Higgs Physics after Higgs

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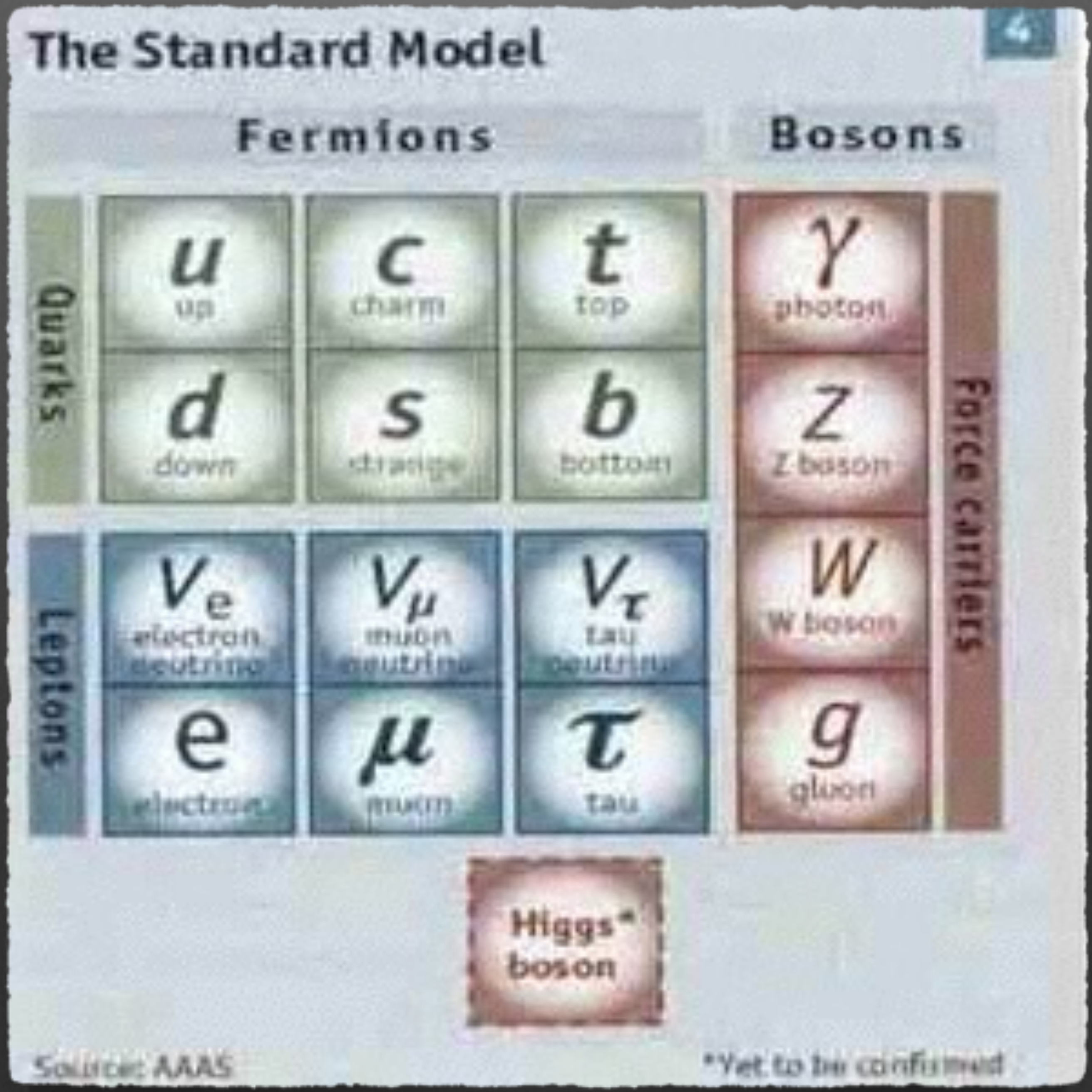
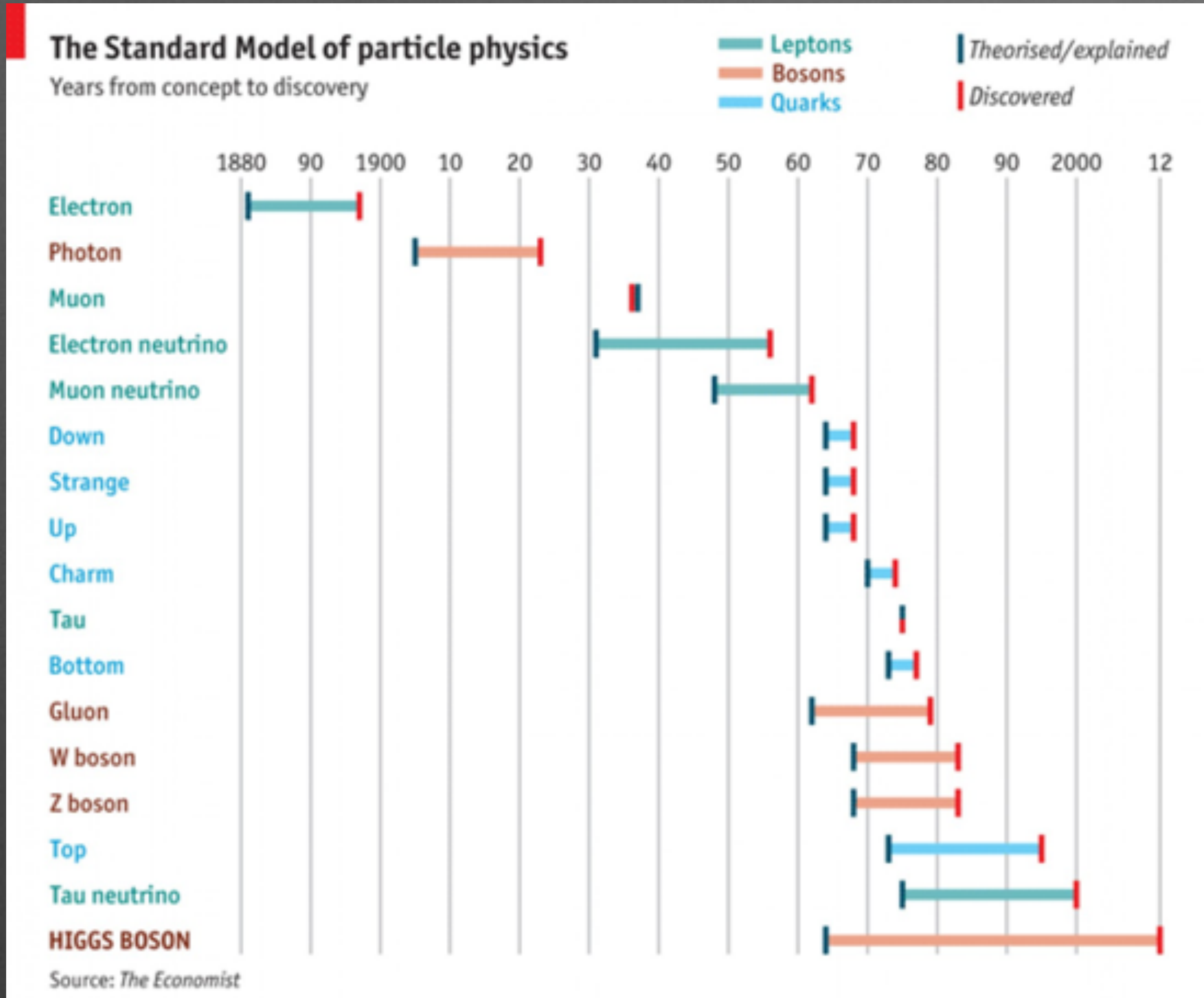
For University of Science and Technology of China, Jul 8th, 2015

Base on Phys.Rev. D90 (2014) 7, 076004 in collaboration with Edmond L. Berger, Steven B. Giddings and Haichen Wang;
arXiv:1410.1855[hep-ph] in collaboration with Tao Liu;
JHEP 1506 (2015) 137 in collaboration with Nathaniel Craig, Francesco D'Eramo, Patrick Draper and Scott Thomas

Introduction

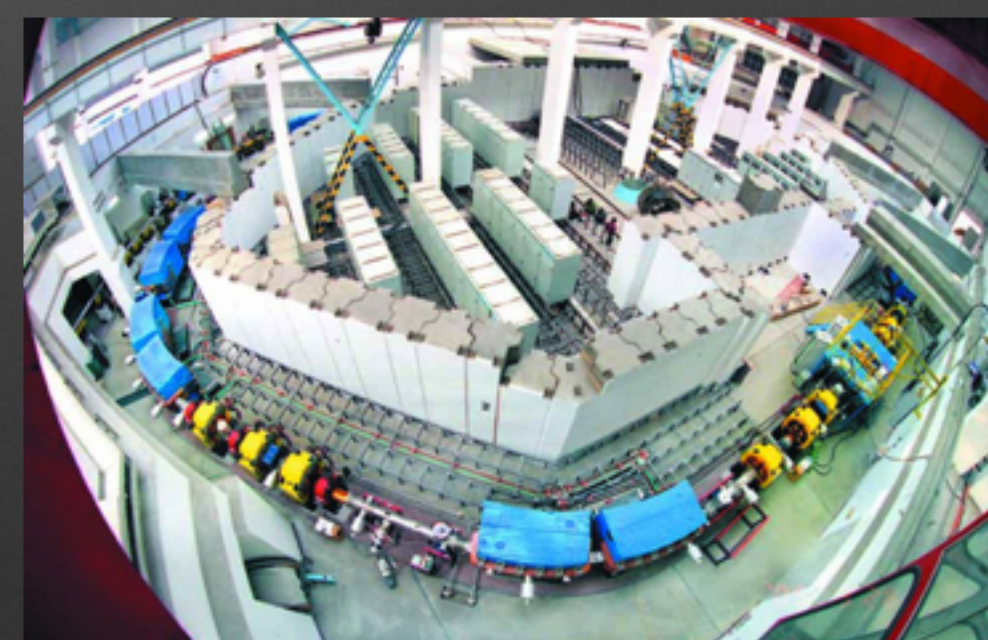
- Particle physics standard model (SM) is one of the most successful physics models.




The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880 90 1900 10 20 30 40 50 60 70 80 90 2000 12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

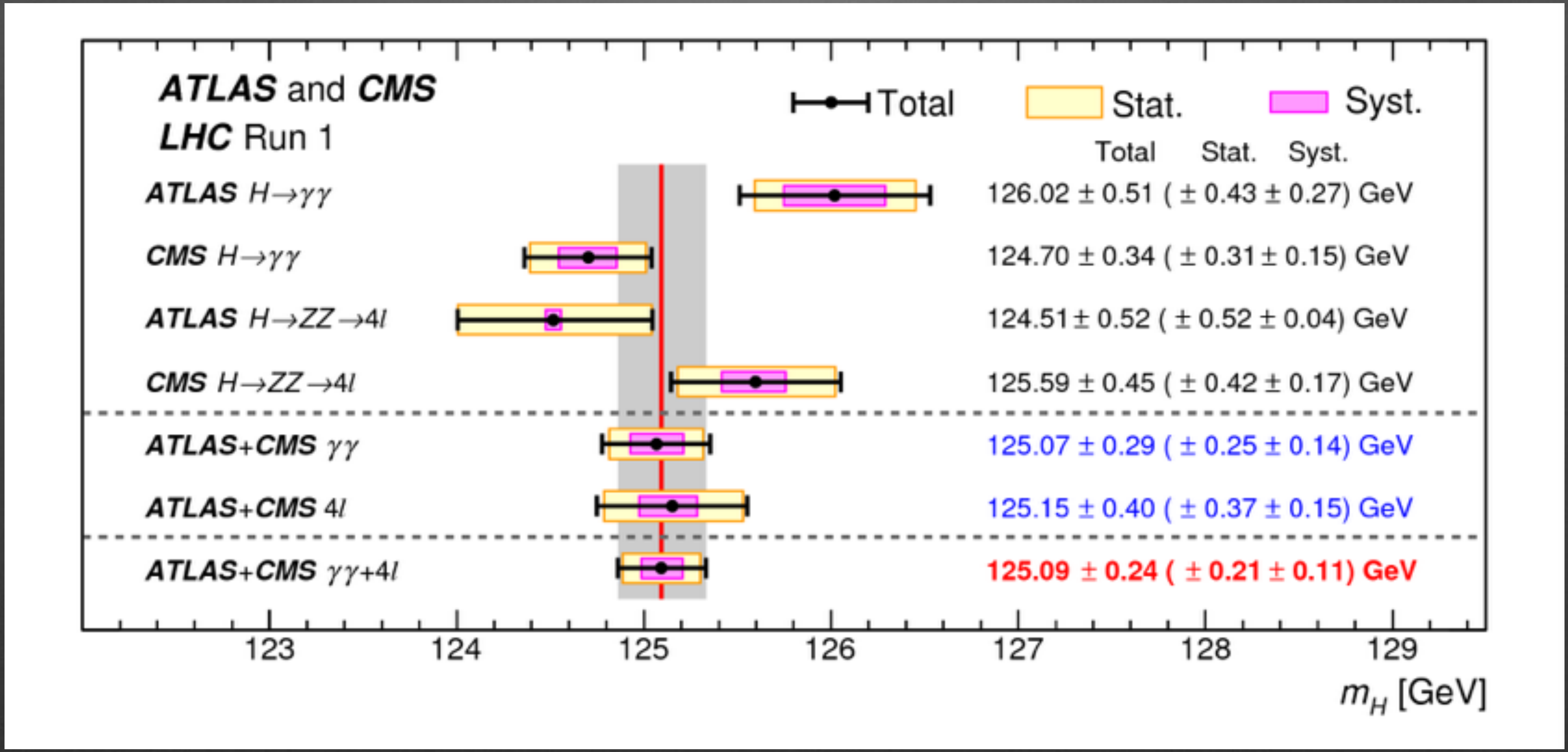

SLAC
NATIONAL
ACCELERATOR
LABORATORY


ALICE
CMS
ATLAS
LHCb



Introduction

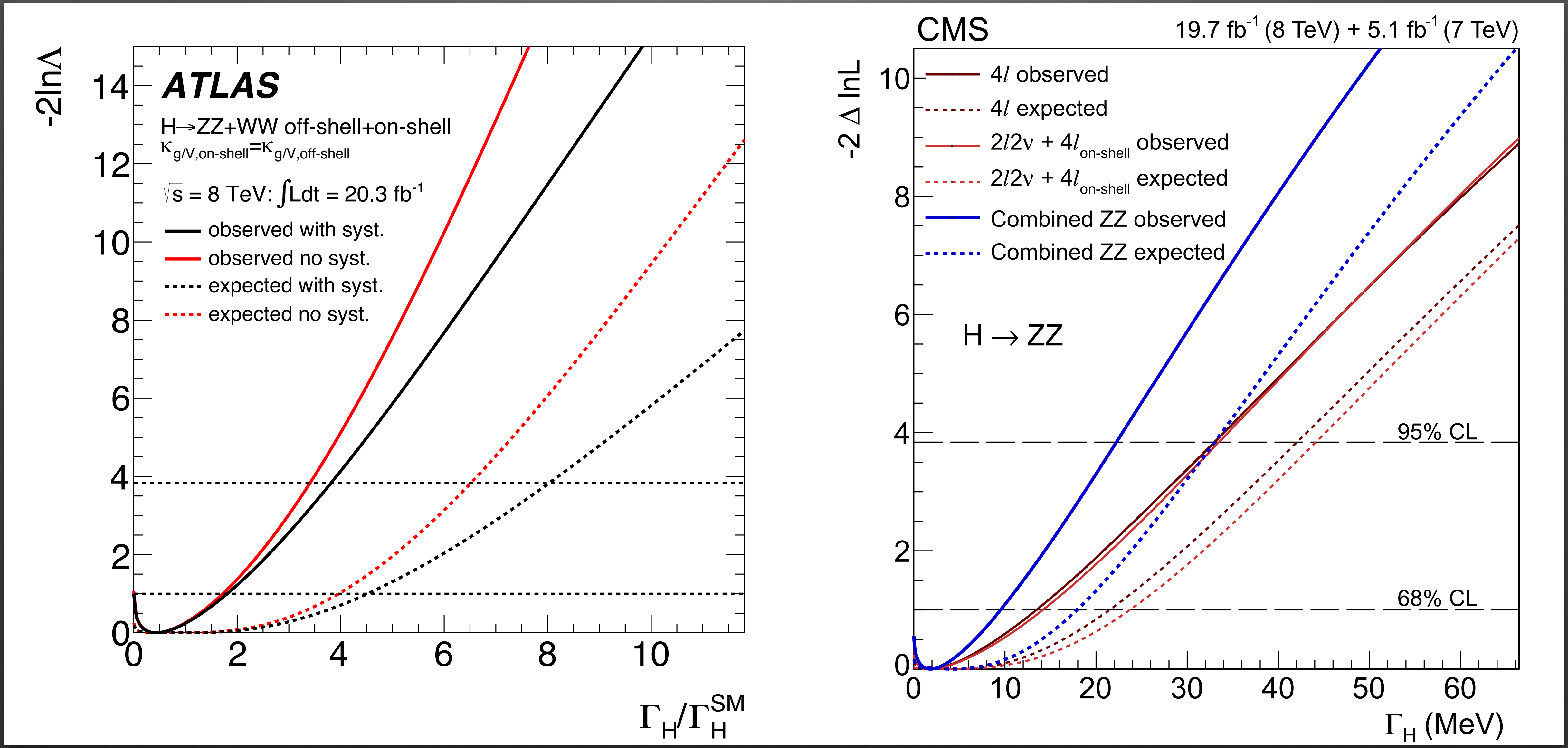
- The mass of the “Higgs” boson



ATLAS and CMS Collaboration, PRL 114, 191803 (2015)

Introduction

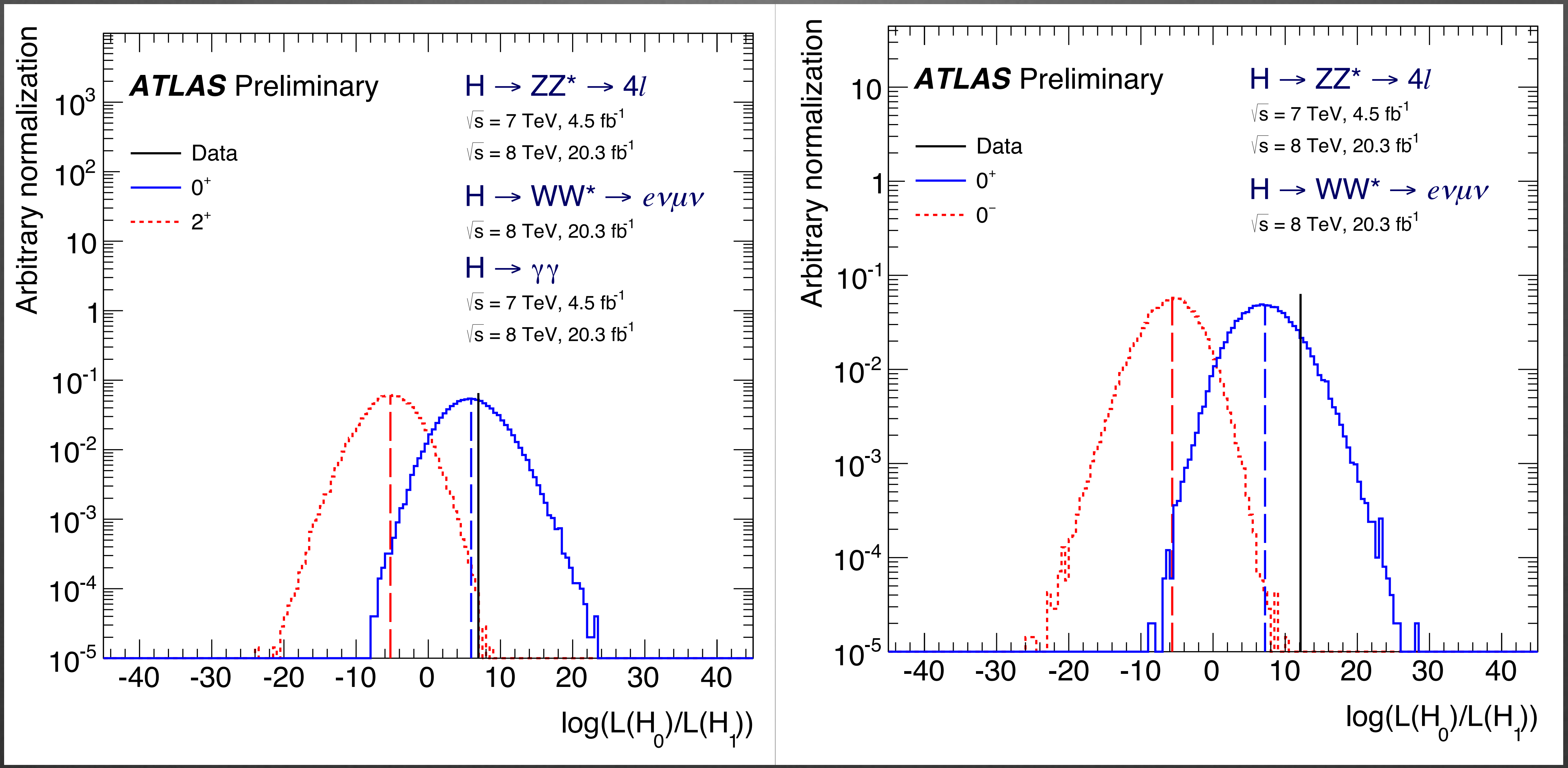
- The width of the “Higgs” boson



ATLAS, arXiv:1503.01060[hep-ex]; CMS Collaboration, PLB 736 (2014) 64-85

Introduction

- The spin of the “Higgs” boson



ATLAS Collaboration, ATLAS-CONF-2015-008

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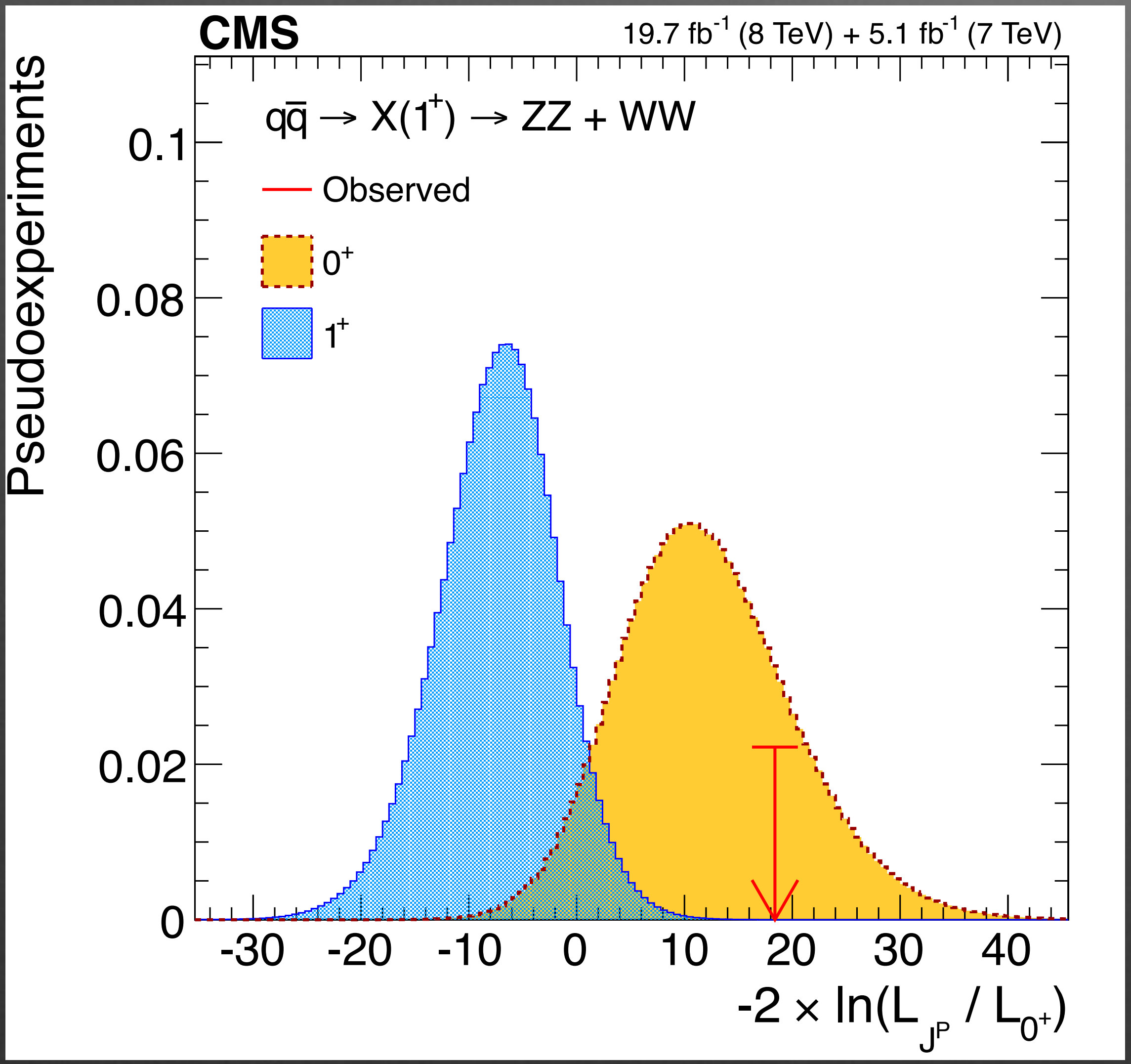
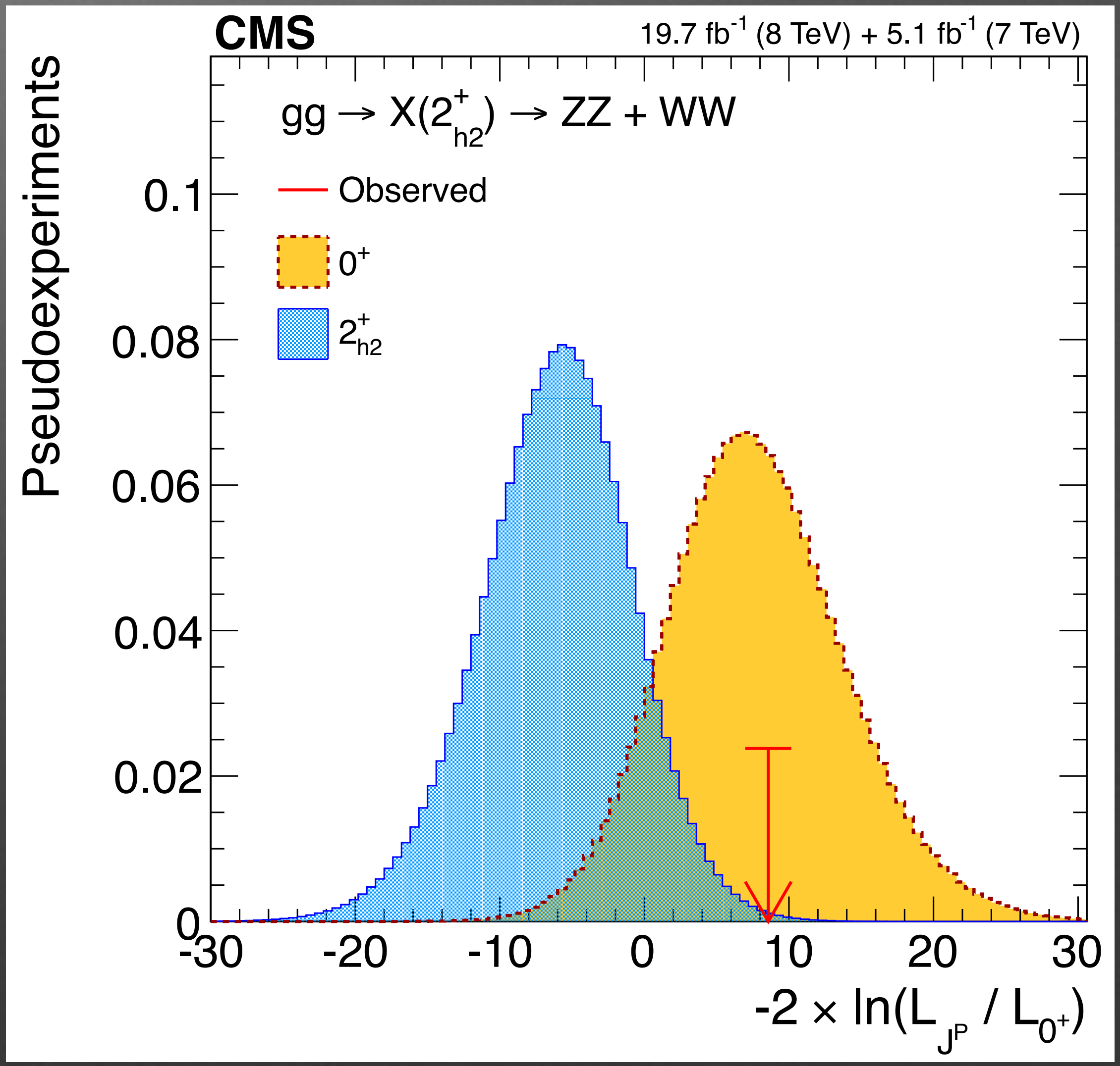
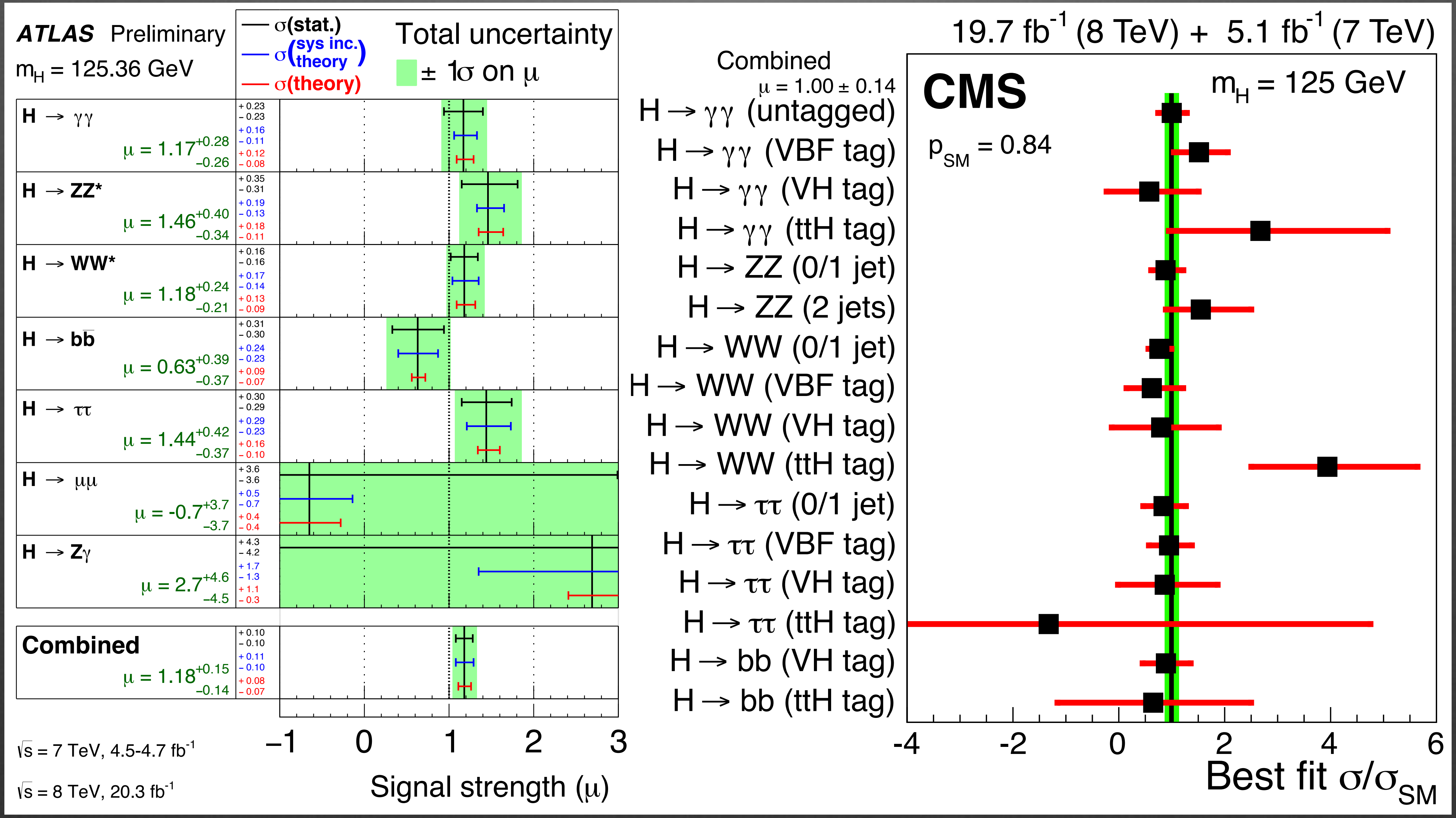




