Higgs Physics at Hadron Colliders - from LHC to a 100 TeV Machine

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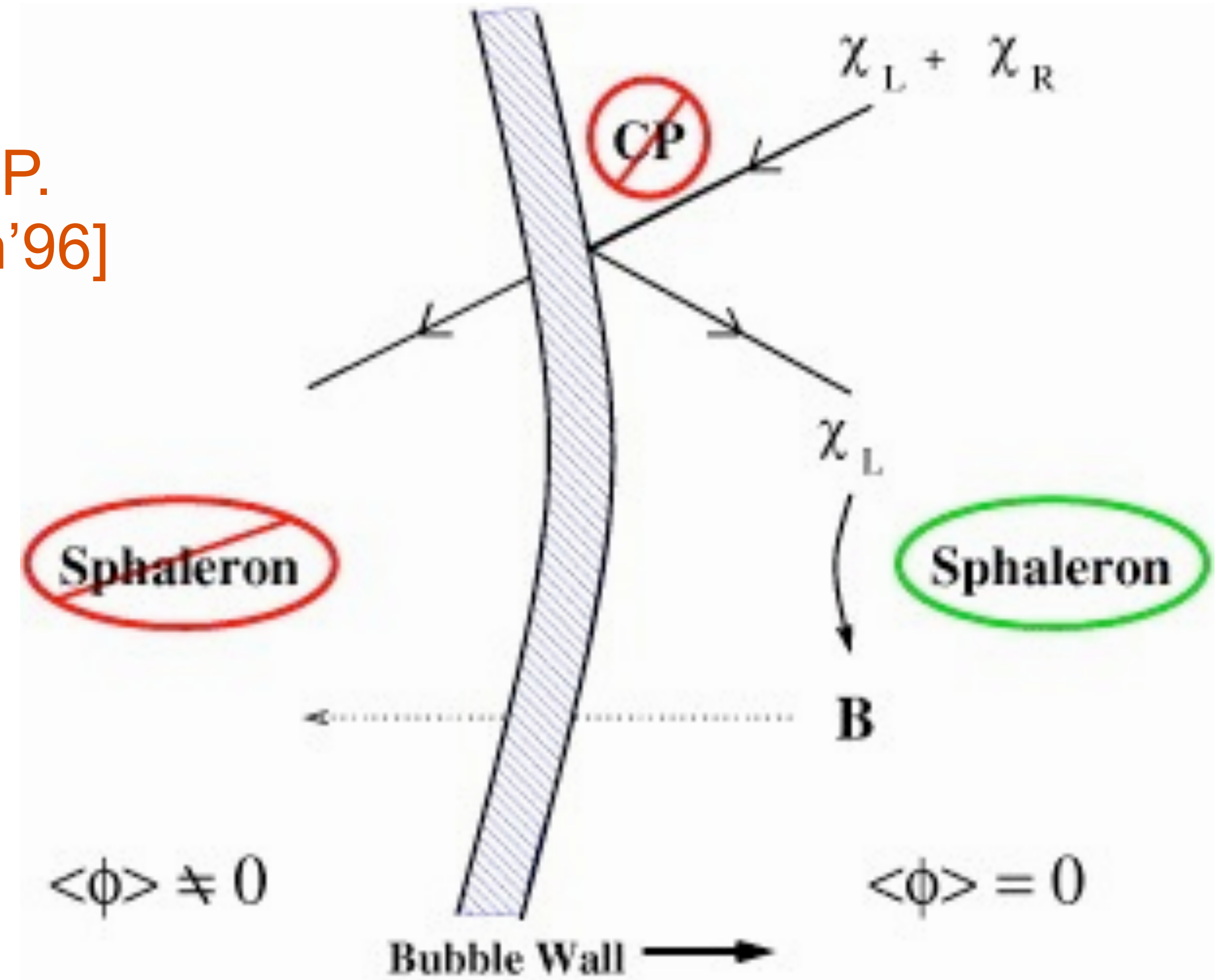
Where is New Physics?

“The world is full of things which nobody by any chance ever observes.”
- Sherlock Holmes

With the discovery of the 125GeV Higgs, how can the HL-LHC or a next-generation hadron collider assist us in exploring NP via Higgs measurements?

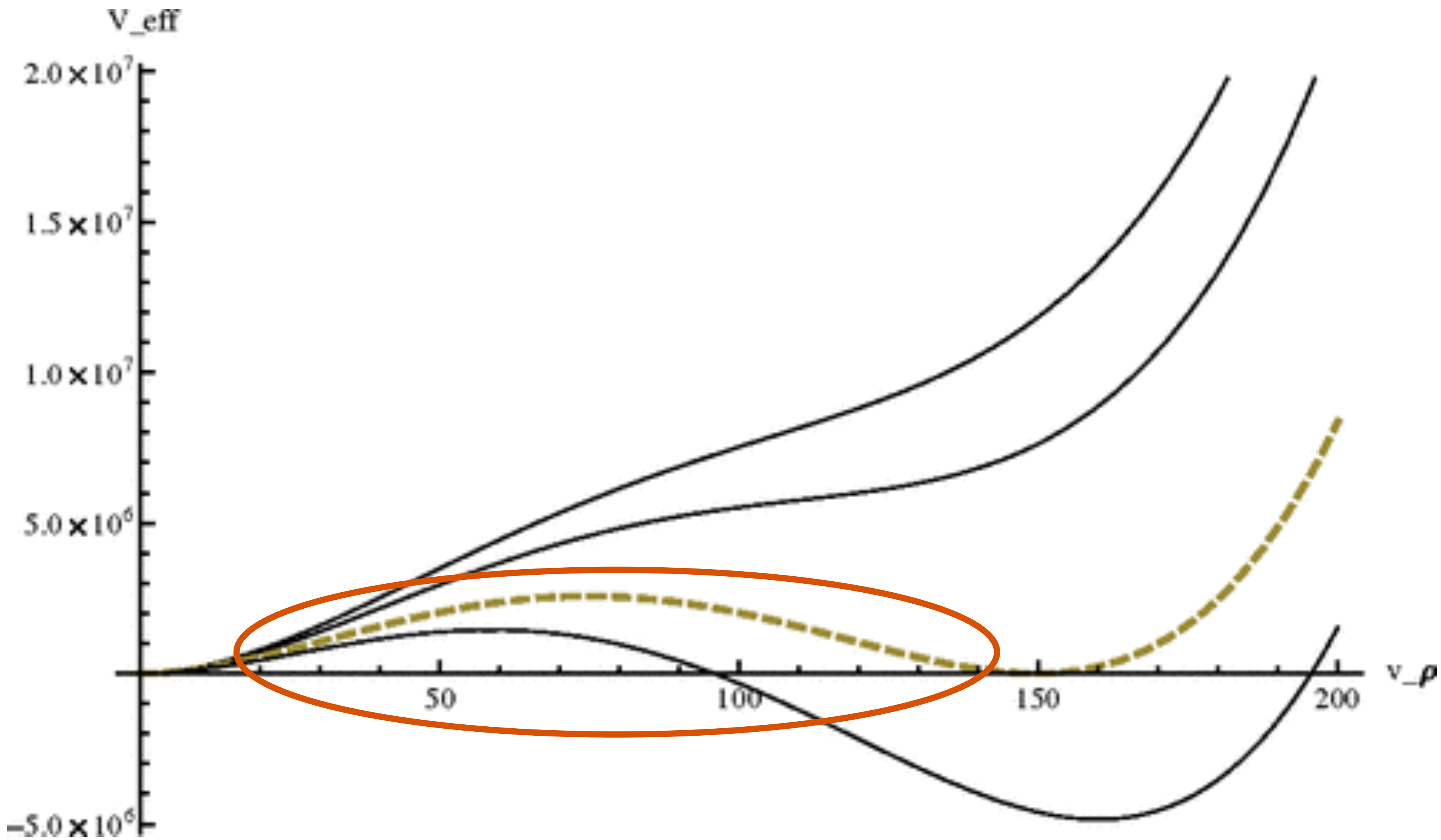
EW Baryogenesis and Higgs Physics

[A. Cohen et al'93, P. Huet and A. Nelson'96]



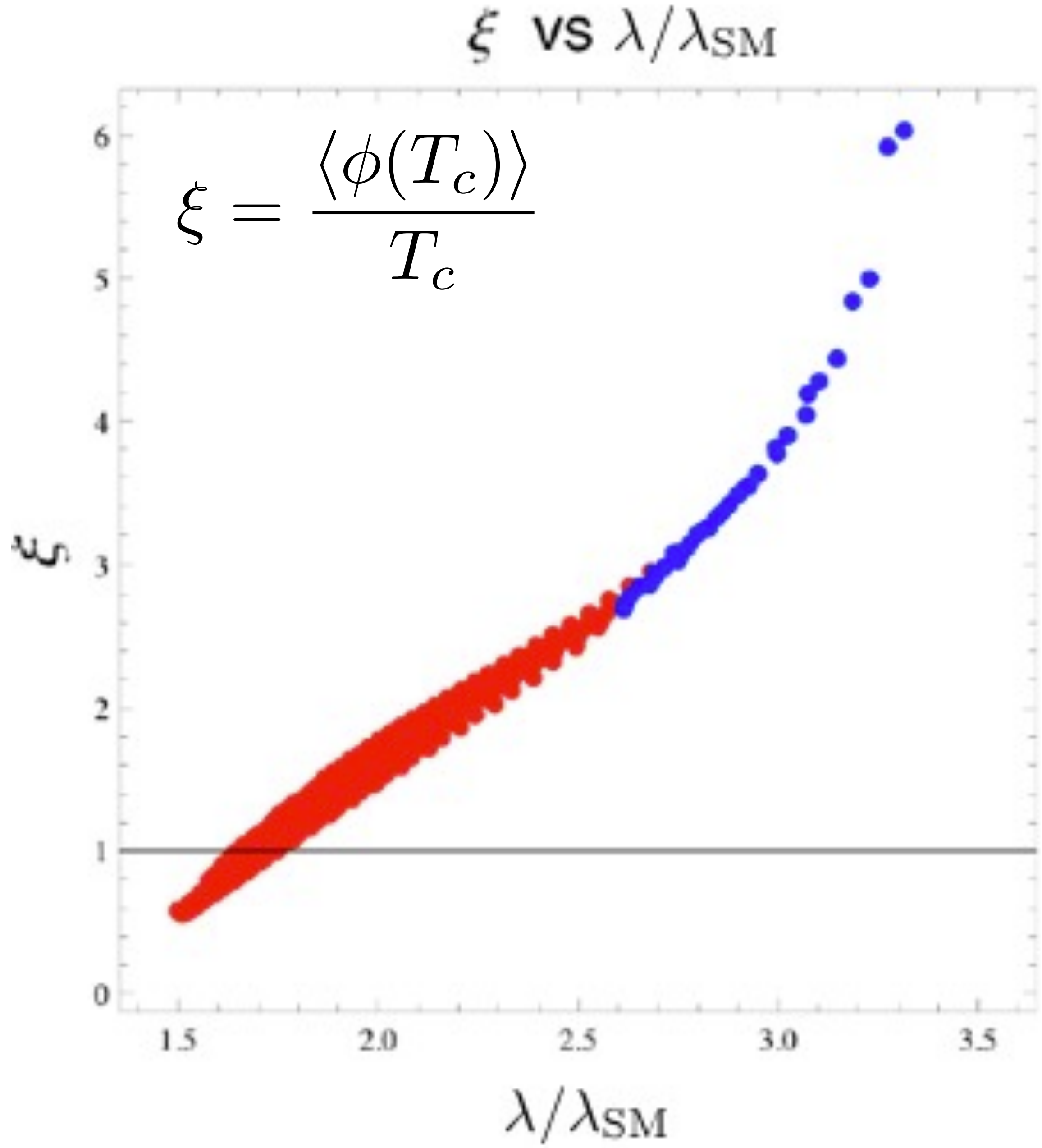
- Baryon asymmetry may be generated during EW phase transition, if strongly first order - electroweak baryogenesis (EWBG) [see talk by J. Shu]
- Strongly correlated with Higgs physics:
  - The related CP-phase must enter Higgs couplings
  - A strongly first order EWPT generically requires a modified Higgs potential

Strongly First Order EWPT



- Need to generate a bump for the Higgs potential at high temperature.
  - Not achievable in the SM
  - How to achieve it in BSM physics?

Mechanism (1): Higher Dim Operators



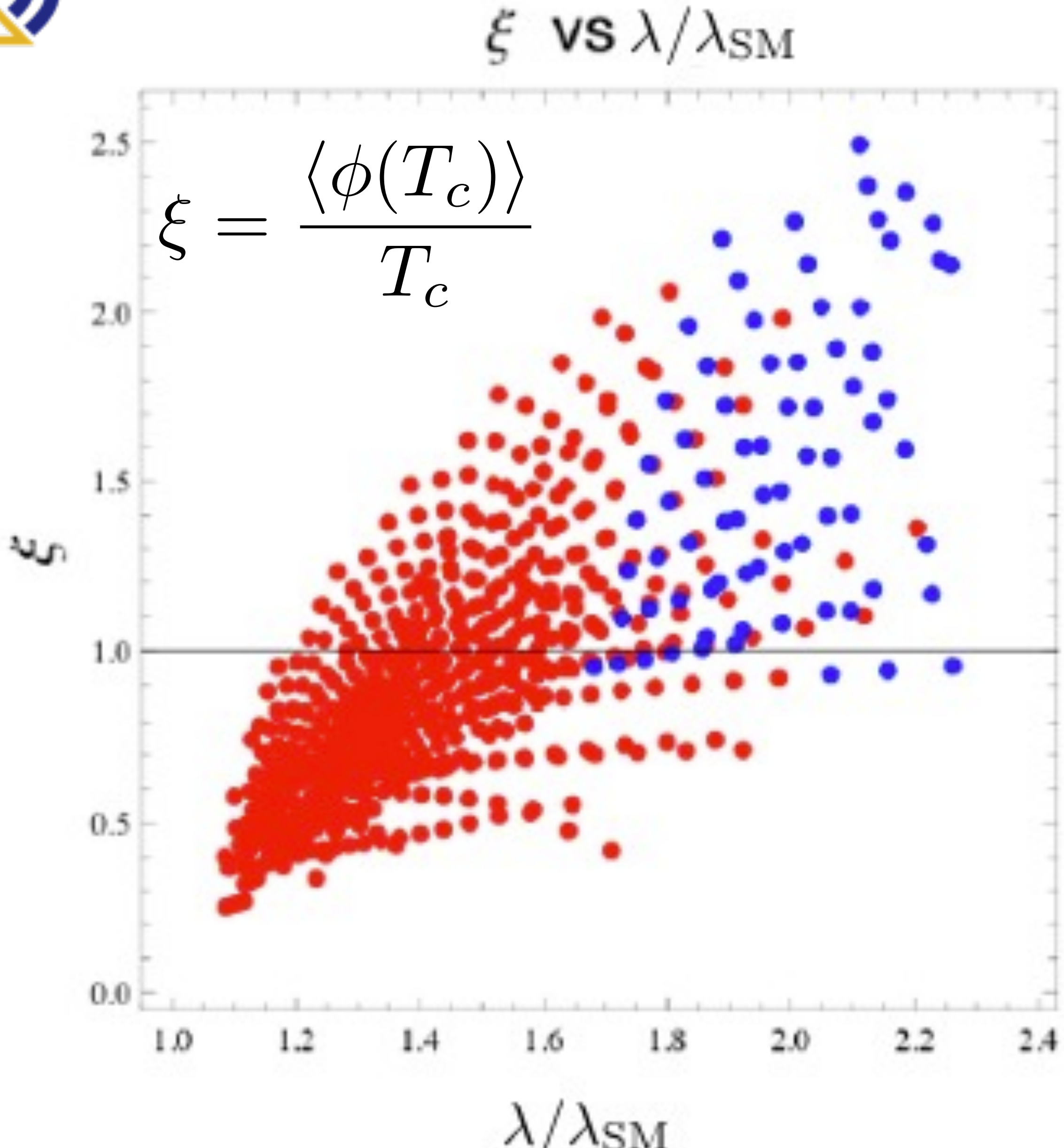
$$V(H) = \mu^2 H^\dagger H + \kappa (H^\dagger H)^2 + \frac{1}{\Lambda^2}(H^\dagger H)^3$$

