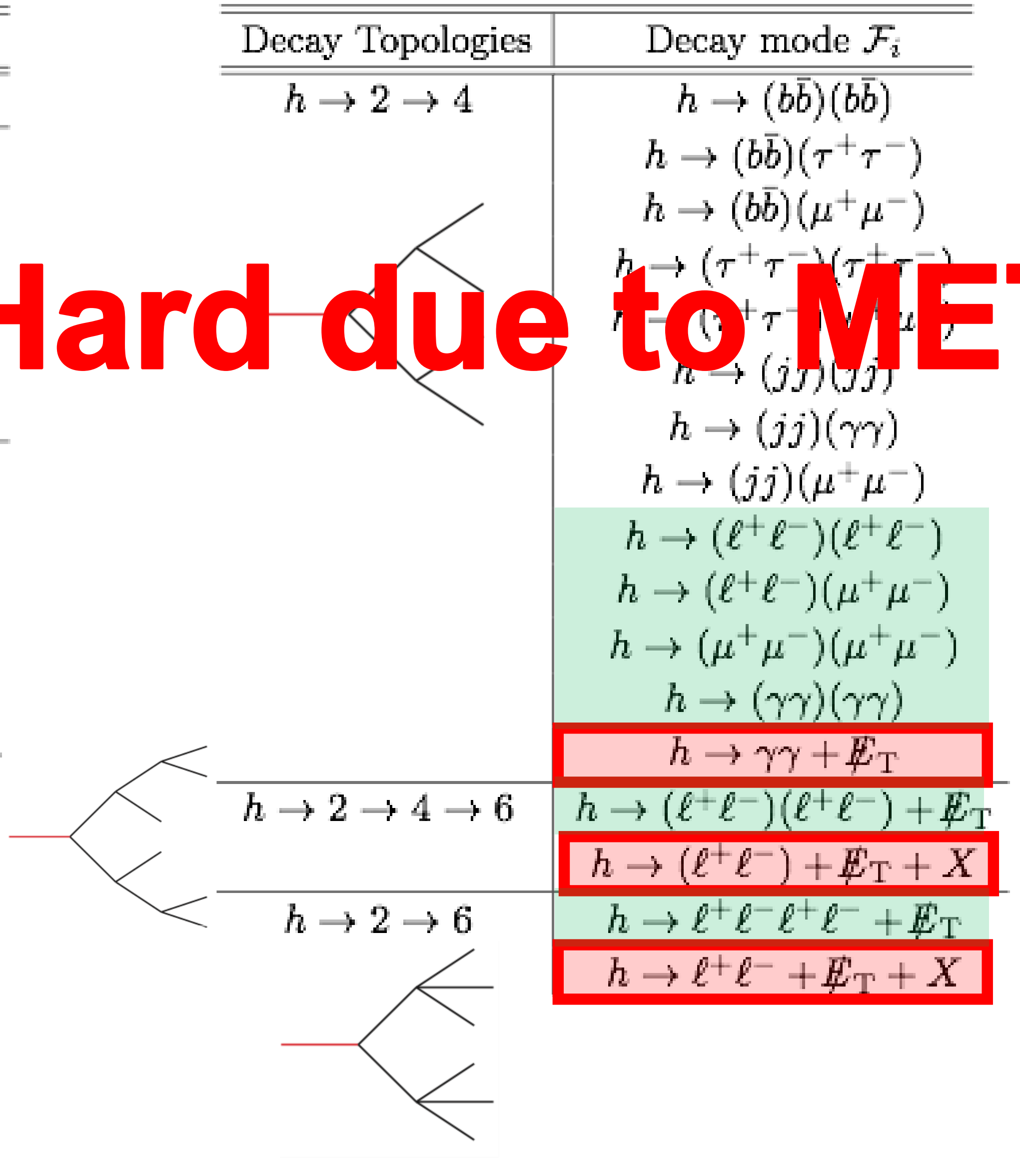
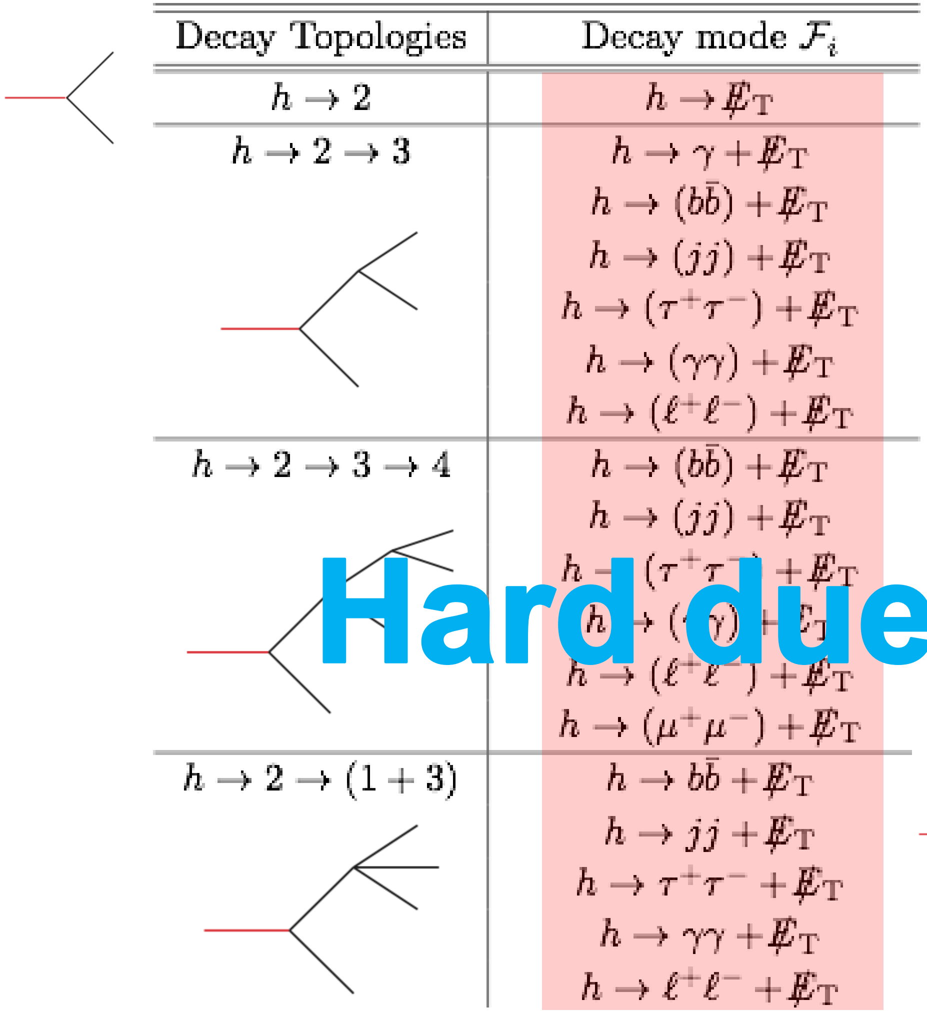
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$ $h \to (jj) + \not{E}_{\mathrm{T}}$ $h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$ $h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$ $h \to (\mu^+\mu^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$ $h \to jj + \not{E}_{\mathrm{T}}$ $h \to \tau^+\tau^- + \not{E}_{\mathrm{T}}$ $h \to \gamma\gamma + \not{E}_{\mathrm{T}}$ $h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$



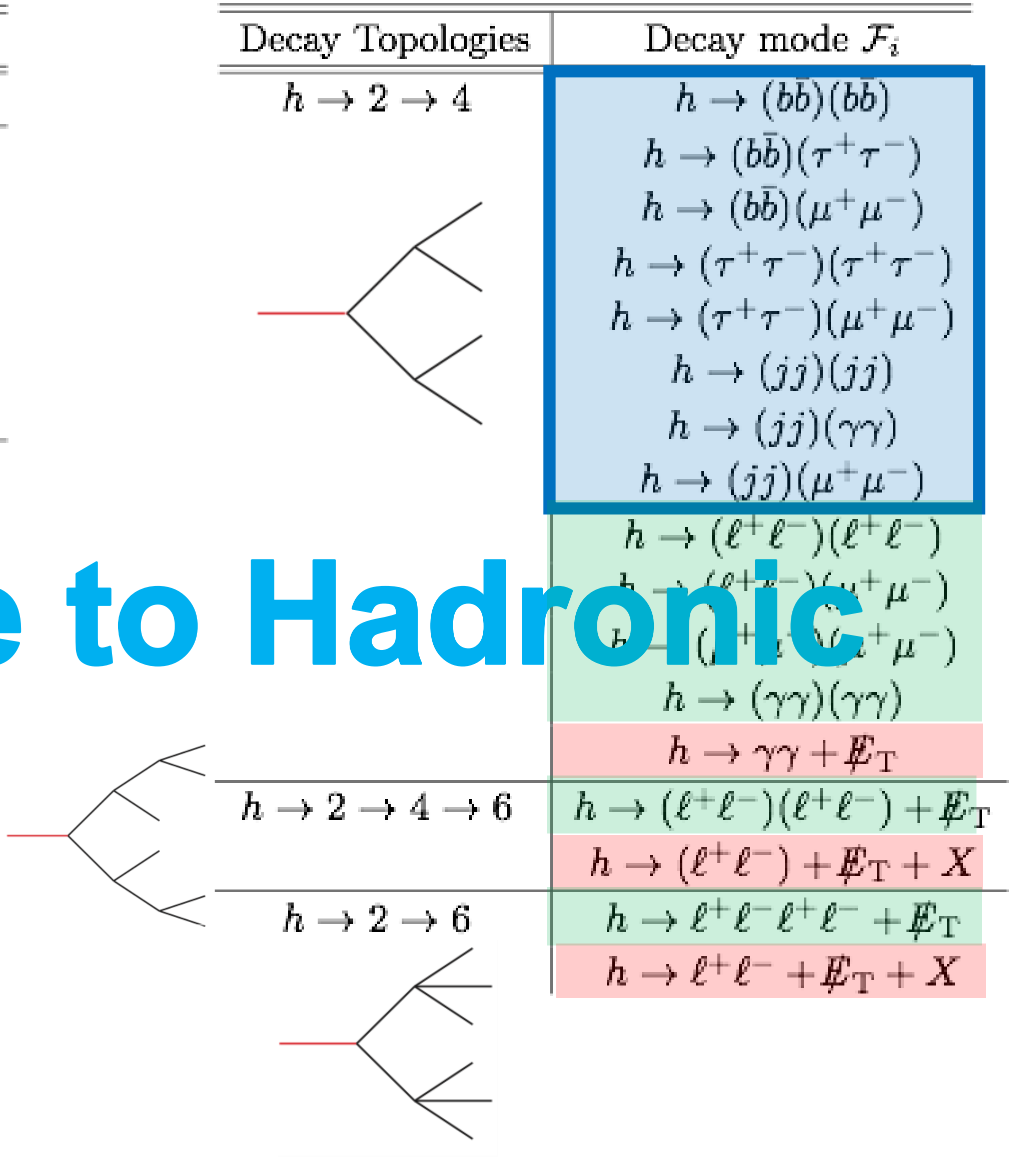
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}} + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}$ $h \to \ell^+\ell^- + \not{E}_{\mathrm{T}} + X$

