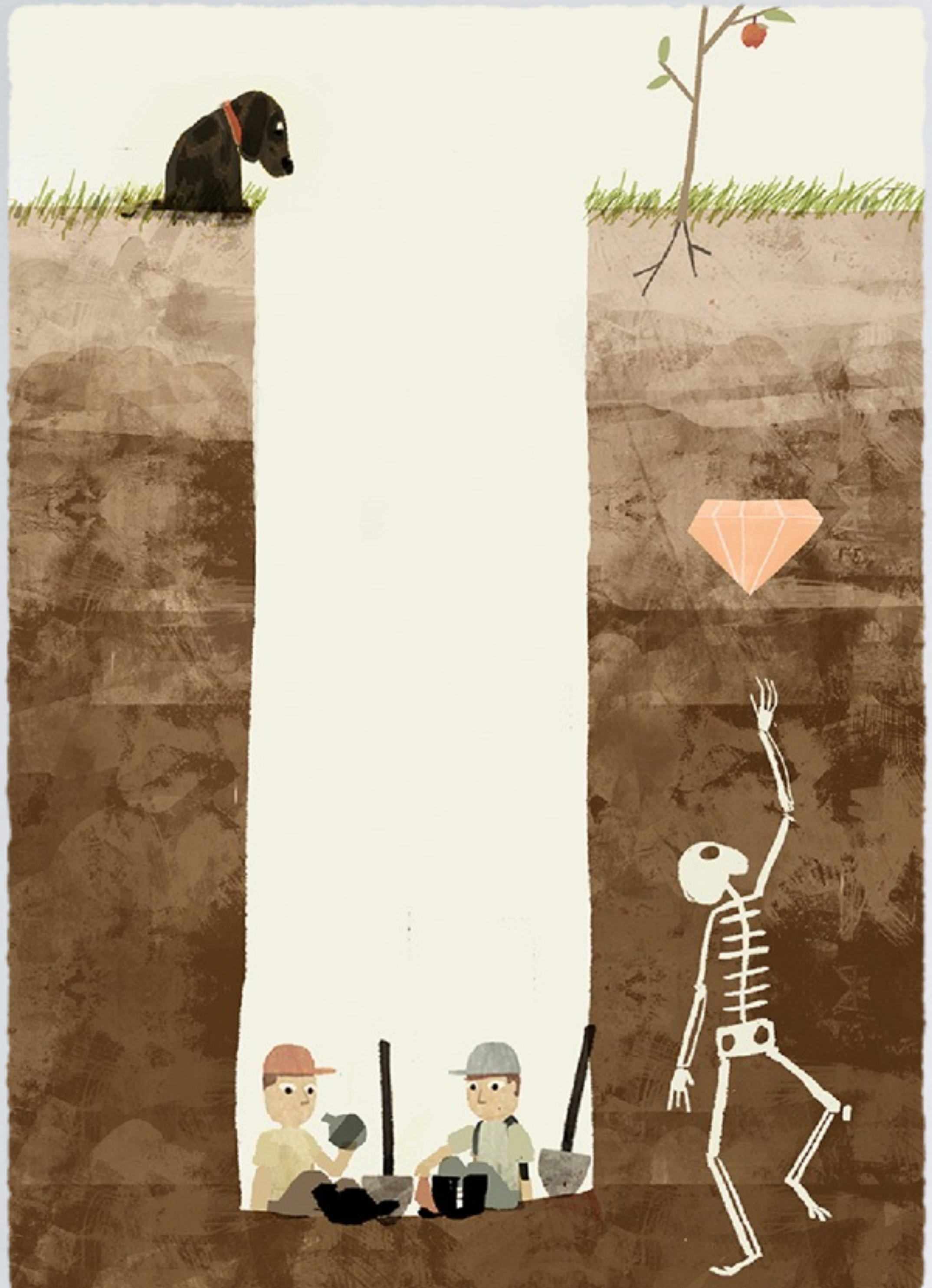
Particle Physics on the Plains, Oct. 13 2018