CMS Collaboration, arXiv:1411.3441[hep-ex]

Introduction

- The interactions between the “Higgs” boson and the other SM particles



ATLAS Collaboration, ATLAS-CONF-2015-007; CMS Collaboration, EPJC 75 (2015) 5, 212

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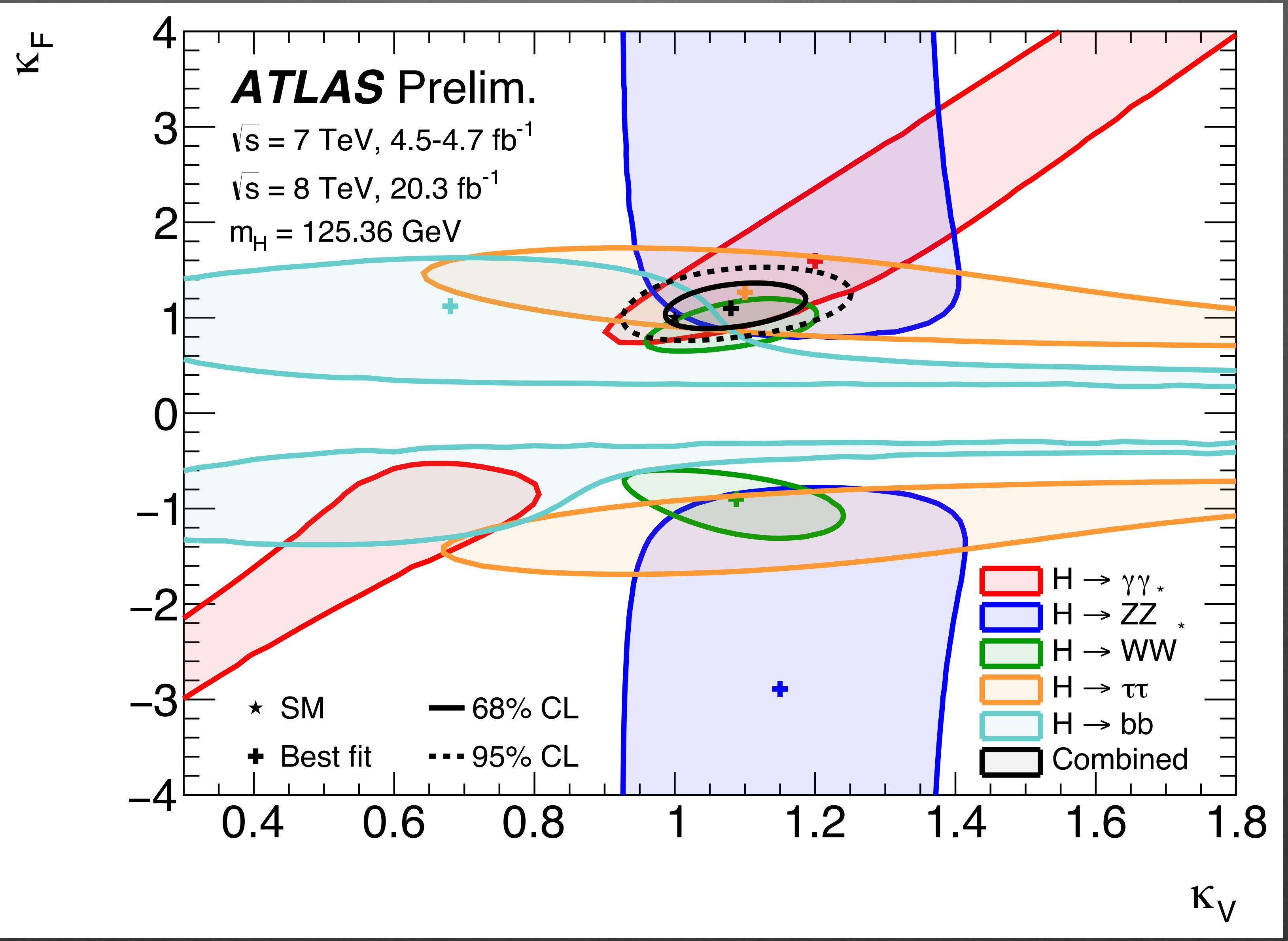

ATLAS Collaboration, ATLAS-CONF-2015-007; CMS Collaboration, EPJC 75 (2015) 5, 212

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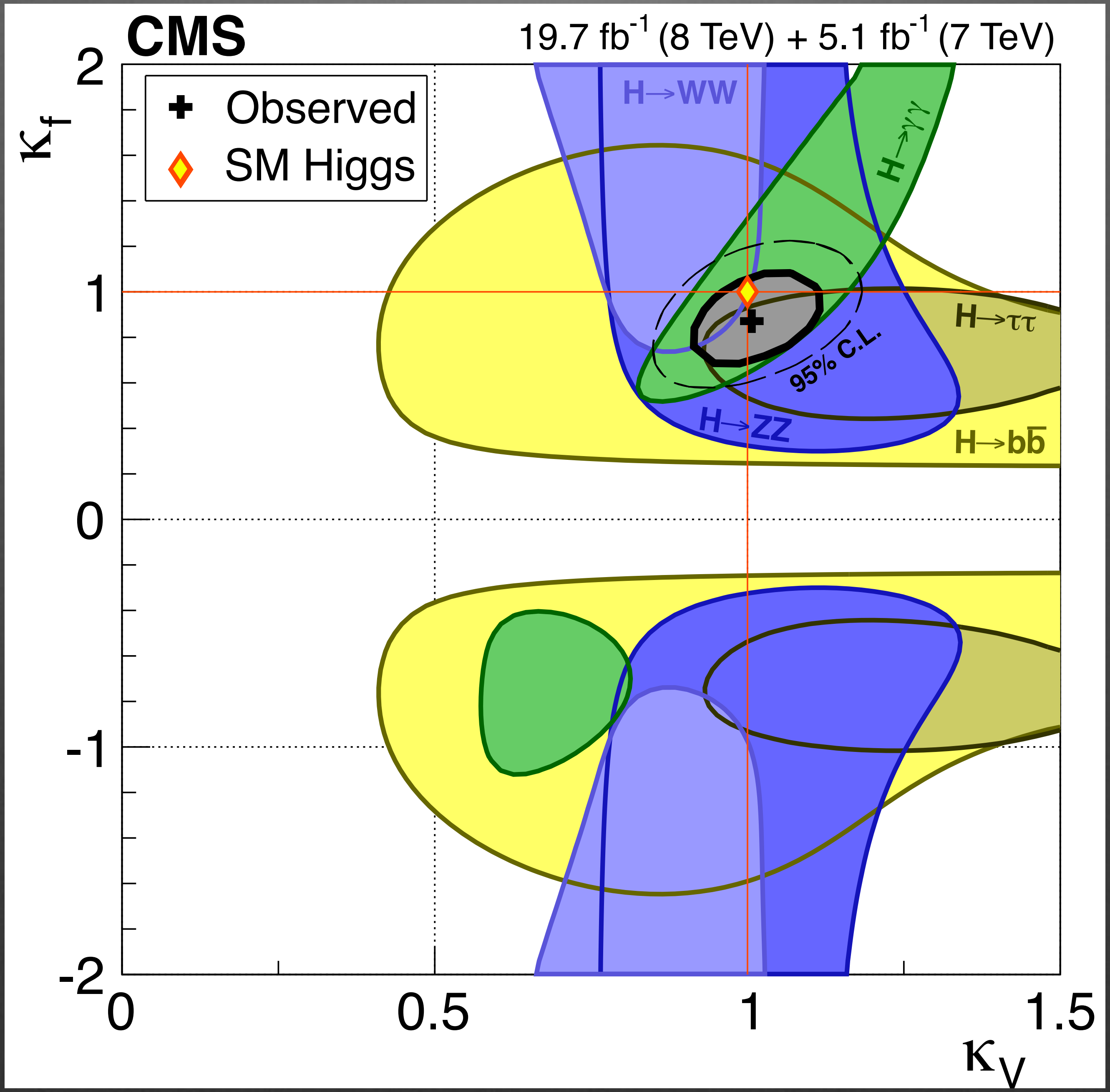
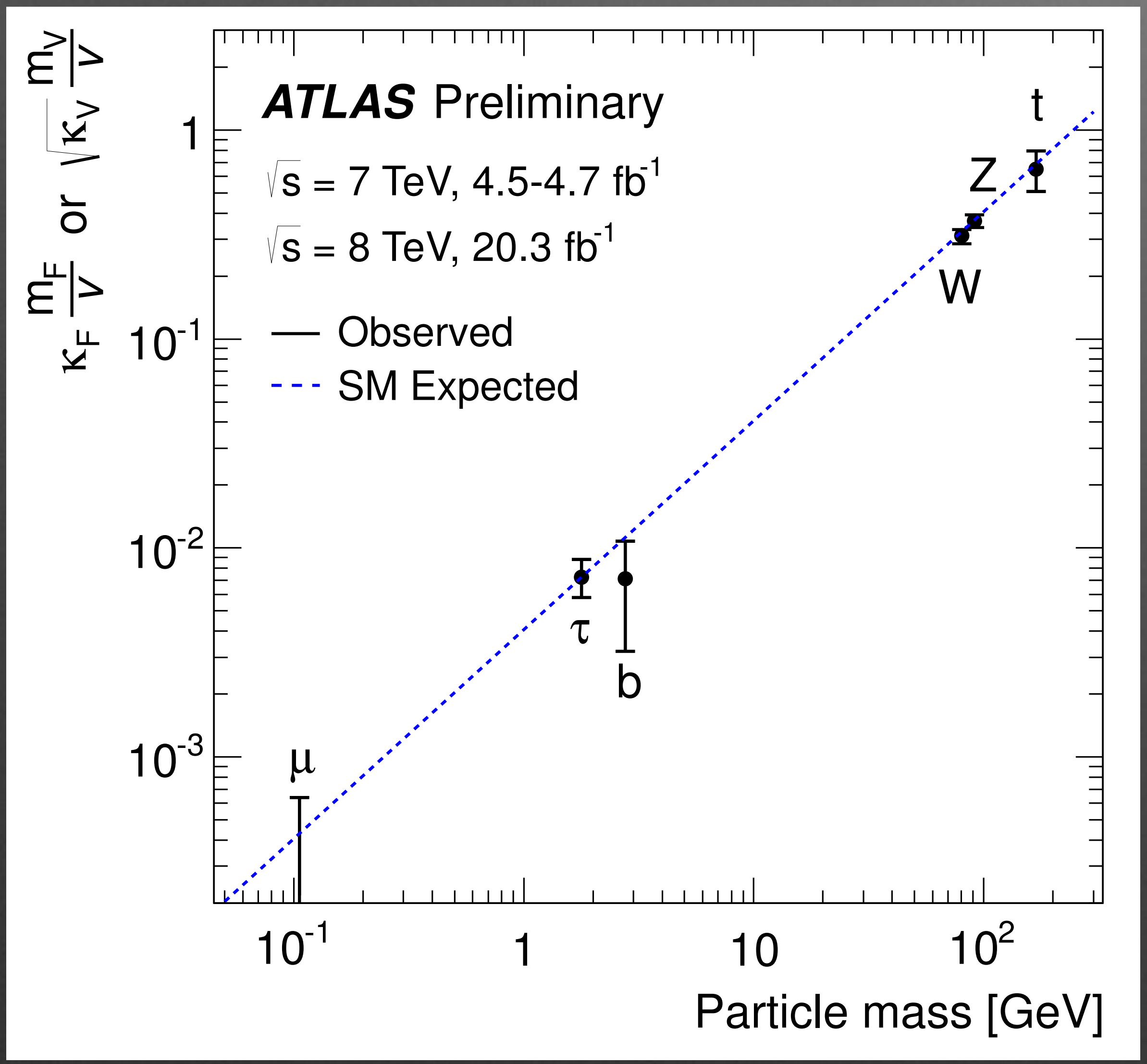
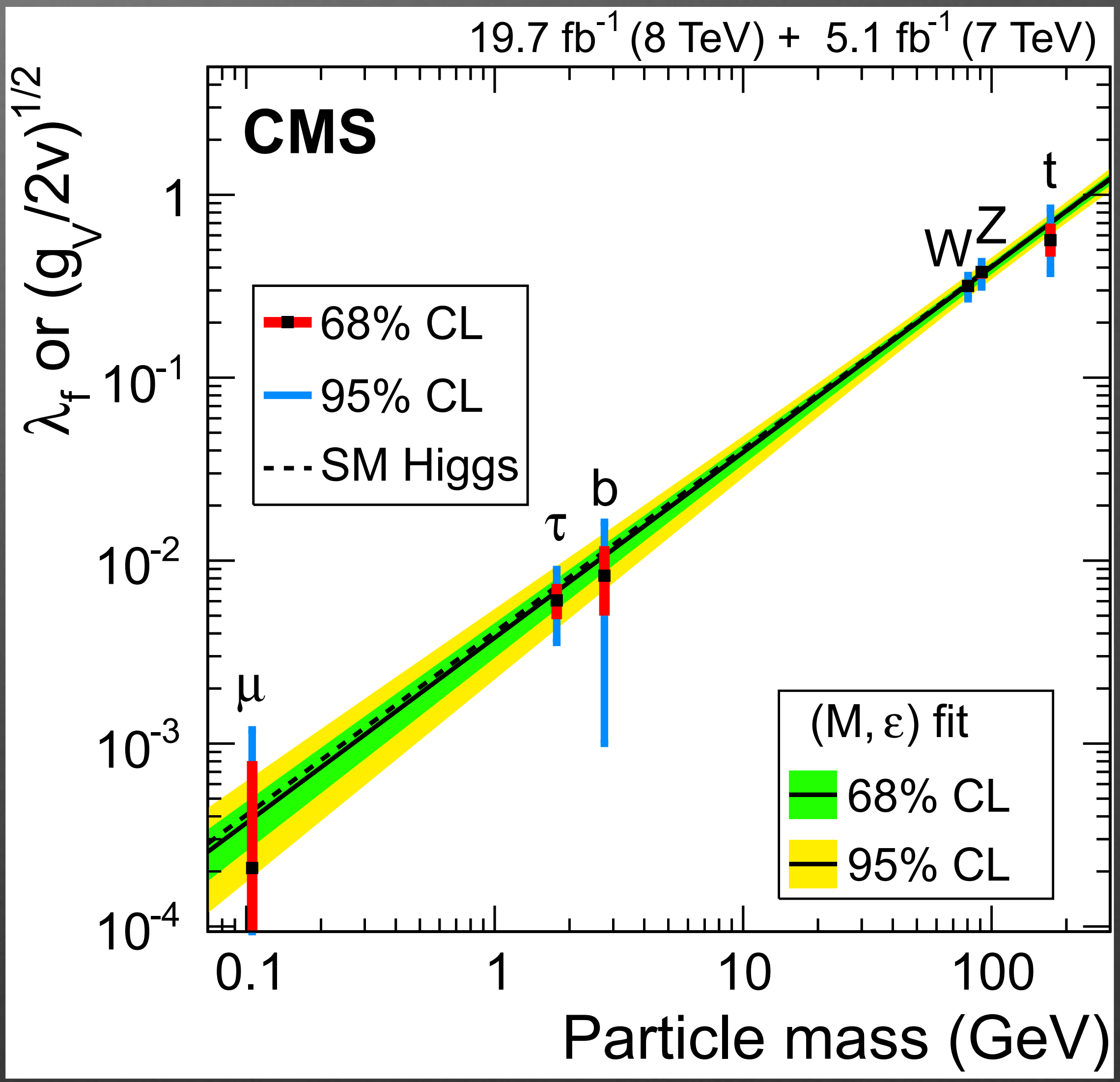


ATLAS Collaboration, ATLAS-CONF-2015-007; CMS Collaboration, EPJC 75 (2015) 5, 212

Introduction

- The origin of the mass of the SM particles





ATLAS Collaboration, ATLAS-CONF-2015-007; CMS Collaboration, EPJC 75 (2015) 5, 212

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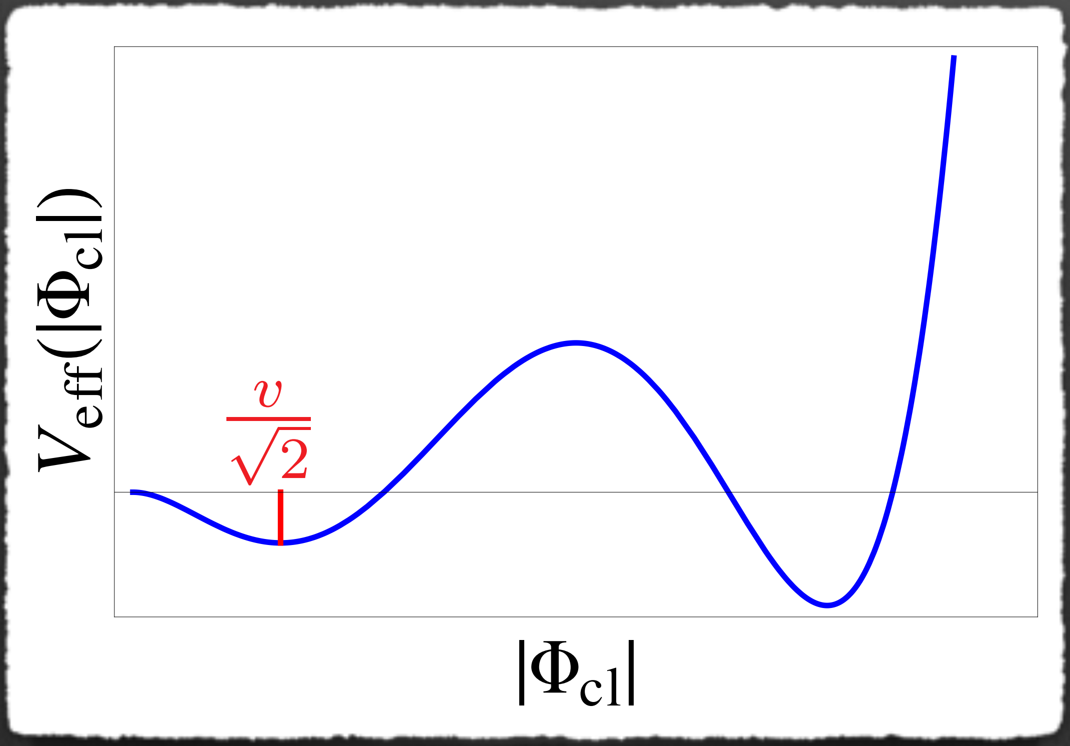
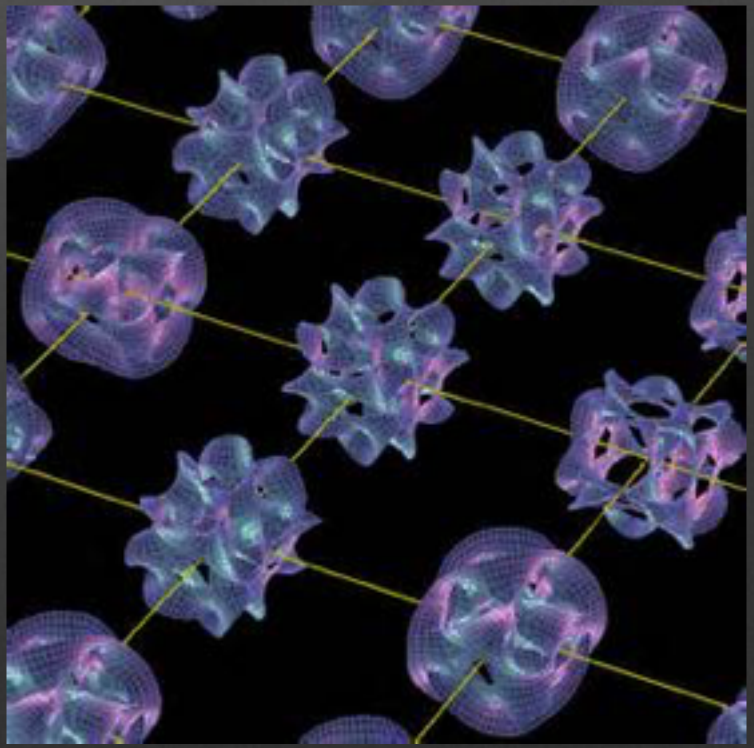
In the next ten years, the most important discovery in high energy physics is that 'the party's over'.

Introduction

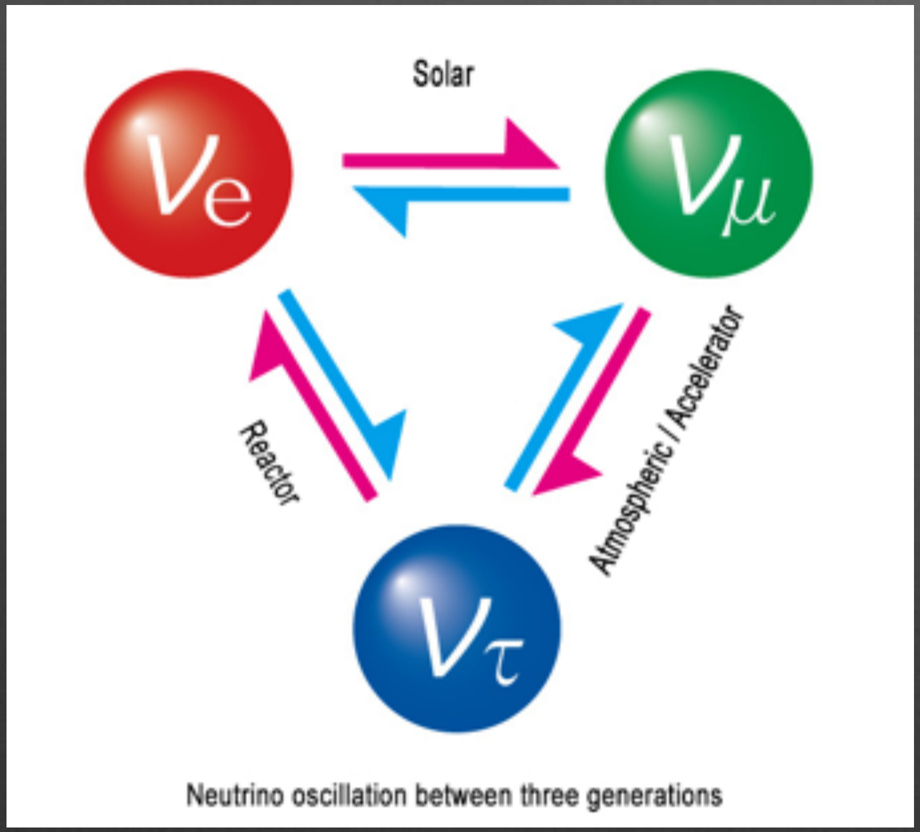
- As a renormalizable theory, there is not any explicit cutoff scale in the SM. But
    - Intrinsic scales: Landau pole (very high), vacuum stability.
    - Scale from Gravity: M_{Pl}.
- The SM must be a low energy effective theory!