Hard due to MET

Coverage & Potential



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_{\mathrm{T}}$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_{\mathrm{T}}$ $h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$ $h \to (jj) + \not{E}_{\mathrm{T}}$ $h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$ $h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$ $h \to (jj) + \not{E}_{\mathrm{T}}$ $h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$ $h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$ $h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$ $h \to (\mu^+\mu^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$ $h \to jj + \not{E}_{\mathrm{T}}$ $h \to \tau^+\tau^- + \not{E}_{\mathrm{T}}$ $h \to \gamma\gamma + \not{E}_{\mathrm{T}}$ $h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
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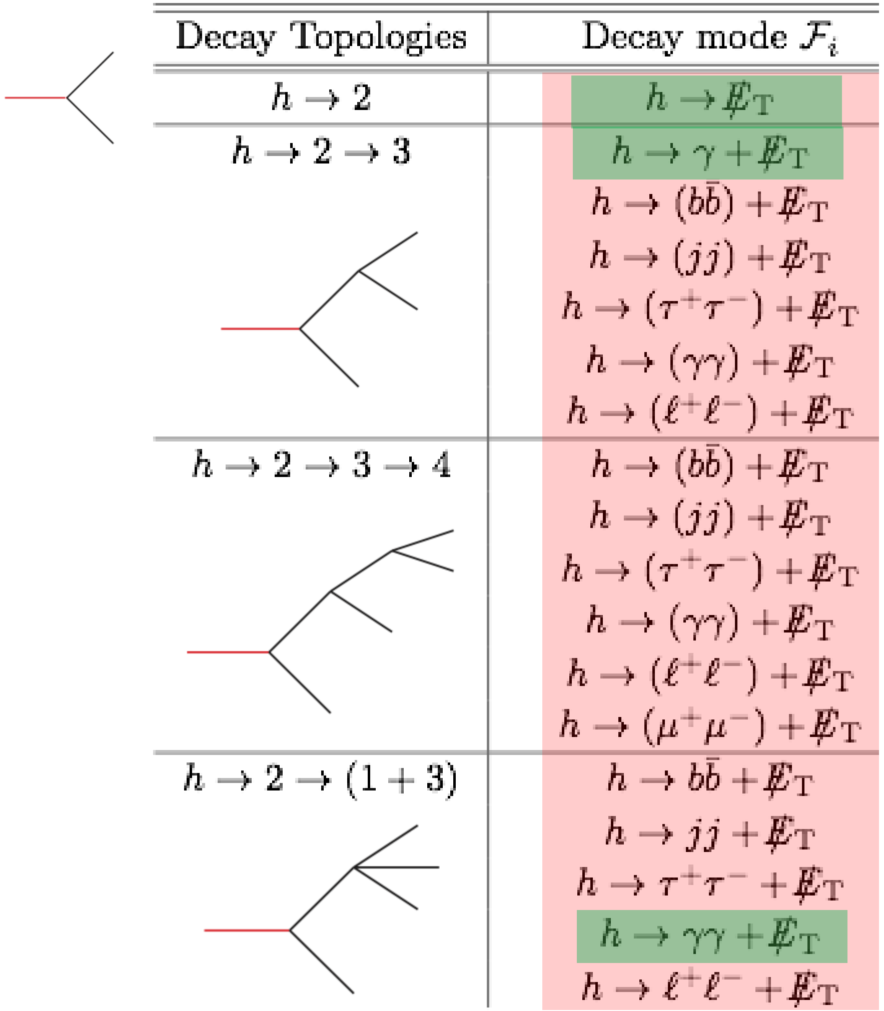
Hard due to Hadronic

Coverage & Potential



Decay Topologies	Decay mode $\mathcal{F}_i$
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$h \to 2 \to 3$	$h \to \gamma + \not{E}_{\mathrm{T}}$
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	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
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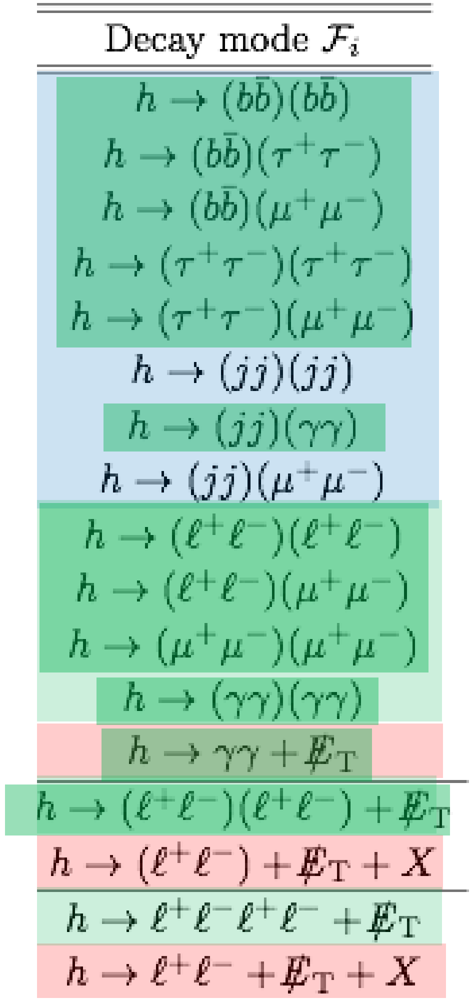
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$

Still a lot of uncharted territory for new searches!

Can be conquered using upcoming LHC runs with advanced **analysis tools** and **new detectors**.

For existing searches, there are new possibilities such as unequal masses, etc.



Decay mode $\mathcal{F}_i$
$h \to (b\bar{b})(b\bar{b})$
$h \to (b\bar{b})(\tau^+\tau^-)$
$h \to (b\bar{b})(\mu^+\mu^-)$
$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
$h \to (jj)(jj)$
$h \to (jj)(\gamma\gamma)$
$h \to (jj)(\mu^+\mu^-)$
$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
$h \to (\gamma\gamma)(\gamma\gamma)$
$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
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$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}} + X$
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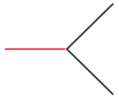
For a comparative study with future colliders, see ZL, L.-T. Wang, H. Zhang, 1612.09284

Coverage & Potential



Decay Topologies	Decay mode $\mathcal{F}_i$
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Still a lot of uncharted territory for

Decay mode $\mathcal{F}_i$
$h \to (b\bar{b})(b\bar{b})$
$h \to (b\bar{b})(\tau^+\tau^-)$
$h \to (b\bar{b})(\mu^+\mu^-)$

- Upcoming LHC runs will push our knowledge of the Higgs boson rare and exotic decays to new territory by an order of magnitude or more; A lot of new search channels to be covered, especially those with missing energy;
- Will achieve some very interesting benchmarks with the improved precision, e.g., probing Higgs decays to mesons, providing non-trivial tests to SM, QCD, and interferences;
- Higgs CPV, Flavor-violating, (a zoo of) Long-lived signatures to be explored (see many talks in this workshop);
- Higgs rare decays such as diphoton, dimuon and gluon-fusion rate are competitive when compared with future lepton collider Higgs factories.

For a comparative study with future colliders, see ZL, L.-T. Wang, H. Zhang, 1612.09284

High Energy Diboson processes as probes

Heavy Higgs portal to SUSY sectors

Big Questions➔ Big Opportunities

1. Fundamental or composite?
2. SUSY?
3. Neutral Naturalness & Beyond?
4. Electroweak Phase Transition?
5. Higgs portal?

Higgs decays to Long-lived particles

HH resonance
Higgs exotic decays

Higgs exotic decays & rare decays

High Energy Diboson processes as probes

Heavy Higgs portal to SUSY sectors

Higgs decays to Long-lived particles

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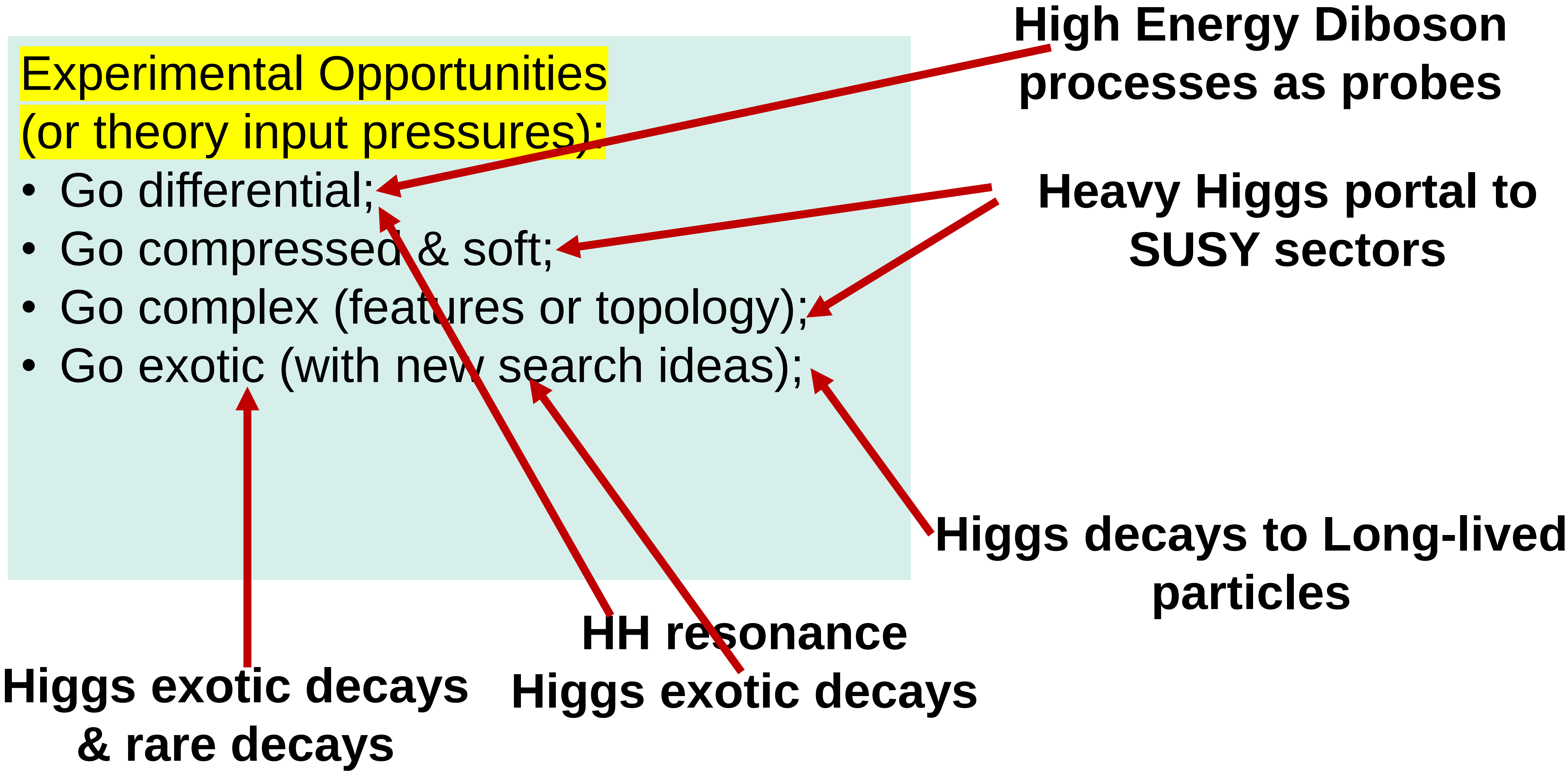
Higgs exotic decays & rare decays



Experimental Opportunities (or theory input pressures):

- Go differential;
- Go compressed & soft;
- Go complex (features or topology);
- Go exotic (with new search ideas);