SAM & DAVE DIG A HOLE, Mac Barnett & Jon Klassen

Hunting for Maverick Top Partners

Jeong Han Kim

KU
THE UNIVERSITY OF KANSAS

J. H. Kim and Ian M. Lewis, [JHEP 1805 (2018) 095]

Haider Alhazmi, **J. H. Kim**, K. C. Kong, Ian M. Lewis, [arXiv:1808.03649]

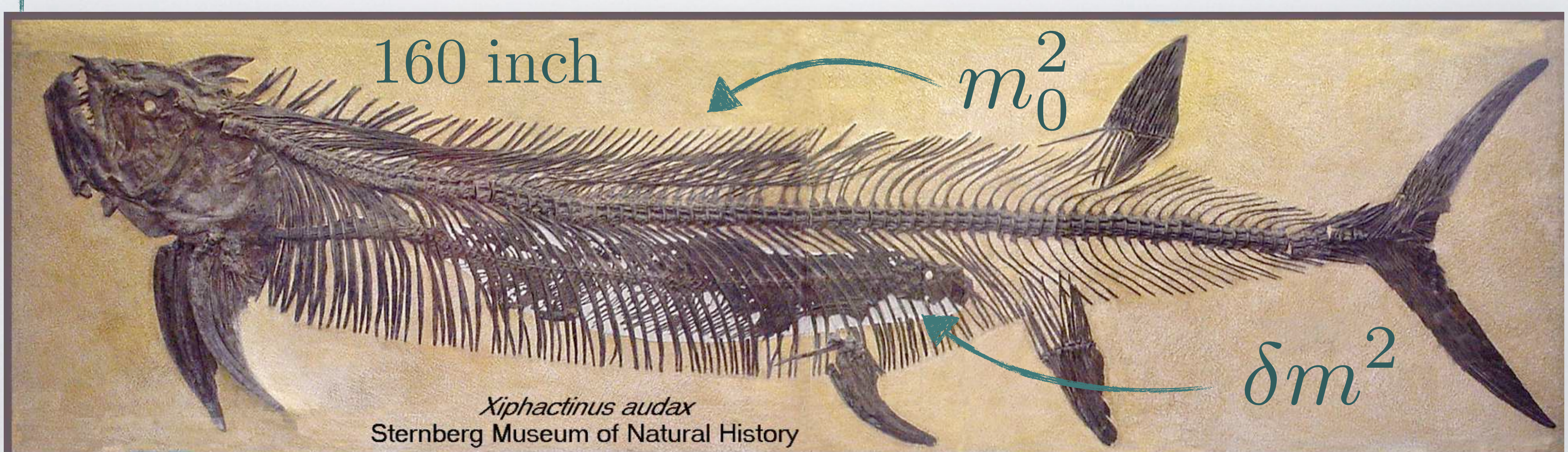
Historical Motivation

V_h

- A historical approach to investigate the EWSB shares the common motivation from a naturalness.
- Due to a radiative instability on m_h^2 .
  - Vector-like top partners (T) are postulated to exist to address the naturalness problem (e.g. composite Higgs or Little Higgs models).