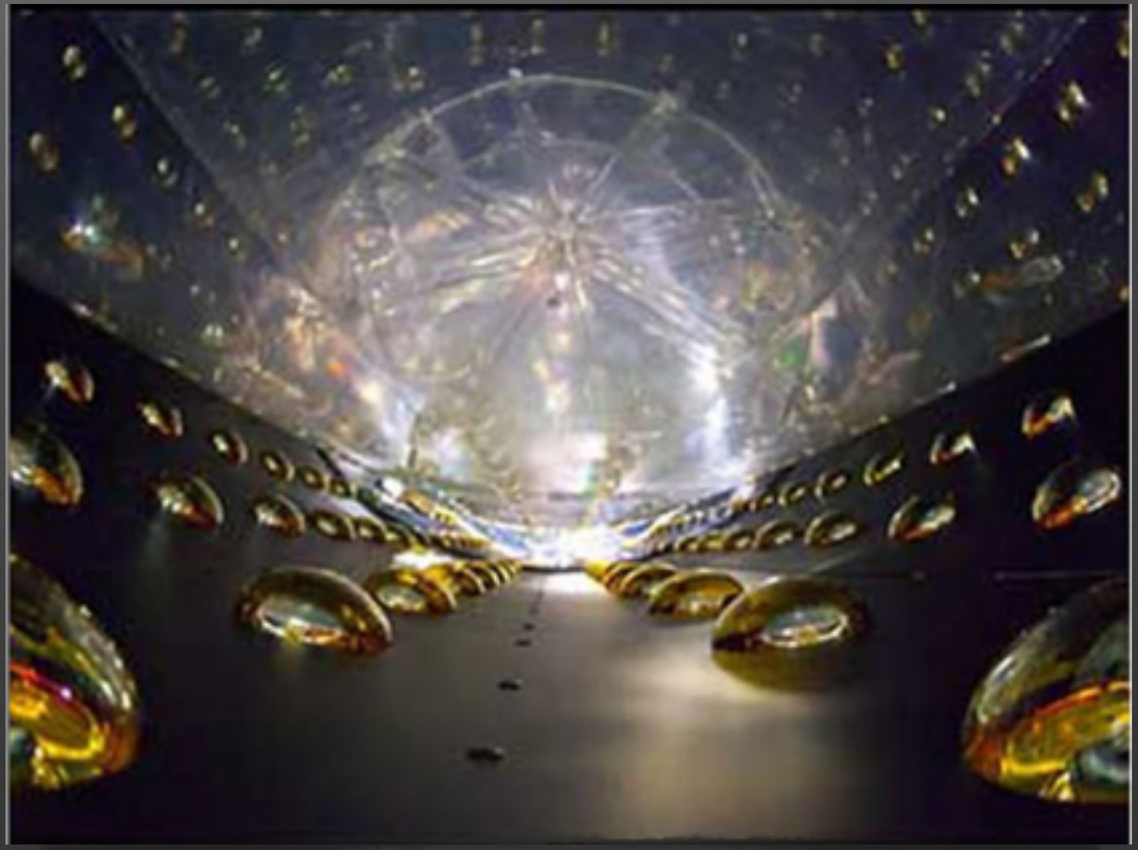




Introduction

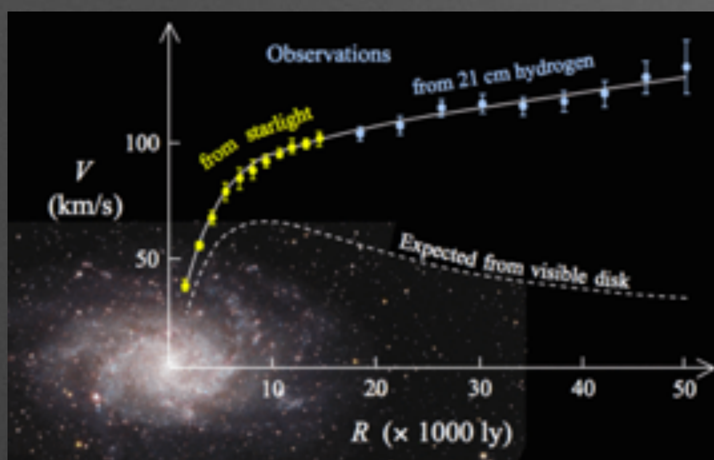
- SM can not be the whole story.
  - Neutrino masses, mixing

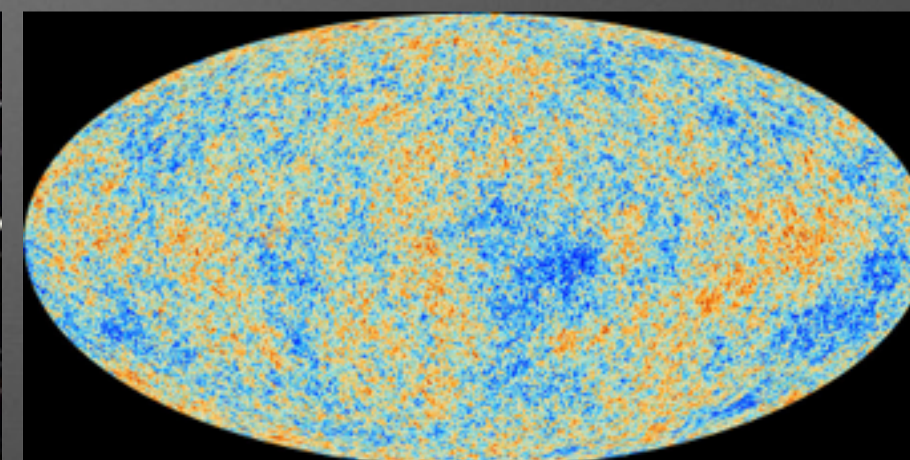


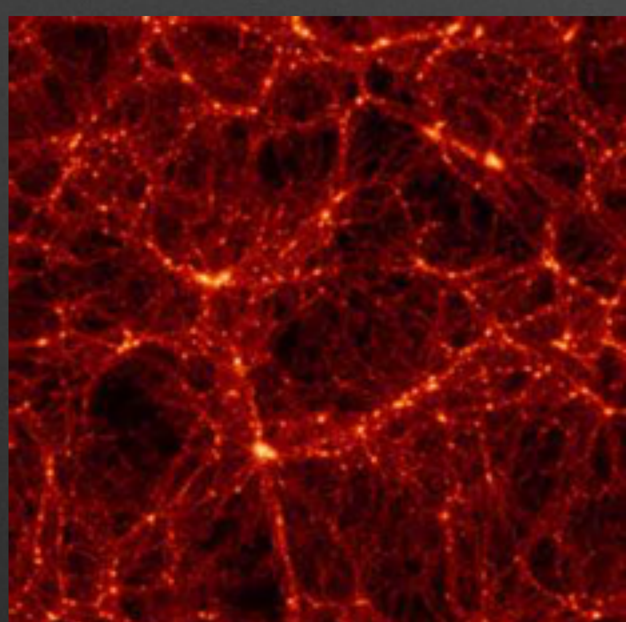


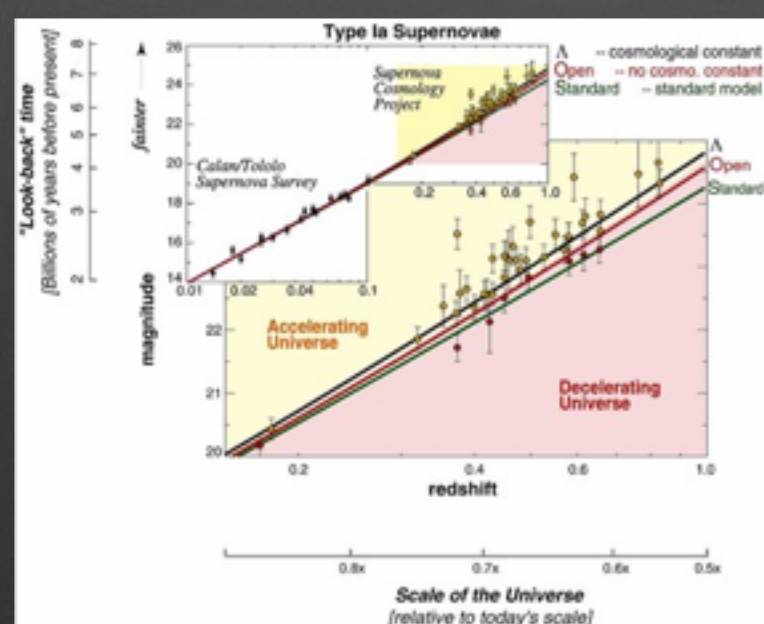
Introduction

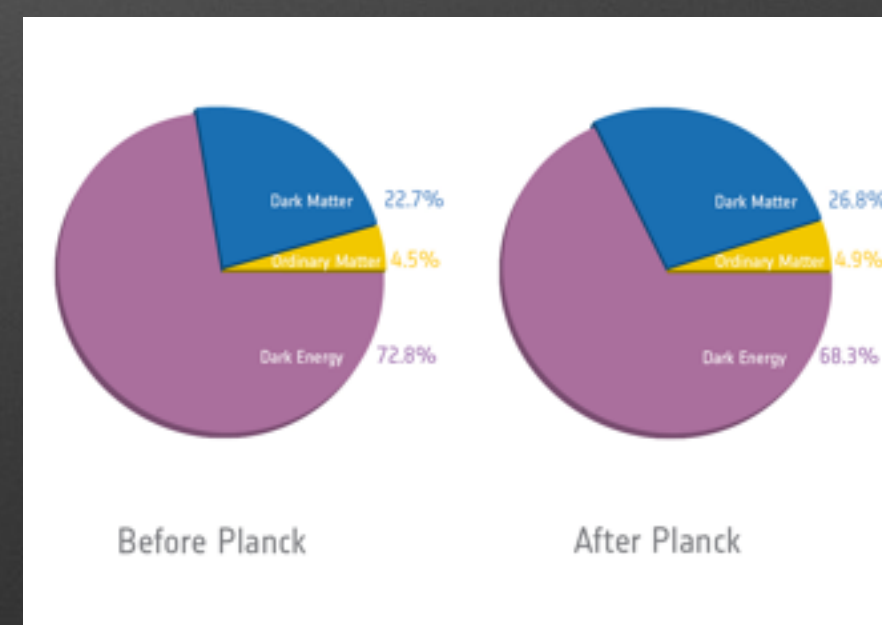
- SM can not be the whole story.
  - Dark matter, dark energy, matter-antimatter asymmetry











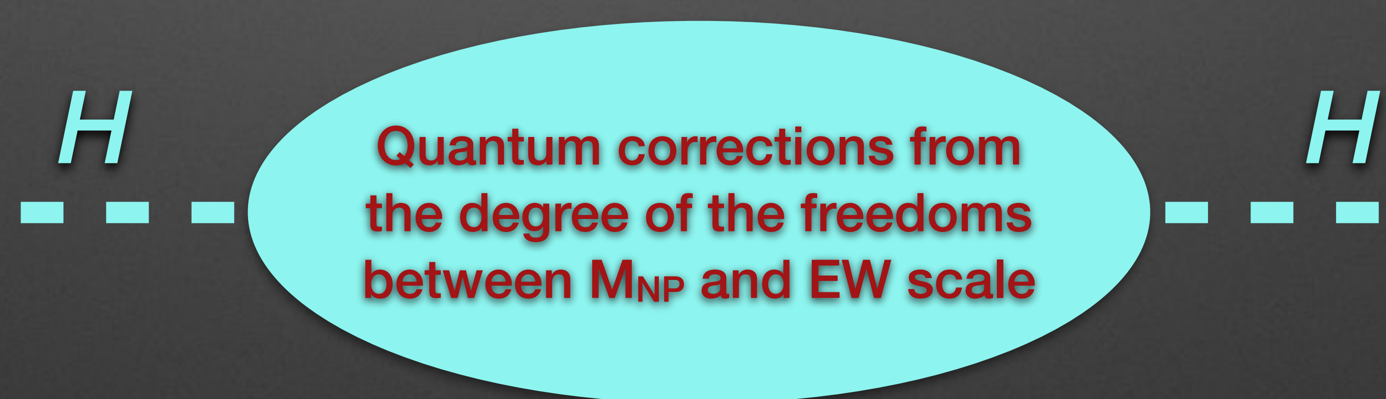
Introduction

- Theoretical problems
  - Physical cutoff scale M_{NP} ➠ Hierarchy problems
    - Hierarchy problem I: Higgs mass

Introduction

- If $M_{NP} \sim M_{Pl}$ (or M_{GUT}) $\gg m_Z \sim m_H$
  - How to stabilize the scalar mass parameter?
  - How to generate such a small mass scale in the UV theory?

M_{NP} scale input of $m_H^2 \sim M_{NP}^2$



$$\delta m_H^2 \sim M_{NP}^2/16\pi^2$$

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    - Hierarchy problem I: Higgs mass
    - Hierarchy problem II: Cosmological constant! Landscape?

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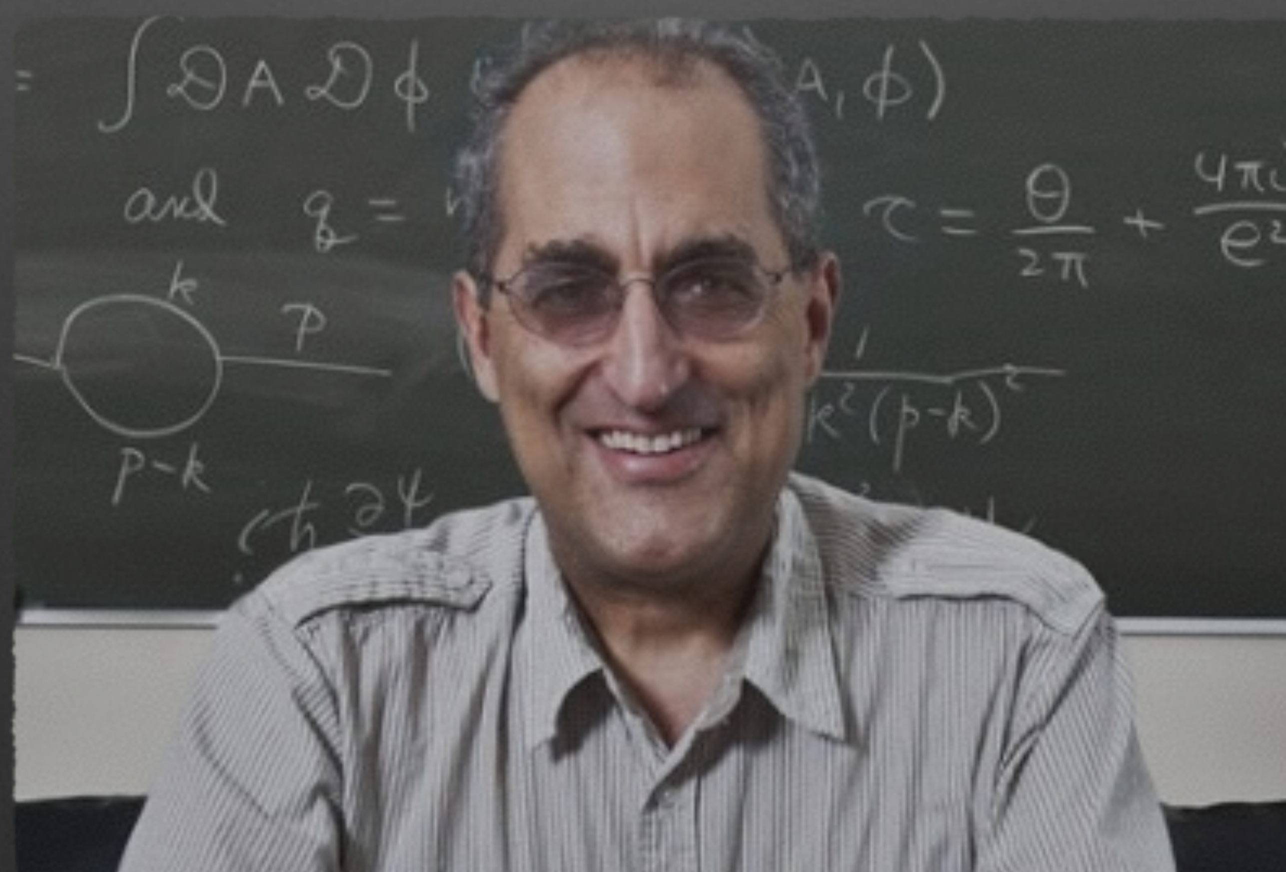

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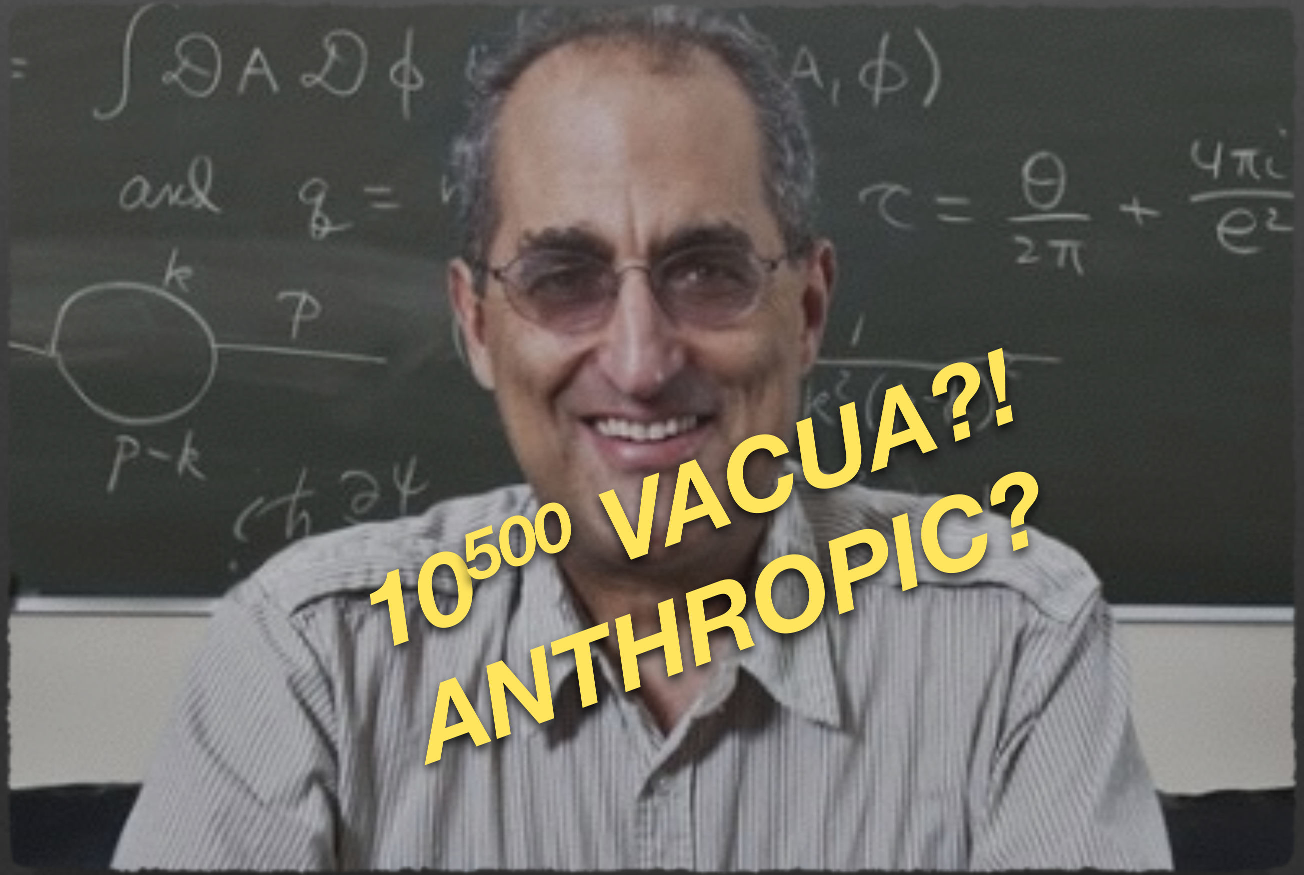
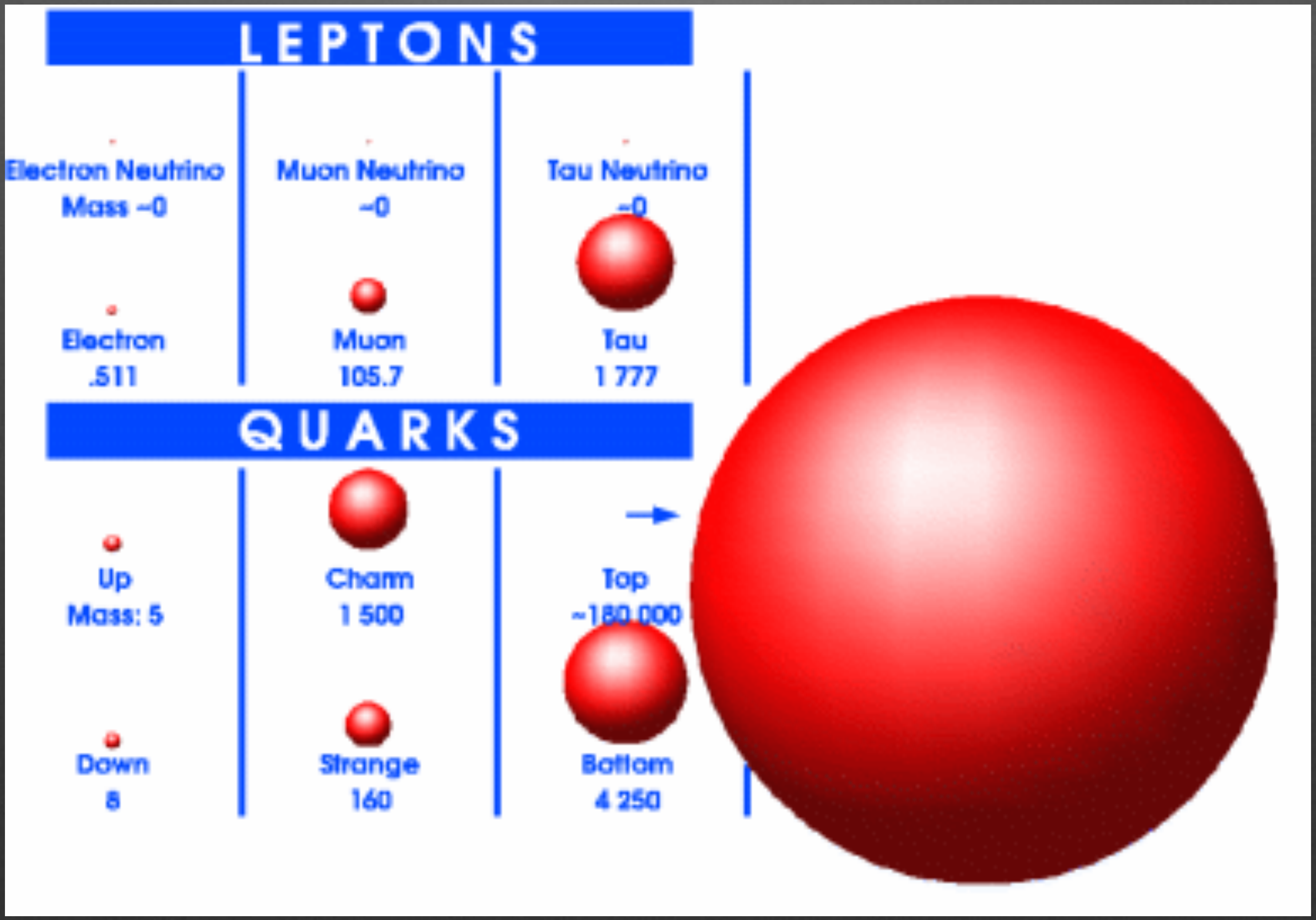


Introduction

- Theoretical problems
    - Fermion mass hierarchy



Introduction

- SM can not be the whole story.
  - Neutrino masses, mixing
  - Dark matter, dark energy, matter-antimatter asymmetry
- Theoretical problems
  - Hierarchy problem
  - Fermion mass hierarchy
  - Vacuum stability
  - Strong CP problem, …
  - Quantum Gravity

Introduction

- New physics must be there!
- But where is it?
  - Hierarchy problem ➠ ~ 1 TeV
  - FCNC ➠ $\gtrsim$ 100~1000 TeV (?)
  - Vacuum stability ➠ $\lesssim 10^6$ TeV
  - Neutrino mass and mixing, dark matter, inflation… Highly model dependent !
  - GUT ➠ ~ 10^{16} GeV
  - Quantum gravity ➠ M_{Pl}
  - …

Higgs Physics after Higgs

- Exotic scalar fields exist in a lot of new physics models.

  2HDM, Z', W', MSSM, NMSSM, Little Higgs model, LR model, Flavor symmetry model …

- Are they necessary? What are the advantages?

Higgs Physics after Higgs

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- Are they necessary? What are the advantages?

- Example: MSSM

  Single Higgs doublet

  ⇒ Weyl fermion with gauge quantum number

  ⇒ anomaly

  Holomorphic principle

  ⇒ H* is forbidden in the superportential

  ⇒ up-type fermion can not get mass

Higgs Physics after Higgs

- Exotic scalar fields exist in a lot of new physics models.

  2HDM, Z', W', MSSM, NMSSM, Little Higgs model, LR model, Flavor symmetry model …

- Are they necessary? What are the advantages?

  - Breaking new symmetries, Required by holomorphic principle in SUSY model, New source for CP violation, Electroweak baryogenesis, Neutrino masses and mixing, …

- Additional scalars ⇒ much more fine-tuning

  - Need to be explained. Strong hint for additional new physics!

Higgs Physics after Higgs

- The exotic scalars will contribute to the scalar potential and modify the behavior of the SM-like Higgs boson.

- If the exotic scalars carry non-trivial quantum numbers of the SM electroweak gauge group, they will interact with the SM gauge bosons and may contribute to the EWSB.

Higgs, or Higgses, that is the question.

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Higgs Physics after Higgs

Modification of the Higgs physics in special new physics models

Alignment limit of the Extended Higgs sector

Rare Higgs processes at Colliders

Modification of the Higgs physics in special new physics models

based on Phys.Rev. D90 (2014) 7, 076004 in collaboration with Edmond L. Berger, Steven B. Giddings and Haichen Wang

Flavor symmetry model

- SM FCNC processes are highly suppressed!
- No signal of exotic FCNC is observed in experiments.
- If there is not special flavor structure in the new physics,

$$\mathcal{C}_{\rm SM} \sim \frac{g_2^4 |V_{\rm CKM}|^2}{16\pi^2 m_W^2}, \quad \mathcal{C}_{\rm NP} \sim \frac{g_{\rm NP}^2}{\Lambda^2}, \quad \Rightarrow \Lambda \sim \frac{4\pi v}{|V_{\rm CKM}|} \sim 100 {\rm TeV}$$

- NP appears above 100 TeV ….
- Or special flavor structure in NP sector to suppress its contribution to FCNC —— MFV

$$\begin{aligned} G_f \equiv & SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R} \\ & \otimes U(1)_B \otimes U(1)_L \otimes U(1)_Y \otimes U(1)_{PQ} \otimes U(1)_{E_R} \end{aligned}$$

G. D'Ambrosio et al. Nucl Phys B 645 (2002) 155-187

Flavor symmetry model

- Yukawa matrices — spurion fields, dynamical degree of freedoms?

- Goldstone modes —> FCNC

- Flavor symmetry model with inverted hierarchy structure.

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm kinetic\,+\,gauge} - (-\lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \bar{\Psi}_u Y_u \Psi_{uR} + M_u \bar{\Psi}_u U_R - \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda'_d \bar{\Psi}_d Y_d \Psi_{dR} + M_d \bar{\Psi}_d D_R + \text{h.c.}) - V(Y_u, Y_d, H).$$

	$SU(3)_{Q_L}$	$SU(3)_{U_R}$	$SU(3)_{D_R}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	**3**	**1**	**1**	**3**	**2**	1/6
U_R	**1**	**3**	**1**	**3**	**1**	2/3
D_R	**1**	**1**	**3**	**3**	**1**	−1/3
Ψ_u	**1**	**3**	**1**	**3**	**1**	2/3
Ψ_d	**1**	**1**	**3**	**3**	**1**	−1/3
Ψ_{uR}	**3**	**1**	**1**	**3**	**1**	2/3
Ψ_{dR}	**3**	**1**	**1**	**3**	**1**	−1/3
Y_u	$\bar{\mathbf{3}}$	**3**	**1**	**1**	**1**	0
Y_d	$\bar{\mathbf{3}}$	**1**	**3**	**1**	**1**	0
H	**1**	**1**	**1**	**1**	**2**	1/2

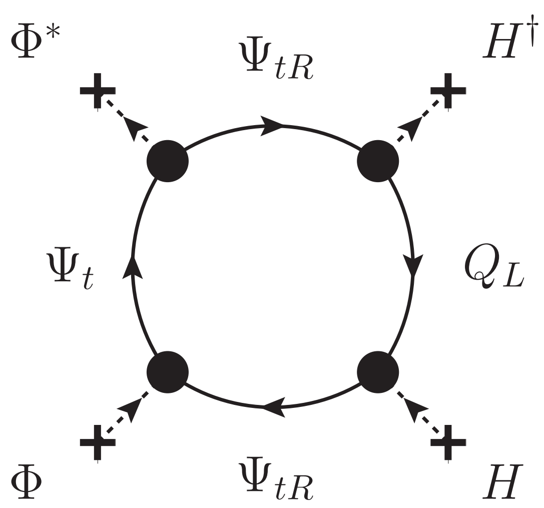
B. Grinstein, M. Rebi, and G. Villadoro, JHEP 1011 067 (2010)

Flavor symmetry model

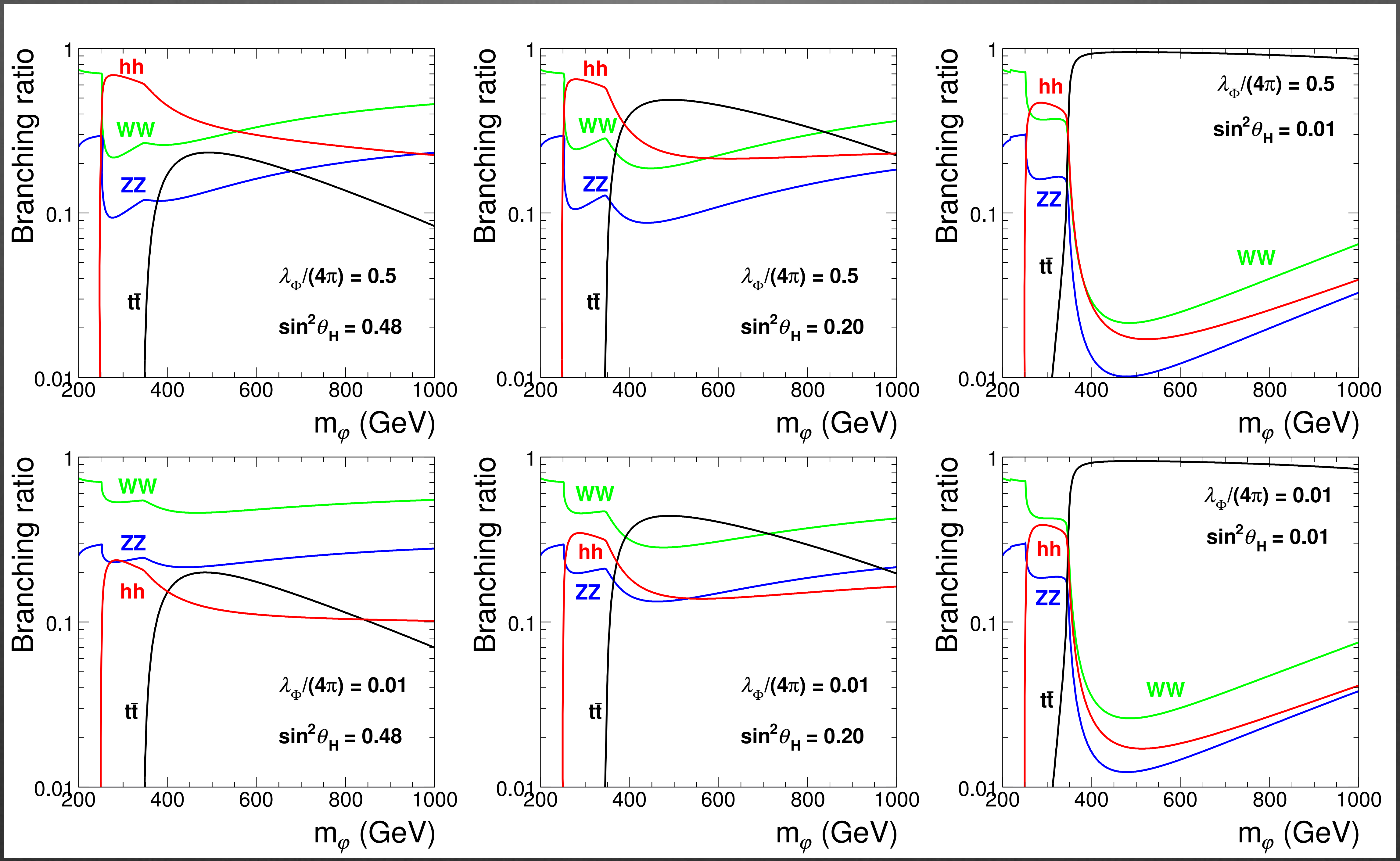
- Low energy effective Lagrangian

$$\mathcal{L}_{\text{top-flavor}} = \lambda \bar{Q}_L \tilde{H} \Psi_{tR} - \lambda' \bar{\Psi}_t \Phi \Psi_{tR} - M \bar{\Psi}_t t_R + \text{h.c.},$$

$$V(H,\Phi) = \frac{\lambda_H}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_\Phi}{2}\left(\Phi^*\Phi\right)^2 - \frac{1}{2}m_H^2\left(H^\dagger H\right) - \frac{1}{2}m_\Phi^2(\Phi^*\Phi) + \xi(\Phi^*\Phi)\left(H^\dagger H\right).$$