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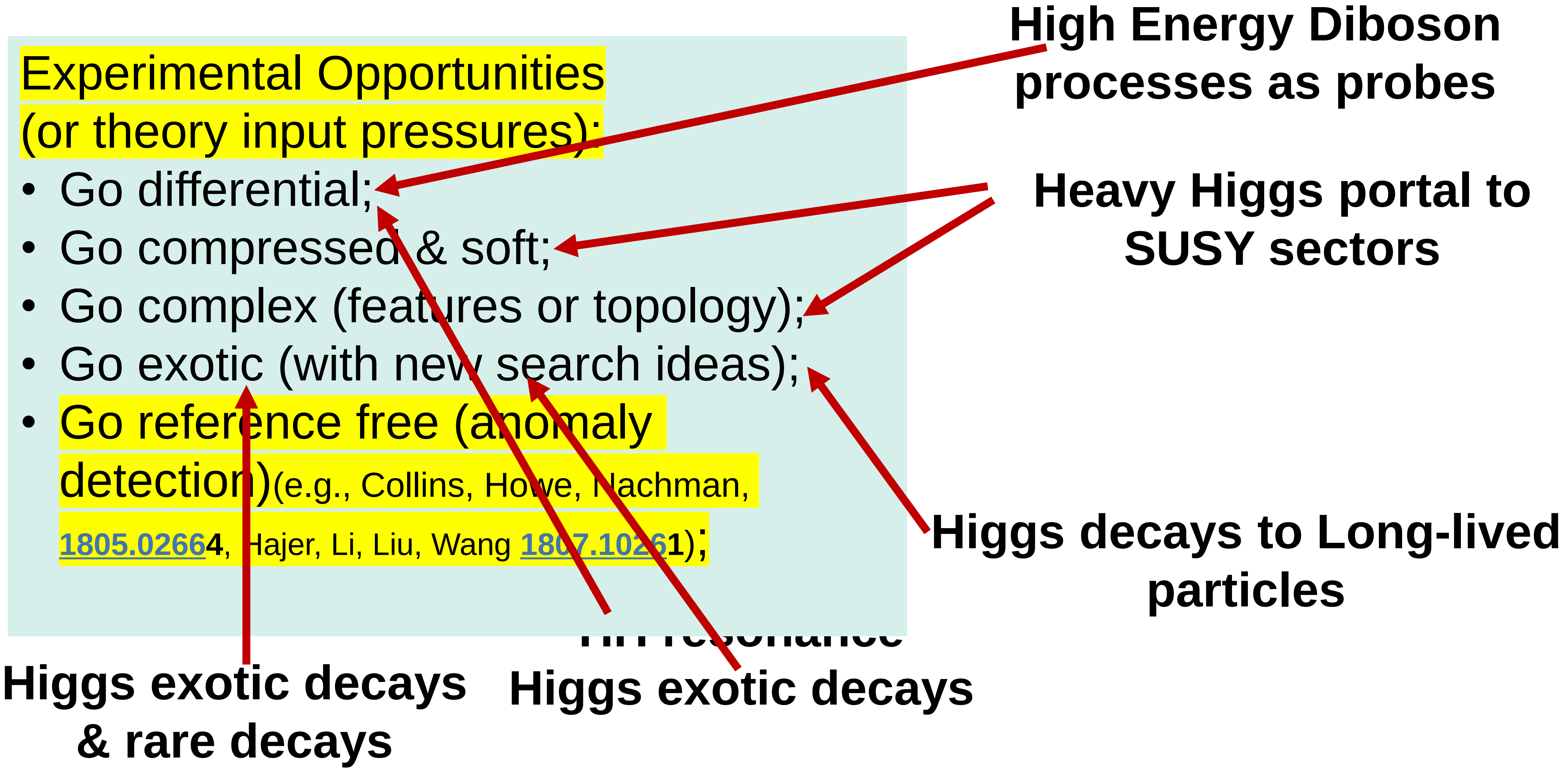
Higgs exotic decays & rare decays



Experimental Opportunities (or theory input pressures):

- Go differential;
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- Go reference free (anomaly detection)(e.g., Collins, Howe, Nachman, [1805.02664](1805.02664), Hajer, Li, Liu, Wang [1807.10261](1807.10261));

High Energy Diboson processes as probes

Heavy Higgs portal to SUSY sectors

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Machine Learning can help handle (see B. Nachman's talk next) and Hardware (upgrades, triggers) are crucial for some of these challenging tasks (see Arial Schwartzmann, S. Pagan Griso, L. Tompkins et al's discussion)

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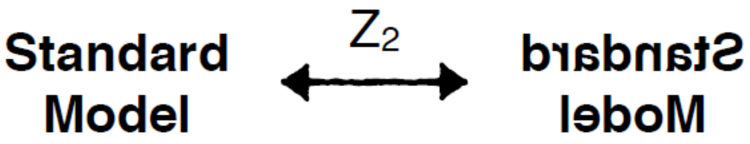
Looking forward to the presentations and discussions at this workshop!

Thank you!

Machine Learning can help handle (see B. Nachman's talk next) and Hardware (upgrades, triggers) are crucial for some of these challenging tasks (see Arial Schwartzmann, S. Pagan Griso, L. Tompkins et al's discussion)

Neutral Naturalness

The original: Twin Higgs [Chacko, Goh, Harnik '05]

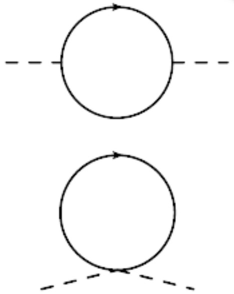


Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \dots\right)\left(|H_A|^2 + |H_B|^2\right)$$

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

$$\mathcal{L} \supset -y_t \underset{\substack{\downarrow \\ h+\dots}}{H_A} Q_3^A \bar{u}_3^A - y_t \underset{\substack{\downarrow \\ f-\frac{h^2}{2f}+\dots}}{H_B} Q_3^B \bar{u}_3^B$$



From N. Craig's Naturalness talk at DPF meeting 2017

Sketching the interference

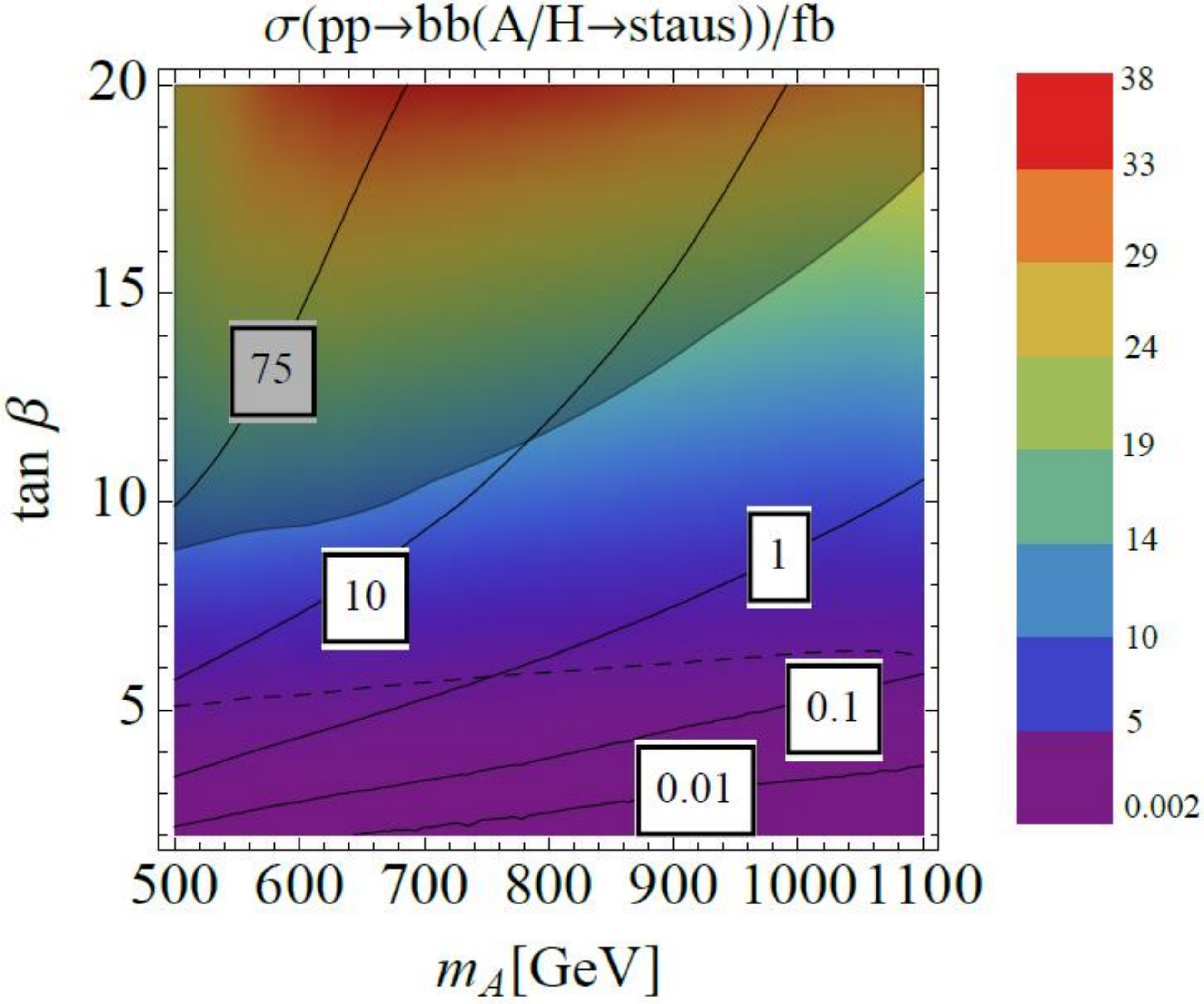
Remarks on strong v.s. weak phase

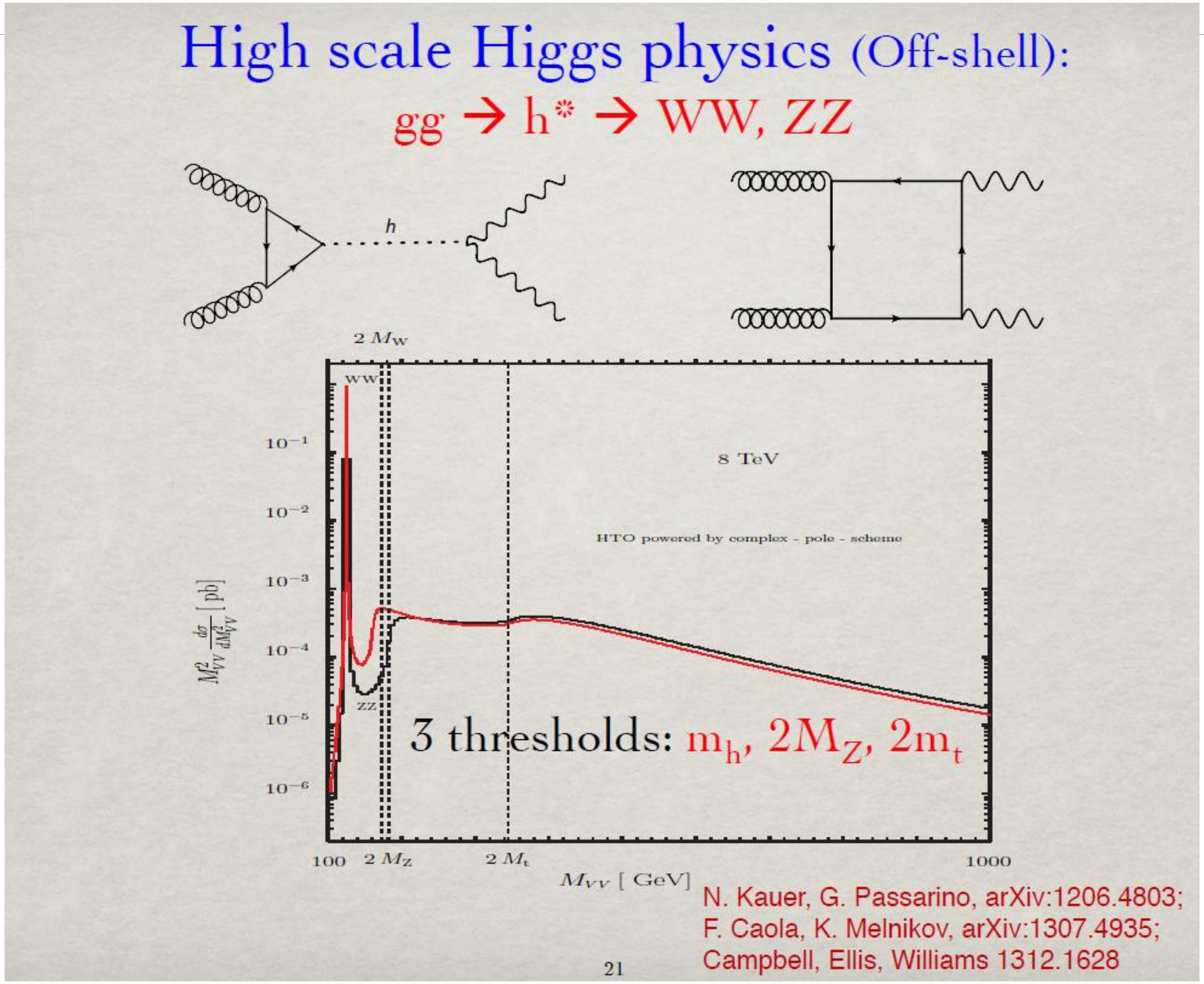
$$A_+ = |A_+|e^{i(\delta+\theta_{CP}/2)}$$
$$A_- = |A_+|e^{i(\delta-\theta_{CP}/2)}$$

$$Im[c_{sig}c_{bkg}^*] = |\mathrm{c}_{\mathrm{sig}}||\mathrm{c}_{\mathrm{bkg}}^*|\sin(\delta_{sig} - \delta_{bkg})$$