- A negative kappa helps achieve EWPT of strongly first order
- Leads to a tri-Higgs coupling at zero temperature

$$\frac{\lambda}{\lambda_{\rm SM}} = 1 + \frac{2v^4}{m_h^2 \Lambda^2} = 1 + \mathcal{O}(1)$$

[A. Noble and M. Perelstein, '07]

Mechanism (2): BSM Scalar (No Mixing with Higgs)

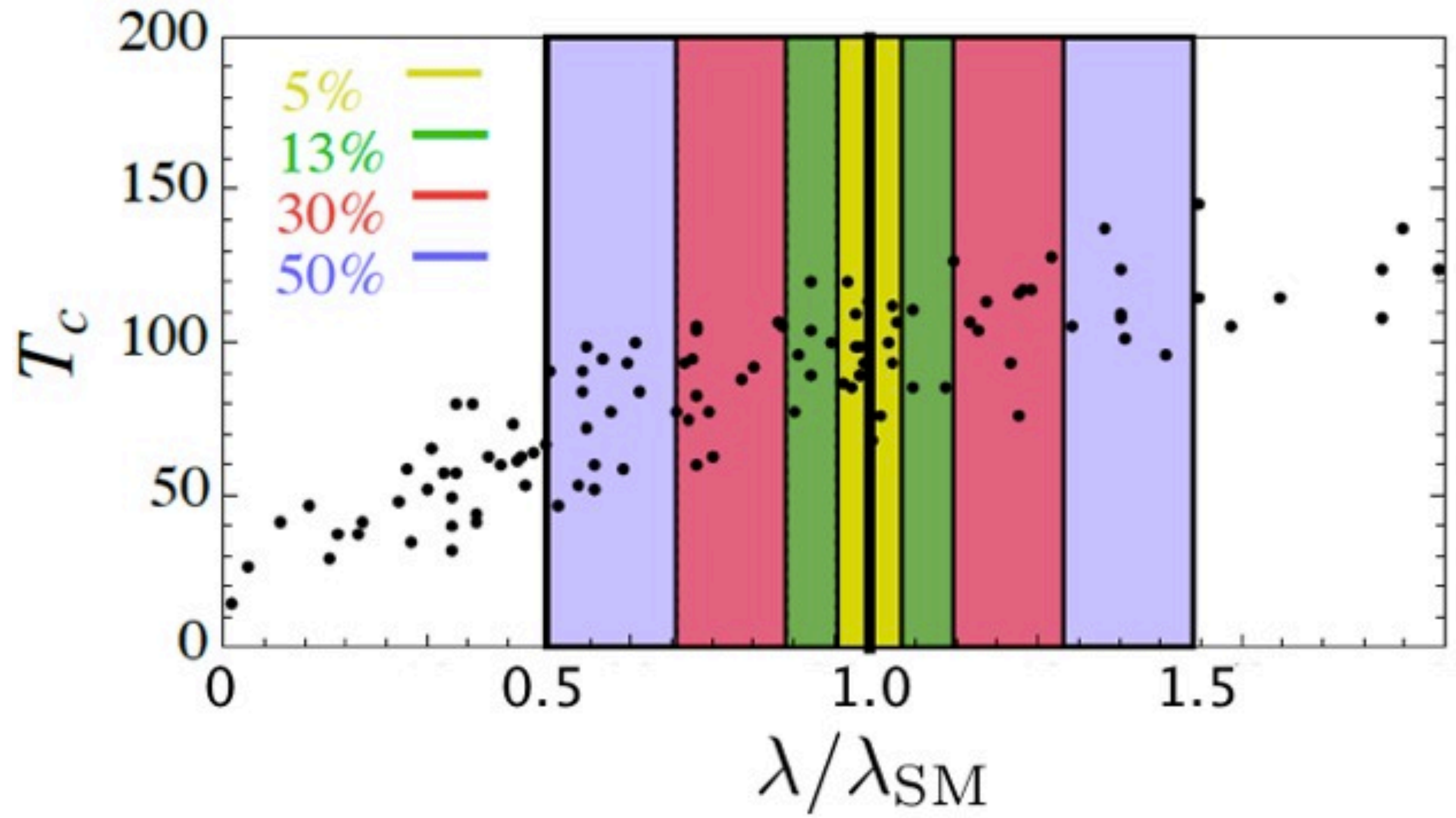


$$V = \frac{1}{2}M_0^2 S^2 + \zeta^2 |H|^2 S^2$$

[A. Noble and M. Perelstein, '07]

- A T * h^3 term can be induced via loop correction
- If colored or electrically charged, may modify Higgs gauge couplings and be probed at HL-LHC or ILC/CEPC [A. Katz, M. Perelstein, '14, also see talk by L.T. Wang]
- Numerically, 20% or more shift in tri-Higgs coupling

Mechanism (3): Higgs-Singlet Mixing



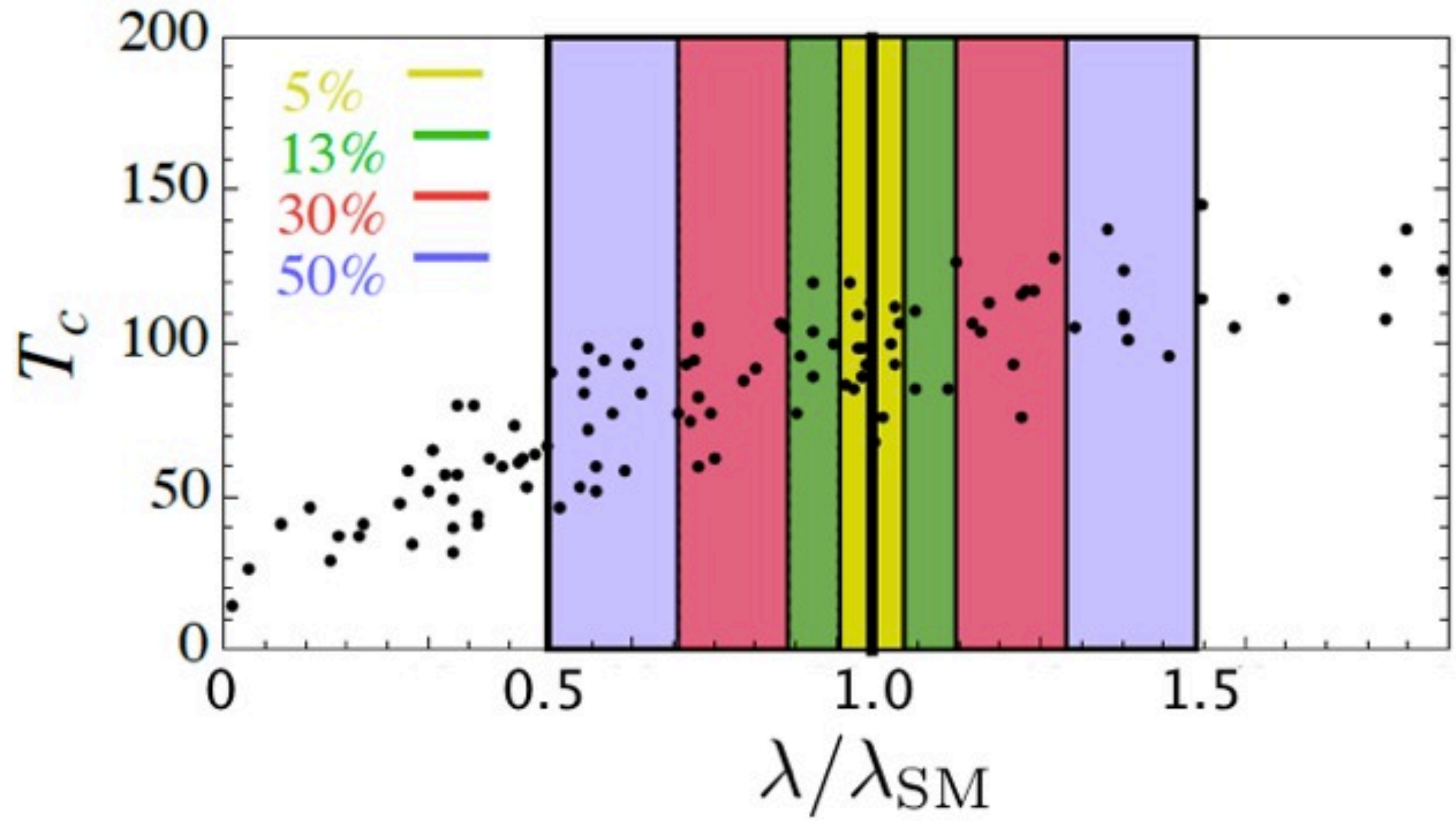
[S. Profumo, M. Ramsey-Musolf et. al. ’14]

$$V^t(H,S) = -\mu^2 H^\dagger H + \lambda'(H^\dagger H)^2 + \frac{a_1}{2}H^\dagger H S + \frac{a_2}{2}H^\dagger H S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

$$\frac{\lambda}{\lambda_{\rm SM}} = \frac{1}{35}\left(\lambda' v\cos^3\theta + \frac{1}{4}(a_1 + 2a_2 x_0)\cos^2\theta\sin\theta + \frac{1}{2}a_2 v\cos\theta\sin^2\theta + \frac{b_3}{3}\sin^3\theta + b_4 x_0\sin^3\theta\right)$$