Flavon physics



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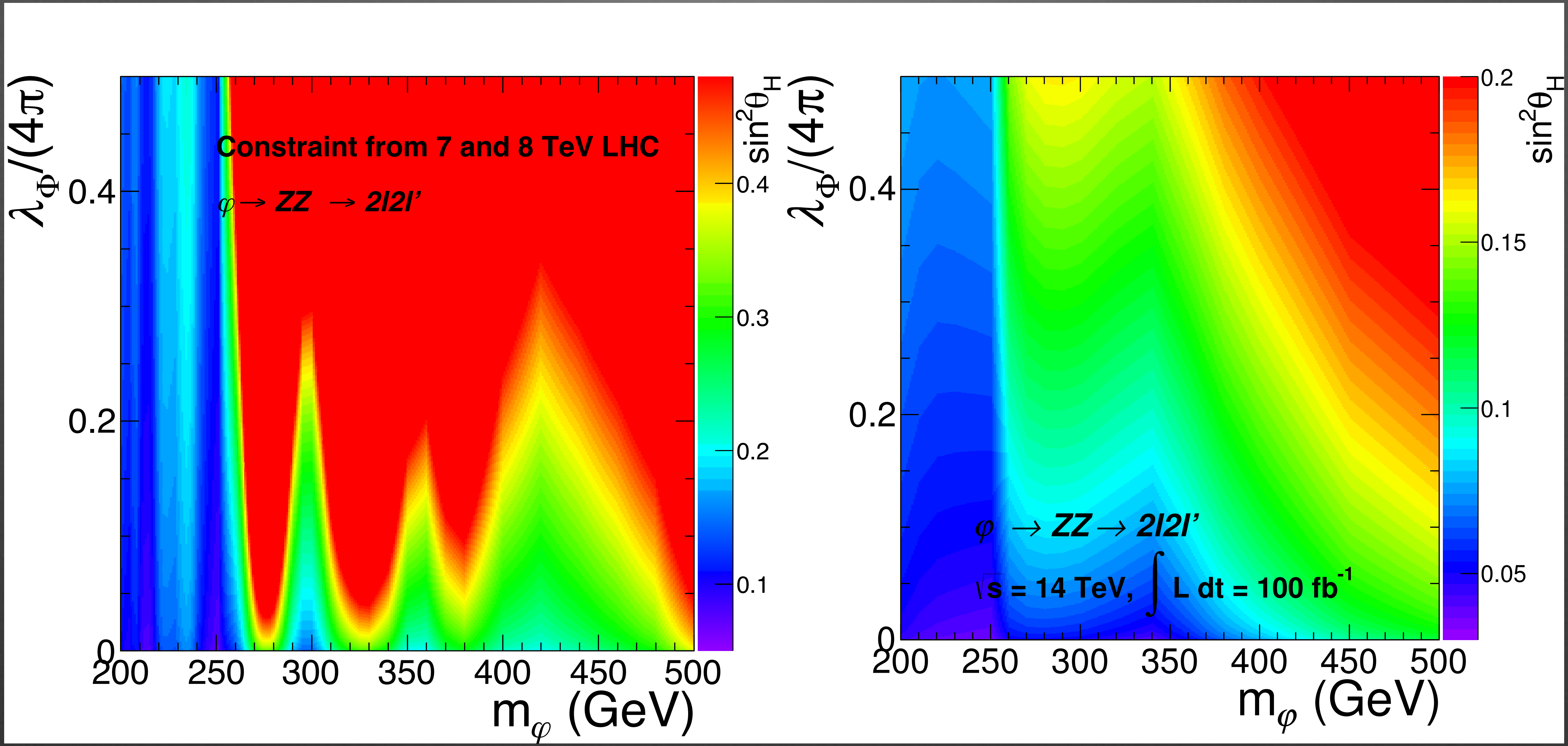

ATLAS Collaboration, ATLAS-CONF-2013-013; CMS Collaboration, PRD 89,092007 (2014)

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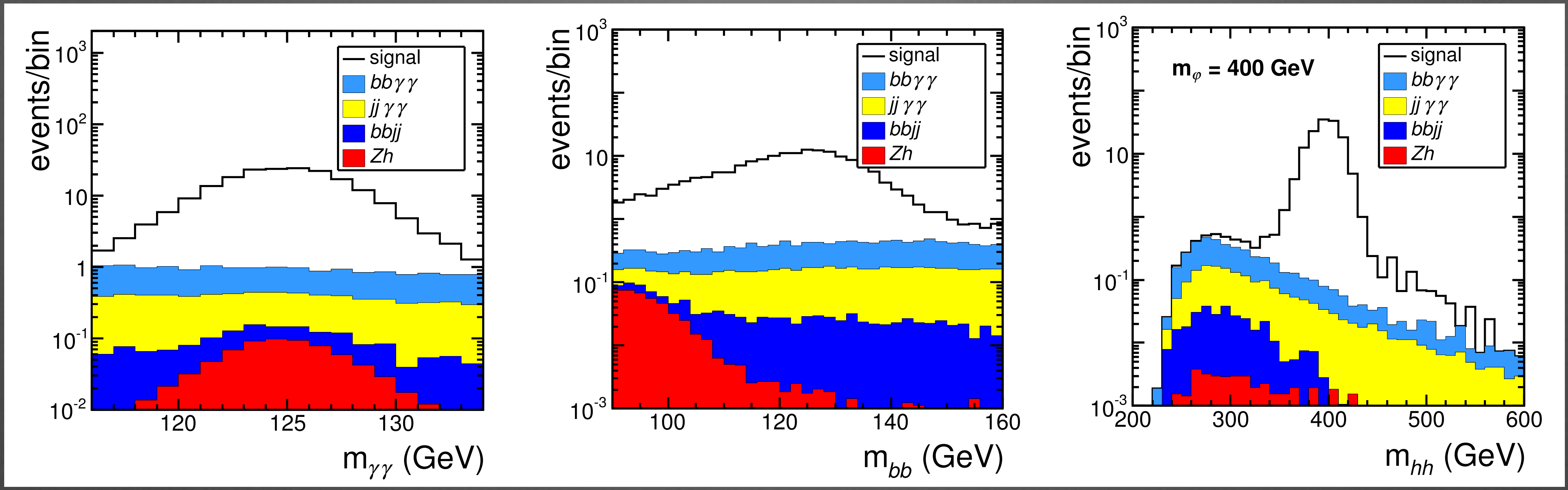
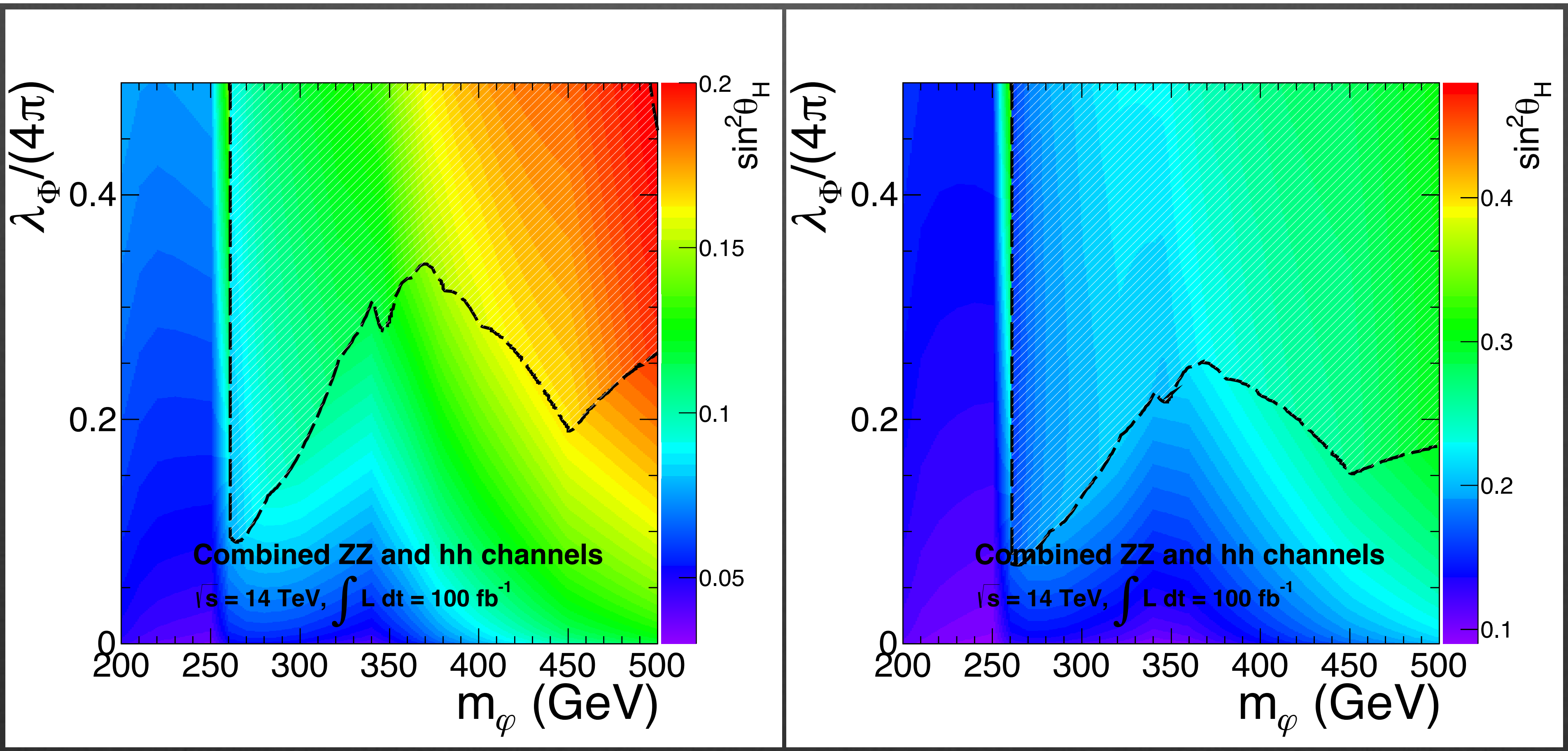


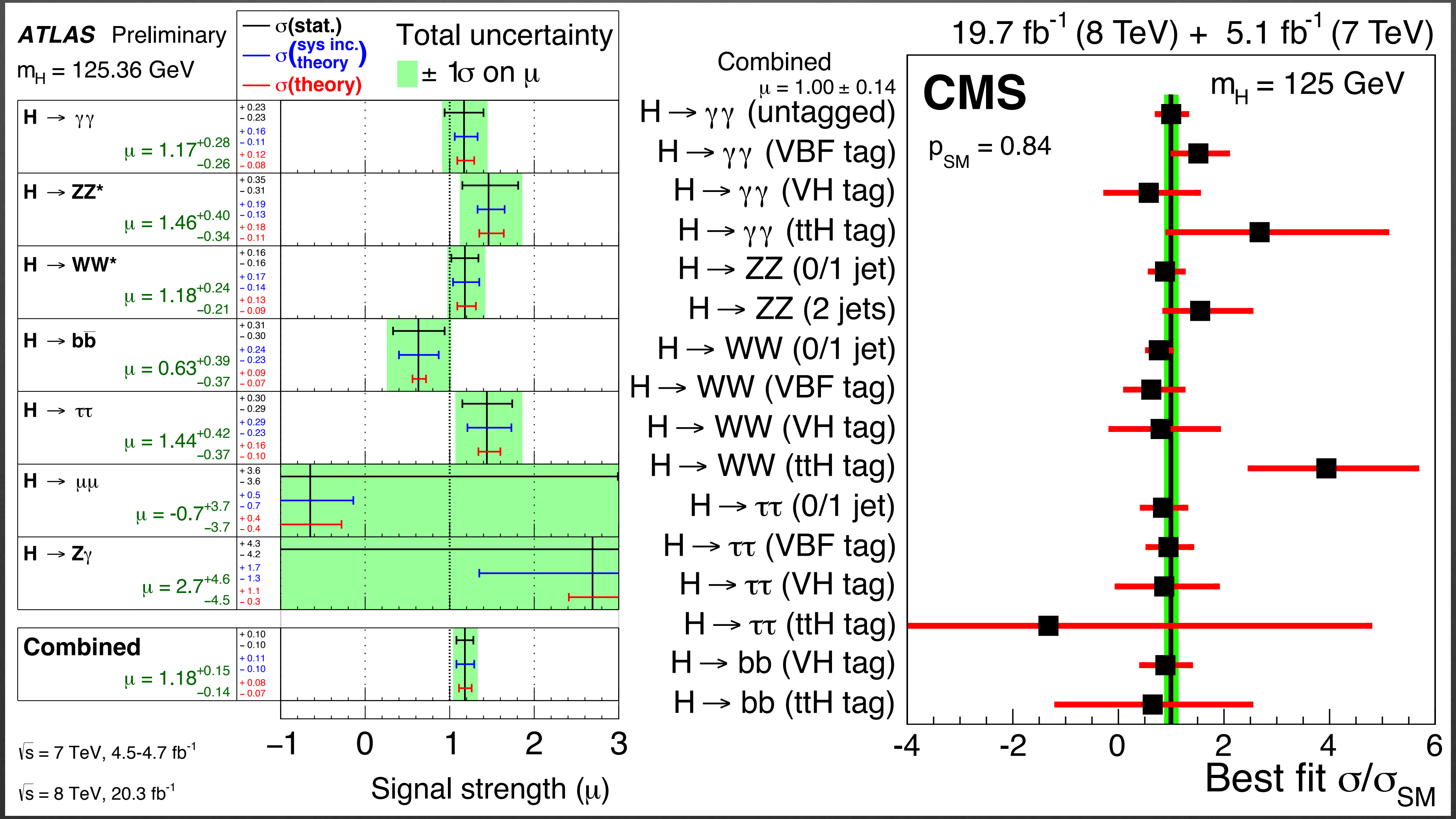


ATLAS Collaboration, ATLAS-PHYS-PUB-2013-016; CMS Collaboration, CMS-PAS-FTR-13-024

Flavon physics

- Strong constraint from precisely measurement of the SM Higgs boson!

$$\mu_{\rm SM} = \cos^2\theta_H$$



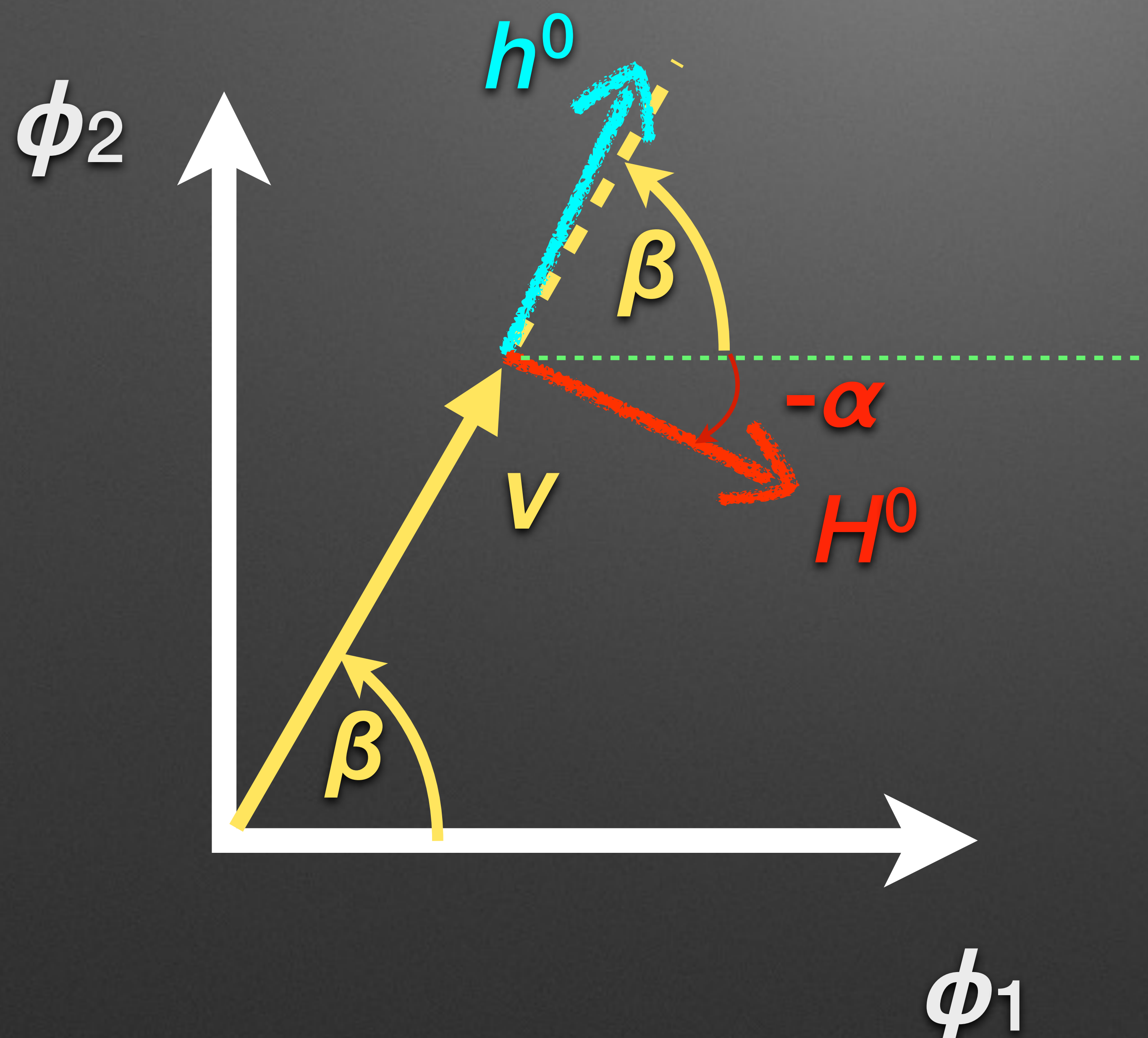
Alignment limit of the Extended Higgs sector

(also see Yun's talk)

based on JHEP 1506 (2015) 137 in collaboration with Nathaniel Craig, Francesco D'Eramo, Patrick Draper and Scott Thomas

Alignment Limit

- Taking NHDM as a simple exercise, it hints that the hWW, hZZ, htt vertices are SM-like.

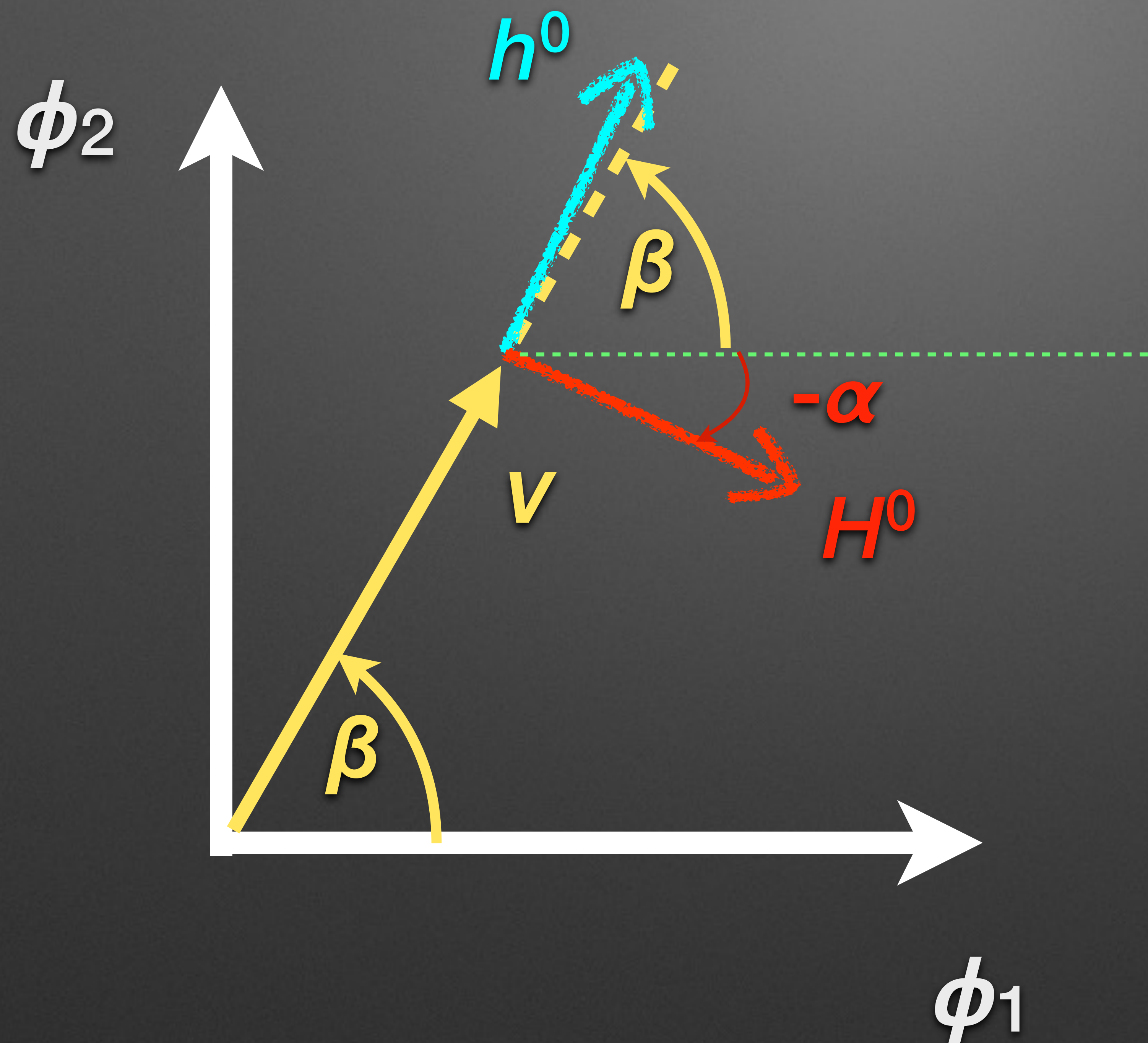


- If the Higgs sector is N-HDM and one of the mass eigenstate is parallel to the vev, it will be the SM-like Higgs boson and other HVV interaction will be suppressed.

N. Craig and S. Thomas, JHEP1211(2012)083; N. Craig, J. Galloway, and S. Thomas, arXiv:1305.2424[hep-hp]; M. Carena, I. Low, N. R. Shah, C. E. Wagner, JHEP1404(2014)015; H. E. Haber, arXiv:1401.0152[hep-hp]

Alignment Limit

- This property is easy to understand:



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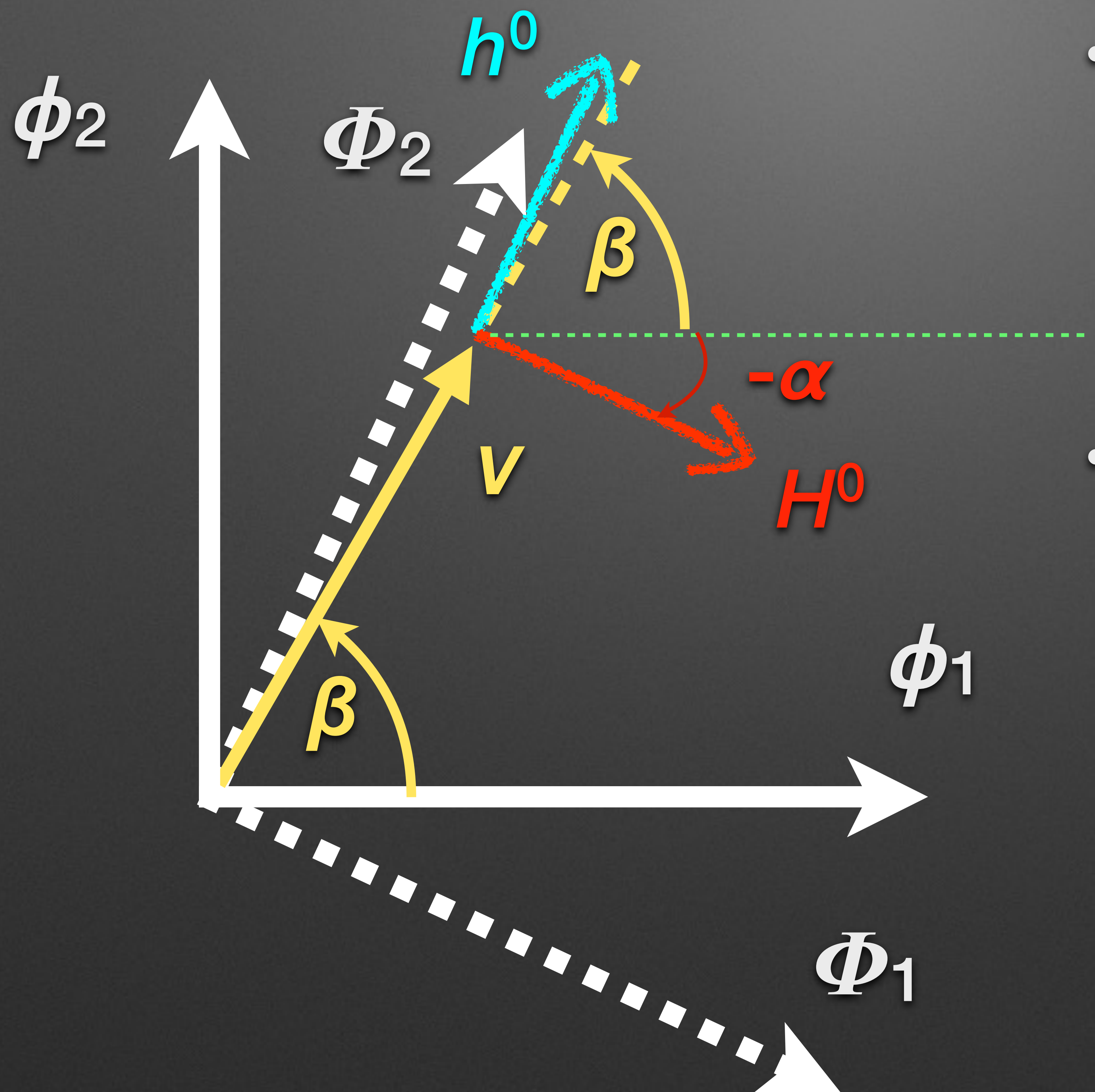

- Φ_1 does not get vev ⇒

  HVV suppressed, Hhh suppressed, hAV suppressed.

- In more general case (more than 2 scalars, other representations), hAZ and hH^+W^- are still suppressed since A and H^+ are orthogonal to the Goldstone modes.

Direct and Indirect Limit

- No tree level FCNC ☛ Glashow-Weinberg theorem.
- Type I and Type II 2HDM
    - Type I: only ϕ_2 couples to the SM fermions.
    - Type II: ϕ_1 only couples to the SM down-type fermions, ϕ_2 only couples to the SM up-type fermions.

S. L. Glashow and S. Weinberg, PRD15(1977)1958.

Direct and Indirect Limit

- No tree level FCNC ☛ Glashow-Weinberg theorem.

- Type I and Type II 2HDM.

- hVV is SM-like ⇔ HVV vanishes.

- Searching additional Higgs bosons with their interactions with SM fermions!

$y_{\rm 2HDM}/y_{\rm SM}$	Type 1	Type 2
hVV	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$
hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
hQd	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
hLe	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
HVV	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
HQd	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
HLe	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

S. L. Glashow and S. Weinberg, PRD15(1977)1958.

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- Searching additional Higgs bosons with their interactions with SM fermions!