For neutral process, without construction of CP-order observables, the rate will be affected in a factorized way:

$$2Im\left[\left(c_{sig}^{+} + c_{sig}^{-}\right)c_{bkg}\right]Im[P(\hat{s})]$$
$$= 2\left|c_{sig}^{+}\right|Im[P(\hat{s})]\,\{\sin\left(\delta_{sig} + \frac{\theta_{CP}}{2} - \delta_{bkg}\right) + \sin\left(\delta_{sig} - \frac{\theta_{CP}}{2} - \delta_{bkg}\right)\}$$
$$= 4\left|c_{sig}^{+}\right|Im[P(\hat{s})]\,\sin\left(\delta_{sig} - \delta_{bkg}\right)\cos(\frac{\theta_{CP}}{2})$$


σ(pp→bb(A/H→staus))/fb
tan β
m_A[GeV]
20
15
10
5
500
600
700
800
900
1000
1100
75
10
1
0.1
0.01
38
33
29
24
19
14
10
5
0.002



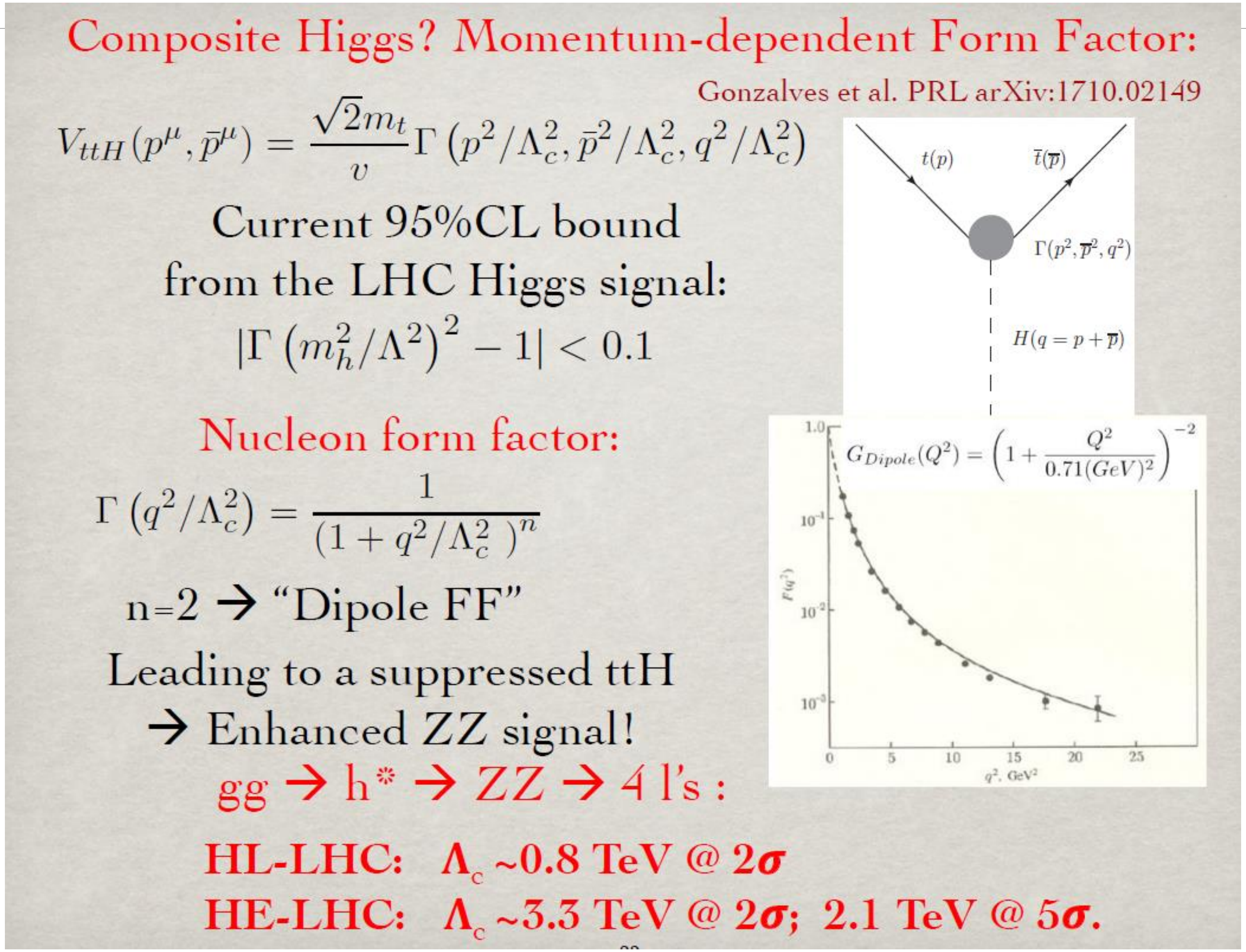
High scale Higgs physics (Off-shell):

gg → h^* → WW, ZZ

3 thresholds: m_h, $2M_Z$, $2m_t$

N. Kauer, G. Passarino, arXiv:1206.4803;
F. Caola, K. Melnikov, arXiv:1307.4935;
Campbell, Ellis, Williams 1312.1628

21



Composite Higgs? Momentum-dependent Form Factor:

Gonzalves et al. PRL arXiv:1710.02149

$$V_{ttH}(p^\mu, \bar{p}^\mu) = \frac{\sqrt{2}m_t}{v}\Gamma\left(p^2/\Lambda_c^2, \bar{p}^2/\Lambda_c^2, q^2/\Lambda_c^2\right)$$

Current 95%CL bound
from the LHC Higgs signal:

$$\left|\Gamma\left(m_h^2/\Lambda^2\right)^2 - 1\right| < 0.1$$

Nucleon form factor:

$$\Gamma\left(q^2/\Lambda_c^2\right) = \frac{1}{(1 + q^2/\Lambda_c^2\ )^n}$$

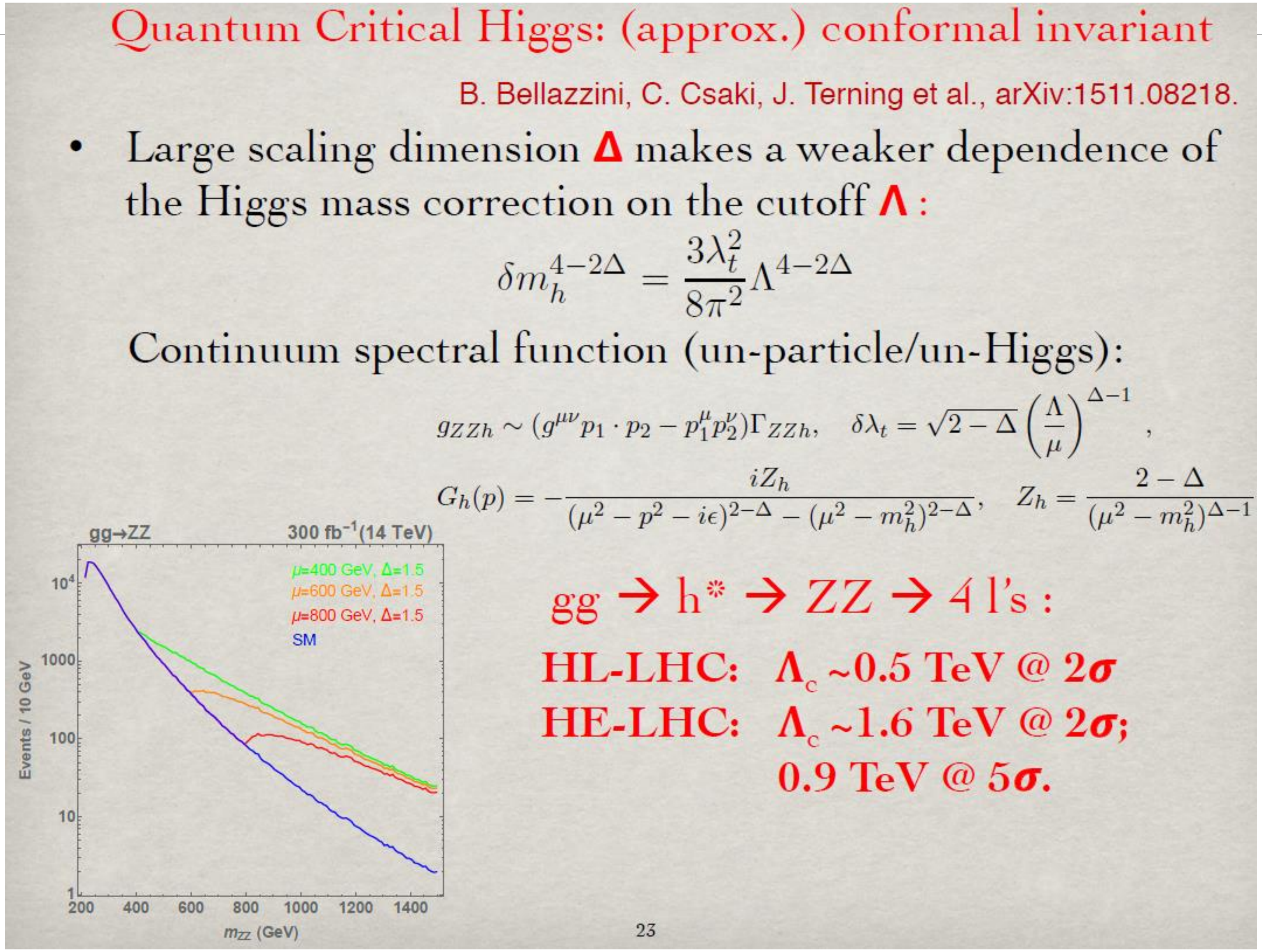
$$G_{Dipole}(Q^2) = \left(1 + \frac{Q^2}{0.71(GeV)^2}\right)^{-2}$$

n=2 → "Dipole FF"

Leading to a suppressed ttH
→ Enhanced ZZ signal!

gg → h* → ZZ → 4 l's :

HL-LHC: Λ_c ~0.8 TeV @ 2σ
HE-LHC: Λ_c ~3.3 TeV @ 2σ; 2.1 TeV @ 5σ.