- Multiple contributions => broad range of lambda

Mechanism (3): Higgs-Singlet Mixing

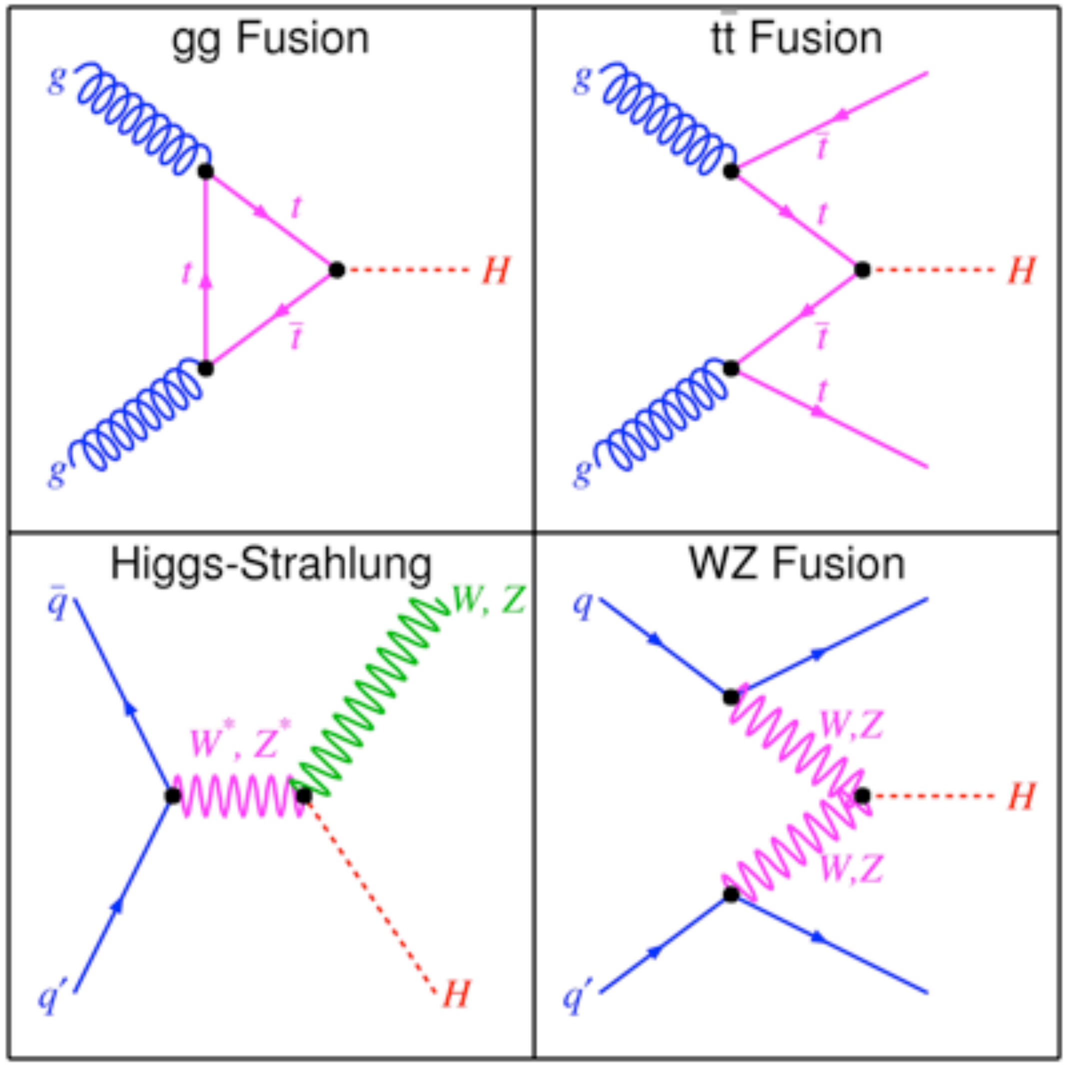


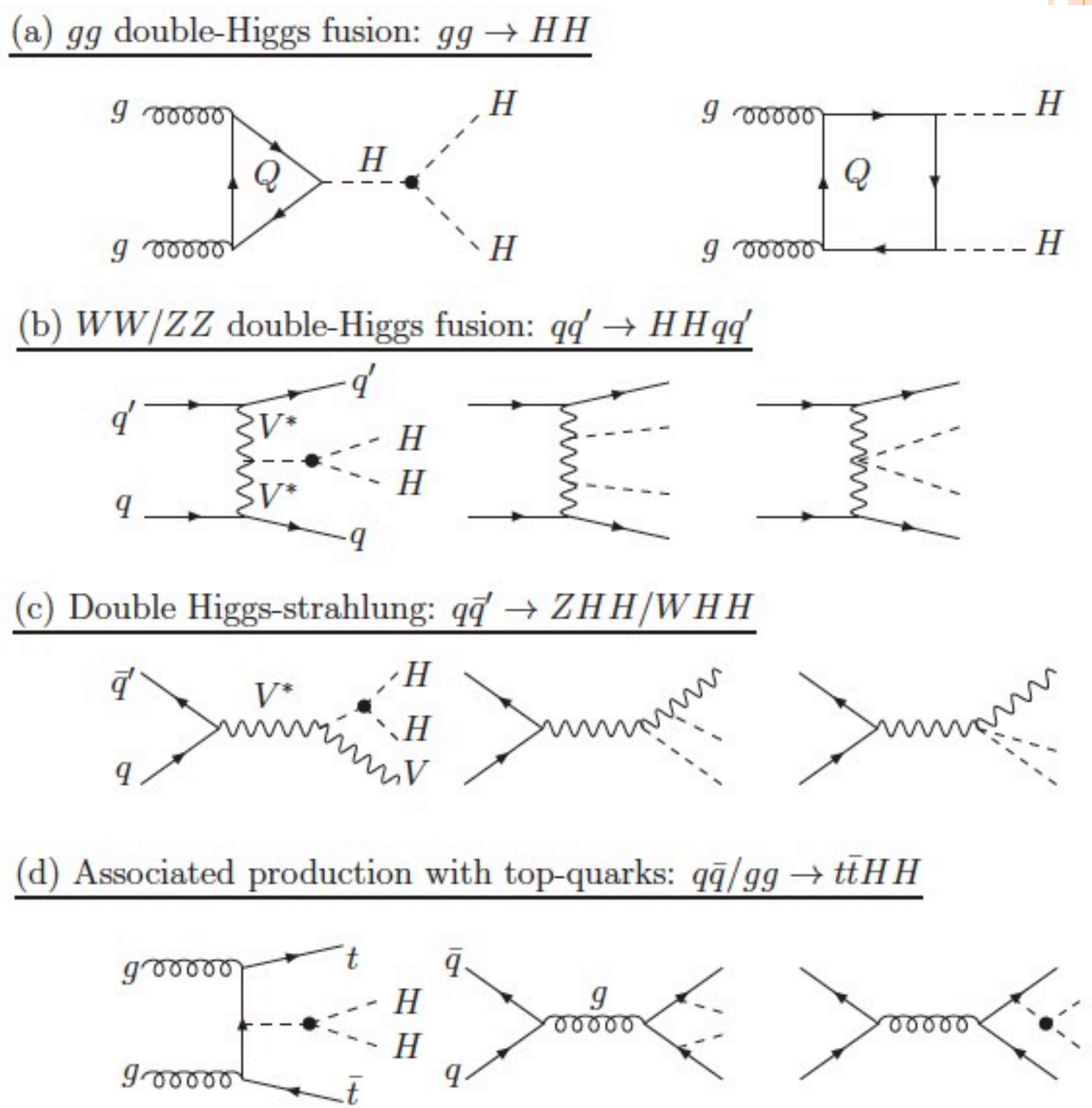
[S. Profumo, M. Ramsey-Musolf et. al. '14]

$$V^t(H,S) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

The measurements of the tri-Higgs coupling provides an efficient probe for the EWPT strength and a direct test of the EWBG feasibility

Di-Higgs Production in the SM





[J. Baglio, A. Djouadi et. al., '13]

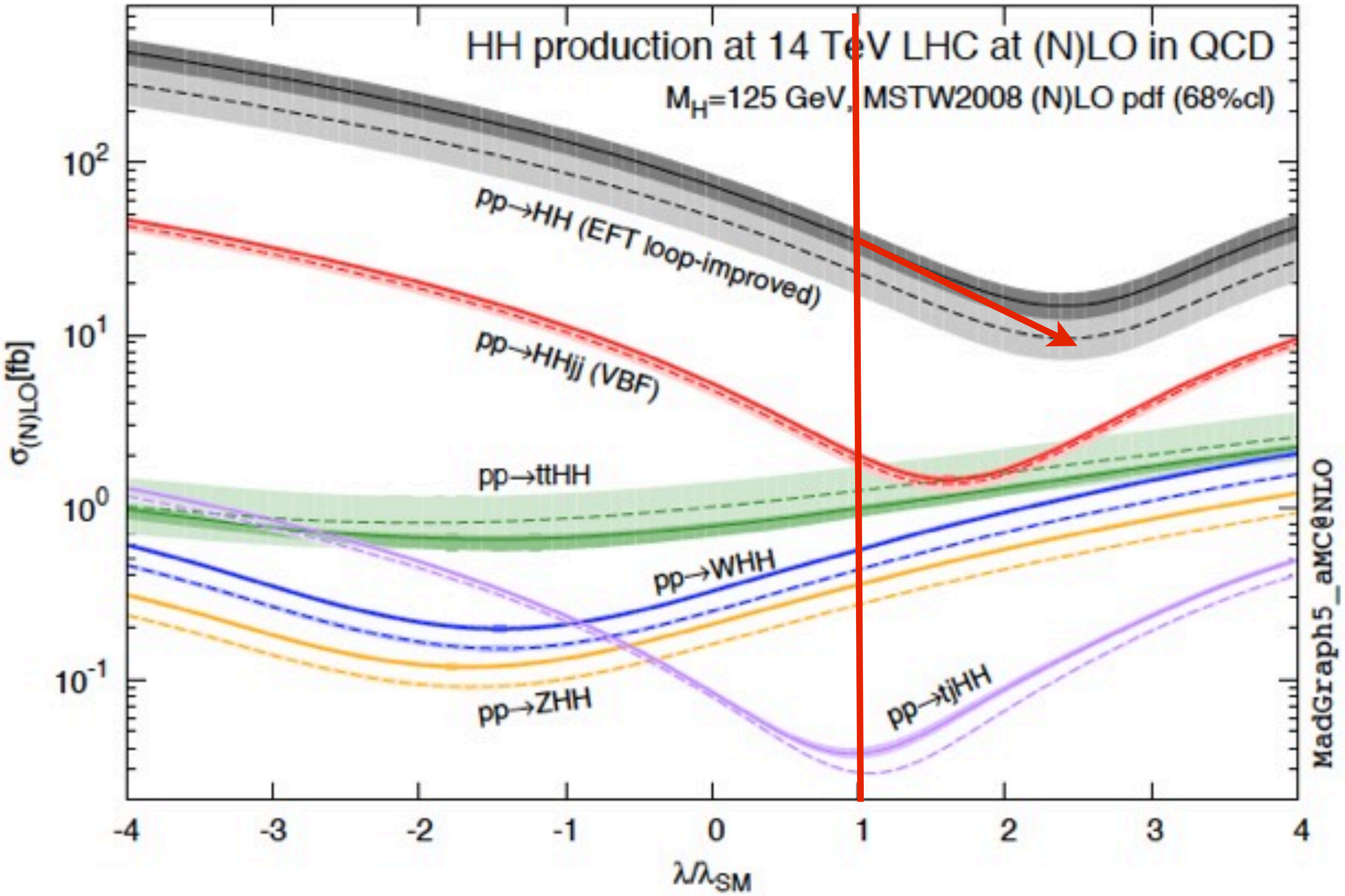
General Comments

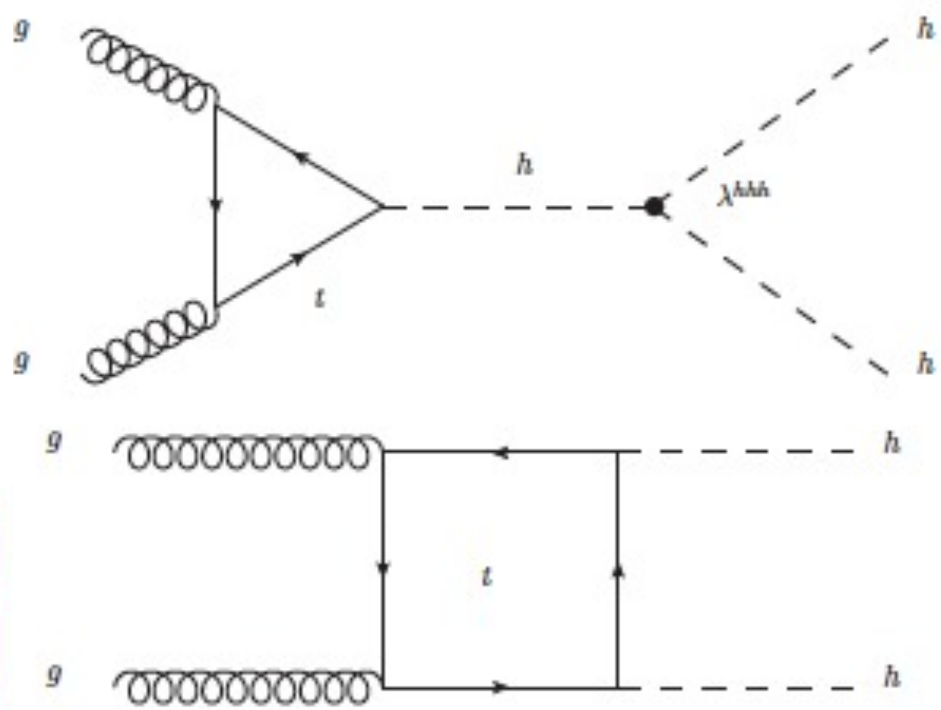
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

[J. Baglio, A. Djouadi et. al., '13]

- Rare process! Mainly studied via the pp -> hh production

Current Focus: pp -> hh

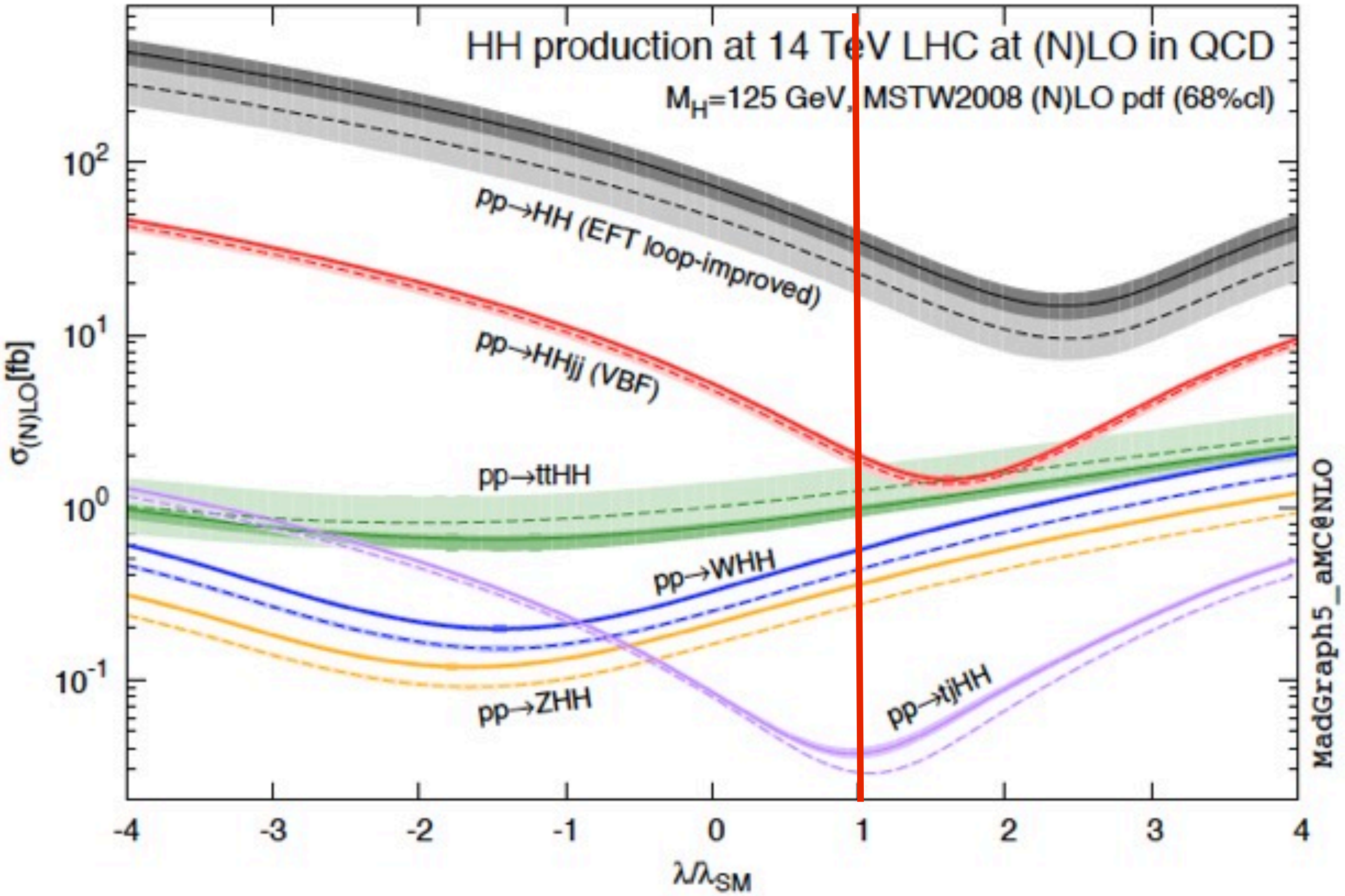




[R. Frederix et. al., '14]