$y_{\rm 2HDM}/y_{\rm SM}$	Type 1	Type 2
hVV	1	1
hQu	$1+\varepsilon/t_\beta$	$1+\varepsilon/t_\beta$
hQd	$1+\varepsilon/t_\beta$	$1-\varepsilon t_\beta$
hLe	$1+\varepsilon/t_\beta$	$1-\varepsilon t_\beta$
HVV	ε	ε
HQu	$\varepsilon-1/t_\beta$	$\varepsilon-1/t_\beta$
HQd	$\varepsilon-1/t_\beta$	$\varepsilon+t_\beta$
HLe	$\varepsilon-1/t_\beta$	$\varepsilon+t_\beta$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

S. L. Glashow and S. Weinberg, PRD15(1977)1958. For anomalous couplings, see H.-Y. Ren, L.-H. Xia, Y.-P. Kuang, PRD90(2014)11, 115002

Direct and Indirect Limit

Channel	$\sqrt{s}$	$\hat{\mu}_a$	ϵ_a(GGH, VBF/VH, TTH)
$Vh \to b\bar{b}$ (0ℓ) [91]	7/8 TeV	$-0.35^{+0.55}_{-0.52}$	$(0.0, 1.0, 0.0)$
$Vh \to b\bar{b}$ (1ℓ) [91]	7/8 TeV	$1.17^{+0.66}_{-0.60}$	$(0.0, 1.0, 0.0)$
$Vh \to b\bar{b}$ (2ℓ) [91]	7/8 TeV	$0.94^{+0.88}_{-0.79}$	$(0.0, 1.0, 0.0)$
$tth \to b\bar{b}$ [92]	7/8 TeV	$1.7^{+1.4}_{-1.4}$	$(0.0, 0.0, 1.0)$
$h \to \tau\tau$ (jj) [93]	7/8 TeV	$3.6^{+2.0}_{-1.6}$	$(0.60, 0.4, 0.0)$
$h \to \tau\tau$ (ℓj) [93]	7/8 TeV	$0.9^{+1.0}_{-0.9}$	$(0.65, 0.35, 0.0)$
$h \to \tau\tau$ $(\ell\ell)$ [93]	7/8 TeV	$3.0^{+1.9}_{-1.7}$	$(0.65, 0.35, 0.0)$
$hjj \to \tau\tau$ (jj) [93]	7/8 TeV	$1.4^{+0.9}_{-0.7}$	$(0.15, 0.85, 0.0)$
$hjj \to \tau\tau$ (ℓj) [93]	7/8 TeV	$1.0^{+0.6}_{-0.5}$	$(0.12, 0.88, 0.0)$
$hjj \to \tau\tau$ $(\ell\ell)$ [93]	7/8 TeV	$1.8^{+1.1}_{-0.9}$	$(0.10, 0.90, 0.0)$
$h \to WW$ $(0j)$ [94]	7/8 TeV	$1.14^{+0.34}_{-0.30}$	$(0.98, 0.02, 0.0)$
$h \to WW$ $(1j)$ [94]	7/8 TeV	$0.96^{+0.45}_{-0.40}$	$(0.87, 0.13, 0.0)$
$h \to WW$ $(2j$ ggH) [94]	7/8 TeV	$1.20^{+0.91}_{-0.84}$	$(0.75, 0.25, 0.0)$
$h \to WW$ $(2j$ VBF) [94]	7/8 TeV	$1.20^{+0.45}_{-0.38}$	$(0.13, 0.87, 0.0)$
$h \to ZZ$ (ggH) [95]	7/8 TeV	$1.66^{+0.5}_{-0.4}$	$(1.0, 0.0, 0.0)$
$h \to ZZ$ (VBF+VH)[95]	7/8 TeV	$0.26^{+1.6}_{-0.9}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (ggH) [96]	7/8 TeV	$1.32^{+0.38}_{-0.38}$	$(1.0, 0.0, 0.0)$
$h \to \gamma\gamma$ (VBF) [96]	7/8 TeV	$0.8^{+0.7}_{-0.7}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (WH) [96]	7/8 TeV	$1.0^{+1.6}_{-1.6}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (ZH) [96]	7/8 TeV	$0.1^{+3.7}_{-0.1}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (ttH) [96]	7/8 TeV	$1.6^{+2.7}_{-1.8}$	$(0.0, 0.0, 1.0)$

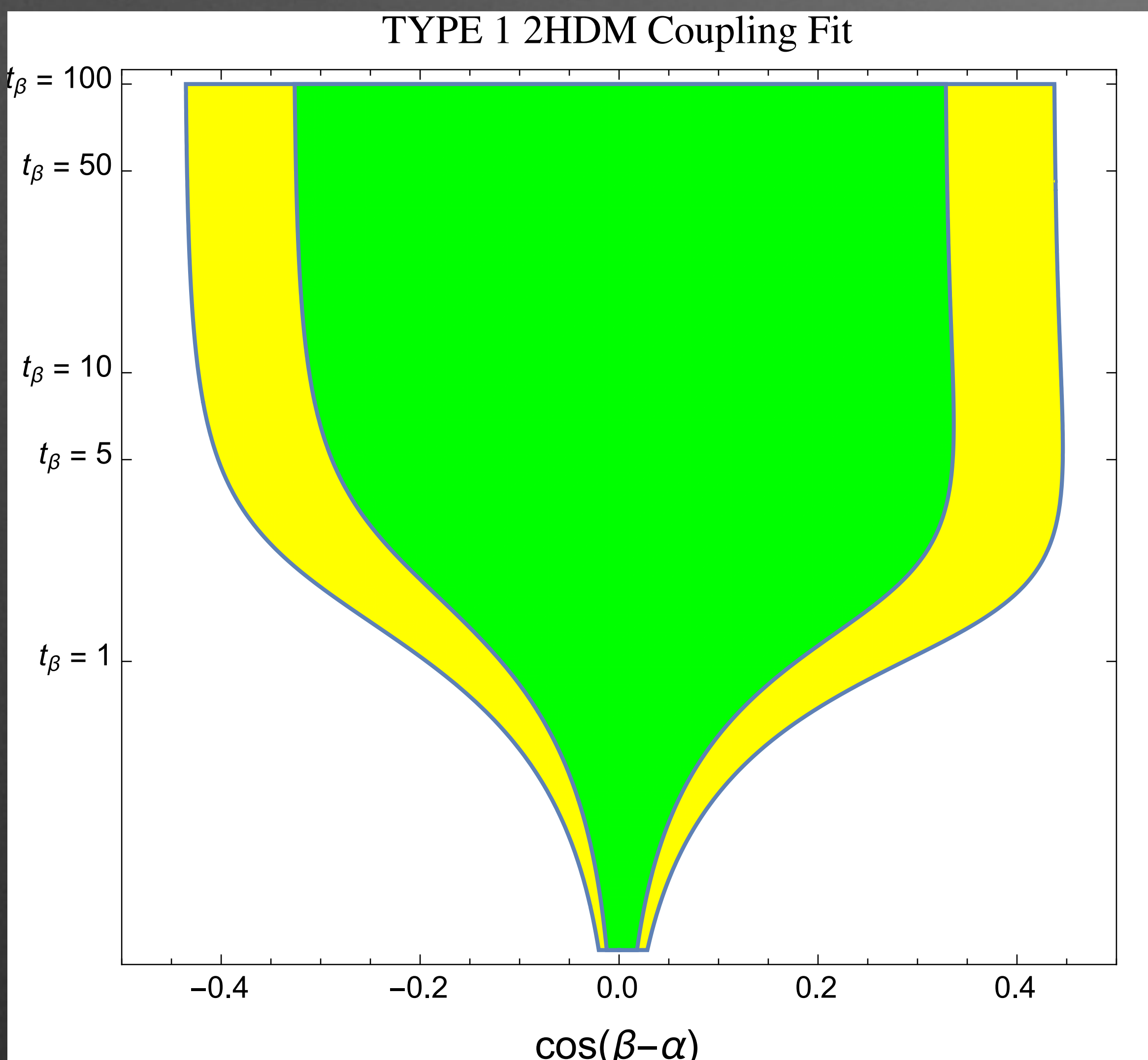
Direct and Indirect Limit

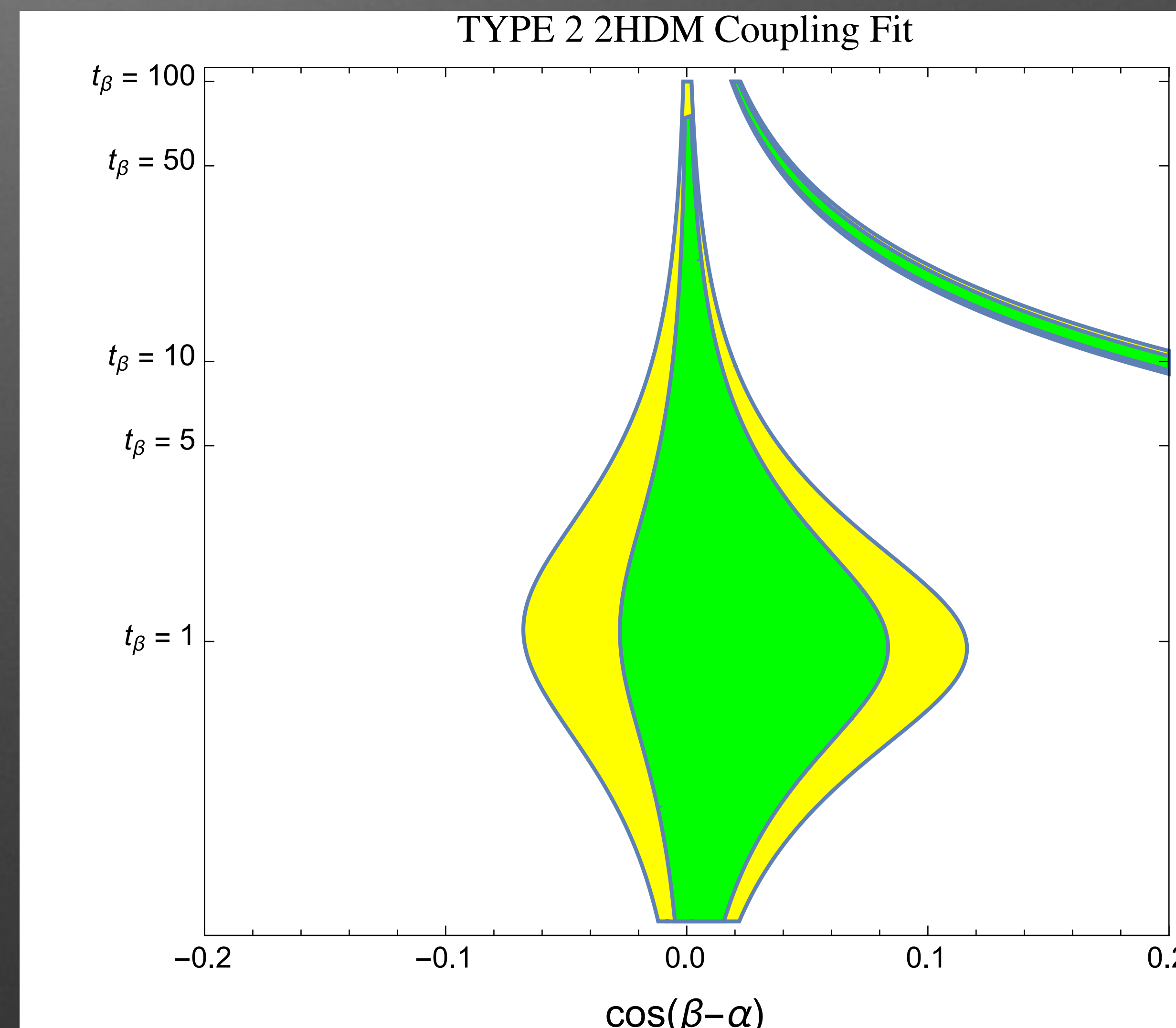
Channel	$\sqrt{s}$	$\hat{\mu}_a$	ϵ_a(GGH, VBF/VH, TTH)
$h \to bb$ [97]	7/8 TeV	$1.0^{+0.53}_{-0.50}$	$(0.0, 1.0, 0.0)$
$tth \to bb$ [98]	7/8 TeV	$0.67^{+1.35}_{-1.33}$	$(0.0, 0.0, 1.0)$
$h \to \tau\tau$ (0,1j) [97]	7/8 TeV	$0.84^{+0.42}_{-0.38}$	$(0.87, 0.13, 0.0)$
$hjj \to \tau\tau$ (2j) [97]	7/8 TeV	$0.95^{+0.43}_{-0.38}$	$(.17, .83, 0.0)$
$Vh \to \tau\tau$ [97]	7/8 TeV	$0.87^{+1.00}_{-0.88}$	$(0.0, 1.0, 0.0)$
$h \to WW$ (0,1j) [97]	7/8 TeV	$0.77^{+0.23}_{-0.21}$	$(0.83, 0.17, 0.0)$
$h \to WW$ (2j) [97]	7/8 TeV	$0.62^{+0.59}_{-0.48}$	$(0.17, 0.83, 0.0)$
$Vh \to WW$ [97]	7/8 TeV	$0.80^{+1.09}_{-0.93}$	$(0.0, 1.00, 0.0)$
$h \to ZZ$ [97]	7/8 TeV	$0.88^{+0.34}_{-0.27}$	$(0.9, 0.1, 0.0)$
$h \to ZZ$ (2j) [97]	7/8 TeV	$1.55^{+0.95}_{-0.66}$	$(0.58, 0.42, 0.0)$
$h \to \gamma\gamma$ (ggH) [99]	7/8 TeV	$1.12^{+0.37}_{-0.32}$	$(1.0, 0.0, 0.0)$
$h \to \gamma\gamma$ (VBF) [99]	7/8 TeV	$1.58^{+0.77}_{-0.68}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (VH) [99]	7/8 TeV	$-0.16^{+1.16}_{-0.79}$	$(0.0, 1.0, 0.0)$
$h \to \gamma\gamma$ (ttH) [99]	7/8 TeV	$2.69^{+2.51}_{-1.81}$	$(0.0, 0.0, 1.0)$

ATLAS Collaboration, JHEP1501(2015)069, PRD90(2014)012015, PRD91(2015)012006, ATLAS-CONF-2014-011, ATLAS-CONF-2014-060, ATLAS-CONF-2014-061;
CMS Collaboration, EPJC71(2014)103076, arXiv:1412.8662[hep-ex], CMS-PAS-HIG-14-010.

Direct and Indirect Limit

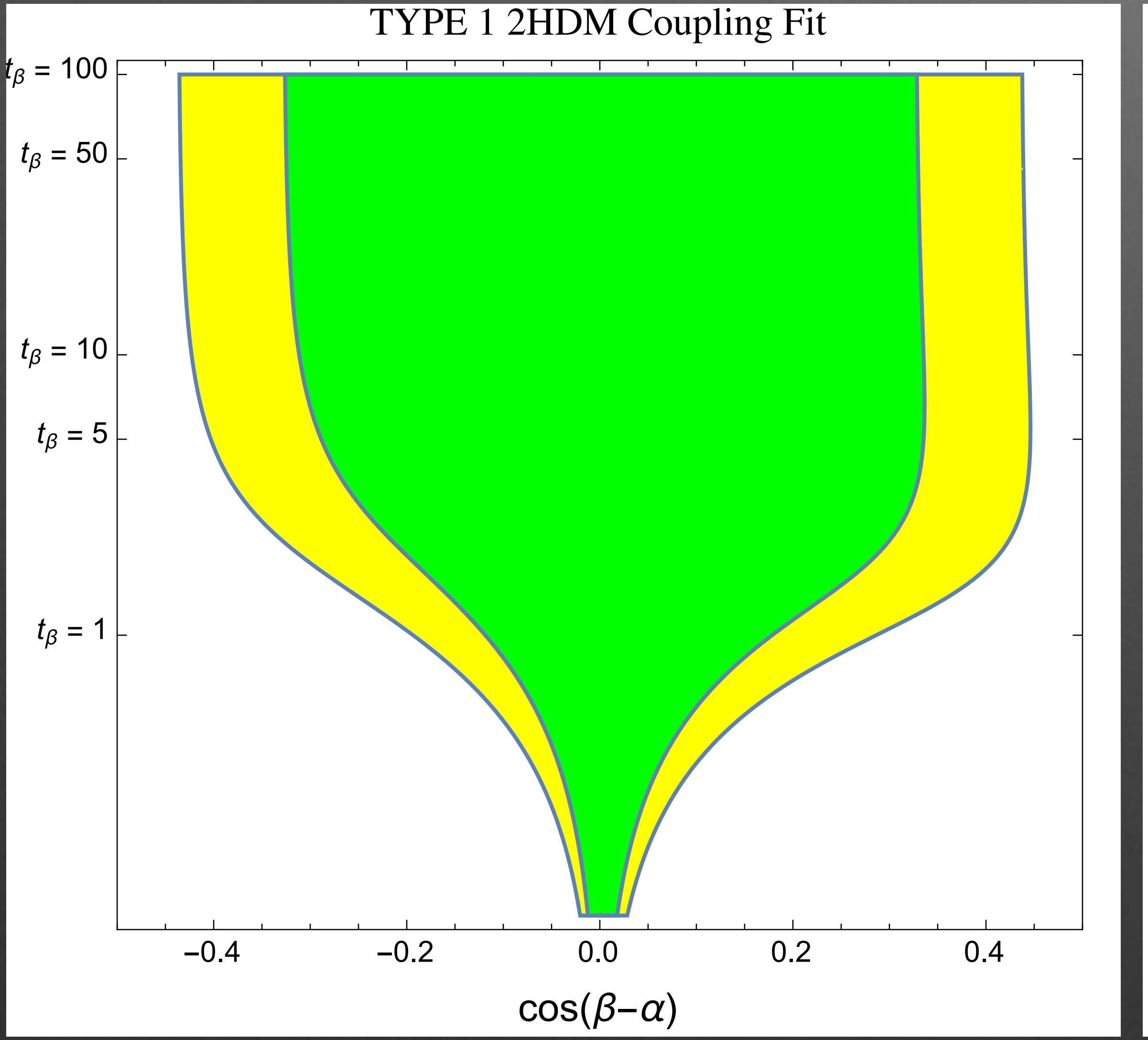
- Constraint from the global-fit of the SM-like Higgs boson observables.

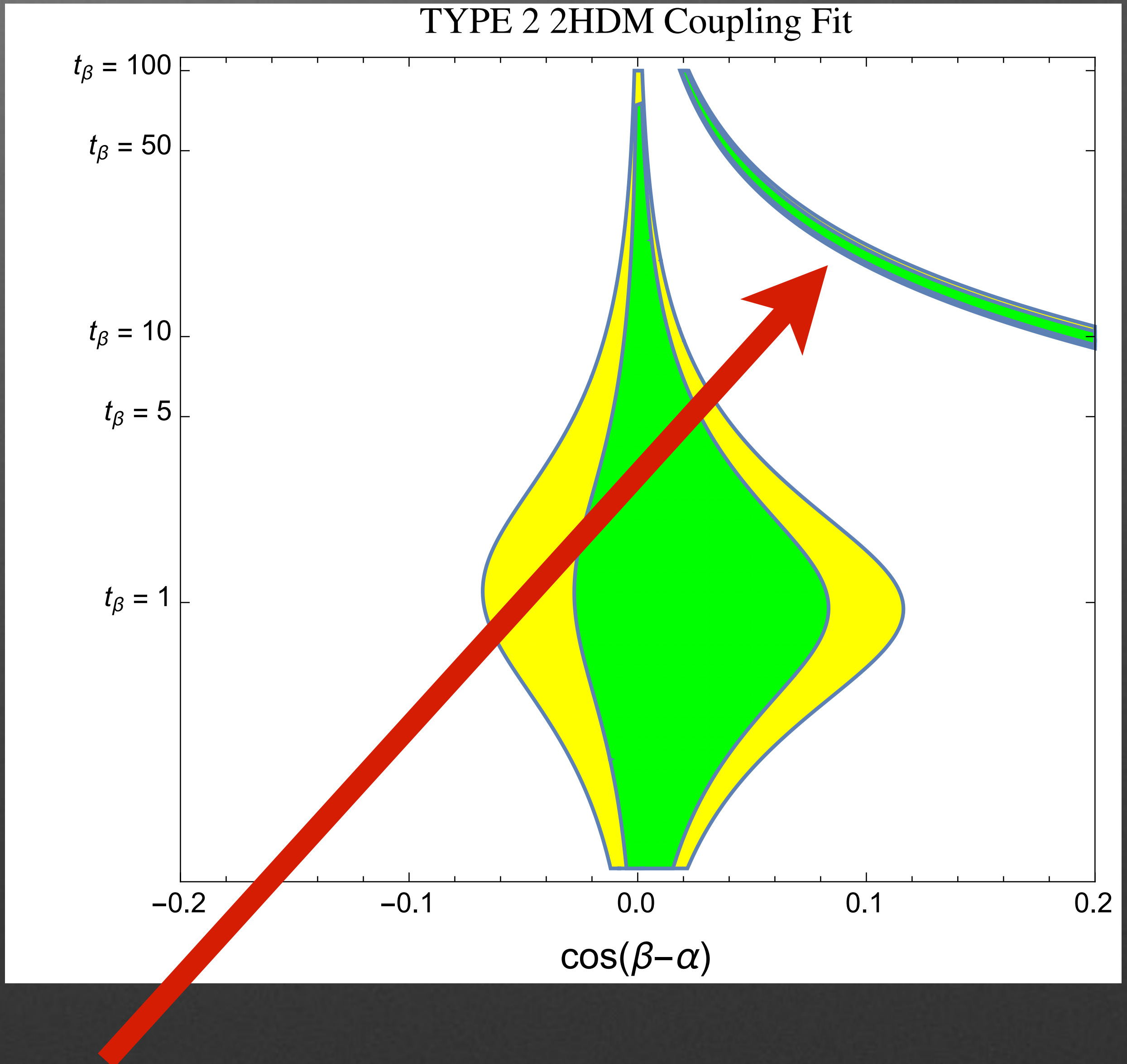




Direct and Indirect Limit

- Constraint from the global-fit of the SM-like Higgs boson observables.





tan*β*cos(*β*-*α*)=2, *hQd* and *hLe* change sign.

Direct and Indirect Limit

- Direct search of the heavy scalars

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to H\,,\,A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to bbH\,,\,bbA\,,\,tbH^{\pm}\,,\,ttH\,,\,ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4\lambda_f^2)$	$gq \to bq'\,bH^{\pm}\,,\,bq\,tH\,,\,bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\,HH^{\pm}\,,\,AH^{\pm}\,,\,H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to hH\,,\,hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to HH\,,\,HA\,,\,AA\,,\,H^+H^-$

Direct and Indirect Limit

- Direct search of the heavy scalars

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4 \lambda_f^2)$	$gg \to H\,,\ A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4 \lambda_f^2)$	$gg \to bbH\,,\ bbA\,,\ tbH^{\pm}\,,\ ttH\,,\ ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4 \lambda_f^2)$	$gq \to bq'\,bH^{\pm}\,,\ bq\,tH\,,\ bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\ HH^{\pm}\,,\ AH^{\pm}\,,\ H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4 \lambda_f^4)$	$gg \to hH\,,\ hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4 \lambda_f^4)$	$gg \to HH\,,\ HA\,,\ AA\,,\ H^+H^-$

Type I large tanβ?

Direct and Indirect Limit

- Direct search of the heavy scalars

		H	A	$H^{\pm}$
Standard Model	WW, ZZ	–		
Decay Channels	$tt, bb, \tau\tau, \mu\mu$	✓	✓	
	$\gamma\gamma$	✓	✓	
	Zh		–	
	hh	–		
	Wh			–
	$tb, \tau\nu$			✓

Direct and Indirect Limit

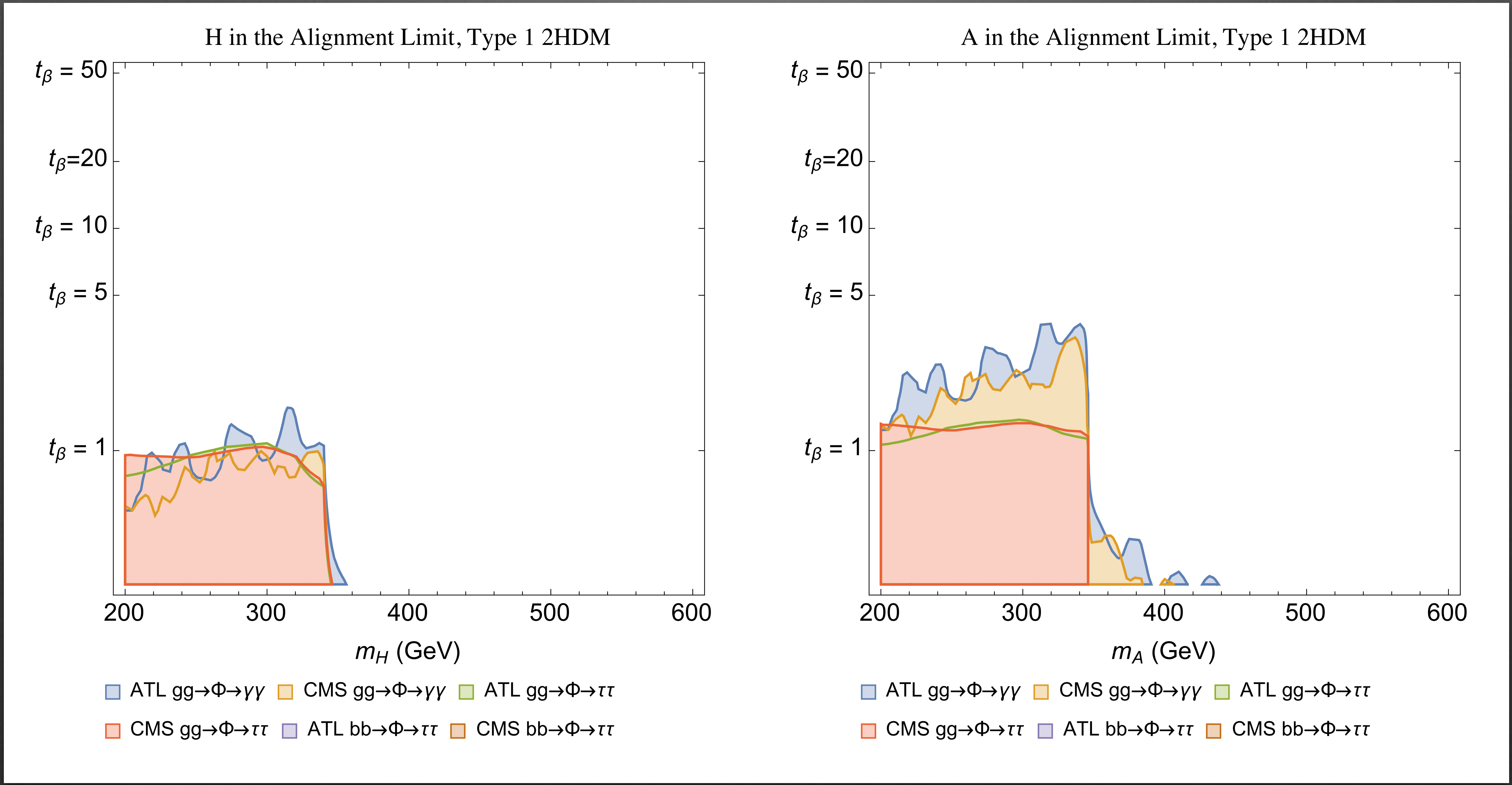
- Results from 7 and 8 TeV LHC

Channel	Collaboration	Reference
$gg \to \Phi \to \gamma\gamma$	ATLAS, 20.3 fb^{-1}	[51]
$gg \to \Phi \to \gamma\gamma$	CMS, 19.7 fb^{-1}	[52]
$gg \to \Phi \to \tau\tau$	ATLAS, 20.3 fb^{-1}	[8]
$b\bar{b} \to \Phi \to \tau\tau$	ATLAS, 20.3 fb^{-1}	[8]
$gg \to \Phi \to \tau\tau$	CMS, 19.7 fb^{-1}	[9]
$b\bar{b} \to \Phi \to \tau\tau$	CMS, 19.7 fb^{-1}	[9]
$gg \to A \to Zh \to \ell\ell + (b\bar{b}, \tau\tau)$	ATLAS, 20.3 fb^{-1}	[1]
$gg \to A \to Zh \to \ell\ell + b\bar{b}$	CMS, 19.7 fb^{-1}	[5]
$gg \to H \to hh \to b\bar{b} + \gamma\gamma$	ATLAS, 20 fb^{-1}	[53]
$gg \to H \to hh \to b\bar{b} + b\bar{b}$	CMS, 17.9 fb^{-1}	[54]
$gg \to H \to hh \to b\bar{b} + \gamma\gamma$	CMS, 19.7 fb^{-1}	[55]
$gg \to H \to ZZ \to 4\ell$	ATLAS, 20.7 fb^{-1}	[56]
$gg \to H \to ZZ$	CMS, 19.7 fb^{-1}	[6]
$gg \to H \to WW$	CMS, 19.7 fb^{-1}	[6]

ATLAS Collaboration, PLB744(2015)163, JHEP1411(2014)056, PRL113(2014)171801, PRL114(2015)081802, ATLAS-CONF-2013-012;
CMS Collaboration, JHEP1410(2014)160, arXiv:1503.04114[hep-ex], arXiv:1504.00936[hep-ex], CMS-PAS-HIG-13-032, CMS-PAS-HIG-14-006, CMS-PAS-HIG-14-011.