Quantum Critical Higgs: (approx.) conformal invariant

B. Bellazzini, C. Csaki, J. Terning et al., arXiv:1511.08218.

- Large scaling dimension **Δ** makes a weaker dependence of the Higgs mass correction on the cutoff **Λ** :

$$\delta m_h^{4-2\Delta} = \frac{3\lambda_t^2}{8\pi^2}\Lambda^{4-2\Delta}$$

Continuum spectral function (un-particle/un-Higgs):

$$g_{ZZh} \sim (g^{\mu\nu} p_1 \cdot p_2 - p_1^\mu p_2^\nu)\Gamma_{ZZh}, \quad \delta\lambda_t = \sqrt{2-\Delta}\left(\frac{\Lambda}{\mu}\right)^{\Delta-1},$$

$$G_h(p) = -\frac{iZ_h}{(\mu^2 - p^2 - i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}, \quad Z_h = \frac{2-\Delta}{(\mu^2 - m_h^2)^{\Delta-1}}$$

gg → h* → ZZ → 4 l's :

HL-LHC: Λ_c ~0.5 TeV @ 2σ

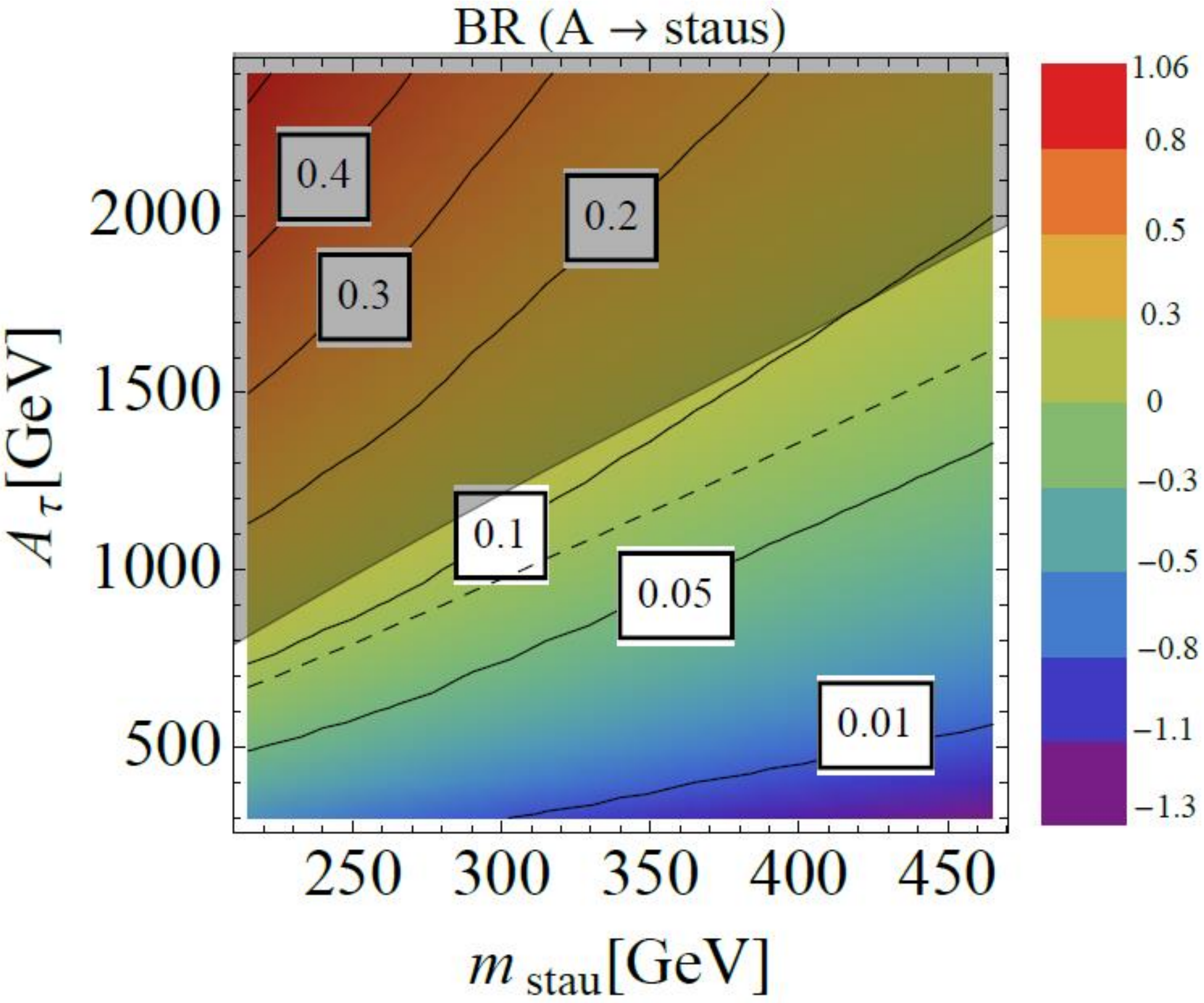
HE-LHC: Λ_c ~1.6 TeV @ 2σ;

0.9 TeV @ 5σ.

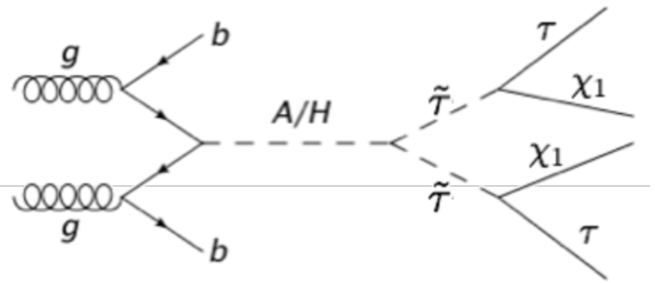
23

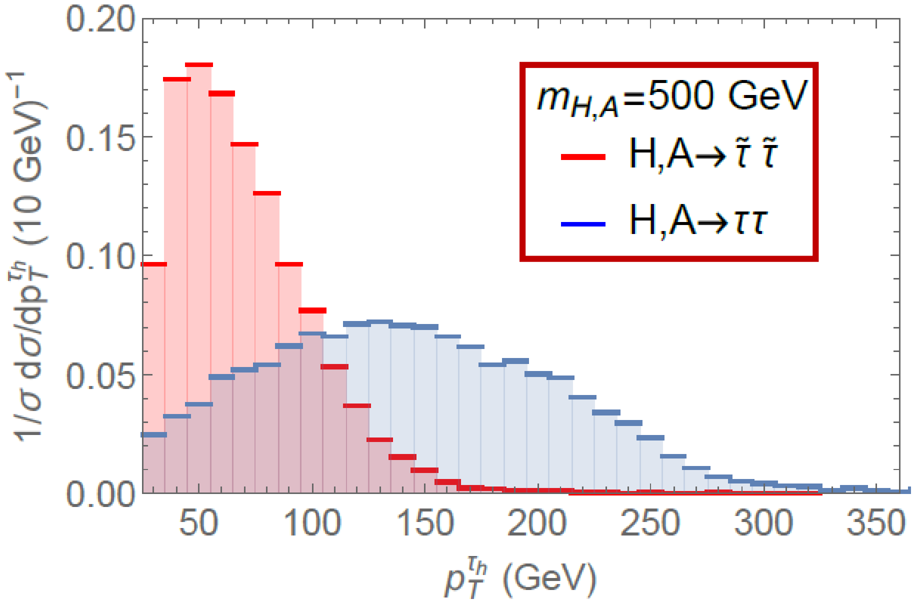
Stau parameter dependence

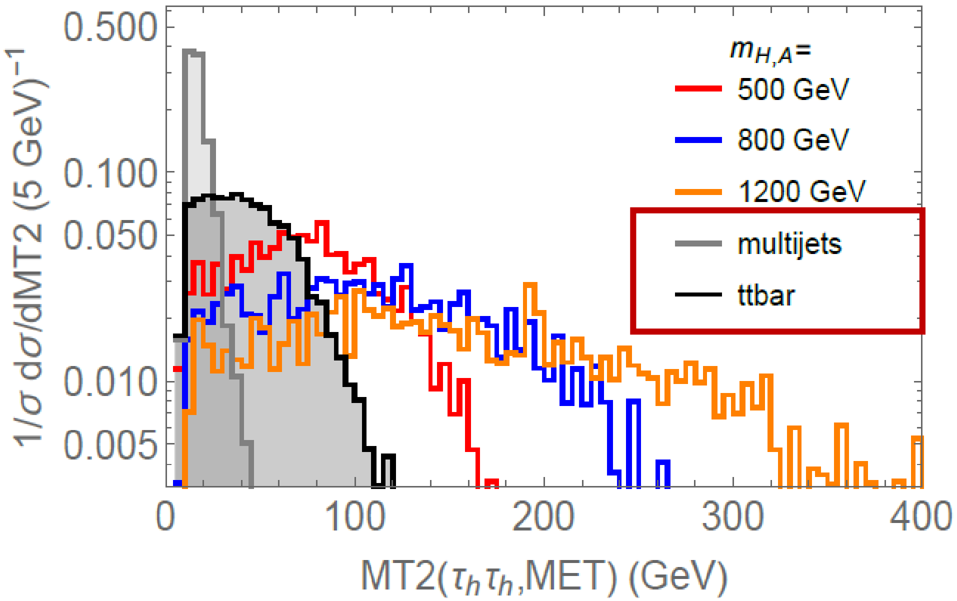
- Trilinear Soft SUSY breaking parameter dependence;
- Shaded region: charge breaking vacuum;
- Dashed lines,
    - larger than A->tautau



Kinematic features







Due to additional decay chain, in comparison with standard H->tautau:

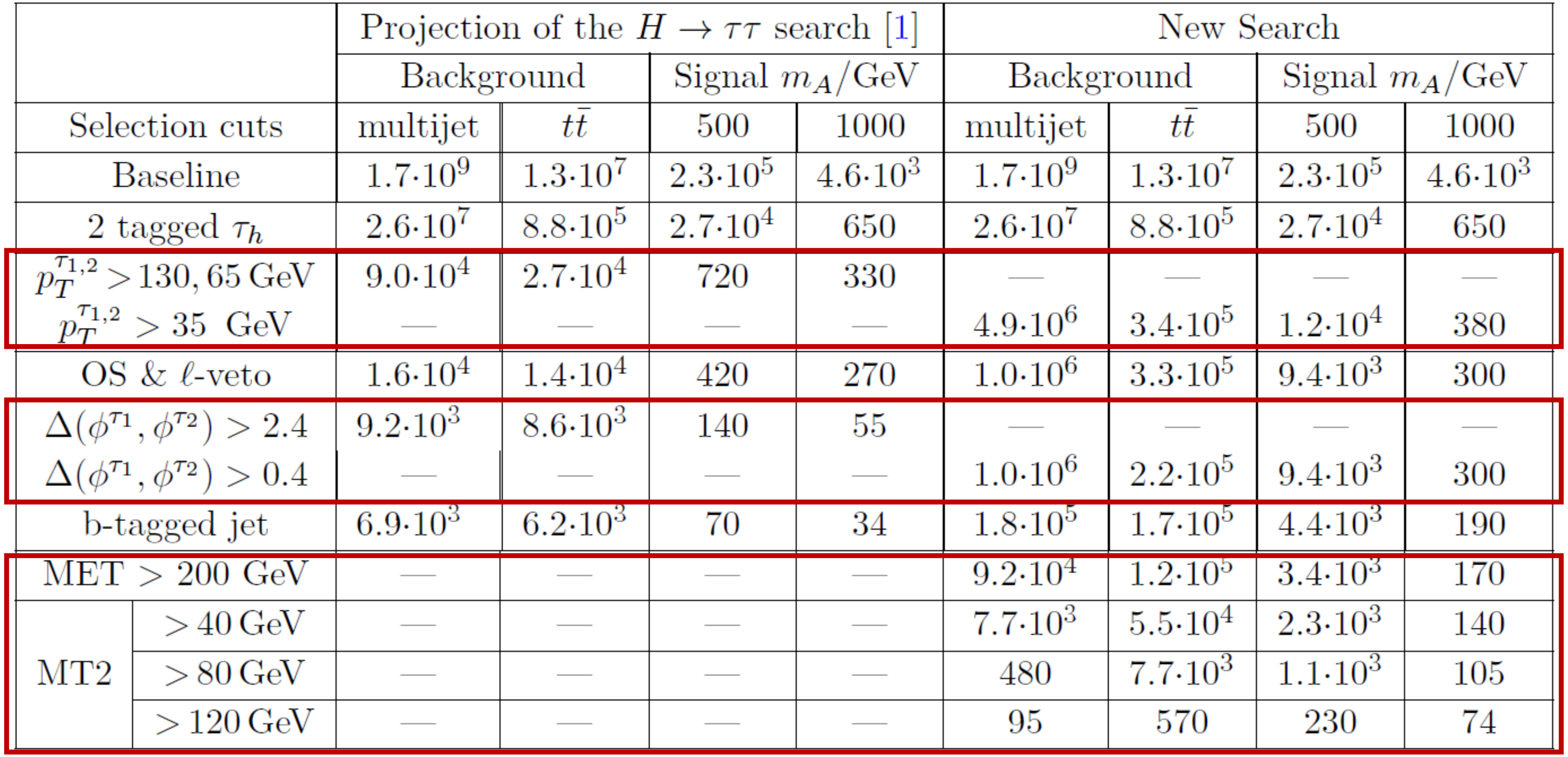
Tau leptons are softer, Additional MT2

In comparison with standard stau pair production:

Additional associated b jets; Harder taus from resonances decay

We recasted H->tautau analysis in four signal regions, finding hadronic taus with additional b-jet most sensitive

New search

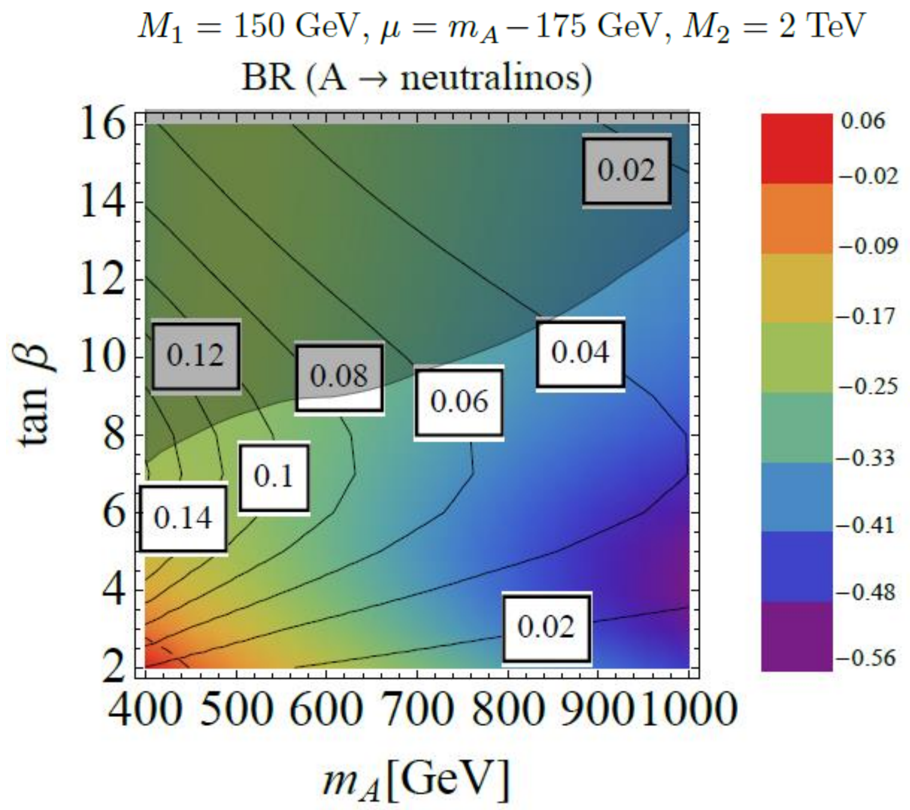


	Projection of the $H \to \tau\tau$ search [1]				New Search			
	Background		Signal m_A/GeV		Background		Signal m_A/GeV	
Selection cuts	multijet	$t\bar{t}$	500	1000	multijet	$t\bar{t}$	500	1000
Baseline	$1.7{\cdot}10^9$	$1.3{\cdot}10^7$	$2.3{\cdot}10^5$	$4.6{\cdot}10^3$	$1.7{\cdot}10^9$	$1.3{\cdot}10^7$	$2.3{\cdot}10^5$	$4.6{\cdot}10^3$
2 tagged τ_h	$2.6{\cdot}10^7$	$8.8{\cdot}10^5$	$2.7{\cdot}10^4$	650	$2.6{\cdot}10^7$	$8.8{\cdot}10^5$	$2.7{\cdot}10^4$	650
$p_T^{\tau_{1,2}} > 130, 65$ GeV	$9.0{\cdot}10^4$	$2.7{\cdot}10^4$	720	330	—	—	—	—
$p_T^{\tau_{1,2}} > 35$ GeV	—	—	—	—	$4.9{\cdot}10^6$	$3.4{\cdot}10^5$	$1.2{\cdot}10^4$	380
OS & ℓ-veto	$1.6{\cdot}10^4$	$1.4{\cdot}10^4$	420	270	$1.0{\cdot}10^6$	$3.3{\cdot}10^5$	$9.4{\cdot}10^3$	300
$\Delta(\phi^{\tau_1}, \phi^{\tau_2}) > 2.4$	$9.2{\cdot}10^3$	$8.6{\cdot}10^3$	140	55	—	—	—	—
$\Delta(\phi^{\tau_1}, \phi^{\tau_2}) > 0.4$	—	—	—	—	$1.0{\cdot}10^6$	$2.2{\cdot}10^5$	$9.4{\cdot}10^3$	300
b-tagged jet	$6.9{\cdot}10^3$	$6.2{\cdot}10^3$	70	34	$1.8{\cdot}10^5$	$1.7{\cdot}10^5$	$4.4{\cdot}10^3$	190
MET > 200 GeV	—	—	—	—	$9.2{\cdot}10^4$	$1.2{\cdot}10^5$	$3.4{\cdot}10^3$	170
MT2 > 40 GeV	—	—	—	—	$7.7{\cdot}10^3$	$5.5{\cdot}10^4$	$2.3{\cdot}10^3$	140
> 80 GeV	—	—	—	—	480	$7.7{\cdot}10^3$	$1.1{\cdot}10^3$	105
> 120 GeV	—	—	—	—	95	570	230	74

$$g_{H\chi_i\chi_j} = \frac{g'}{2} Z_{i1}(Z_{j3}\sin\beta + Z_{j4}\cos\beta) + (i \leftrightarrow j)$$

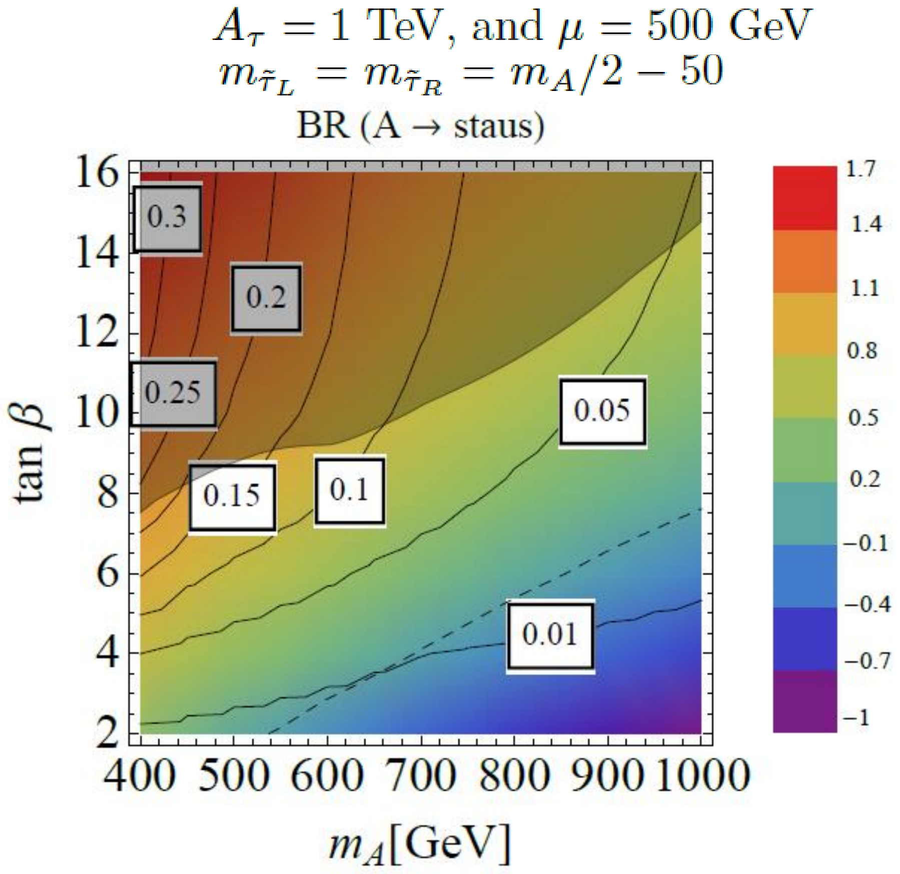
$$g_{A\chi_i\chi_j} = \frac{g'}{2} Z_{i1}(Z_{j3}\sin\beta - Z_{j4}\cos\beta) + (i \leftrightarrow j).$$

Branching fractions



$M_1 = 150$ GeV, $\mu = m_A - 175$ GeV, $M_2 = 2$ TeV

BR (A → neutralinos)



$A_\tau = 1$ TeV, and $\mu = 500$ GeV

$m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = m_A/2 - 50$

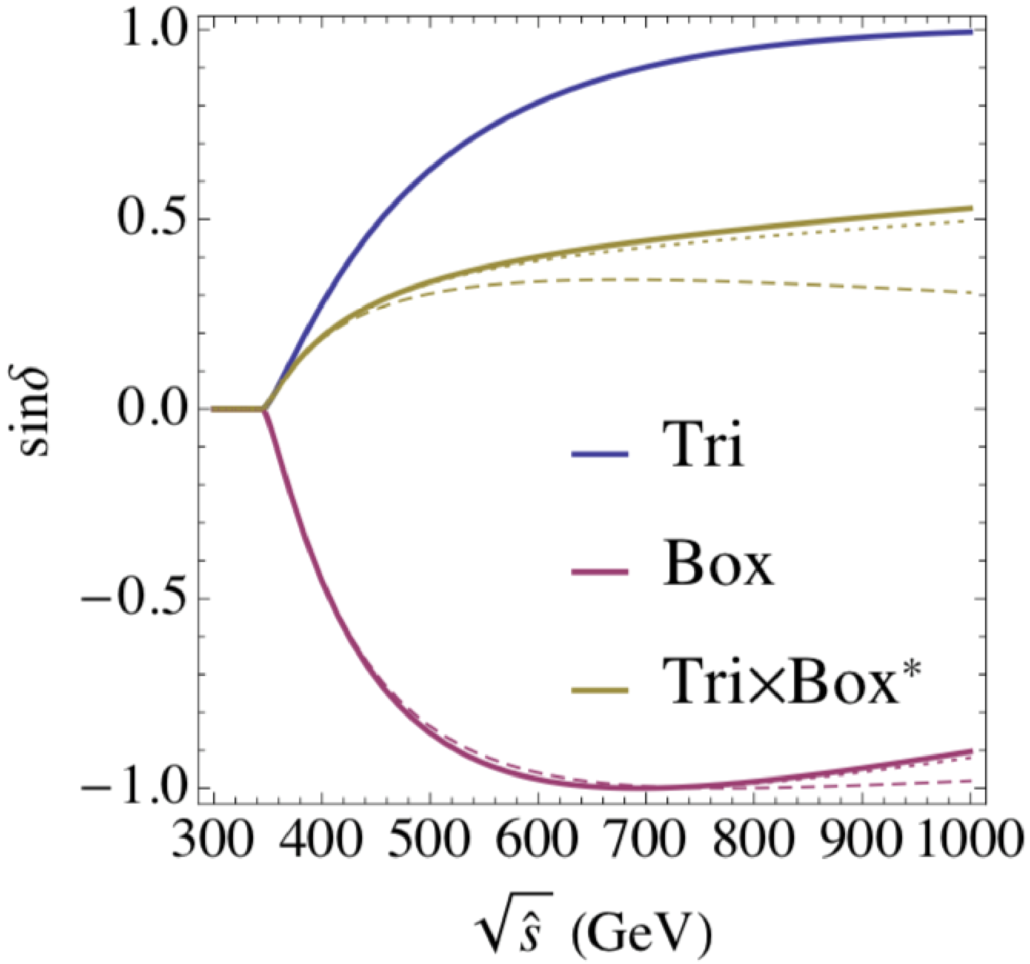
BR (A → staus)