- Good: simple topology; large production xsection (golden channel hh -> bb +di-photon, [see talk by W. Yao])
- Bad: negative correlation with lambda; with a positive shift in lambda
  - Lower signal rate
  - Weaker dependence on the tri-Higgs coupling

Complementary Method: pp -> tthh



$$\frac{\Delta\lambda}{\lambda} = \frac{\left.\frac{\Delta\lambda}{\lambda}\right|_{\lambda/\lambda_{\rm SM}=1}}{\frac{\lambda}{\lambda_{\rm SM}} \exp\left(\frac{\lambda/\lambda_{\rm SM}-1}{3}\right)}$$

for pp -> tthh, with

$$0 < \frac{\lambda}{\lambda_{\rm SM}} < 4$$

- Positive correlation with tri-Higgs coupling in the SM neighborhood
- With a positive shift in lambda
  - higher signal rate
  - stronger dependence on the tri-Higgs coupling

[TL, H. Zhang, '14]

Illustration: pp -> tthh with hh -> bbbb

$\sqrt{s}$	$pp \to t\bar{t}hh$	$pp \to hh$
14 TeV	$0.981^{+2.3+2.3\%}_{-9.0-2.8\%}$	$34.8^{+15+2.0\%}_{-14-2.5\%}$
100 TeV	~ 90	~ 1200

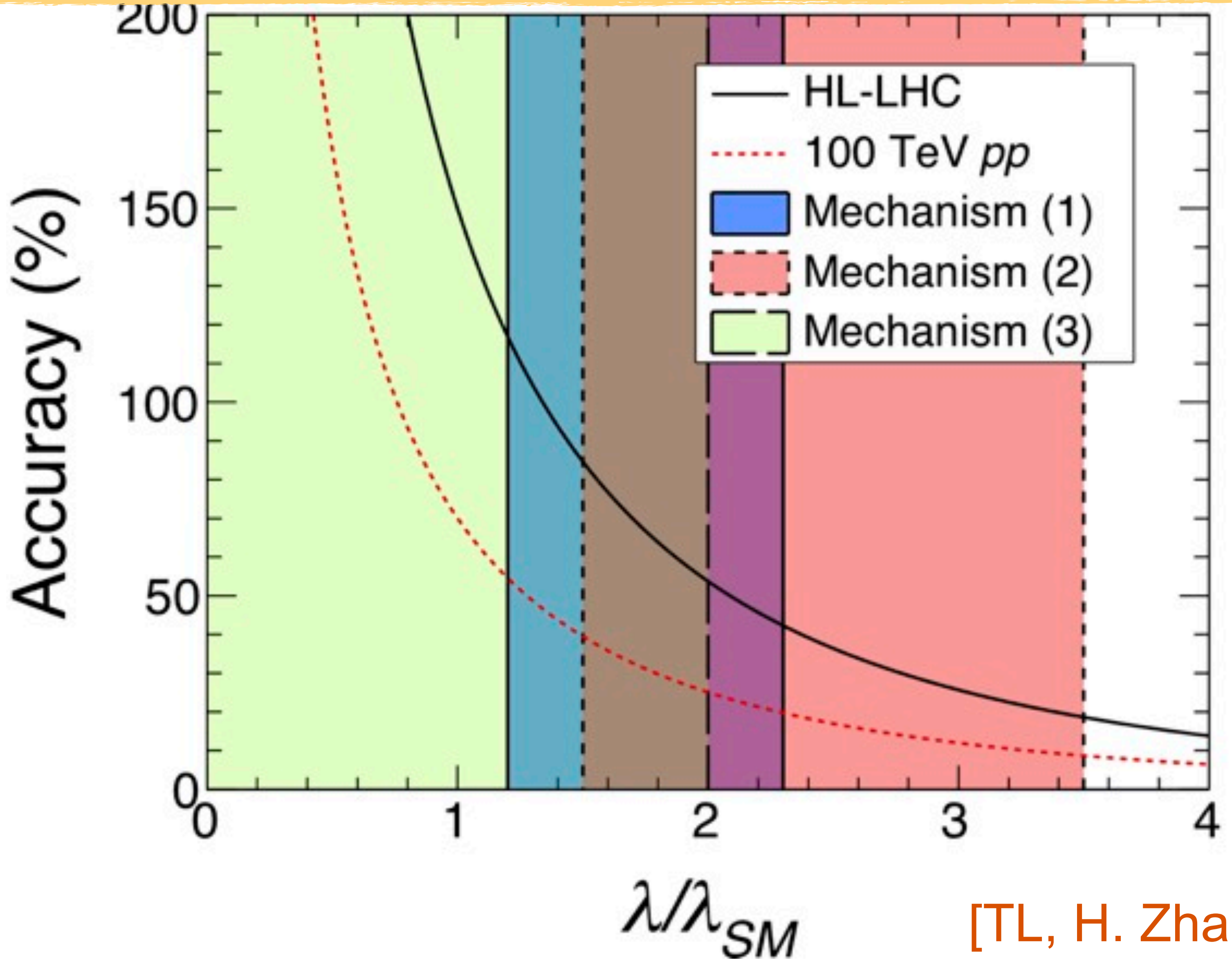
pp > tthh > ttbbbb VS pp > hh > bb + di-photon

Relatively low Xsection * high Br = 300 ab

Relatively high Xsection * low Br = 35 ab

- HL-LHC: > 2.0 sigma statistical significance is achievable; [TL, H. Zhang, '14]
- Comparable to that of the pp -> hh -> bb + diphoton (cut-based): 1.3-2.3 sigma [Y. Yao, '13; V. Barger et. al. '13; ATL-PHYS-PUB-2014-019]

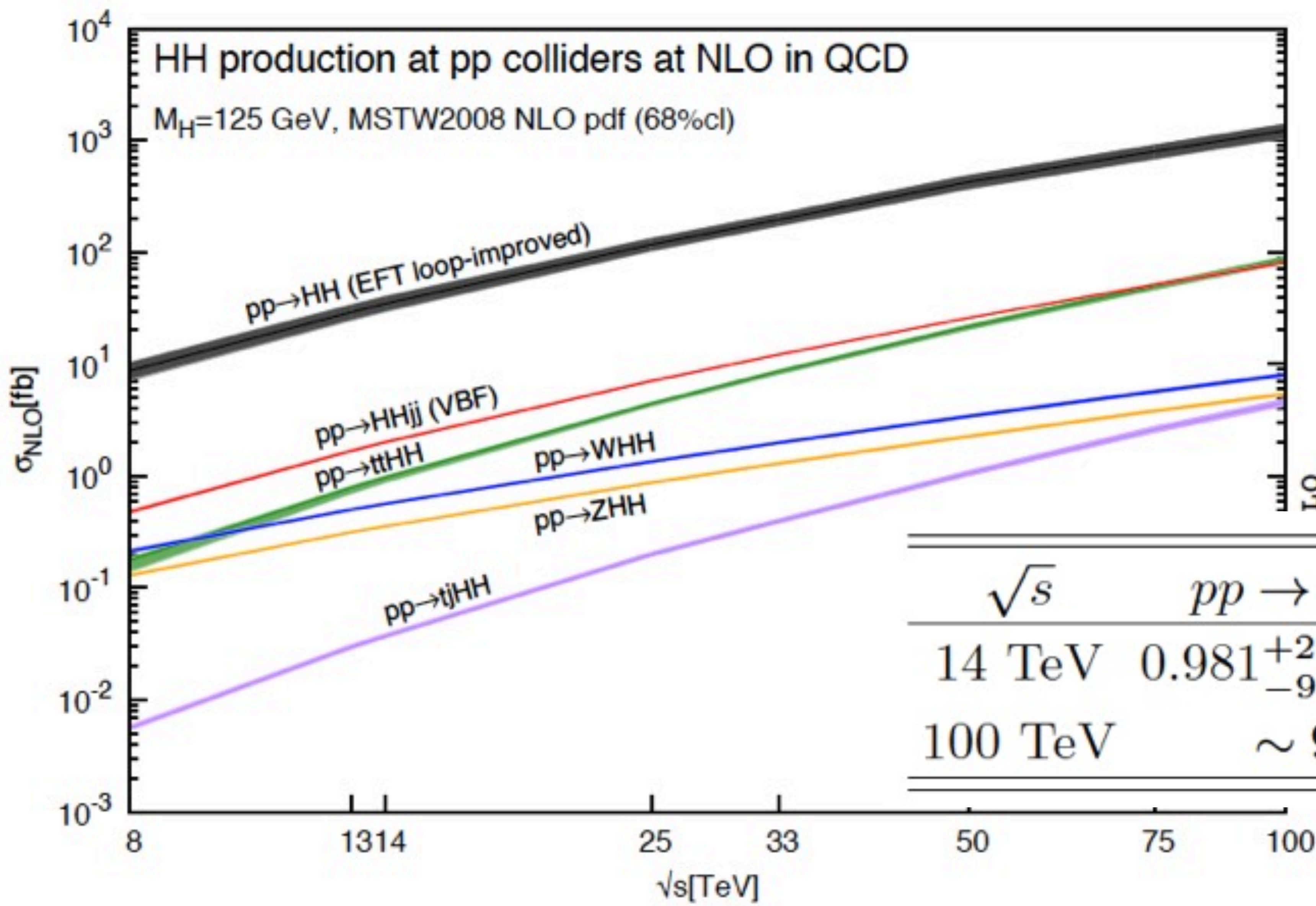
Tri-Higgs Coupling Measurement via pp -> tthh



[TL, H. Zhang, '14]

- Assuming that NP enters tri-Higgs coupling only, if any
  - Mechanism (1) and (2): HL-LHC shows a good sensitivity
  - Mechanism (3): HL-LHC shows some sensitivity

Gains from 100 TeV pp Collider



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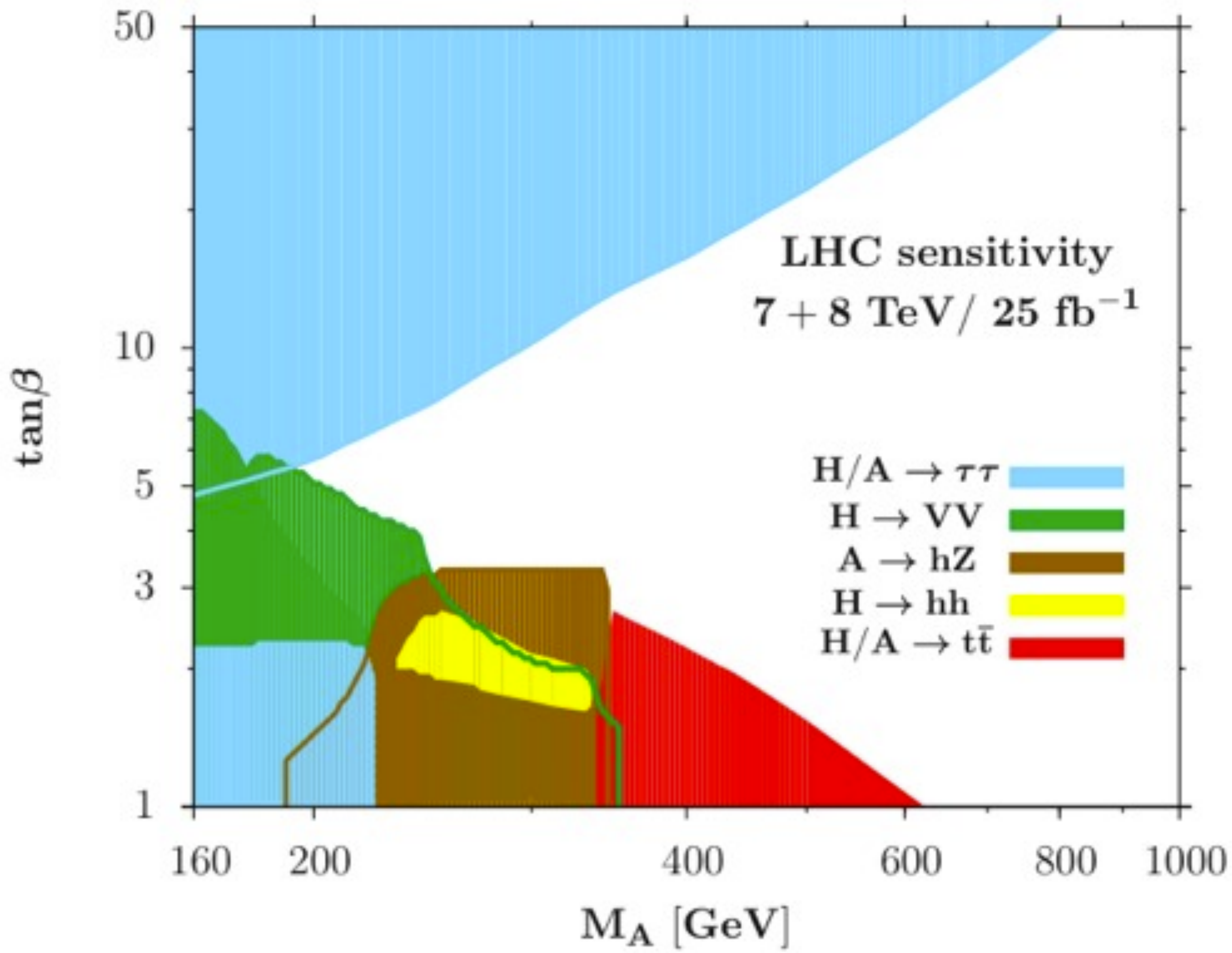
- The pp ->tthh production increases fast, as the energy scale increases, making more channels be accessible: tt + bbbb,bb diphoton, bb tautau, etc
- What is the best strategy for di-Higgs measurement?
- To what extent can we test EWPT of strongly first order?

BSM Higgs Bosons

- An extended Higgs sector extensively exists in NP
  - Singlet: SM + S
  - Doublet: 2HDM, MSSM
  - Triplet: Type II see-saw, L-R model
  - Mixture: 2HDM + S, NMSSM

- For illustration, we focus on the MSSM Higgs bosons (no CP-violation assumed): H, A, Hc
  - Higgs mass spectrum and couplings only depend on two parameters (in additional to the SM ones) at tree-level: tan_beta, mA/mHc
  - So we can make a sensitivity projection on mA/mHc - tan_beta plane
  - Assume a decoupled spectrum of superparticles.