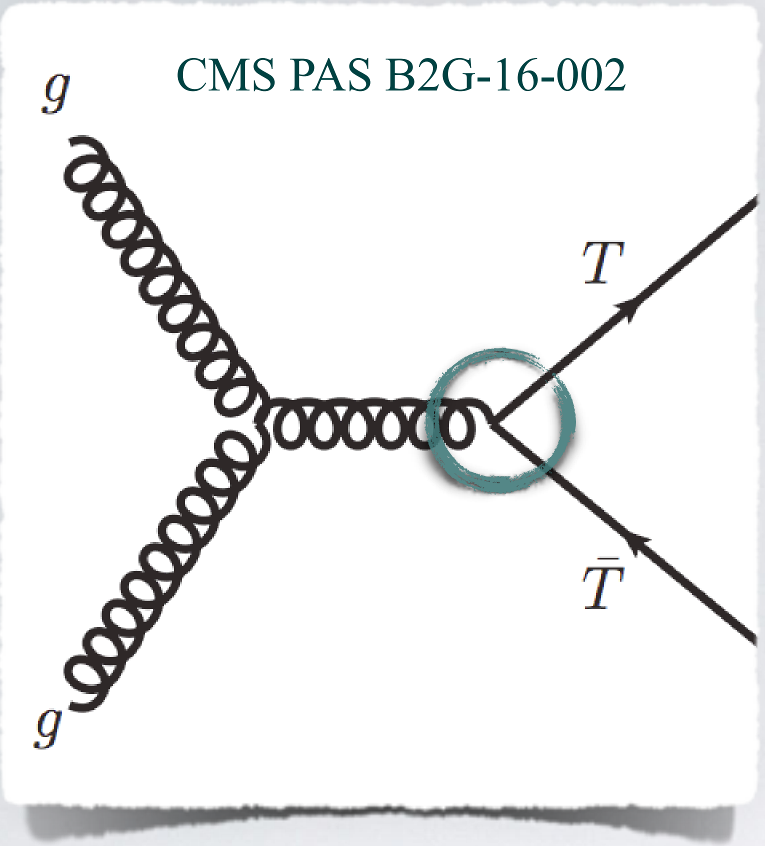
h

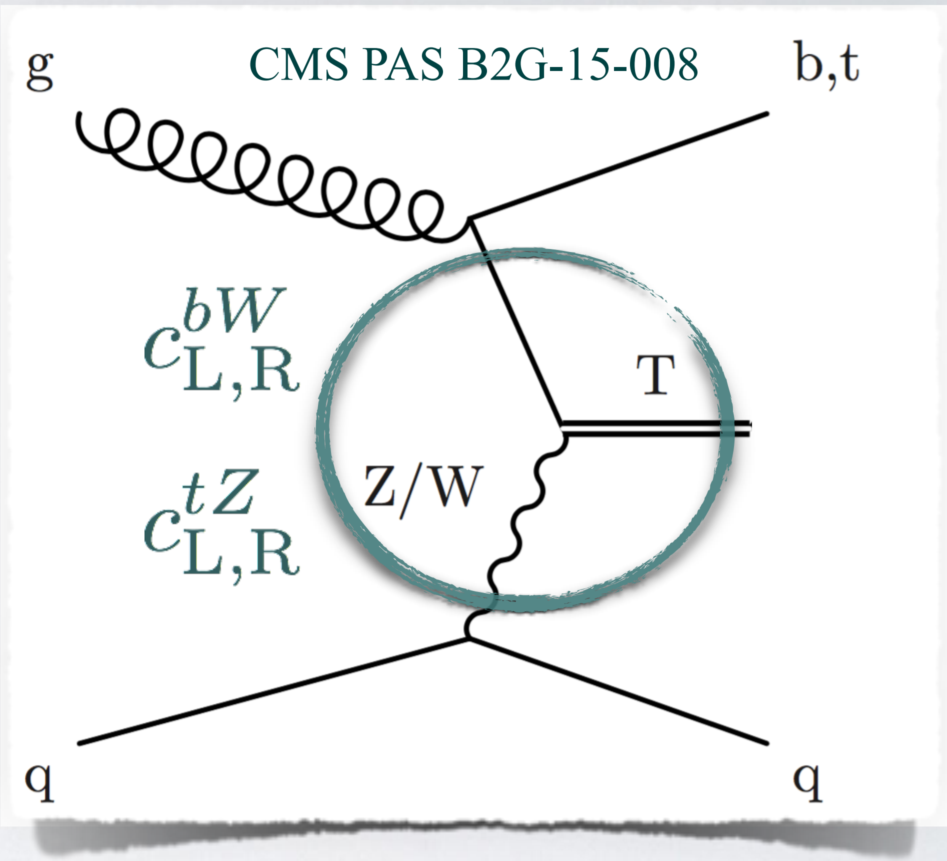
$m_h^2 =$



Sternberg Museum in Kansas

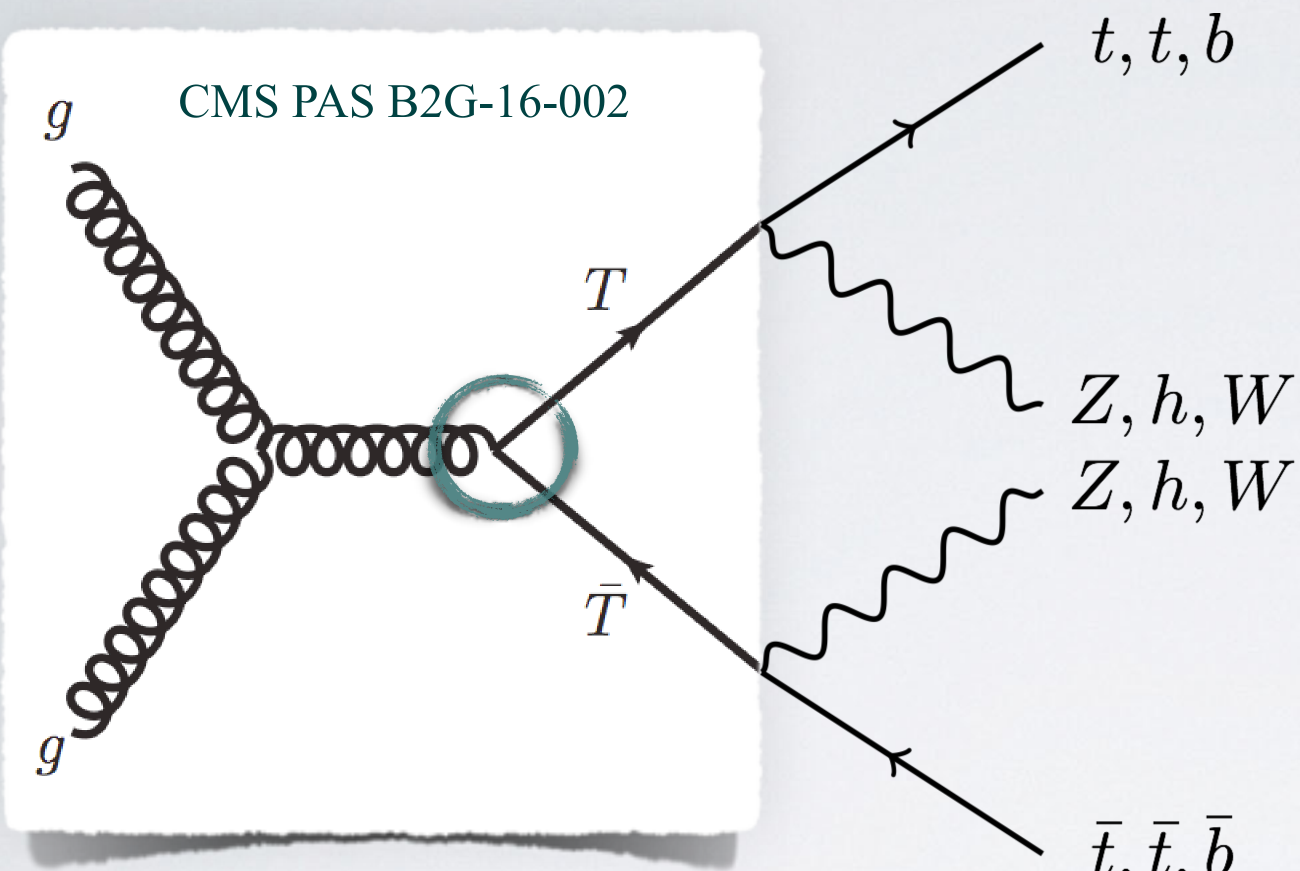