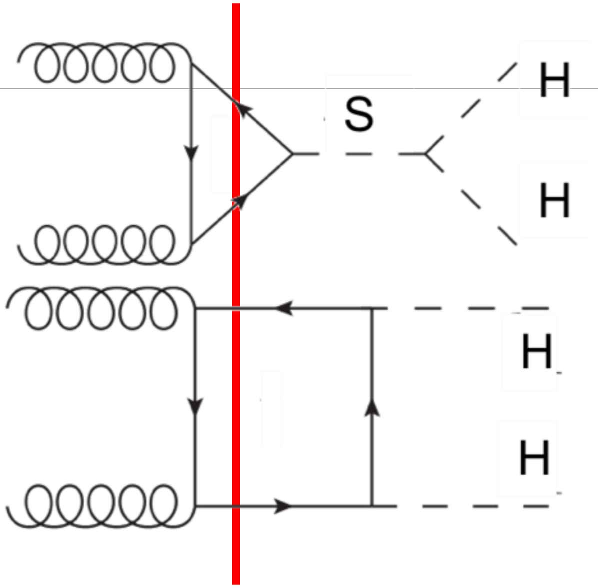
Mass and tan\beta dependence;

In general one can achieve O(1~10%) in the region of interests.

S. Gori, ZL, B. Shakya, 1811.11918

Strong Phases





Solid/Dotted/Dashed, scattering angle of 0/0.5/1;

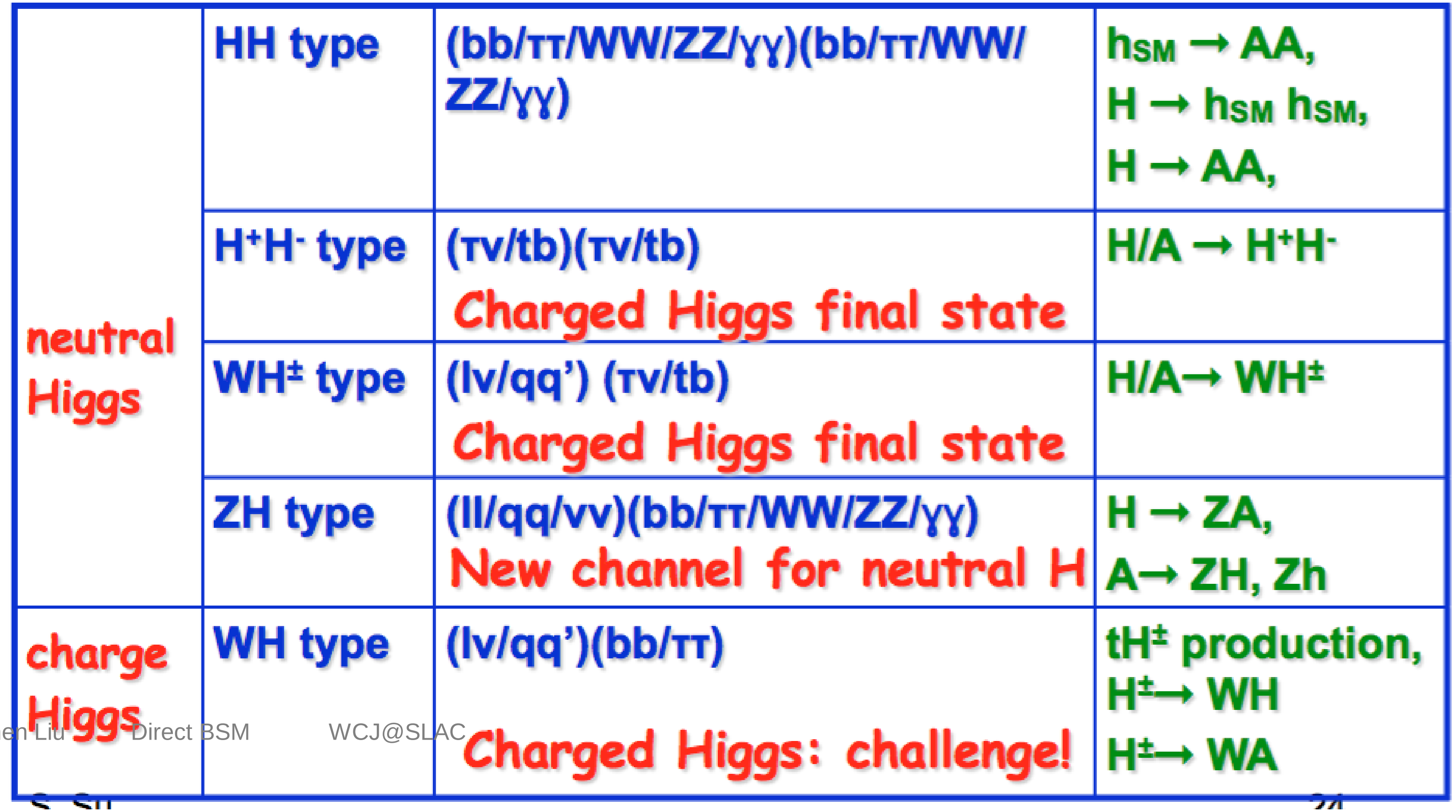
- Blue: the phase of the triangle diagram;
- Magenta: the phase of the box diagram;
- Yellow: the relative phase between them;

The consequent on-shell interference does not vanish in the narrow width limit!

M. Carena, ZL, M. Riembau, 1801.00794

Heavy Higgs (alignment) into bosons
--Suggested Figures

Heavy Higgs exotic decays (Shufang’s works, with her slides in this folder)



neutral Higgs	HH type	(bb/ττ/WW/ZZ/γγ)(bb/ττ/WW/ZZ/γγ)	h_{SM} → AA, H → h_{SM} h_{SM}, H → AA,
	H^+H^- type	(τv/tb)(τv/tb) Charged Higgs final state	H/A → H^+H^-
	$WH^\pm$ type	(lv/qq’) (τv/tb) Charged Higgs final state	H/A→ $WH^\pm$
	ZH type	(ll/qq/vv)(bb/ττ/WW/ZZ/γγ) New channel for neutral H	H → ZA, A→ ZH, Zh
charge Higgs	WH type	(lv/qq’)(bb/ττ) Charged Higgs: challenge!	$tH^\pm$ production, $H^\pm$→ WH $H^\pm$→ WA

Heavy Higgs through

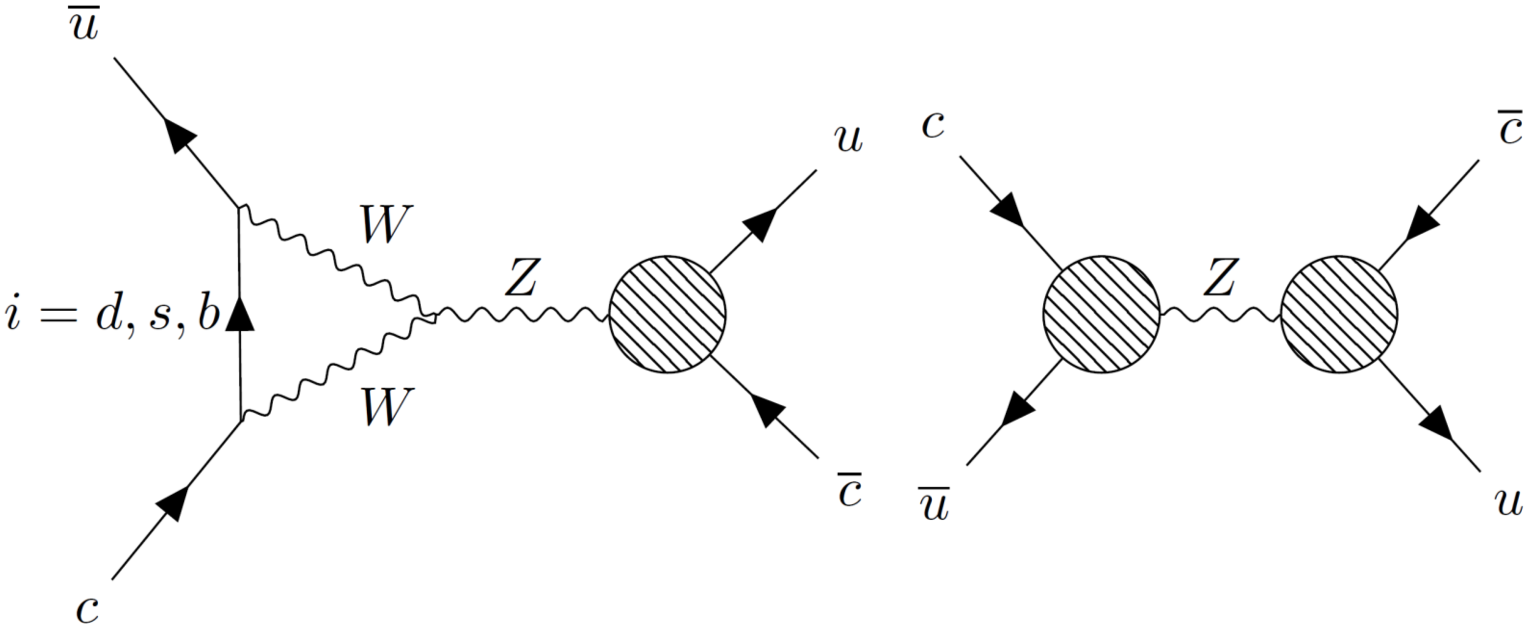
Heavy Higgs exotic decays (in NMSSM, more Higgs bosons available)

$$H_1 \to A_1A_1, \quad ZA_1,$$
$$H_2 \to A_1A_1, \quad ZA_1, \quad H_1H_1,$$
$$H_3 \to A_1A_1, \quad H_1H_1, \quad ZA_1, \quad W^\pm H^\mp, \quad A_1A_2, \quad H_1H_2, \quad H_2H_2, \quad H^+H^-$$
$$H^\pm \to W^\pm A_1, \quad W^\pm H_2, \quad W^\pm H_1,$$
$$A_1 \to ZH_1,$$
$$A_2 \to A_1H_1, \quad A_1H_2, \quad W^\pm H^\mp, \quad ZH_1, \quad ZH_2, \quad ZH_3, \quad A_1H_3,$$

N. Christensen, T. Han, Z. Liu, S. Su **arXiv:1303.2113**
also S. King, M. M¨uhlleitner, R. Nevzorov, K. Walz, **arXiv:1408.1120**
and CERN YR4

Constraints from flavor

- This type of model contributes to FCNCs, strongest constraint form D-Dbar mixing
- For $\Delta C = 2$, 2 classes of processes:



Constraints from flavor (cont.)