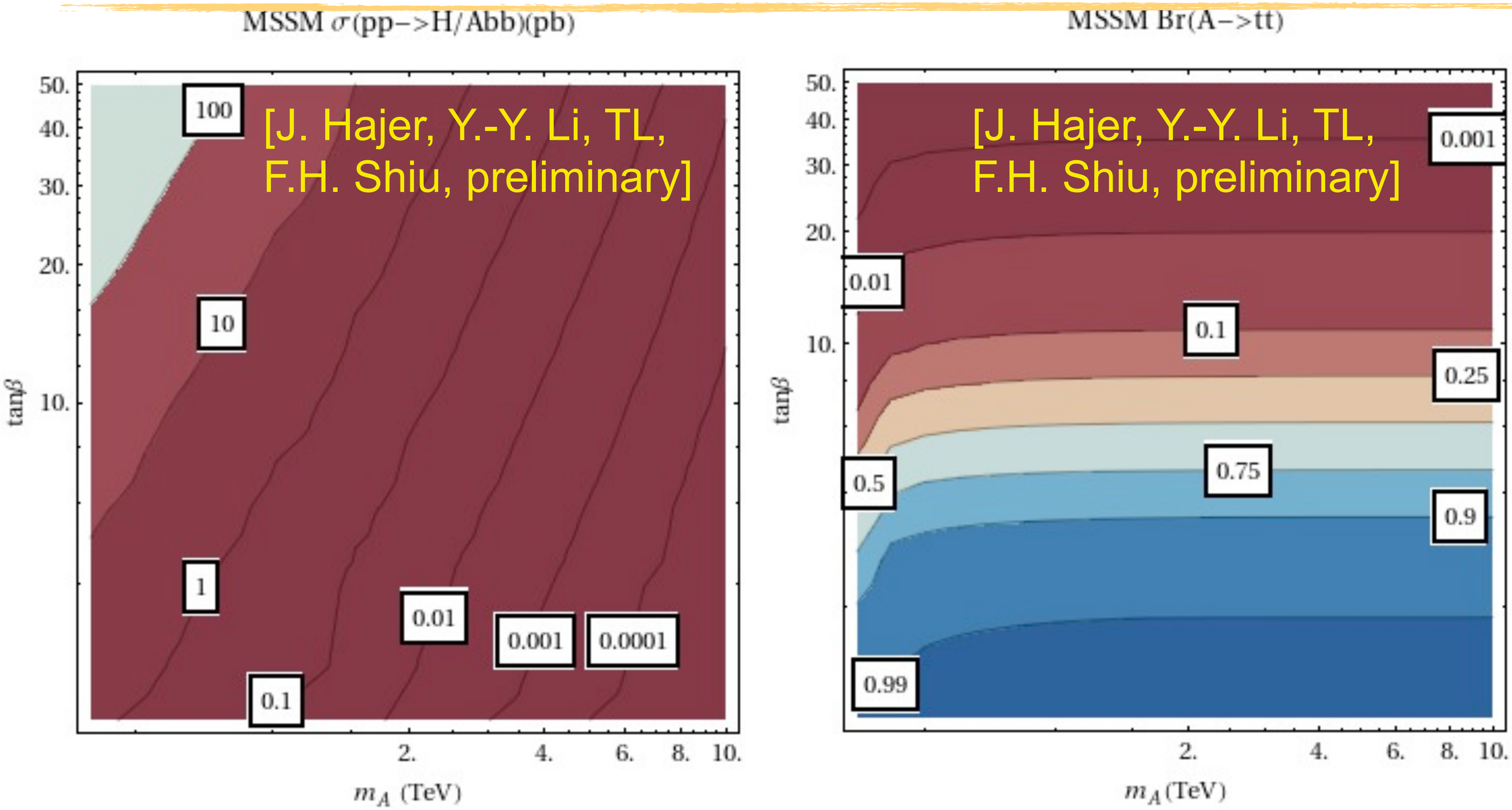
Neutral Higgs Bosons in the MSSM



[A. Djouadi, '13]

- High tan_beta: pp -> bb H/A -> bb tautau, bbbb
- Low tan_beta: pp -> H or A -> VV, hZ, tt, etc.
- What are the gains from 100 TeV pp-collider?

Gains from 100 TeV pp-Collider

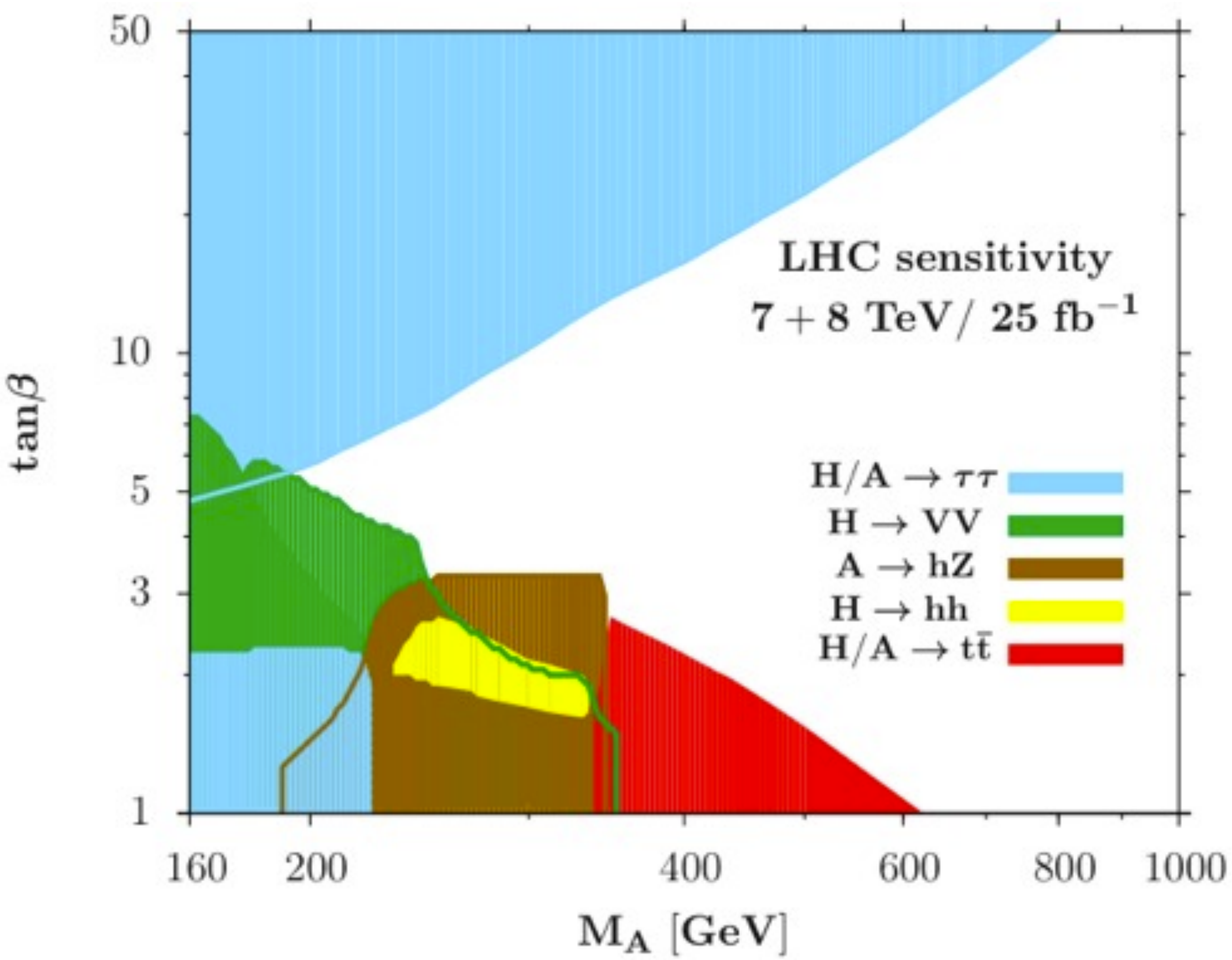


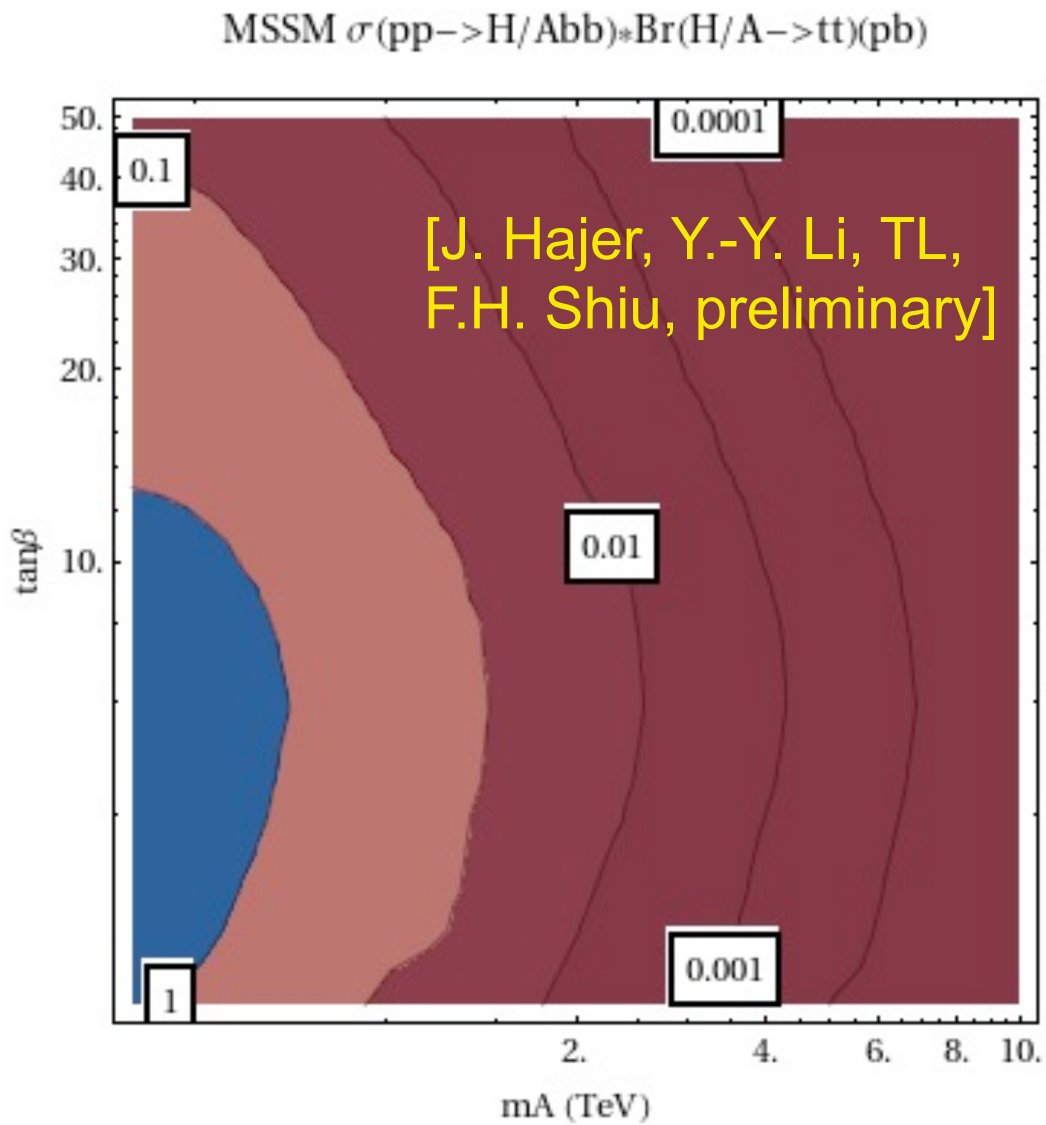
- New mass domain (1-10 TeV scale) becomes accessible
- Production xsection of bbH/A (TeV scale) : roughly two order increase
- H/A -> tt is fully turned on, whereas H -> VV, hh and A -> hZ are suppressed

$$g_{HVV} = g_{hZA} = g_{hW^\mp H^\pm} = g_{Hhh} \propto \cos(\beta - \alpha) \to 0$$

Gains from 100 TeV pp-Collider

[A. Djouadi, '13]