Productions of *T* at the LHC

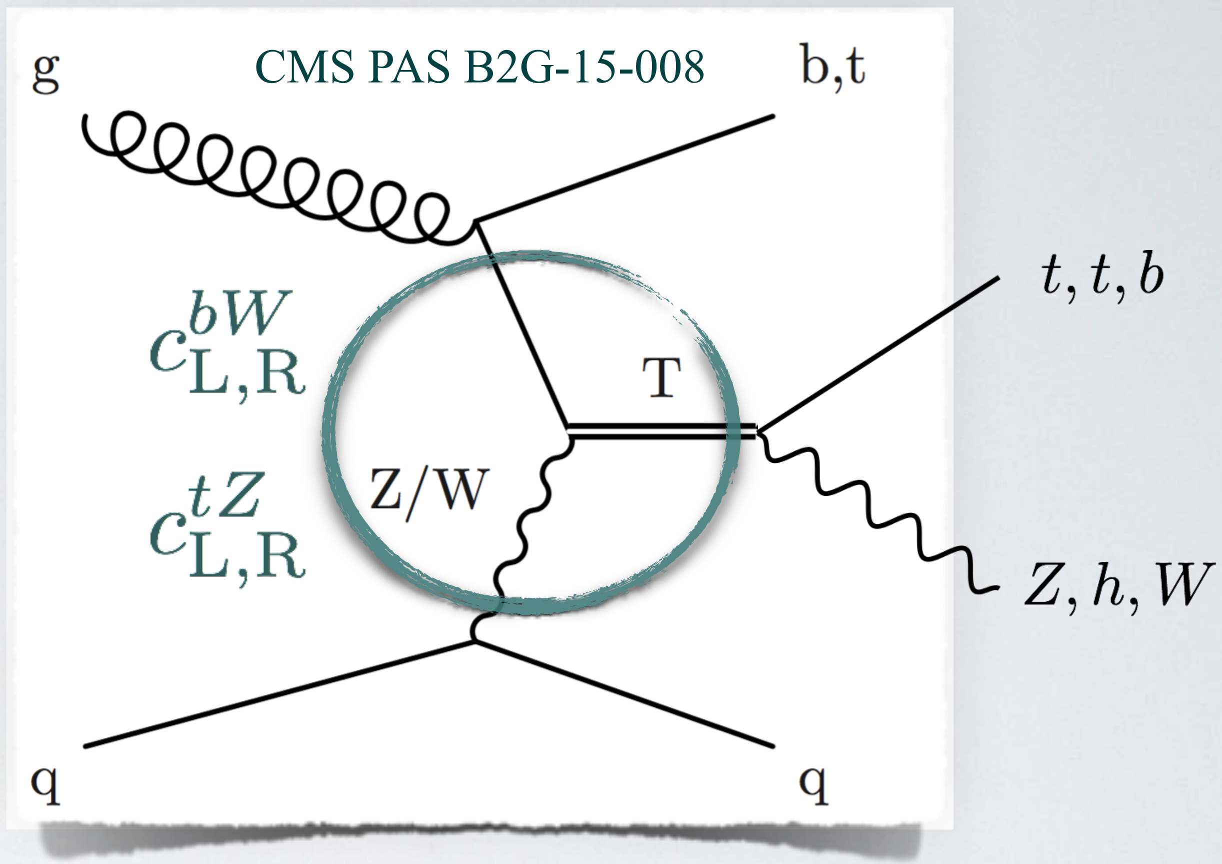




- Typically the *T* can be produced in pair or in single.
- The vertex responsible to create *T* in pair is the strong coupling.
- The single production is induced by EW coupings.
- Restricted to *T* decays to *tZ*, *th* and *bW*.