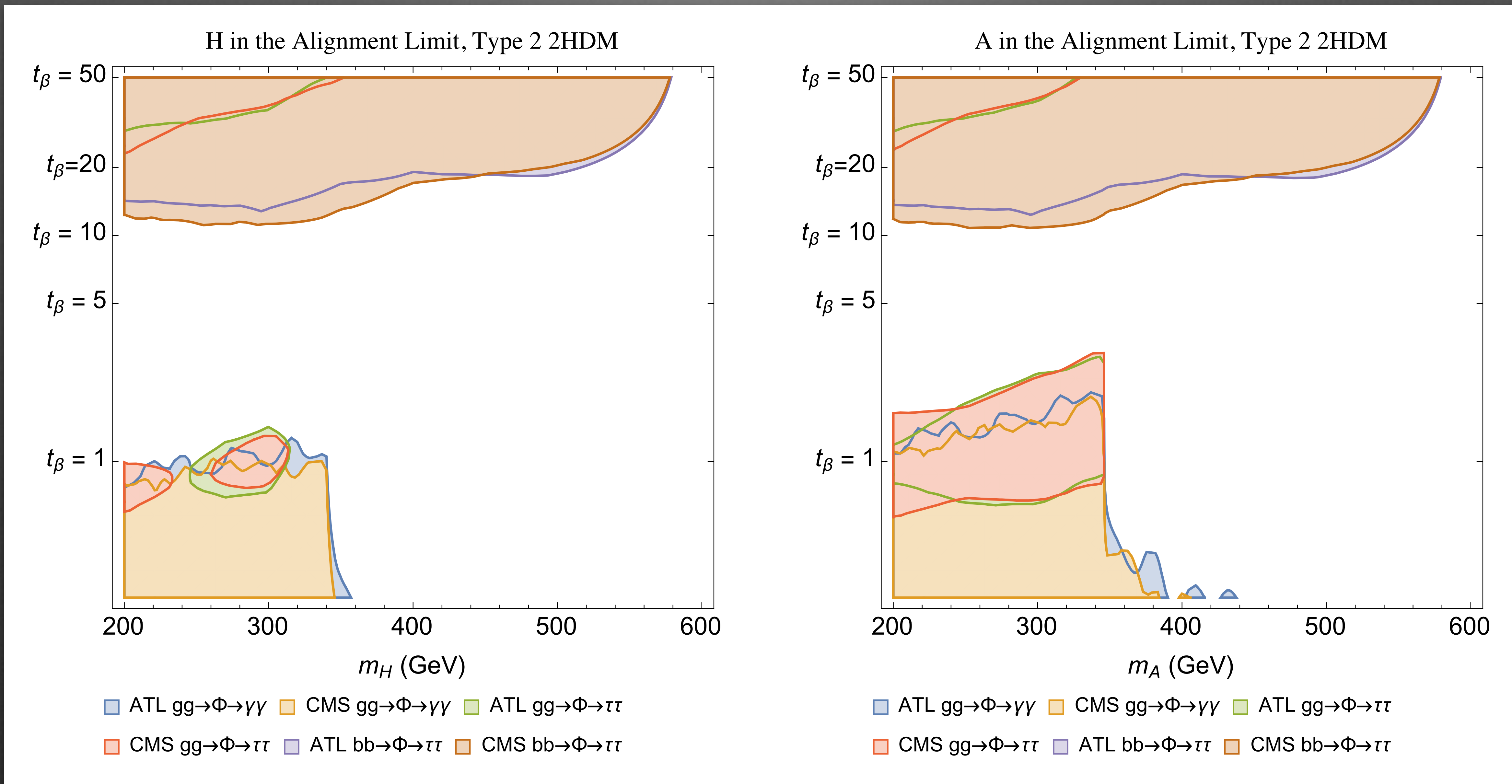
Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type I 2HDM)



Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type II 2HDM)

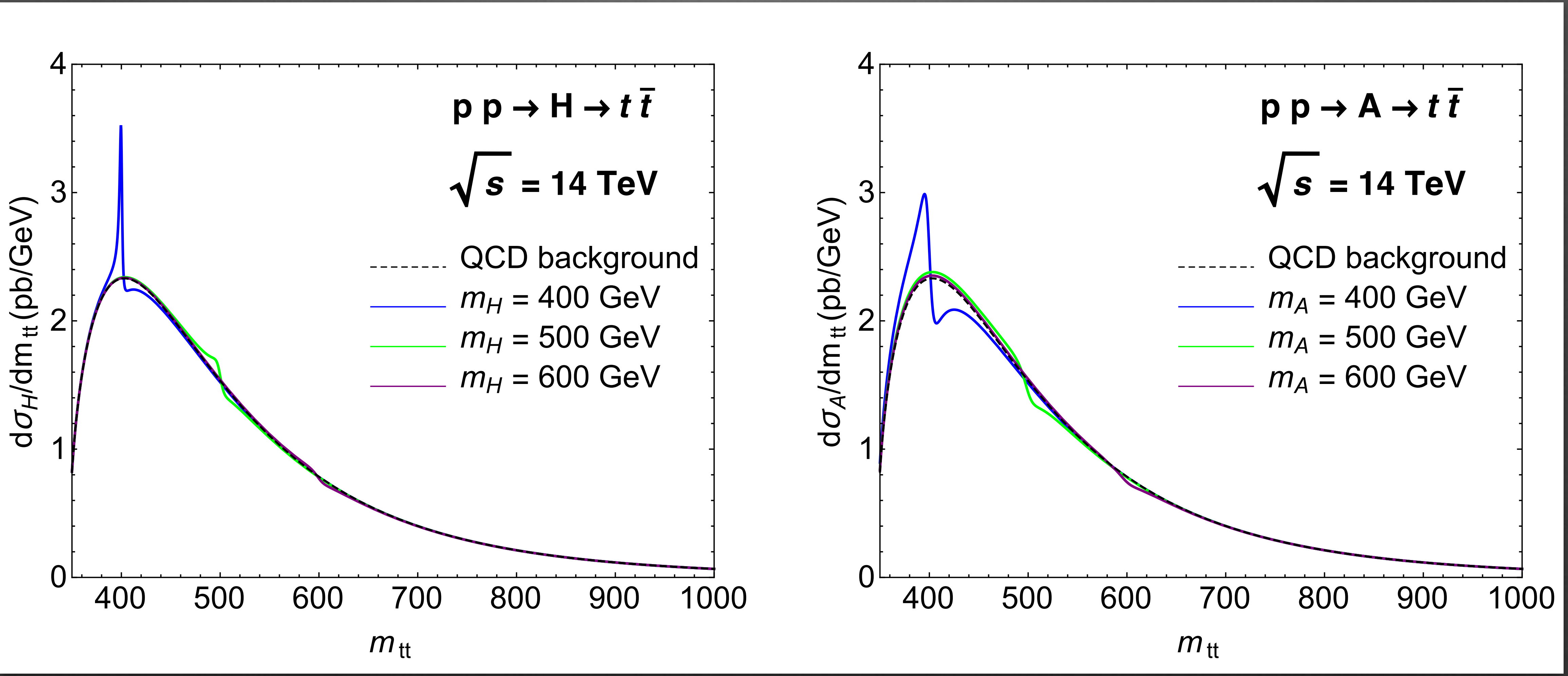


14 TeV LHC

- Direct searching of the heavy scalars
  - $pp \to H/A \to tt$
  - $pp \to bbH/bbA \to ttbb$
  - $pp \to ttH/ttA \to tttt$
  - $pp \to bbH/bbA \to bb$+missing E_T
  - $pp \to ttH/ttA \to tt$+missing E_T
  - $pp \to tbH^{\pm} \to tbtb$

$pp \to H/A \to tt$

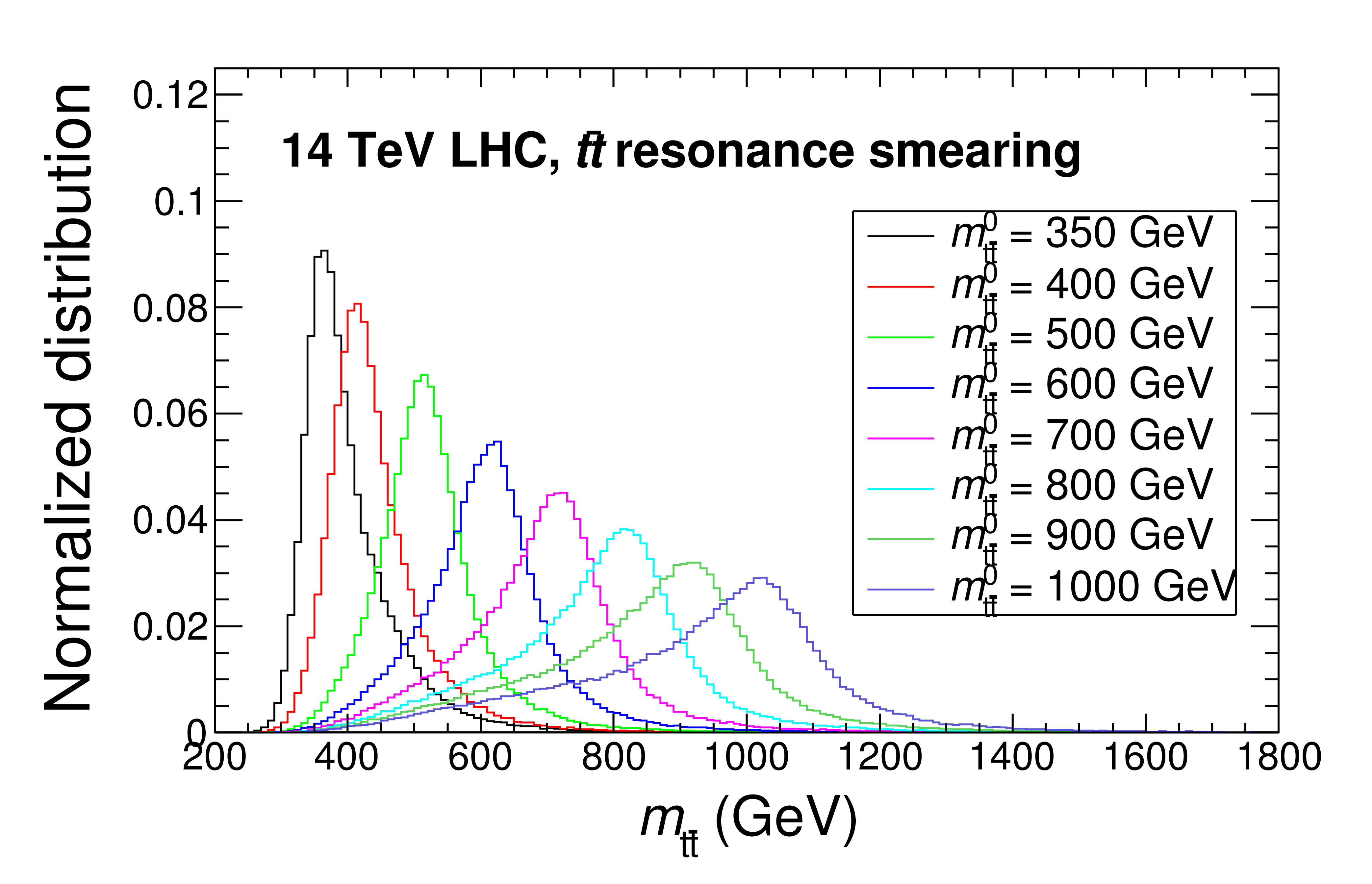
- Huge SM background and significant interference effect!



D. Dicus, A. Strange, and S. Willenbrock, PLB333(1994)126; R. Frederix and F. Maltoni, JHEP0901(2009)047, A. Djouadi, L.Maiani, A. Polosa, J. Quevillon, and V. Riquer, arXiv:1502.05653[hep-ph]

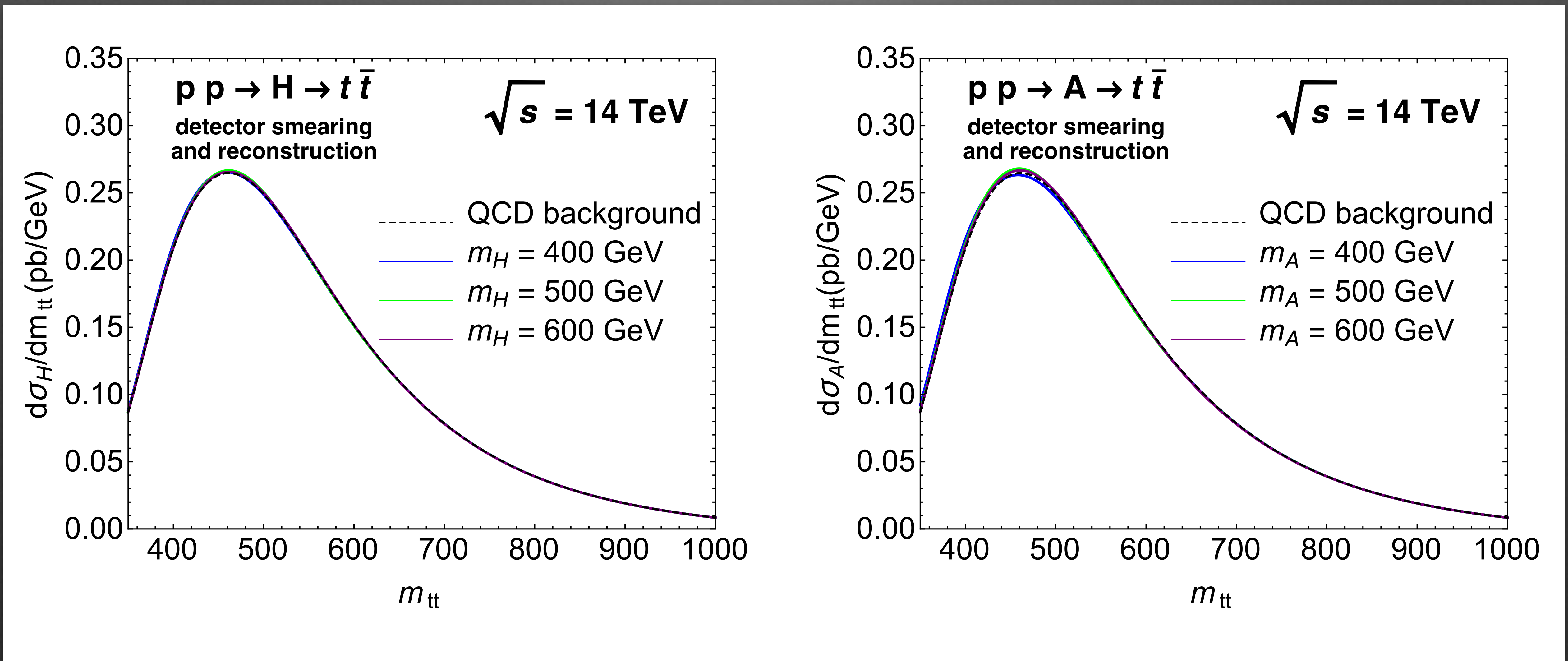
$pp \to H/A \to tt$

- Detector smearing effect from final state top quark reconstruction



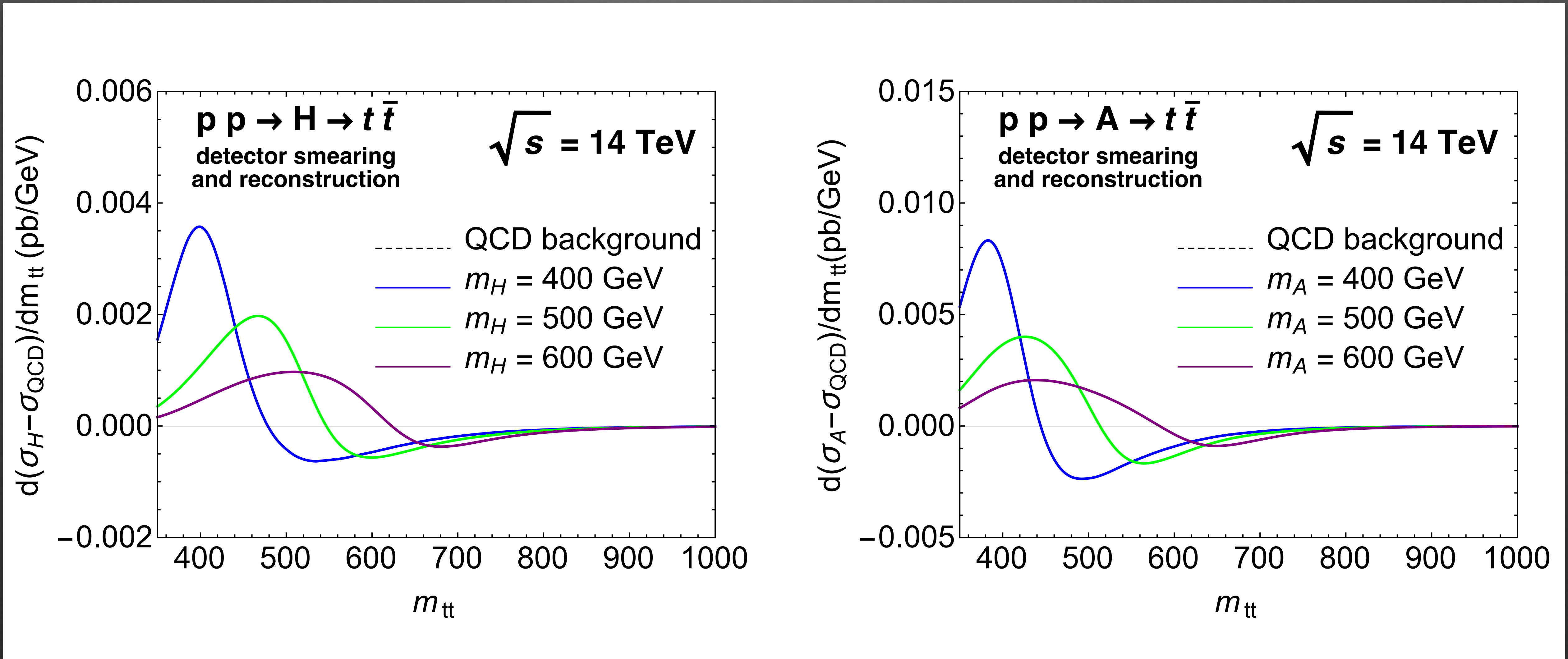
$pp \to H/A \to tt$

- Detector smearing effect from final state top quark reconstruction



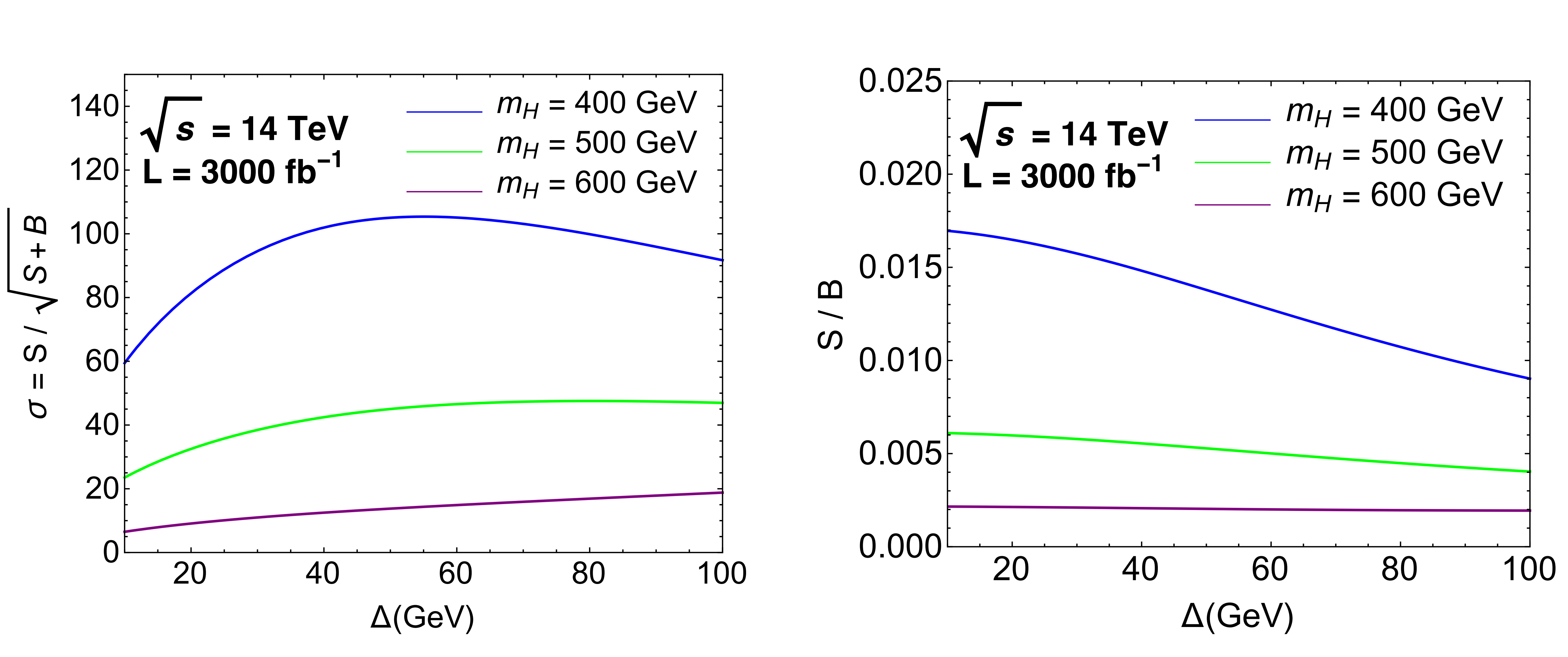
$pp \to H/A \to tt$

- Detector smearing effect from final state top quark reconstruction



$pp \to H/A \to tt$

- Difficult at 14 TeV LHC!
- bbH and ttH channels are needed!



T. Han, G. Valencia, Y. Wang, PRD70(2004)034002; Sunghoon Jung, Jeonghyeon Song, and Yeo Woong Yoon, arXiv:1505.00291[hep-ph], Yu-Ping Kuang, Ling-Hao Xia, Phys. Lett. B747 (2015) 193-199

pp→tbH±→tbtb

- Charge Higgs boson

$$\mathcal{L}_{\mathrm{eff}} = y_{tb} H^{+} \bar{t} (P_L \sin\theta + P_R \cos\theta) b + \mathrm{h.c.}$$

- In our simulation, the decay branching ratio to tb final state is assumed to be 100%

- The dominant SM backgrounds are

  - *pp→ttbb*
  - *pp→ttbj*
  - *pp→ttjj*

Also see K. A. Assamagan and N. Gollub, EPJC39S2(2005)25; E. L. Berger, T. Han, J. Jiang and T. Plehn, PRD71(2005)115012; J. Hajer, Y.-Y Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617[hep-ph]

$pp \to tbH^{\pm} \to tbtb$

- Both signal and bkgds are generated at parton level using MadGraph5 with CTEQ6L1 p.d.f and 5-flavor scheme. The parton showering and hadronization of the parton level events are done using PYTHIA6.4.

- Detector simulation is done with Delphes 3.

- Jets are reconstructed using anti-k_T algorithm with R=0.5.

- Basic BTagging algorithm in Delphes is used. The b-tagging efficiency is tuned with Drell-Yan process to be

$$\epsilon_b = 70\%, \quad \epsilon(c \to b) = 25\%, \quad \epsilon(udsg \to b) = 2\%$$

CMS Collaboration, arXiv:1307.7135[hep-ex]

$pp \to tbH^{\pm} \to tbtb$

- Basic cuts:
  - one and only one charged lepton with

$$p_T^{\ell} > 15\mathrm{GeV}, \quad |\eta^{\ell}| < 2.5, \quad I_{\mathrm{iso},\mu}(\Delta R = 0.3) < 0.1$$

  - missing transverse energy $\not{E}_T > 30\mathrm{GeV}$
  - at least 6 jets with $p_T^j > 20\mathrm{GeV}, \quad |\eta^j| < 4.5$
  - at least 4 of the 6 jets are tagged as b-jets with

$p_T^b > 40\mathrm{GeV}, \quad |\eta^b| < 2.5$ and $p_T^{b_1} > 150\mathrm{GeV}$

$pp \to tbH^{\pm} \to tbtb$

- Top quark reconstruction (semi-leptonic):
  - reconstructing hadronic decaying W with non-b jets
  - solving neutrino 4-momentum using mass-shell equation of the leptonic decaying W (If there are two solutions, keep both. If there is no real solution, we make a minimal modification of the missing transverse energy to get one.)

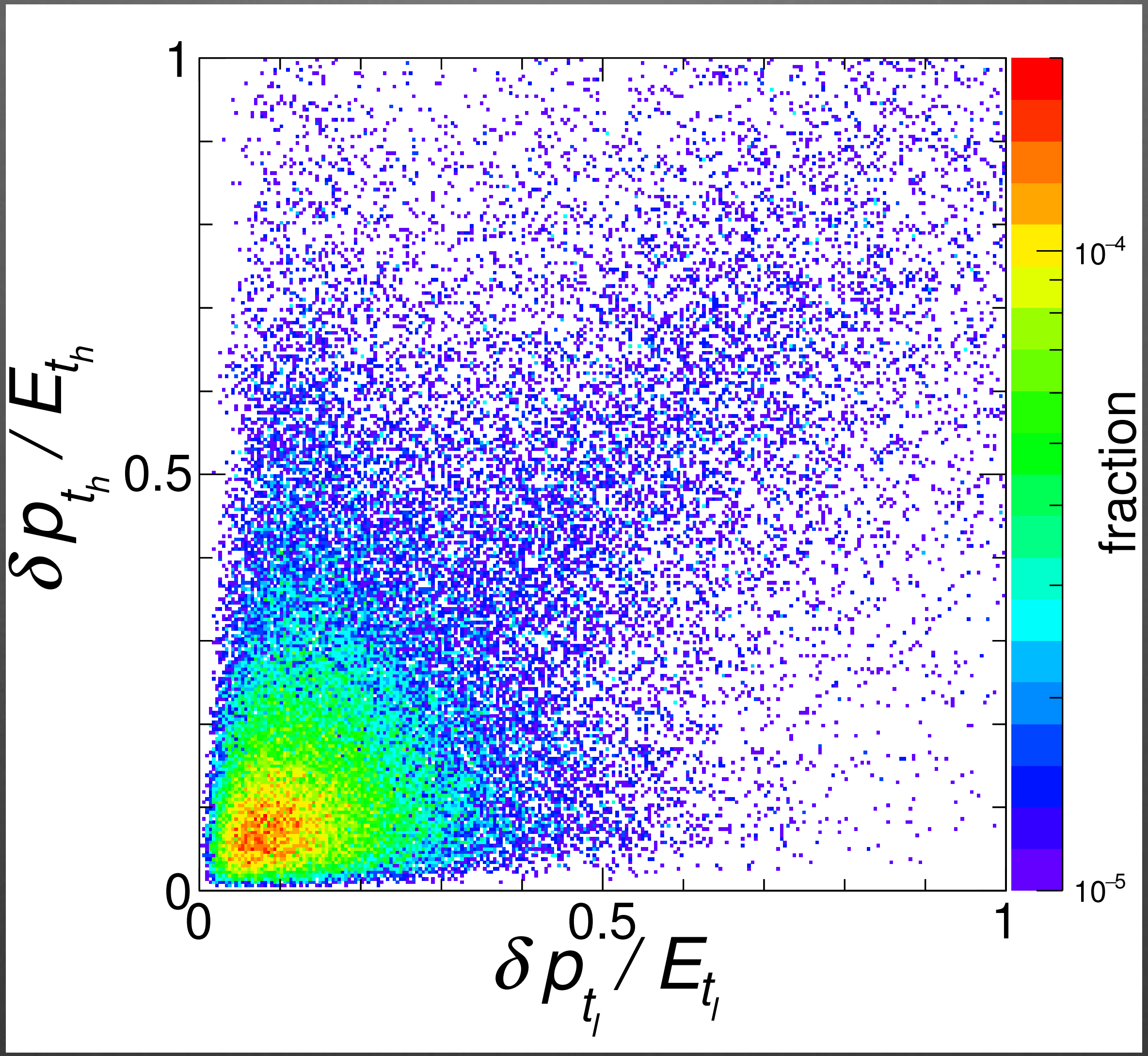
$$\chi^2 = \frac{(m_{W_h b_h} - m_t)^2}{\sigma_h^2} + \frac{(m_{W_\ell b_\ell} - m_t)^2}{\sigma_\ell^2}$$

  - σ_h=50GeV, σ_l=25GeV, requiring χ<5

V. Barger, T. Han, D. G. E. Walker, PRL100(2008)031801

$pp \to tbH^{\pm} \to tbtb$

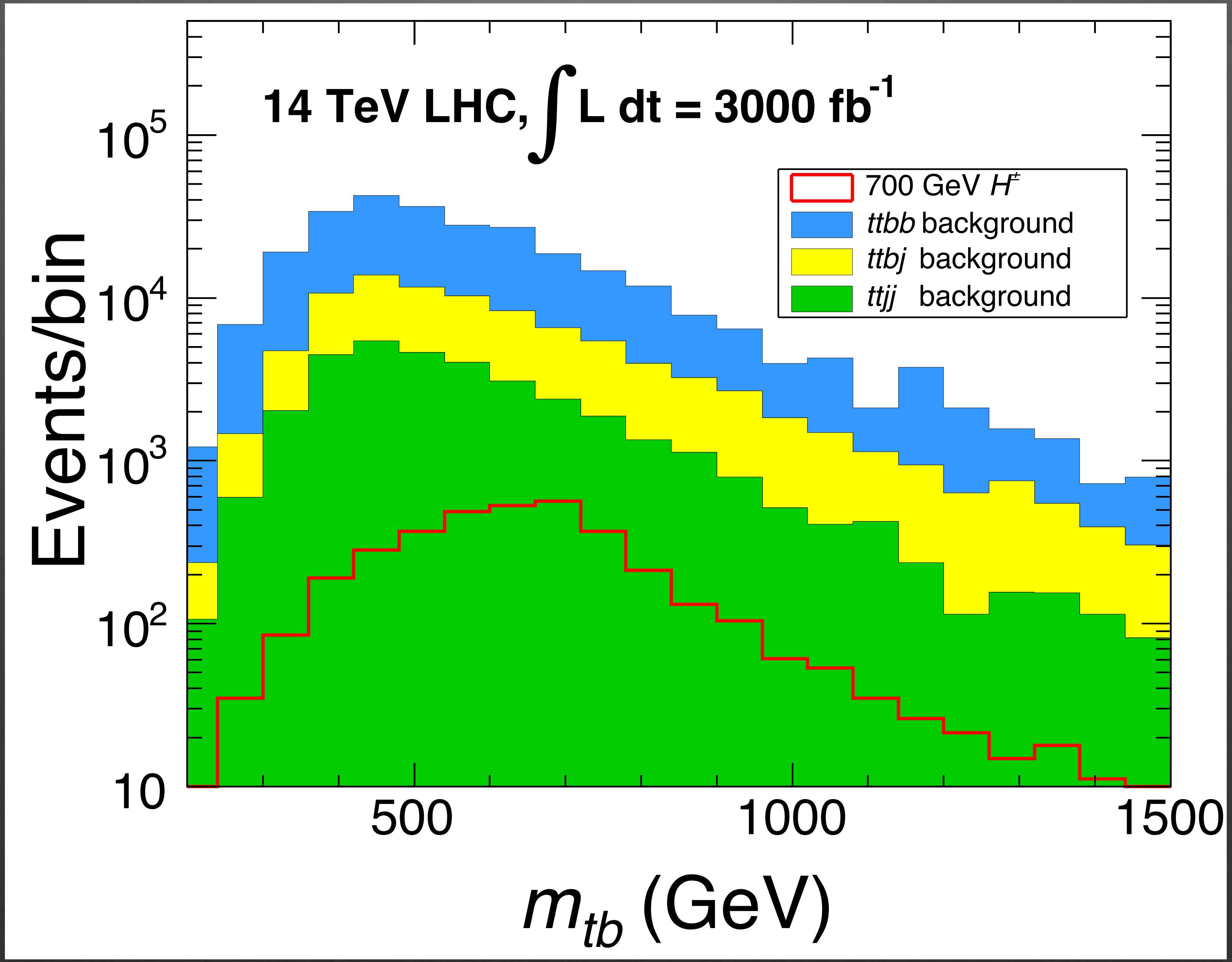
- Top quark reconstruction (semi-leptonic)