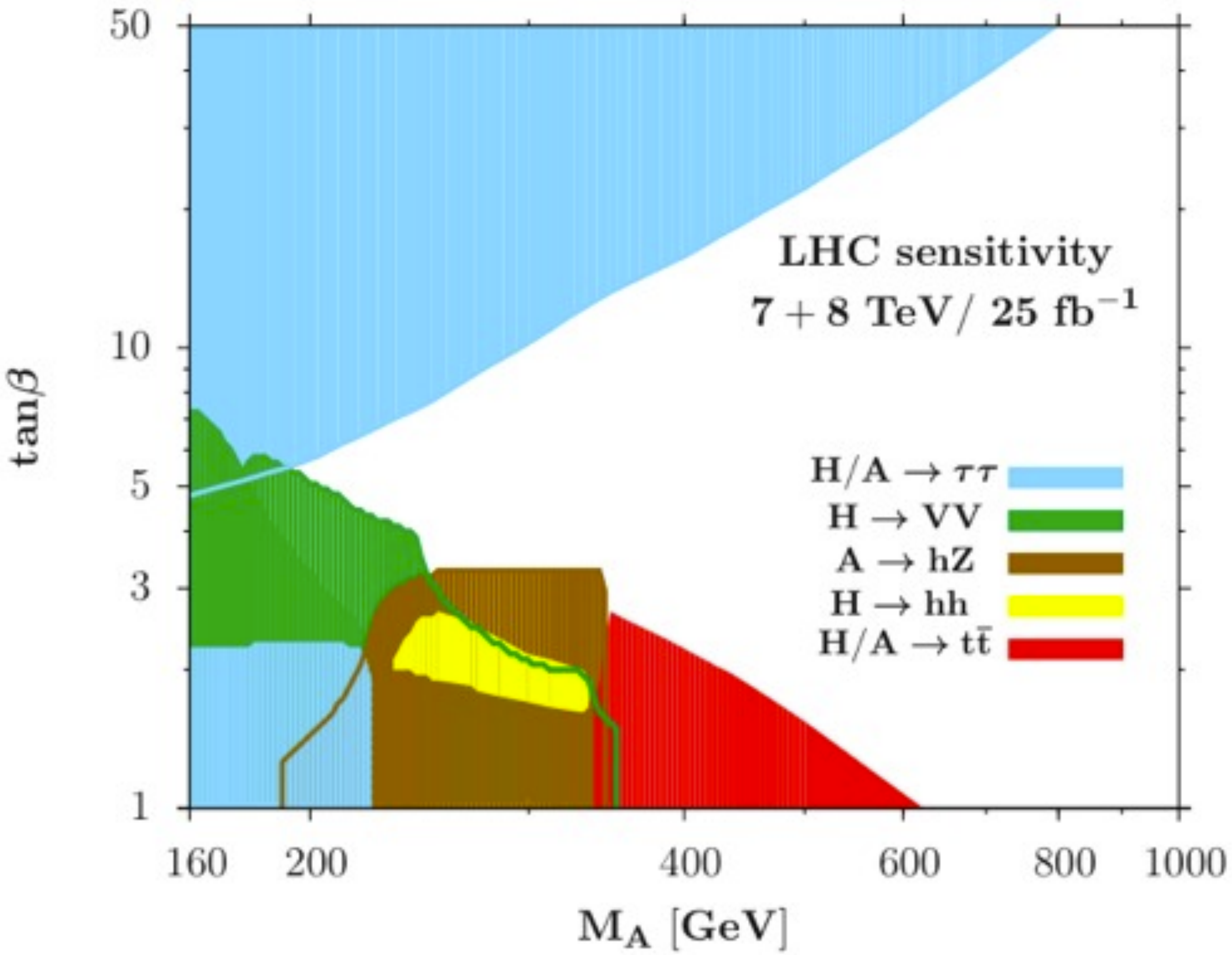


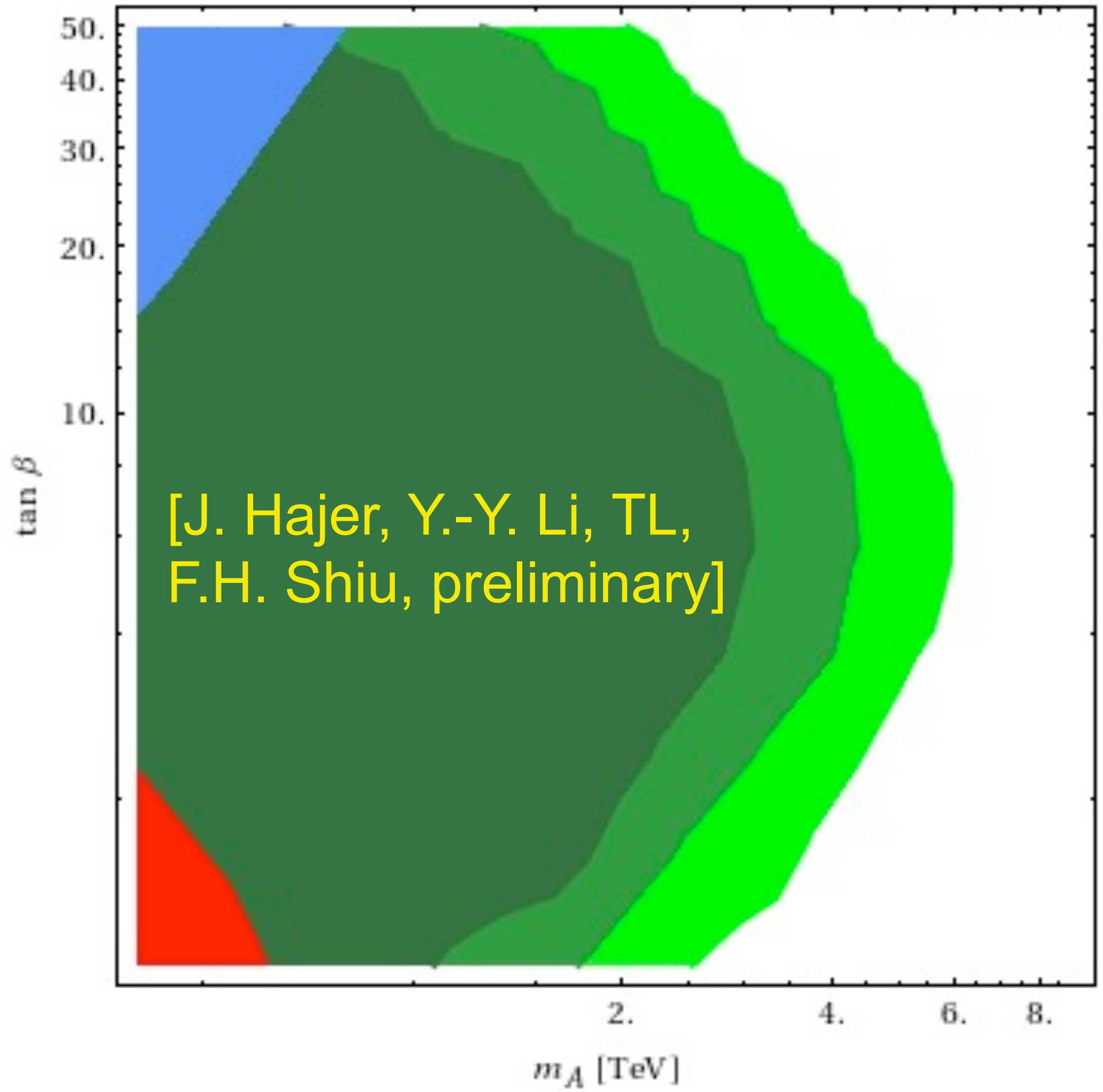


- Particularly, the difficult wedge region (centered around tan_beta ~ 5) can be efficiently probed by pp -> bbH/A -> bbtt

[J. Hajer, Y.-Y. Li, TL, F.H. Shiu]

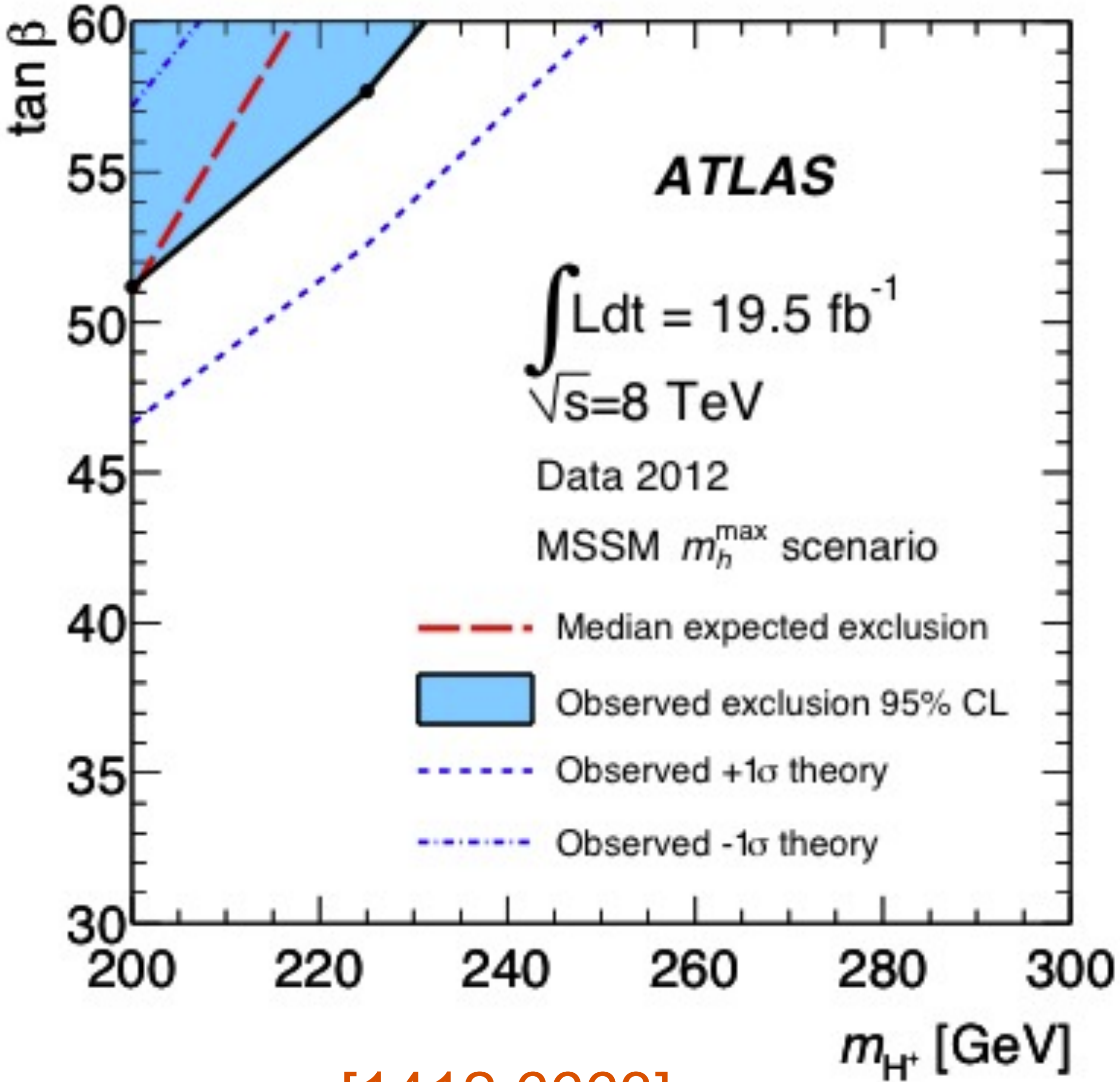
Numerical Results



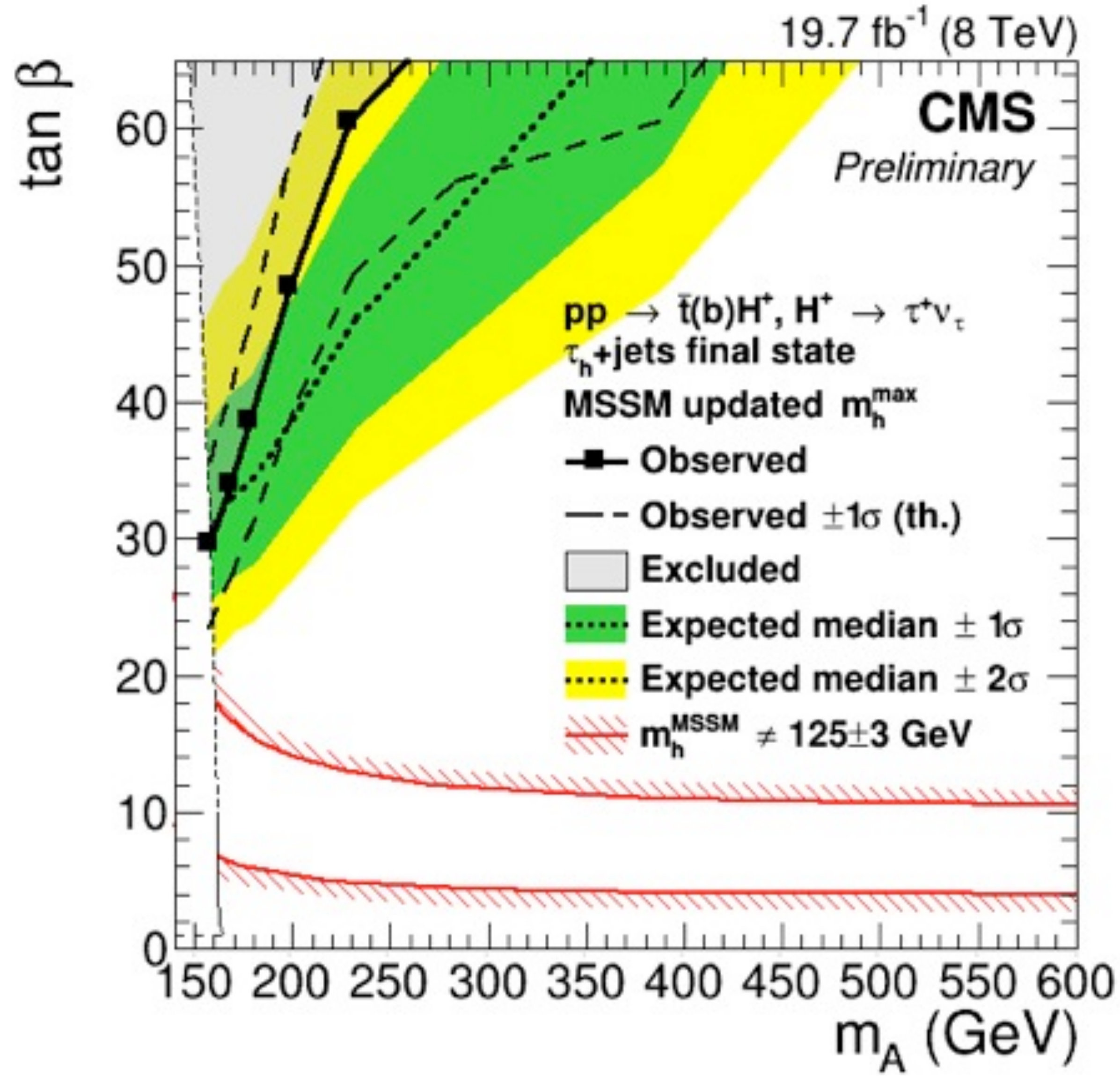


- With 30/ab of data, excluded up to ~ 6TeV via bbH/A->bbtt, based on semi-leptonic tt decay (for tan_beta ~ 5-10)
- Small tan_beta: gg -> H, ttH, with H -> tt have a good sensitivity (in progress)
- Large tan_beta: bbH -> bbtautau continues to play a significant role

Charged Higgs Bosons in the MSSM



[1412.6663]