- Contributes to 2 different $\Delta C = 2$, $d = 6$ operators:

$$\bar{c}_L u_R \bar{c}_R u_L \text{ and } \bar{c}_R \gamma_\mu u_R \; \bar{c}_R \gamma^\mu u_R$$

- Parametrically, the corresponding Wilson coefficients are given by

$$\frac{1}{16\pi^2}\frac{v^2}{M_Z^2}\frac{M_b^2}{M_W^2}\frac{c_{Hu}}{\Lambda^2}|V_{ub}||V_{cb}|\left(U_{R,uu}^\dagger U_{R,uc}\right) \lesssim 1.6 \times 10^{-7}\left(\frac{1}{1\text{ TeV}}\right)^2$$

$$3\left|\frac{c_{Hu}}{\Lambda^2} v\left(U_{R,uu}^\dagger U_{R,uc}\right)\right|^2 \lesssim 5.7 \times 10^{-7}\left(\frac{1}{1\text{ TeV}}\right)^2$$

[1] O. Gedalia et al, 0906.1879

Constraints from flavor (cont.)

- Consider 2 generation universal theories

$$U^{\dagger}_{R,uu}U_{R,uc} \to U^{\dagger}_{R,uu}U_{R,uc} + U^{\dagger}_{R,uc}U_{R,cc} = -U^{\dagger}_{R,ut}U_{R,tc}$$

- Dominated by

$$\frac{\Delta\Gamma(Z \to c\bar{c})}{\Gamma(Z \to c\bar{c})} \approx 1.6\%$$

$$\to \frac{c_{Hu}}{\Lambda^2_{\text{TeV}}} \lesssim 0.163$$

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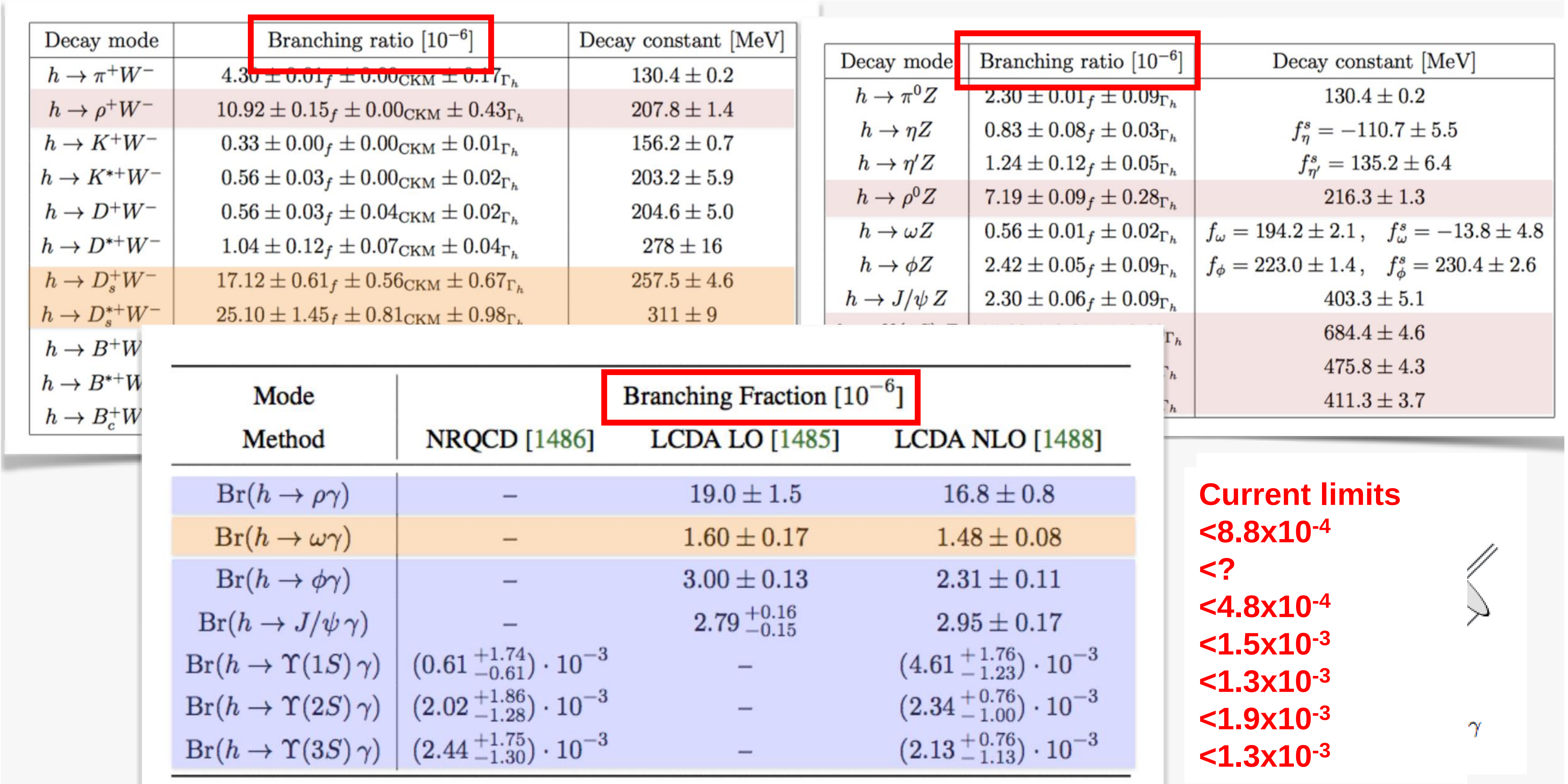
[1] PDG, Phys.Rev.D**98**, 030001

Higgs decays to mesons



Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^+ W^-$	$4.30 \pm 0.01_f \pm 0.00_{\text{CKM}} \pm 0.17_{\Gamma_h}$	130.4 ± 0.2
$h \to \rho^+ W^-$	$10.92 \pm 0.15_f \pm 0.00_{\text{CKM}} \pm 0.43_{\Gamma_h}$	207.8 ± 1.4
$h \to K^+ W^-$	$0.33 \pm 0.00_f \pm 0.00_{\text{CKM}} \pm 0.01_{\Gamma_h}$	156.2 ± 0.7
$h \to K^{*+} W^-$	$0.56 \pm 0.03_f \pm 0.00_{\text{CKM}} \pm 0.02_{\Gamma_h}$	203.2 ± 5.9
$h \to D^+ W^-$	$0.56 \pm 0.03_f \pm 0.04_{\text{CKM}} \pm 0.02_{\Gamma_h}$	204.6 ± 5.0
$h \to D^{*+} W^-$	$1.04 \pm 0.12_f \pm 0.07_{\text{CKM}} \pm 0.04_{\Gamma_h}$	278 ± 16
$h \to D_s^+ W^-$	$17.12 \pm 0.61_f \pm 0.56_{\text{CKM}} \pm 0.67_{\Gamma_h}$	257.5 ± 4.6
$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\text{CKM}} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		
$h \to B^{*+} W$		
$h \to B_c^+ W$		

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^0 Z$	$2.30 \pm 0.01_f \pm 0.09_{\Gamma_h}$	130.4 ± 0.2
$h \to \eta Z$	$0.83 \pm 0.08_f \pm 0.03_{\Gamma_h}$	$f_\eta^s = -110.7 \pm 5.5$
$h \to \eta' Z$	$1.24 \pm 0.12_f \pm 0.05_{\Gamma_h}$	$f_{\eta'}^s = 135.2 \pm 6.4$
$h \to \rho^0 Z$	$7.19 \pm 0.09_f \pm 0.28_{\Gamma_h}$	216.3 ± 1.3
$h \to \omega Z$	$0.56 \pm 0.01_f \pm 0.02_{\Gamma_h}$	$f_\omega = 194.2 \pm 2.1\,, \quad f_\omega^s = -13.8 \pm 4.8$
$h \to \phi Z$	$2.42 \pm 0.05_f \pm 0.09_{\Gamma_h}$	$f_\phi = 223.0 \pm 1.4\,, \quad f_\phi^s = 230.4 \pm 2.6$
$h \to J/\psi\, Z$	$2.30 \pm 0.06_f \pm 0.09_{\Gamma_h}$	403.3 ± 5.1
	Γ_h	684.4 ± 4.6
		475.8 ± 4.3
		411.3 ± 3.7

Mode Method	NRQCD [1486]	Branching Fraction $[10^{-6}]$ LCDA LO [1485]	LCDA NLO [1488]
$\text{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\text{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\text{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\text{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\text{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\text{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\text{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

Current limits

$<8.8\text{x}10^{-4}$

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$<4.8\text{x}10^{-4}$

$<1.5\text{x}10^{-3}$

$<1.3\text{x}10^{-3}$

$<1.9\text{x}10^{-3}$

$<1.3\text{x}10^{-3}$

From Exotic Higgs group report talk by Cécile Caillol, Mar. 2018

Higgs decays to mesons

- Results from 1607.03400, 1507.03031, 1501.03276, 1712.02758, 1507.03031
- Most results from 8 TeV puts an upper bound of ~1.5x10^{-3}
- 13 TeV 36 fb^{-1} start to lead us to realm of 10^{-4}
- Upcoming LHC runs will lead us to the realm of ~10^{-5} **
- We will be able to measure these these rare decays of the Higgs boson, providing very nontrivial test of the Higgs boson properties, QCD and interference
- Many new modes to measure H->mesons+W, mesons+Z, etc. (Study and recommendation ongoing)

$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\text{CKM}} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		

684.4 ± 4.6
475.8 ± 4.3

- HL will push our knowledge of the Higgs boson rare and exotic decays to new territory by an order of magnitude or more; A lot of new search channels to be covered, especially those with missing energy;
- Will achieve some very interesting benchmarks with the improved precision, e.g., probing Higgs decays to mesons, providing non-trivial tests to SM, QCD, and interferences;
- Higgs CPV, Flavor-violating, (a zoo of) Long-lived signatures to be explored (see many talks in this workshop);
- Higgs rare decays such as diphoton, dimuon and gluon-fusion rate are competitive when compared with future lepton collider Higgs factories.

Interferences in $gg \rightarrow S \rightarrow t\bar{t}$

$gg \rightarrow S \rightarrow t\bar{t}$ is a well—motivated channel for the hunt of heavy scalars
The interference effect augmented by the strong phase generated by the top loop generates interesting shapes. **(The effect is always there regardless of the width!)**

Opportunities to increase the observational aspects resides on both the theoretical side (including nearly degenerate bosons, CP phases, additional contributions form light quarks, and heavy colored particles) and experimental side (reducing the systematics with copious tops produced at the LHC, **starting to face this challenge by using line-shape profile search** ATLAS-2016-073**, and move on from there**.)

Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang **arXiv:1504.04630** and J. Hajer, Y.-Y. Li, T. Liu J. Shiu **arXiv:1504.07617**, S. Gori, I.-W. Kim, N. Shah, K. Zurek **arXiv:1602.02782** **,** N. Craig, J. Hajer, Y. Li, T. Liu, H. Zhang, **arXiv:1605.08744**, B. Hespel, F. Maltoni, E. Vryonidou **arXiv:1606.04149**),H+jet, charged Higgs searches, and how stable such effects are against QCD corrections (see a case study in W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer **arXiv:1511.05584**), ttbar differential observables (W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer **arXiv:1702.06063**). Also other decay channels may have such effect large (see in Jung, Sung, Yoon, **arXiv:1510.03450**, **arXiv:1601.00006**).

Interference effect is important for many BSM bump hunting, especially for the case of better and better limits. (as the relative strength of the interference pieces increases relatively to the B.W. piece.)