- Additional cuts: $\Delta R_{b_1 b_2} > 0.9$

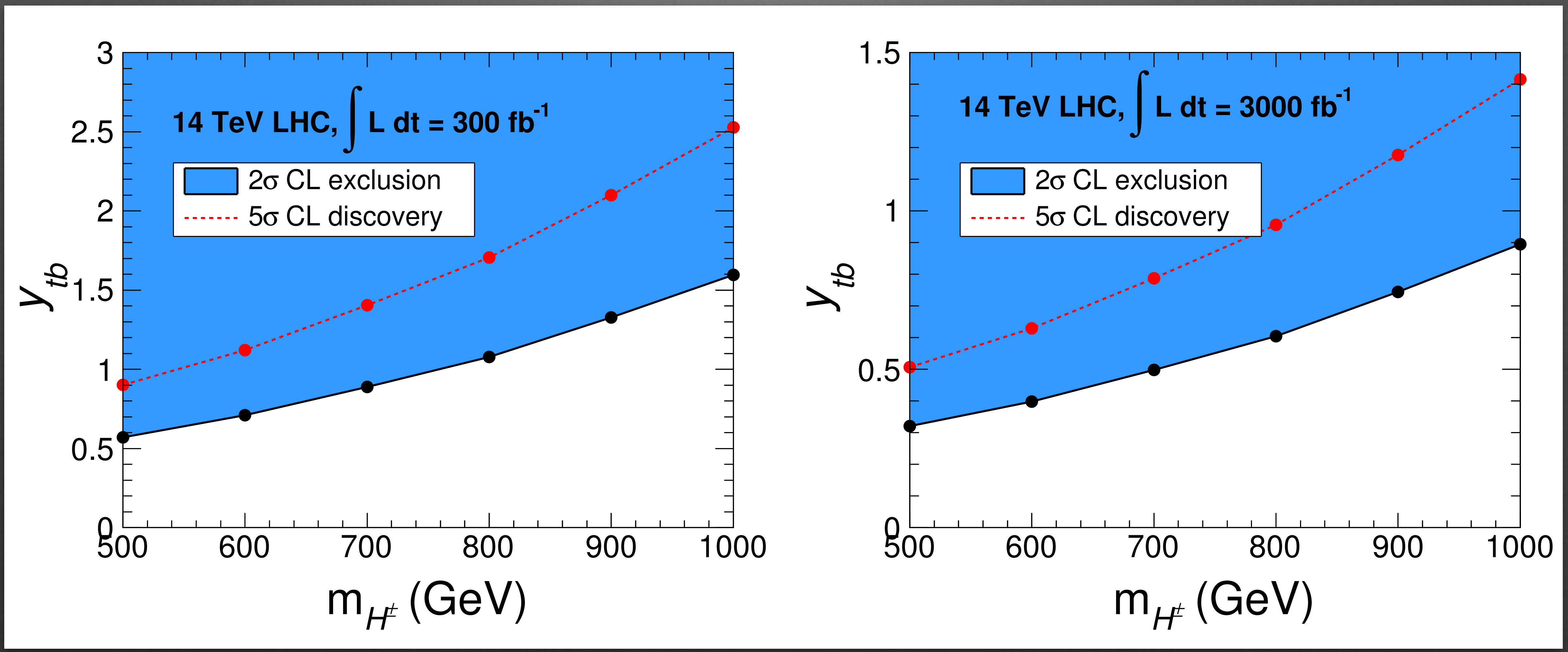
$pp \to tbH^{\pm} \to tbtb$

- Invariant mass distribution of the leading top and the leading b-jet



$pp \to tbH^\pm \to tbtb$

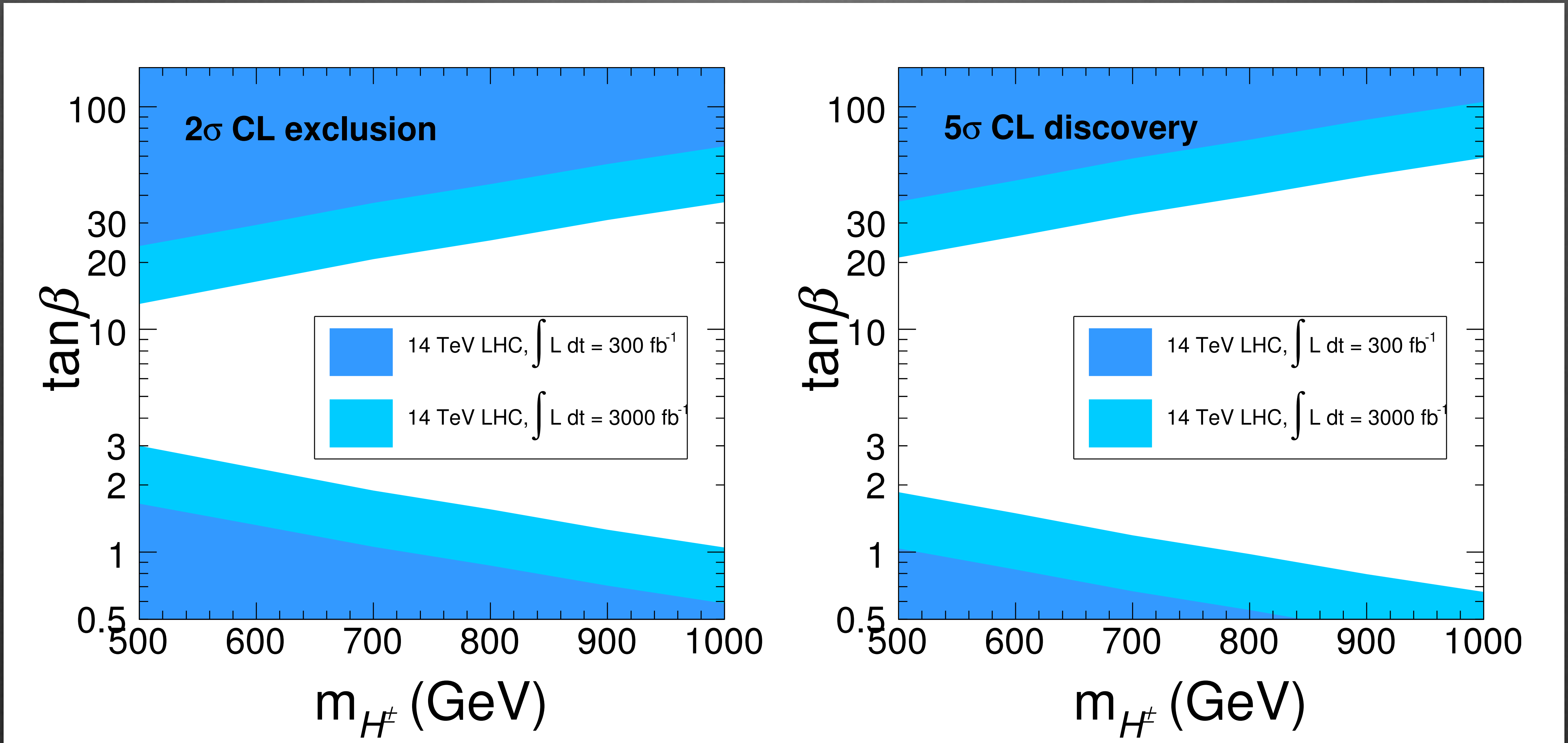
- Constraint to the 2HDM



$pp \to tbH^{\pm} \to tbtb$

- Constraint to the 2HDM (Type II)

$$\mathcal{L}_{\text{Type II}} = \frac{\sqrt{2}}{v} H^+ \bar{t}(P_L m_t \cot\beta + P_R m_b \tan\beta) b + \text{h.c.}$$



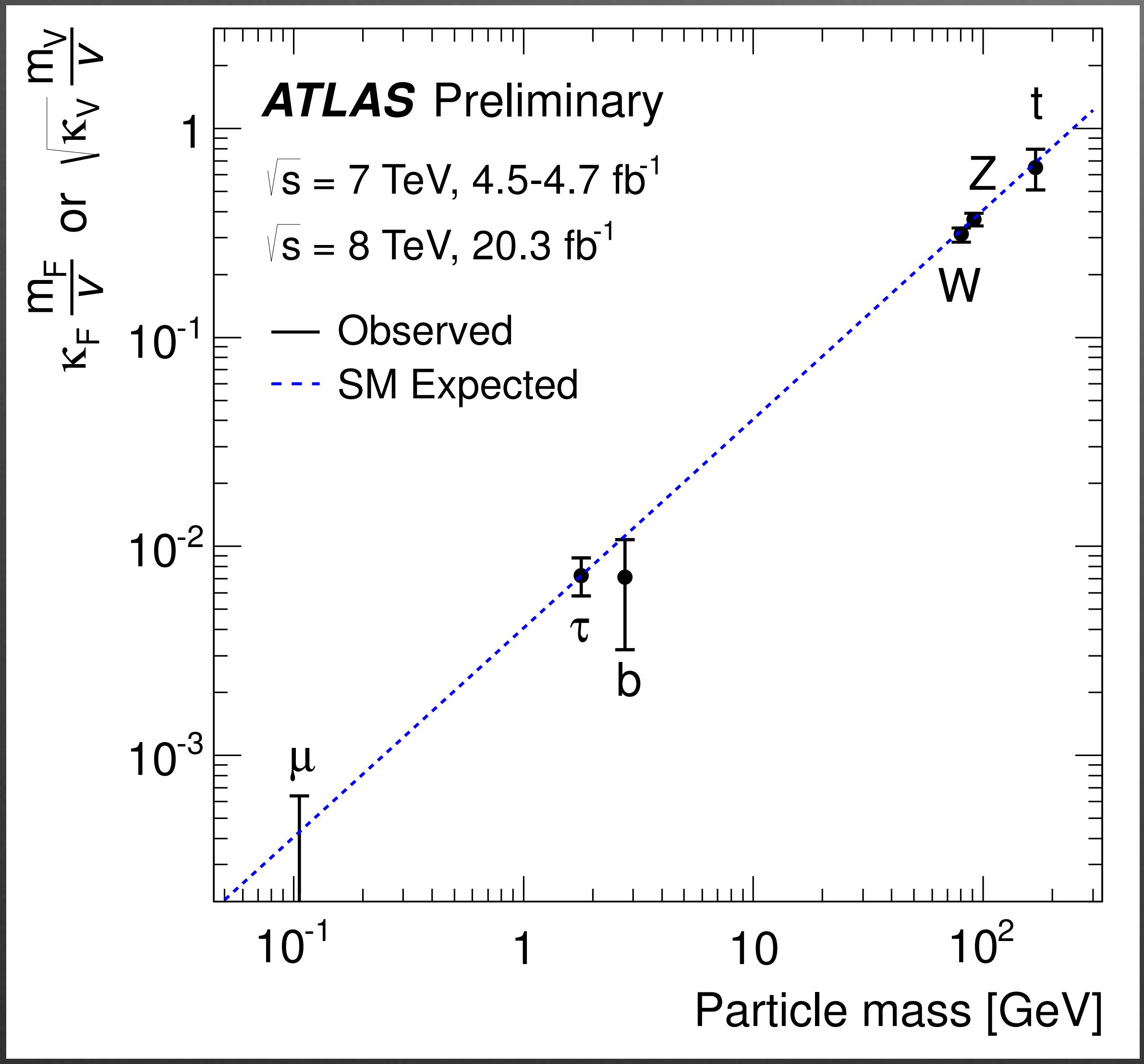
With boosted-top tagging tech. and BDT method, see J. Hajer, Y.-Y Li, T. Liu, and J. F. H. Shiu, arXiv: 1504.07617[hep-ph]

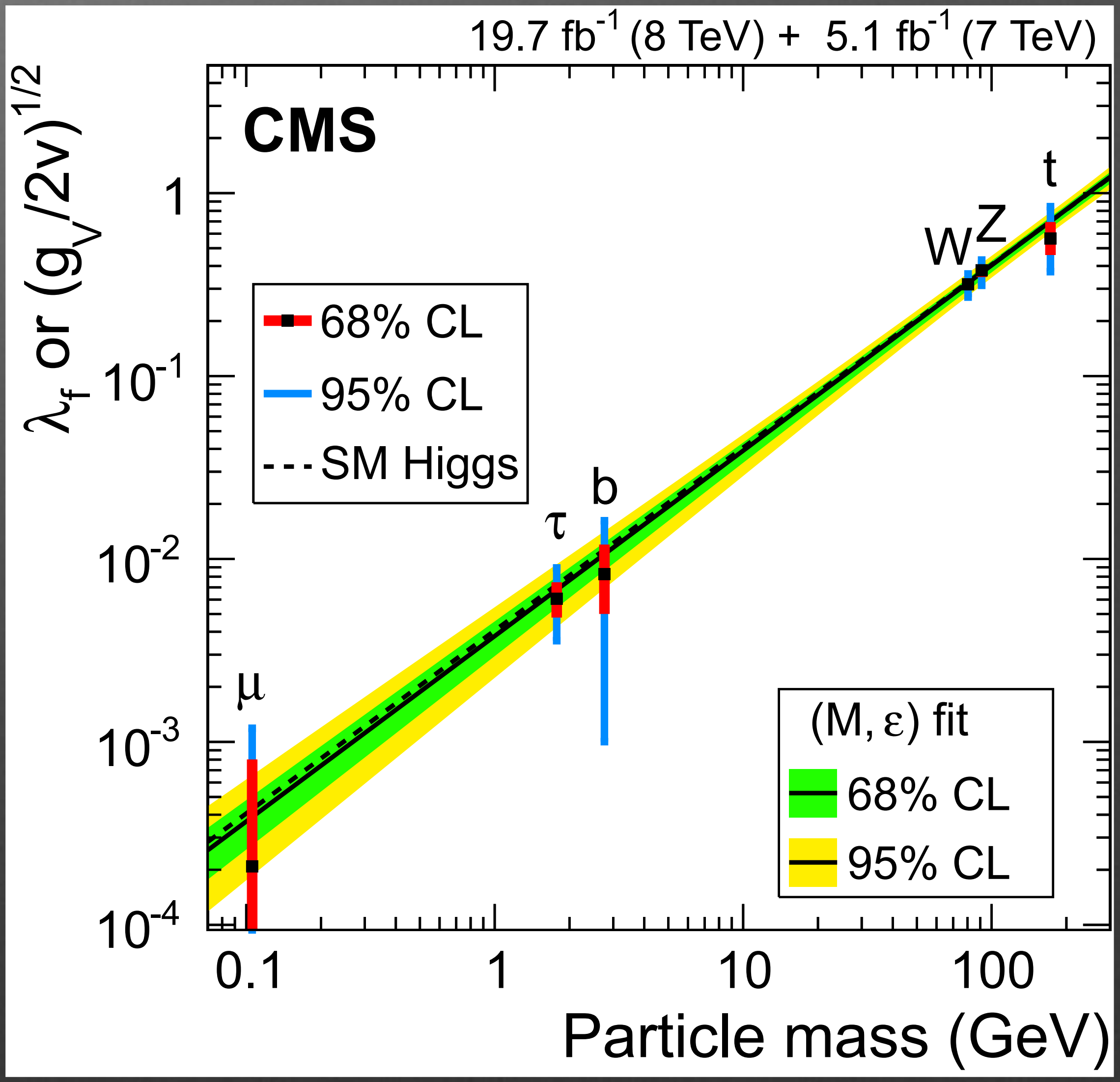
Rare Higgs processes at Colliders

based on arXiv:1410.1855[hep-ph] in collaboration with Tao Liu

Rare Higgs processes

- Who gives Higgs boson mass?

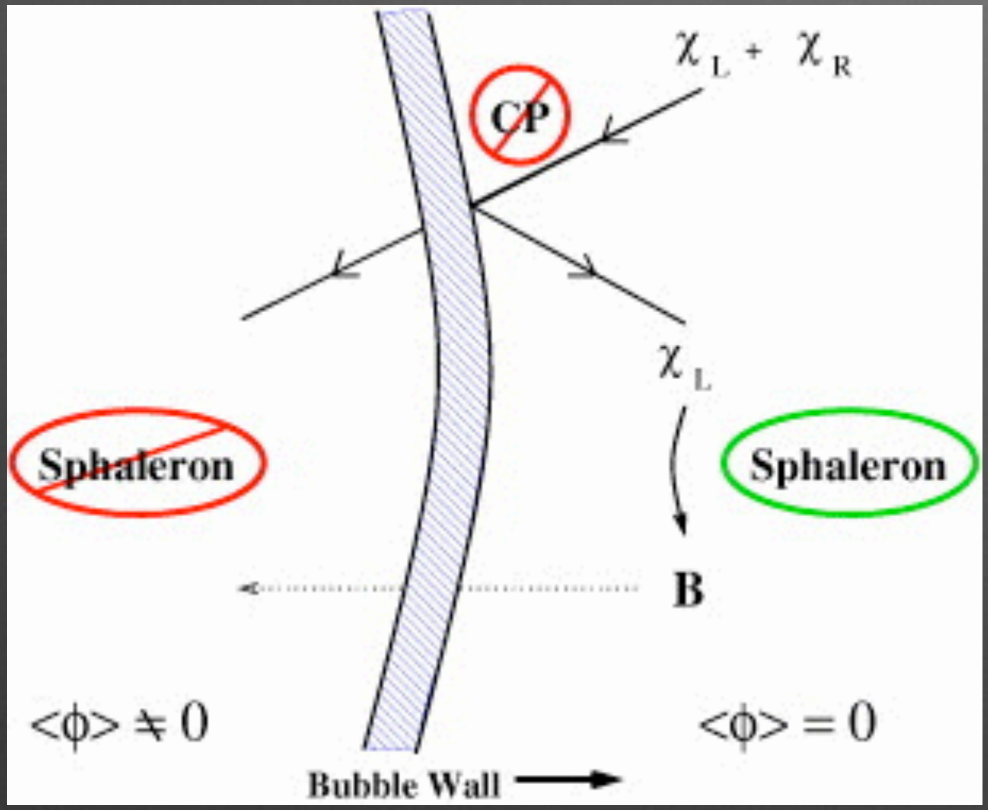




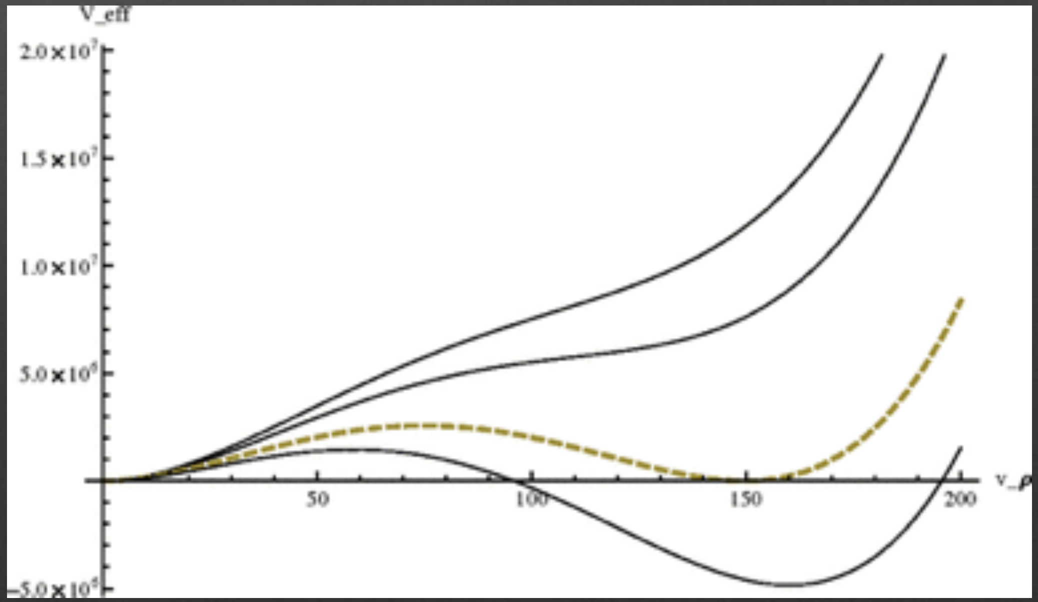
ATLAS Collaboration, ATLAS-CONF-2015-007; CMS Collaboration, EPJC 75 (2015) 5, 212

Rare Higgs processes

- How to realize the 1st order electroweak phase transition in the electroweak baryogenesis?



$$\frac{\langle \phi(T_c) \rangle}{T_c} > 1$$



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

Rare Higgs processes

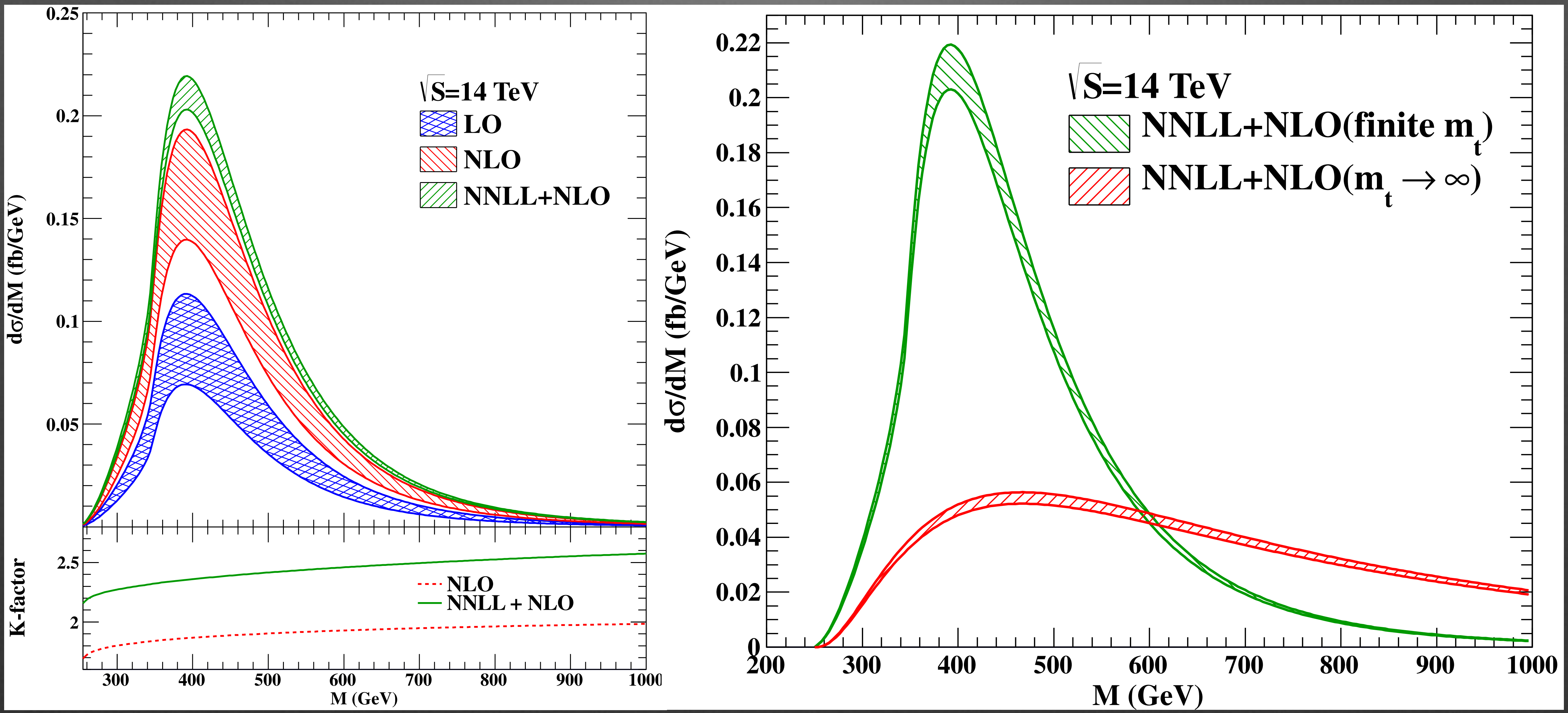
- It is extremely important to measure the Higgs self-interaction!

	$\sqrt{s} = 14$ TeV	
	(LO)	NLO
HH (EFT loop-improv.)	$(22.8^{+32\%}_{-23\%})$	$34.8^{+15+2.0\%}_{-14-2.5\%}$
$HHjj$ (VBF)	$(1.839^{+8.9\%}_{-7.7\%})$	$2.017^{+1.3+2.5\%}_{-1.0-1.9\%}$
$t\bar{t}HH$	$(1.245^{+36\%}_{-25\%})$	$0.981^{+2.3+2.3\%}_{-9.0-2.8\%}$
W^+HH	$(0.283^{+1.1\%}_{-1.3\%})$	$0.364^{+1.7+2.1\%}_{-1.1-1.6\%}$
W^-HH	$(0.152^{+1.1\%}_{-1.4\%})$	$0.201^{+1.7+2.2\%}_{-1.1-1.8\%}$
ZHH	$(0.273^{+1.1\%}_{-1.3\%})$	$0.356^{+1.7+1.9\%}_{-1.2-1.5\%}$
$tjHH(\cdot 10^{-3})$	$(28.79^{+0.0\%}_{-1.2\%})$	$37.27^{+4.7+2.6\%}_{-2.7-3.0\%}$

R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, PLB 732 (2014) 142

Rare Higgs processes

- Higher order calculations are still needed and might give important corrections!



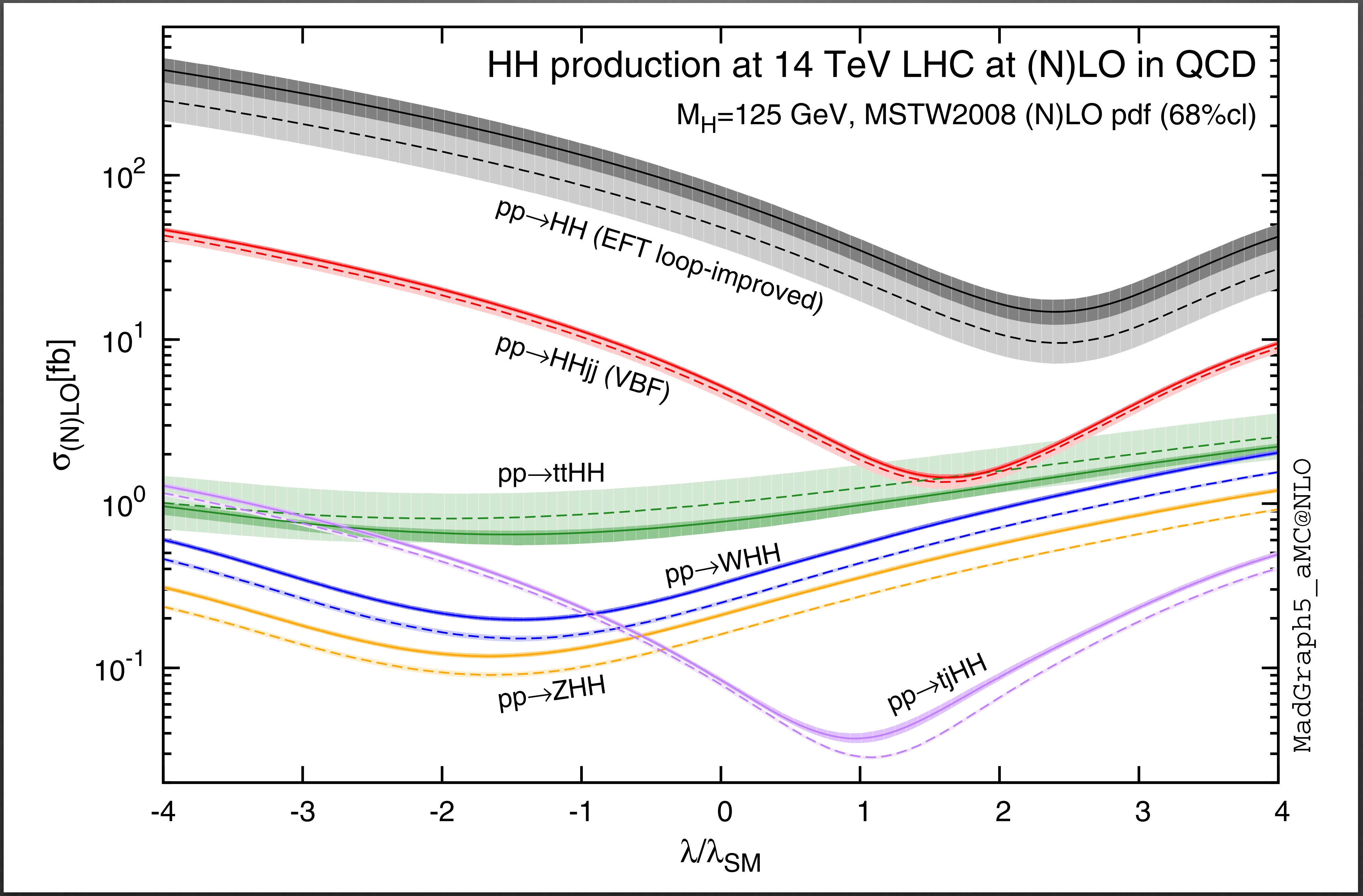
D.-Y. Shao, C.-S. Li, H.-T. Li, J. Wang, JHEP 07 (2013) 169

Rare Higgs processes

- *hh* channel: the largest cross section.
- $bb\gamma\gamma$ final state (3000fb^{-1}):
  - cut based method ~ 2σ, MVA >> 5σ (V. Barger, et al., PLB 728(2014)433)
  - cut based method 1.3σ (ATLAS Collaboration, ATL-PHYS-PUB-2014-019)
- $bb\tau\tau$ final state (3000fb^{-1}): ~ 9σ (J. Baglio, et al., JHEP 04(2013)151)
- *bbWW* final state (3000fb^{-1}): cut based method ~ 6.7σ, BDT ~ 8σ (A. Papaefstathiou, et al., PRD 78, 011301(2013))
- *hhjj* channel: checking *VVhh* coupling constant. ($bb\tau\tau jj$ mode (3000fb^{-1}): ~2.3σ, M. J. Dolan, et al., PRL 112, 101802(2014))
- But the total cross sections of *hh* and *hhjj* channels are not monotonic functions of λ!

Rare Higgs processes

- tthh channel cross section is monotonic functions of λ in a wide region.



R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, PLB 732 (2014) 142

Rare Higgs processes

- Preliminary simulation at 14 TeV and 100 TeV pp collider.