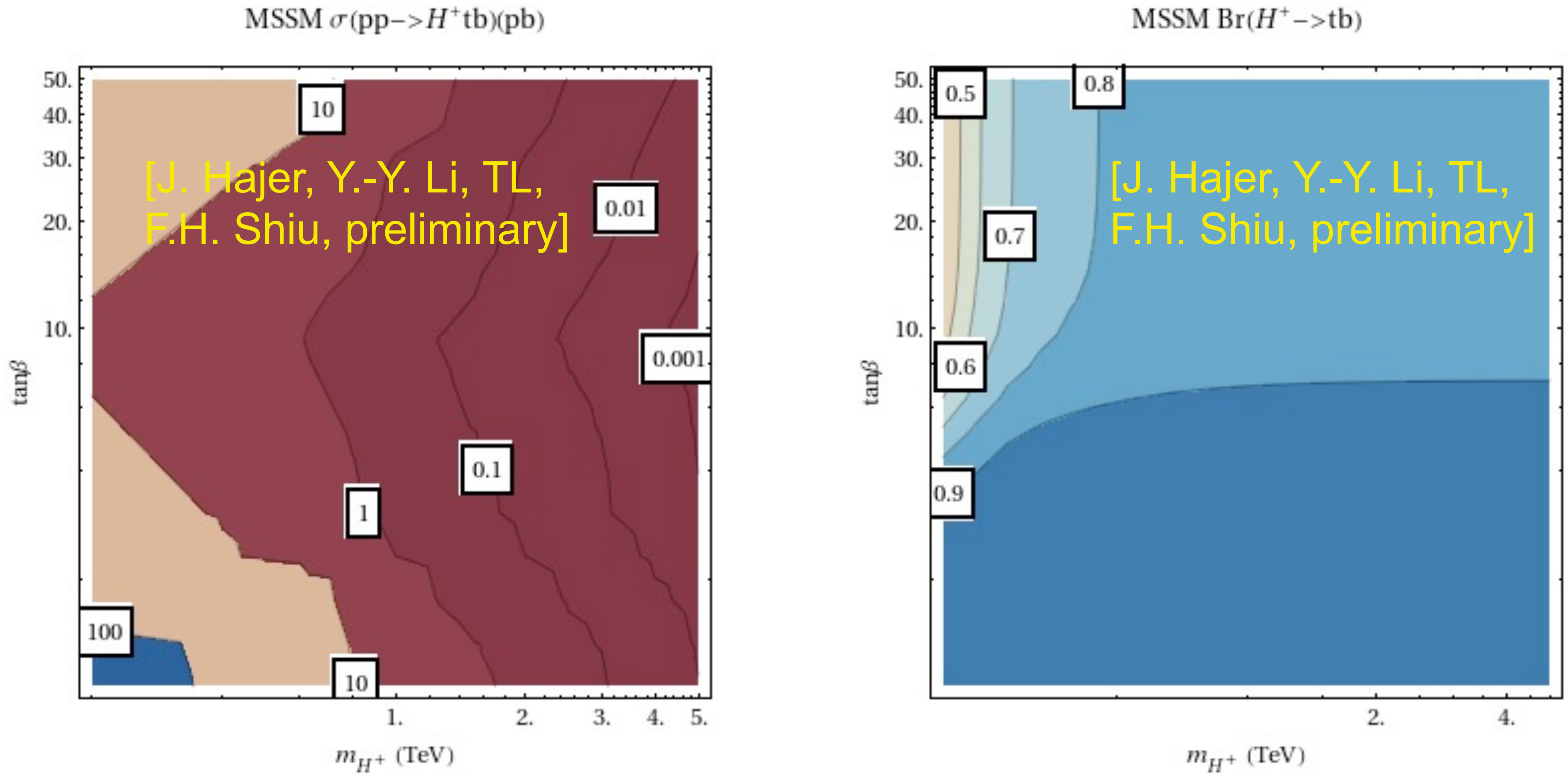


[CMS-HIG-14-020]

- Currently, pp -> tb Hc -> tb tau nu plays a leading role for mHc > mt + mb

$$g_{H^+\bar{\nu}l} = \frac{1}{\sqrt{2}v} m_l \tan\beta(1+\gamma_5)$$

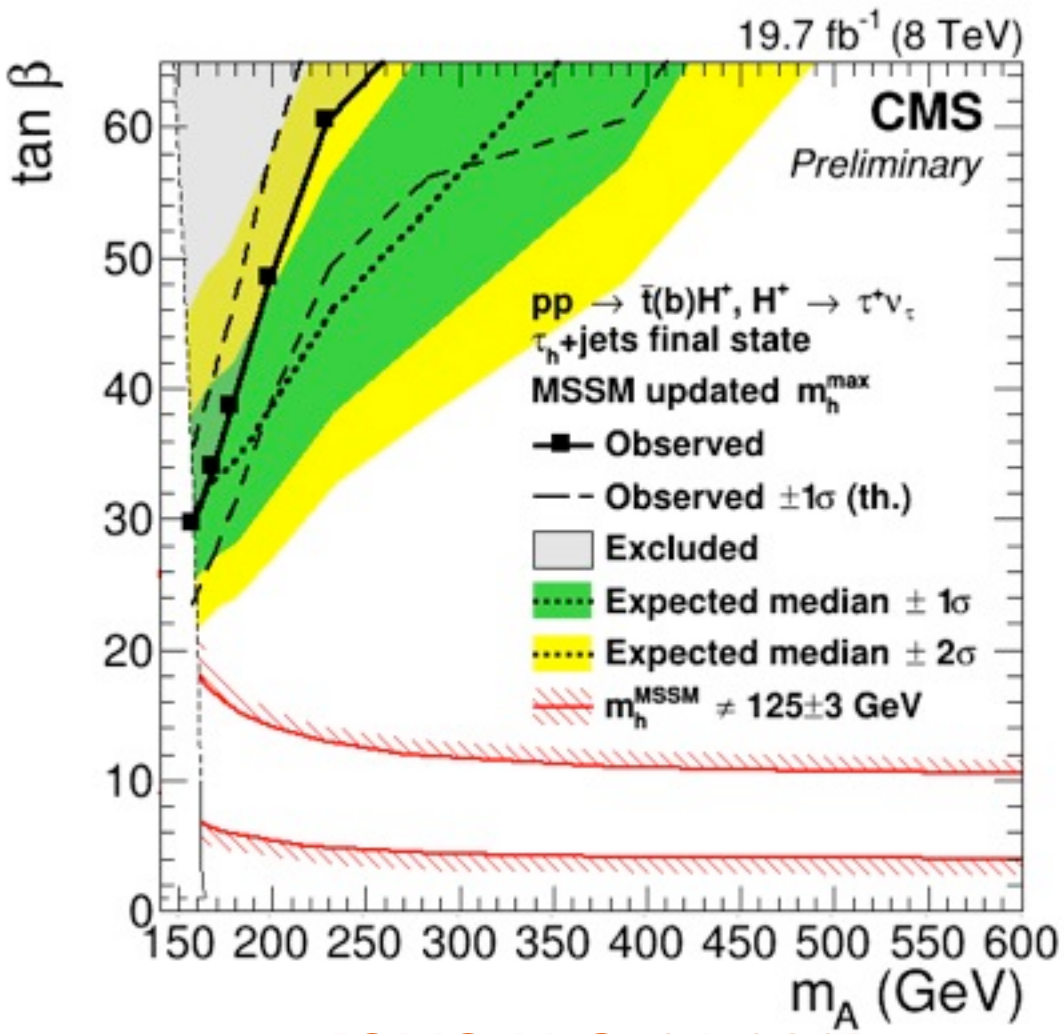
Gains from 100 TeV pp-Collider



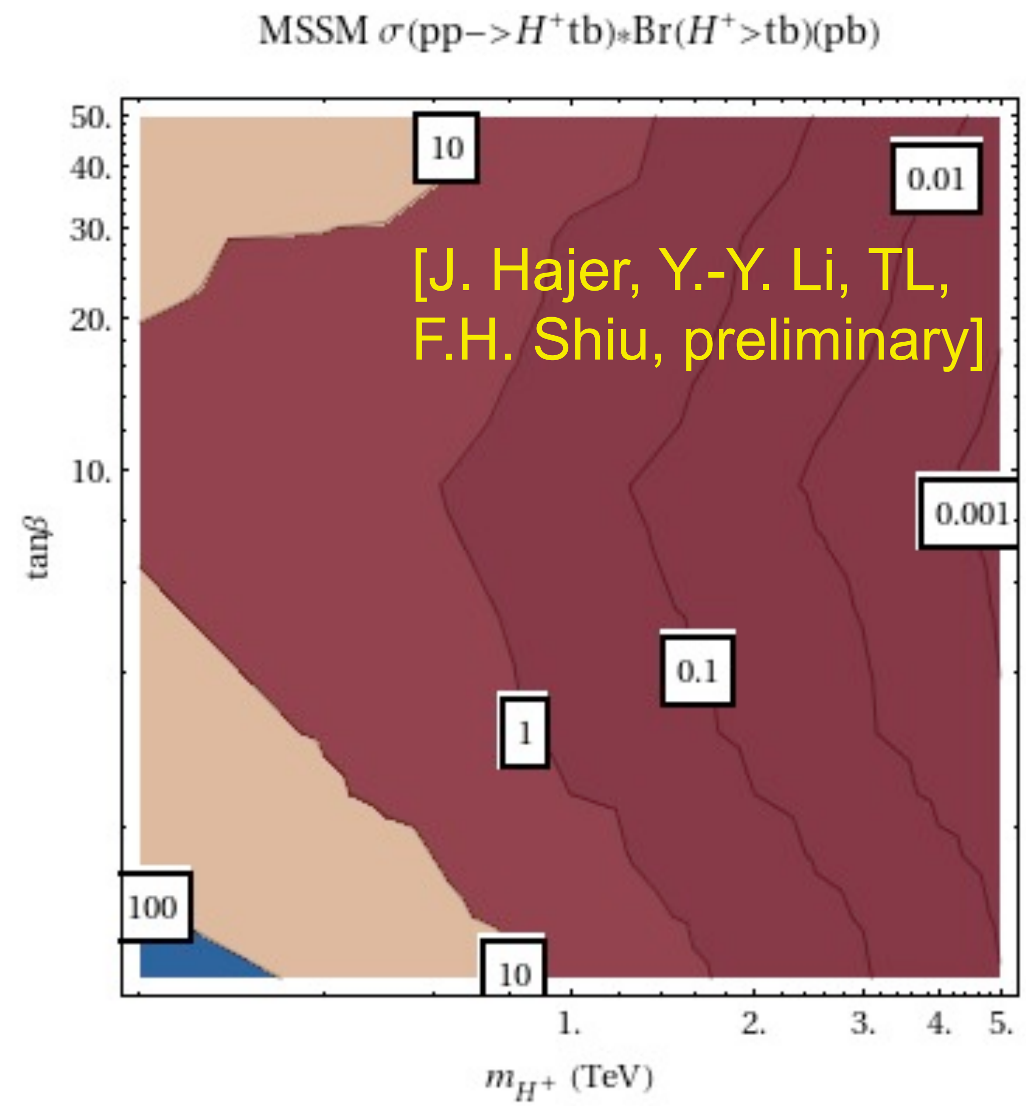
- New mass domain (1-10 TeV scale) becomes accessible
- Production xsection of tbHc (mHc of TeV scale) : roughly two order increase
- Hc -> tb dominates (particularly for low tan_beta)

$$g_{H^+\bar{u}d} = \frac{1}{\sqrt{2}v} V^*_{ud}[m_d \tan\beta(1+\gamma_5) + m_u \cot\beta(1-\gamma_5)]$$

Gains from 100 TeV pp-Collider



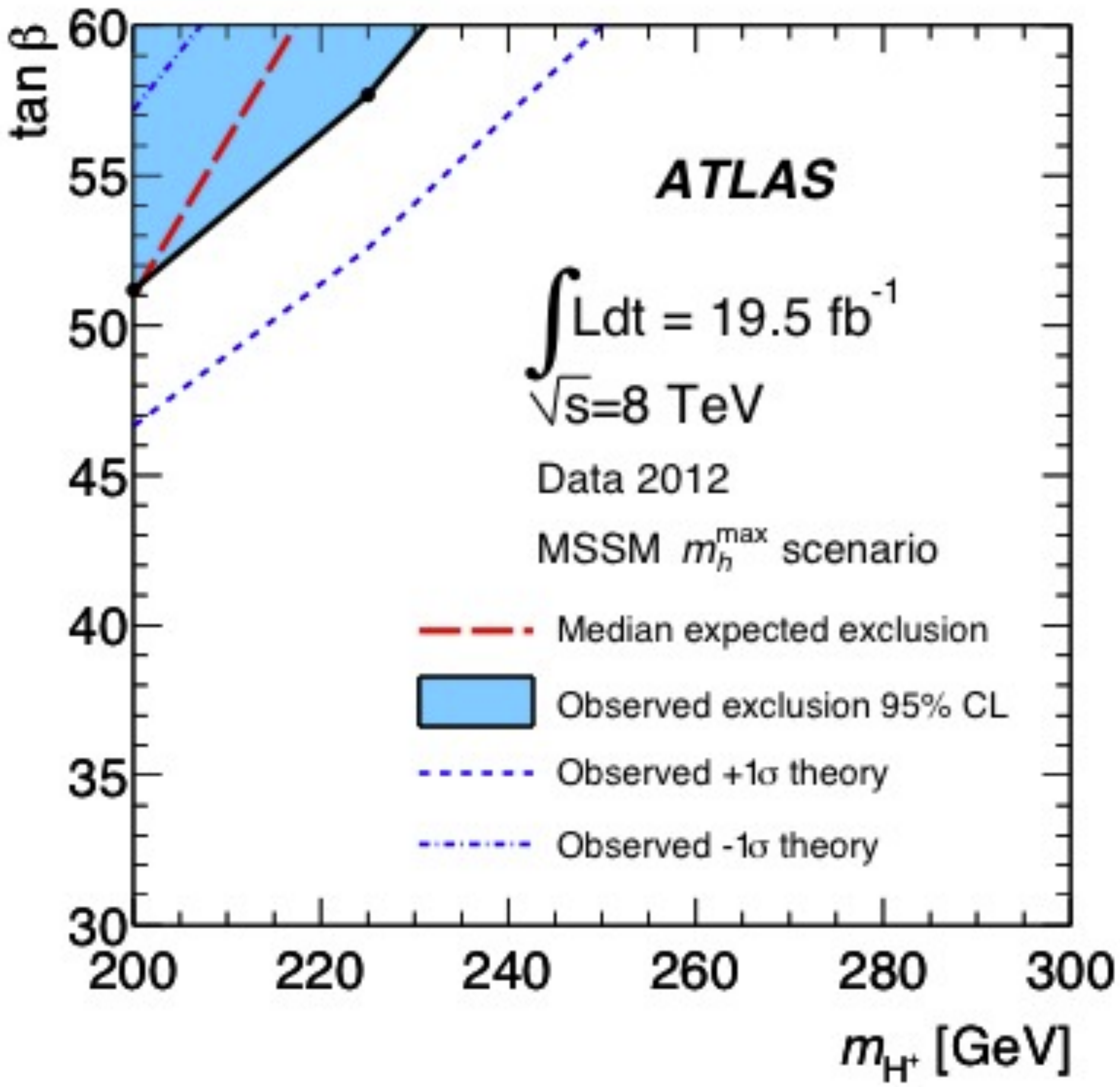
[CMS-HIG-14-020]

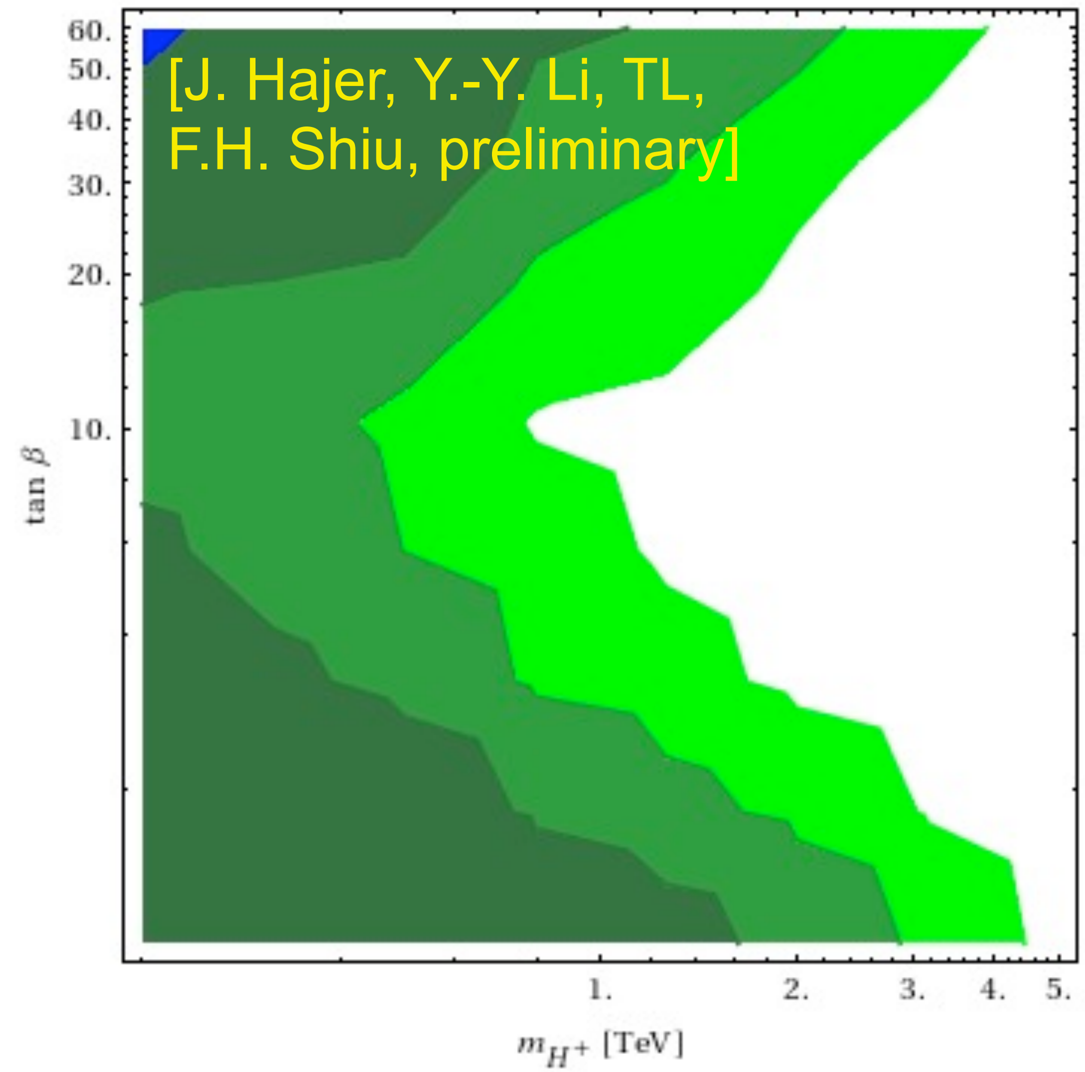


- The difficult low tan_beta region can be probed via pp -> btHc -> btbt

[J. Hajer, Y.-Y. Li, TL, F.H. Shiu]

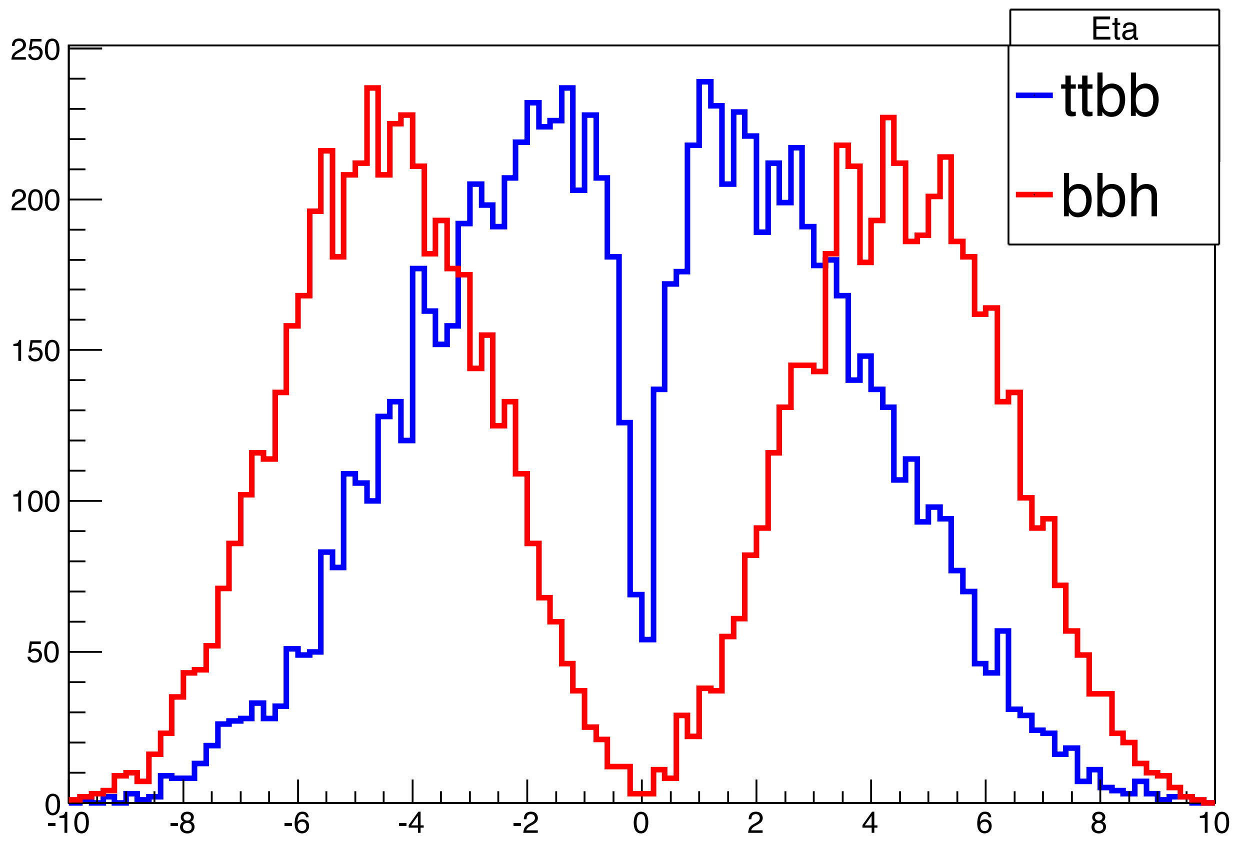
Numerical Results

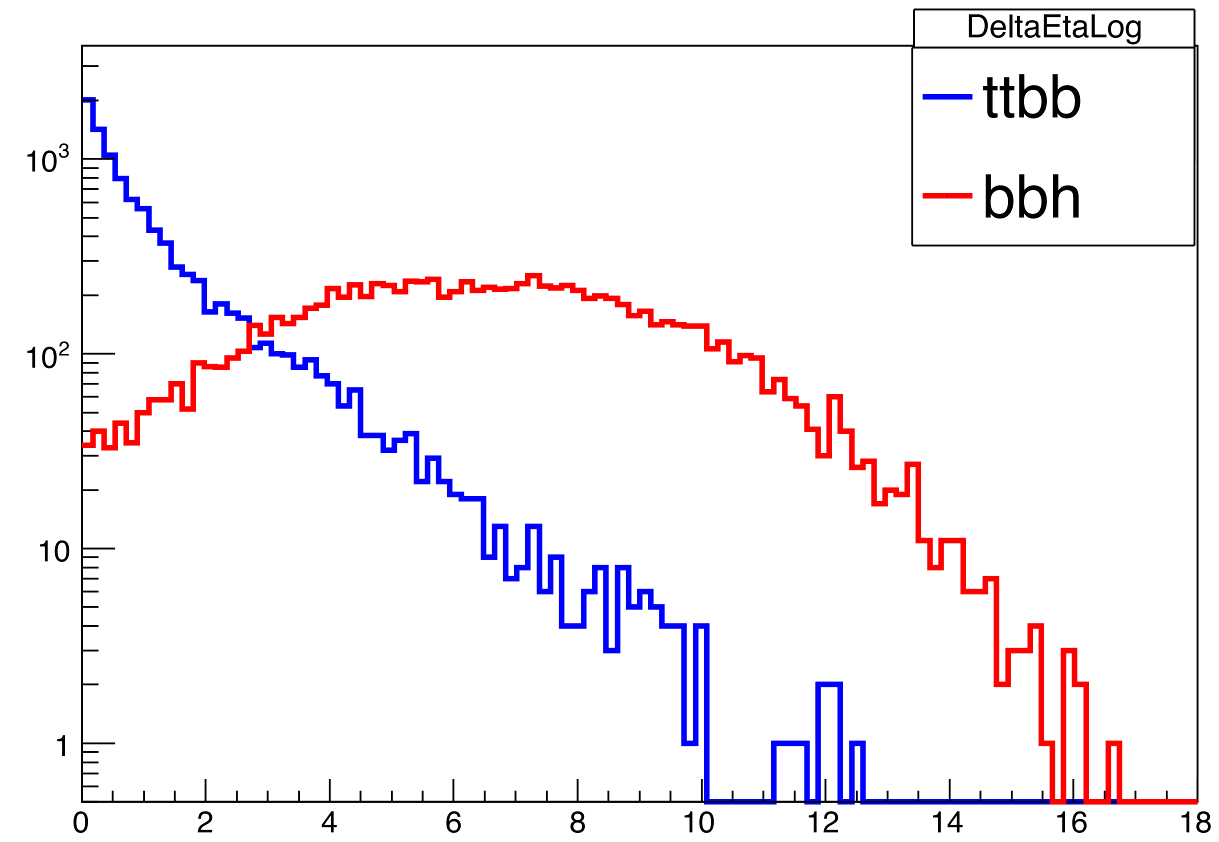




- With 30/ab of data, excluded up to ~ 5 TeV (semileptonic tt decay) via tbHc ->tbtb, for both large and small tan_beta regions
- For intermediate tan_beta, a smarter way is needed

Forward VS Central for 100 pp Collider





- With a forward detector
  - More rapidity units is covered
  - more instrumentation like tracker is affordable
- Higher sensitivities or stronger exclusion limits are expected
- Technically feasible (cal, e.g., up to 7.0)?


Thank you!

Higgs Quartic Coupling

- In a more general context, to reconstruct the full Higgs potential, we need to measure Higgs quartic self-coupling
- The relations among Higgs mass, its quartic and the cubic couplings are model dependent

$$\mathcal{L}_{\mathrm{D6}} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2}\mathcal{O}_i \quad \mathcal{O}_1 = \frac{1}{2}\partial_\mu(\phi^\dagger\phi)\,\partial^\mu(\phi^\dagger\phi) \quad \mathcal{O}_2 = -\frac{1}{3}(\phi^\dagger\phi)^3$$

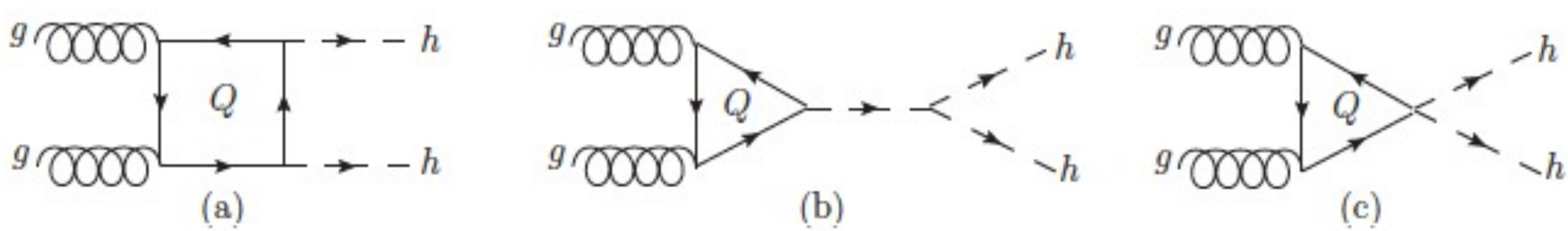
$$\mathcal{L}_{\mathrm{mass}} = -2\lambda v^2\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{3 f_2 v^2}{16\Lambda^2\lambda} + \mathcal{O}(\Lambda^{-4})\right)H^2$$

$$\begin{aligned}\mathcal{L}_{\mathrm{self}} = &-\frac{m_H^2}{2v}\left[\left(1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2 f_2 v^4}{3\Lambda^2 m_H^2}\right)H^3 - \frac{2 f_1 v^2}{\Lambda^2 m_H^2}H\,\partial_\mu H\,\partial^\mu H\right] \\ &-\frac{m_H^2}{8v^2}\left[\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4 f_2 v^4}{\Lambda^2 m_H^2}\right)H^4 - \frac{4 f_2 v^2}{\Lambda^2 m_H^2}H^2\,\partial_\mu H\partial^\mu H\right]\end{aligned}$$

- HL-LHC (impossible): gg -> hhh, 0.4fb
- 100 TeV (extremely challenging): 4fb; ~ 10 events for hhh -> bbbb + diphoton
- New strategies are needed!

Disentanglement from NP

- The di-Higgs production may receive contributions from various sources.
- E.g, both pp > tthh or pp > hh can be kinematically modified by $$\frac{t\bar{t}hh}{\Lambda}$$



- How to disentangle the contributions of tri-Higgs coupling and other NP to di-Higgs production?
- For recent studies on the case of pp > hh, e.g, see [C. Chen and I. Low. '14]