$\sqrt{s} = 14$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}hb\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	39.0	390.6	353.1	222.7	126.8	98.2
Di-Higgs rec.	33.0	269.3	242.1	171.0	93.5	76.8
Top rec.	19.5	160.7	149.0	102.8	54.6	47.1

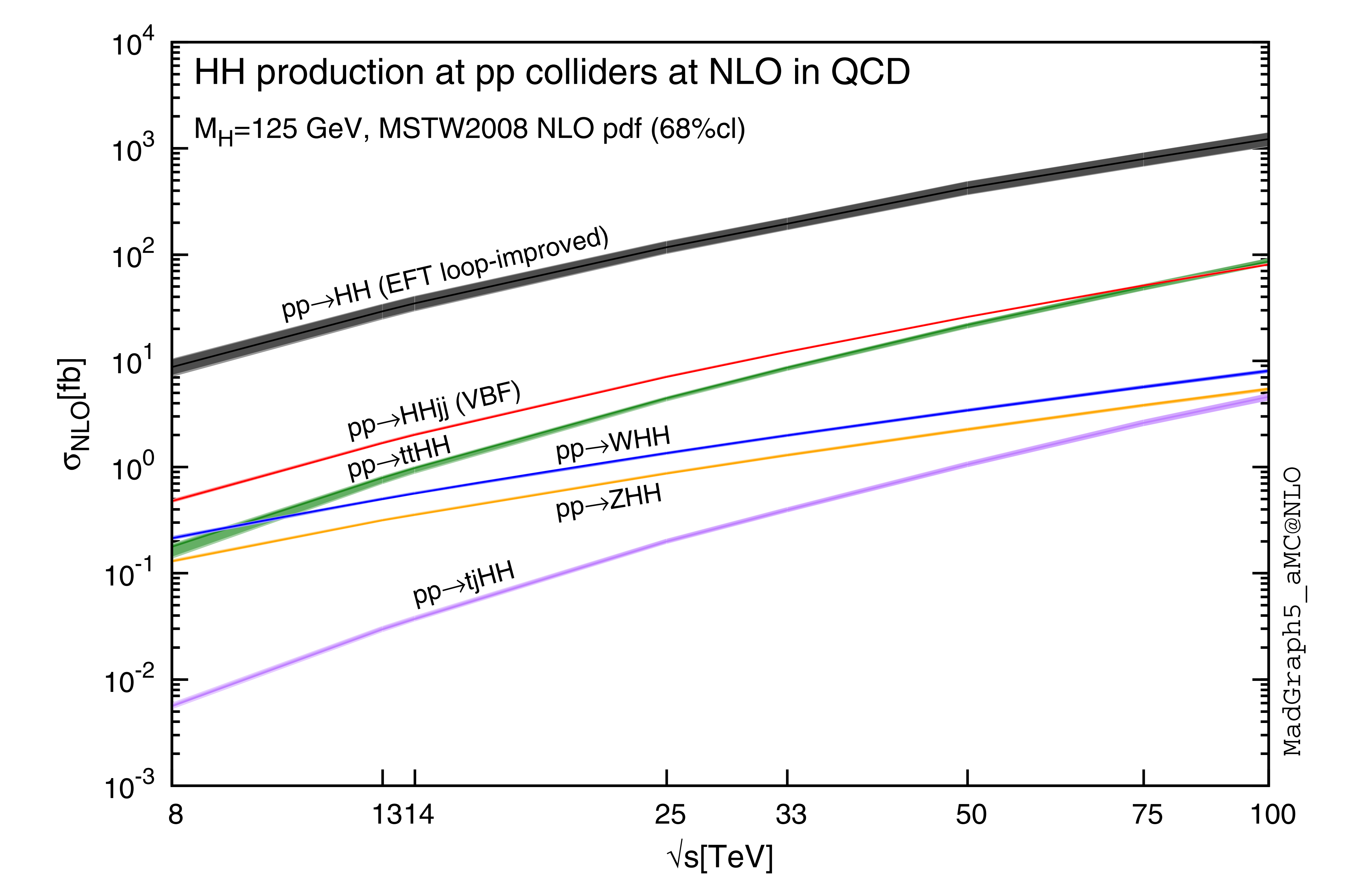
$$S/\sqrt{B} = 2.0\sigma$$

$$S/\sqrt{B} = 1.5\sigma$$

See also C. Englert, F. Krauss, M. Spannowsky, J. Thompson, PLB 743 (2014) 93

Rare Higgs processes

- Preliminary simulation at 14 TeV and 100 TeV pp collider.



R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, PLB 732 (2014) 142

Rare Higgs processes

- Preliminary simulation at 14 TeV and 100 TeV pp collider.

$\sqrt{s} = 100$ TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}hb\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	830.5	72678.7	13322.6	10231.8	3252.0	1995.7
Di-Higgs rec.	608.4	31679.7	6285.2	5689.9	1504.0	1193.3
Top rec.	240.1	10384.4	2189.1	2208.6	428.0	384.9

- More investigations are needed to increase the significance of this channel.

- Data driven bkgd, QCD uncertainty!

- λ dependence?

Conclusion and Outlook

Conclusion

- A lot of new physics models predict the extension of the SM Higgs sector.
- The direct and indirect constraints from the LHC to the additional Higgs bosons are investigated in detail.
- The Alignment limit is preferred by the precisely measurement of the SM-like Higgs boson. Additional Higgs bosons decouple from the SM gauge bosons.
- Searching for the heavy additional Higgs bosons at the 14 TeV LHC via their interactions with the SM top quark and bottom quark are studied.
- We are on the way of hunting for the rest of Higgs bosons.

Outlook

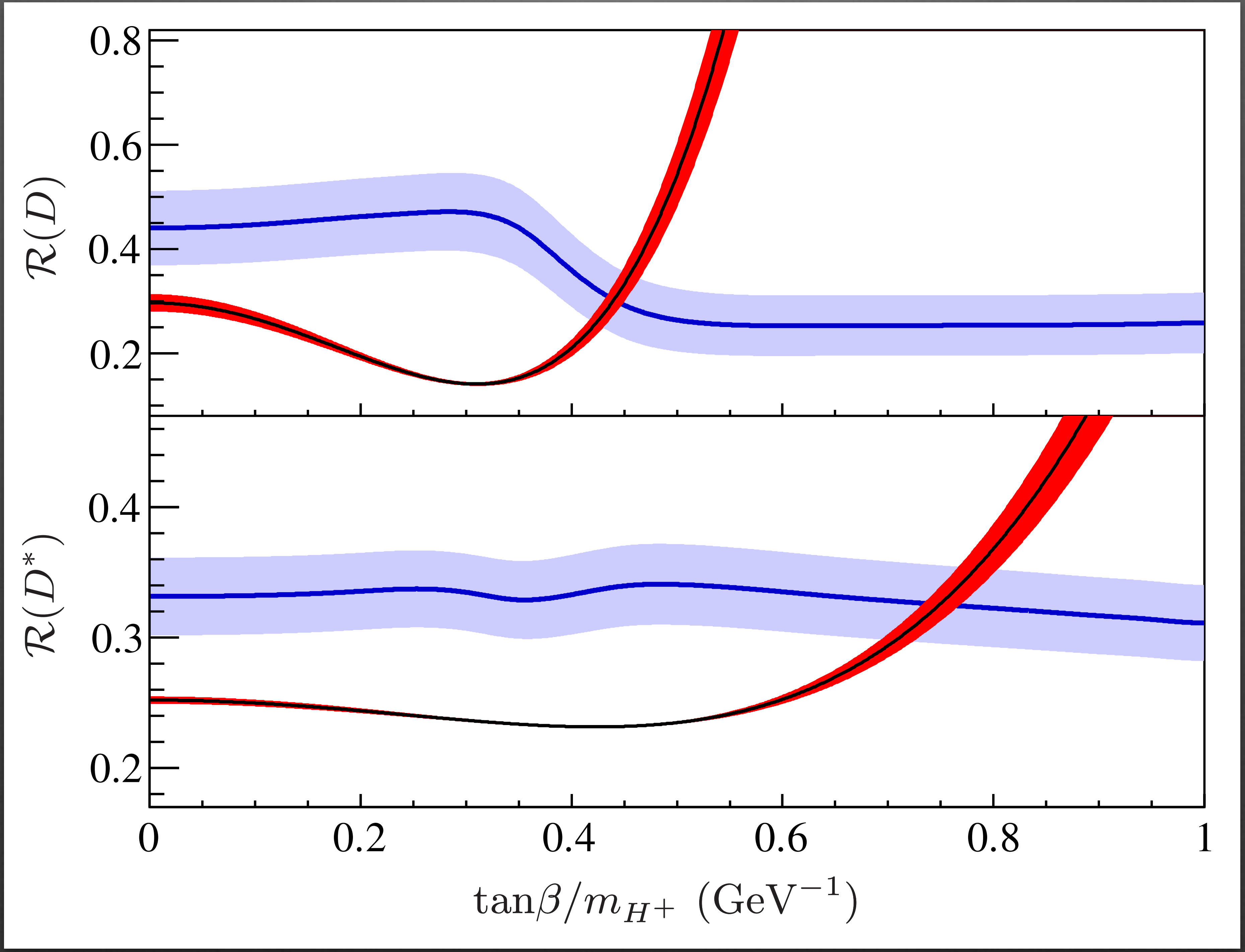
- The SM, although is very successful, needs to be modified at some cutoff scale. Many new physics models have been proposed to explain the problems of the SM.

- Our aim is discovering the new physics (the next generation SM). This is a very challenging mission. Maybe it will excess the limit of the ability of the LHC and next generation colliders (CEPC, SppC, …) are necessary.

- SM is behind us after the discovery of the SM-like Higgs boson. We are just at the start point of the trip of exploring the new unknown world. Many challenges are waiting for us. We should work harder and harder, and never stop.


Thank you!

Backup


0.8
0.6
0.4
0.2
$\mathcal{R}(D)$
0.4
0.3
0.2
$\mathcal{R}(D^*)$
0
0.2
0.4
0.6
0.8
1
$\tan\beta/m_{H+}$ (GeV^{-1})

Introduction

- Lots of TeV scale new physics models are proposed for solving the (Higgs mass) hierarchy problem and other motivations.

  MSSM, NMSSM, Little Higgs, Universal Extra Dimension, RS, LR-symmetry, Flavor symmetry, 2HDM, Z', W', …

- How to discover them?

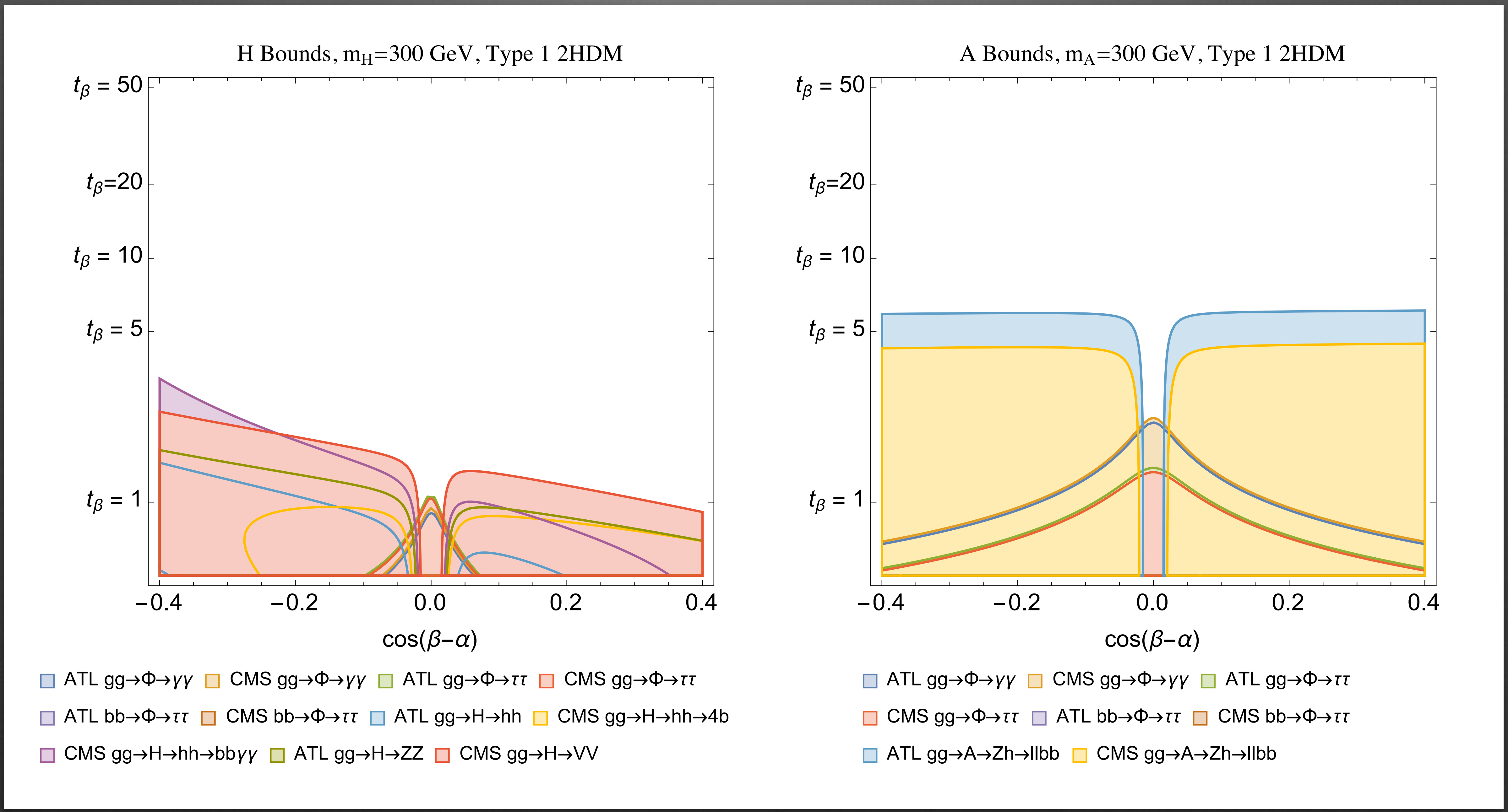
- How to distinguish them?

Introduction

- Direct search:
  - Searching for the new particles predicted by the new physics model at high energy colliders.
  - Measuring their properties at high energy colliders.
- Discoveries in direct search give definitive answers.
- Indirect search:
  - Searching for the signal of the high dimensional effective operators induced by the new physics, at high energy colliders, from precisely observables, or astrophysical and cosmological observables.
- Indirect search is an important guide for new physics search.

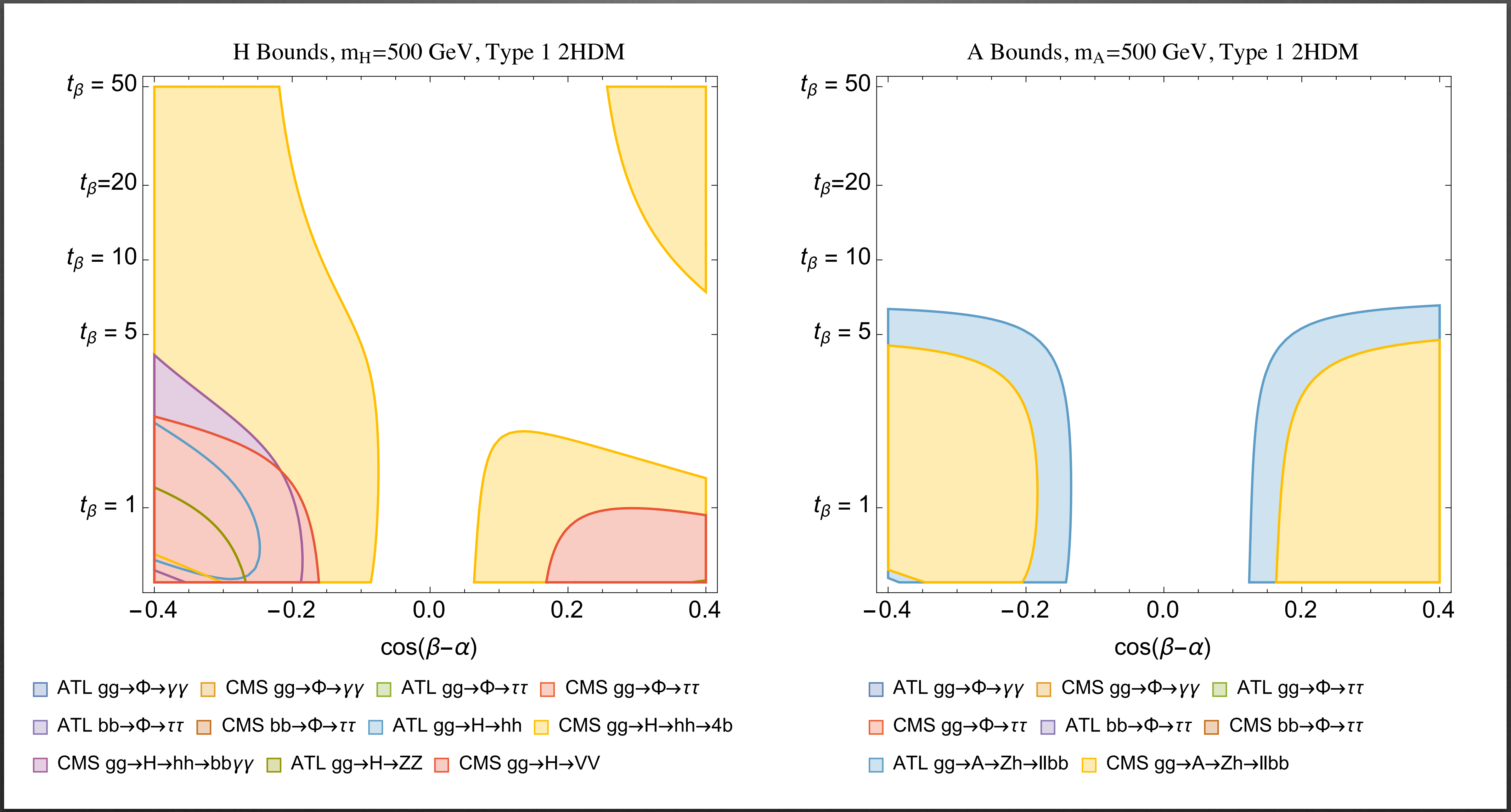
Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type I 2HDM)



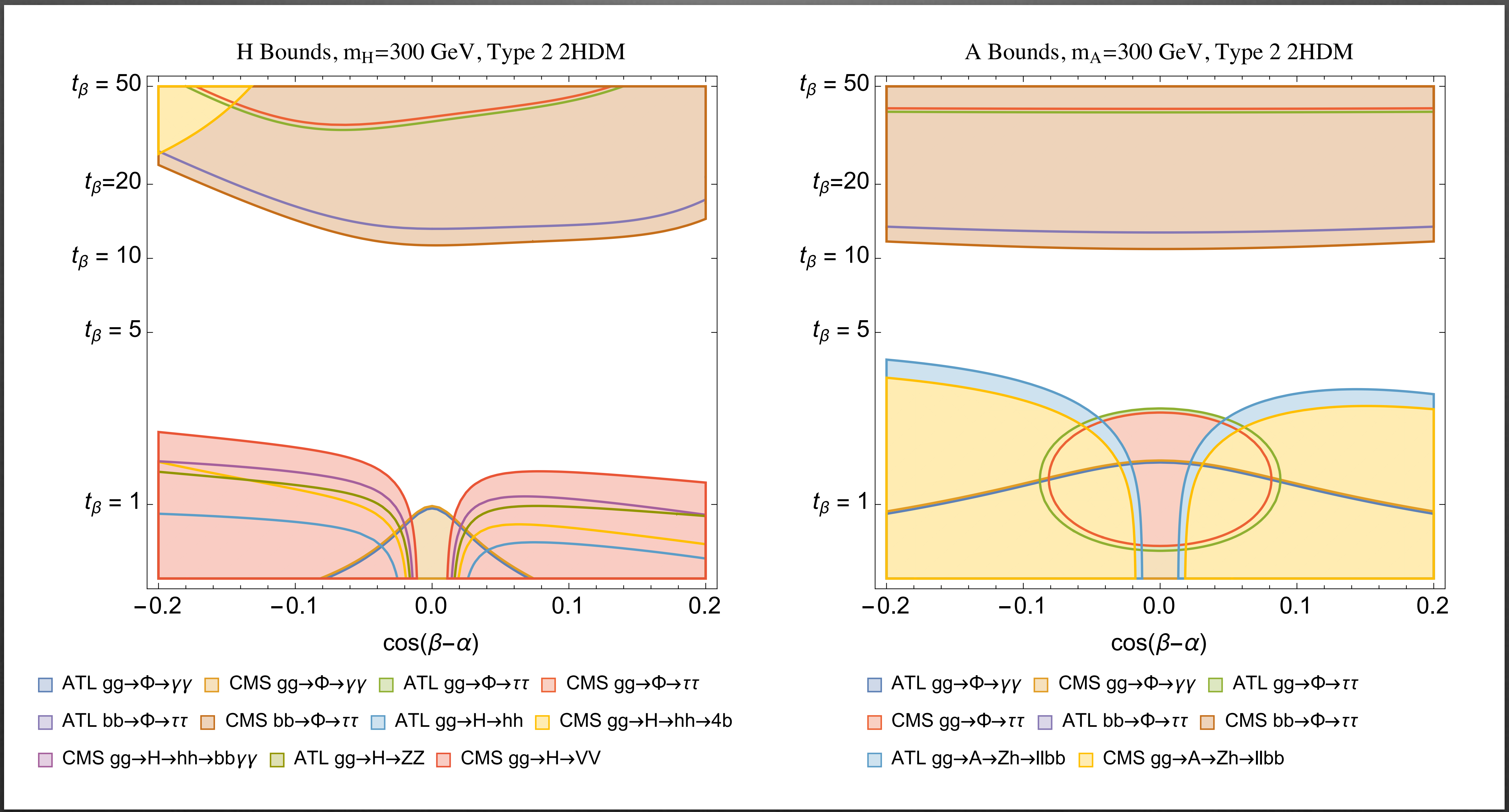
Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type I 2HDM)



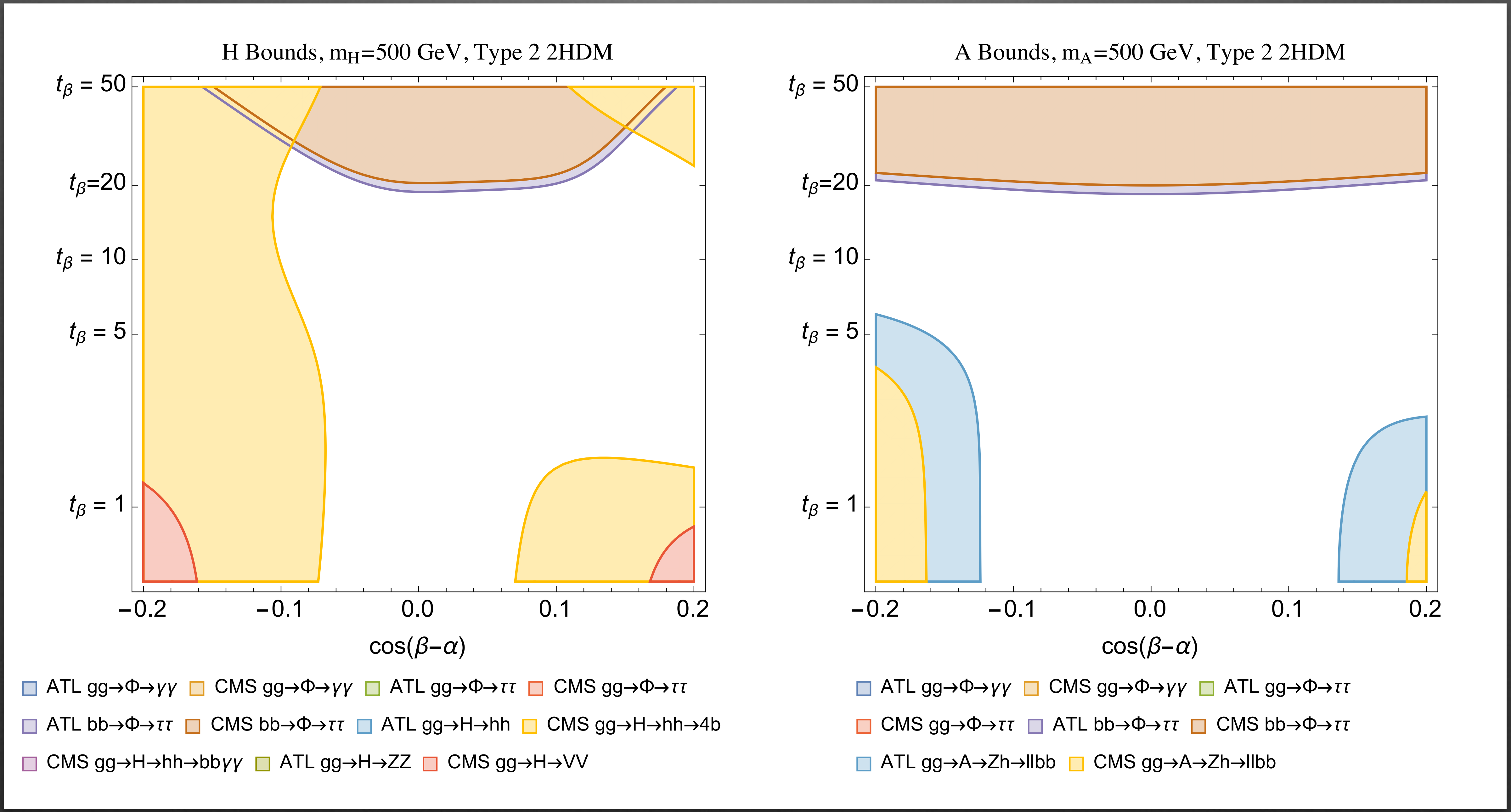
Direct and Indirect Limit

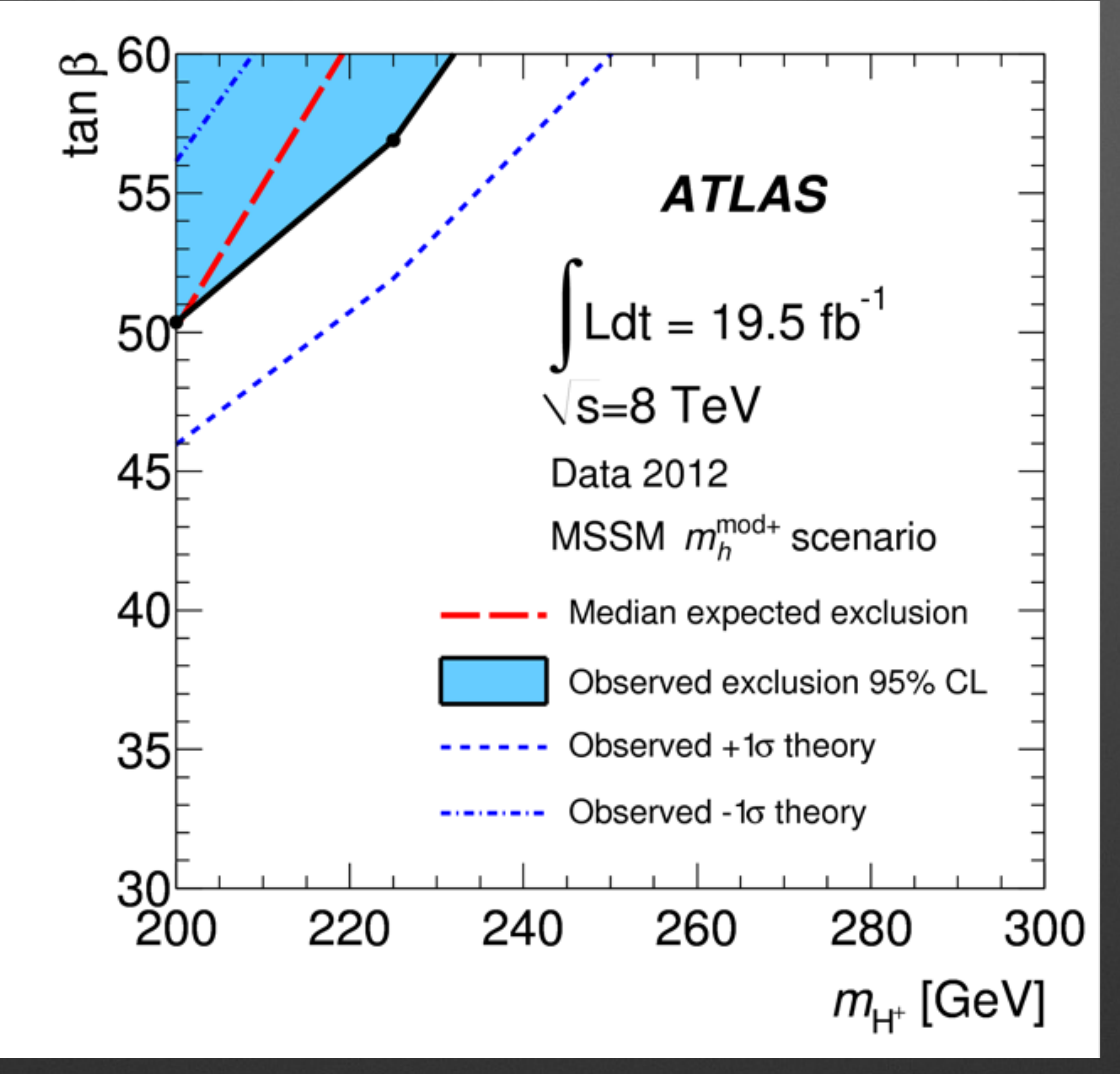
- Results from 7 and 8 TeV LHC (Type II 2HDM)



Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type II 2HDM)





tan β
60
55
50
45
40
35
30
200
220
240
260
280
300
m_{H^+} [GeV]
ATLAS
$\int Ldt = 19.5\ fb^{-1}$
$\sqrt{s}$=8 TeV
Data 2012
MSSM m_h^{mod+} scenario
Median expected exclusion
Observed exclusion 95% CL
Observed +1σ theory
Observed -1σ theory