Productions of T at the LHC





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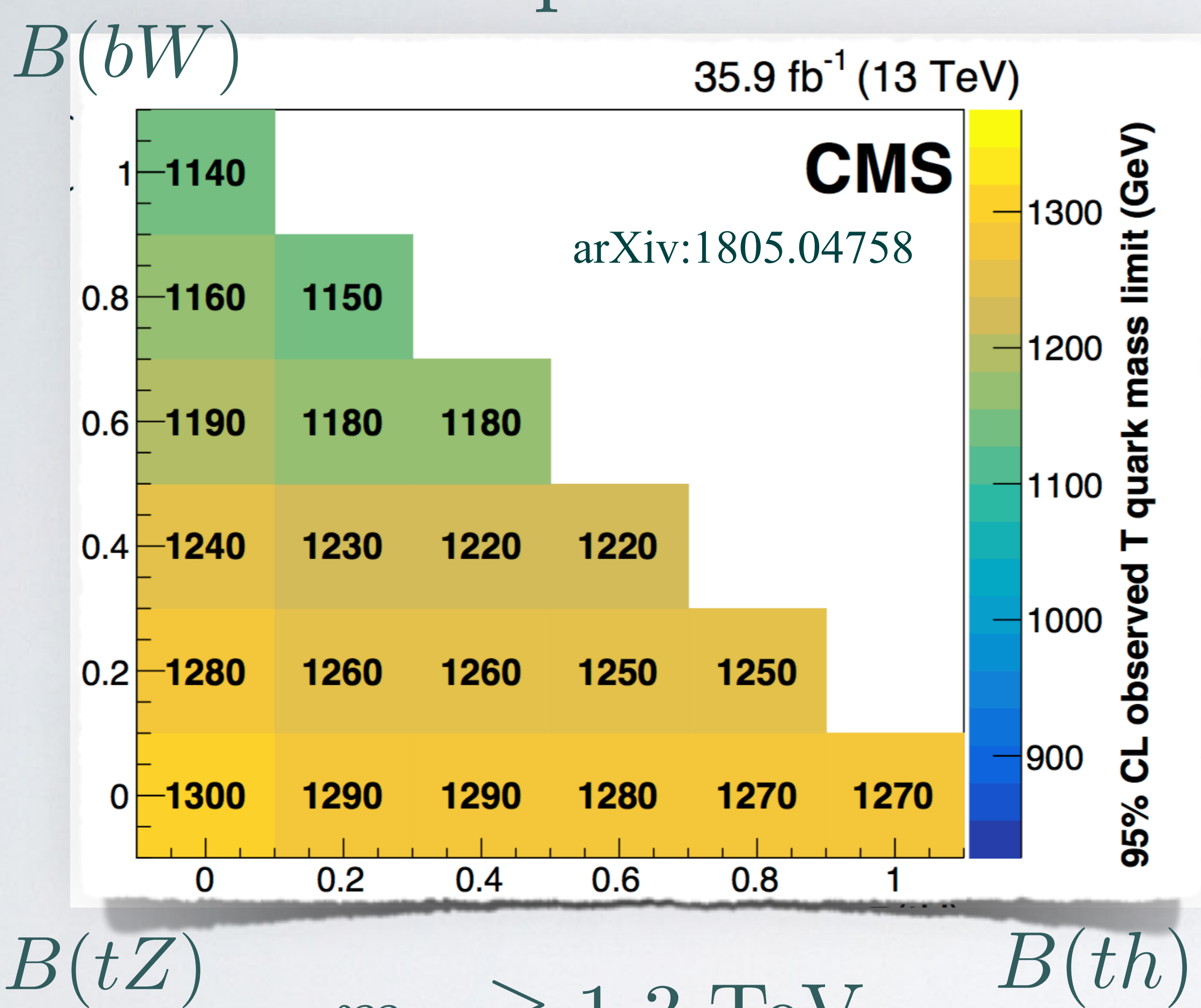
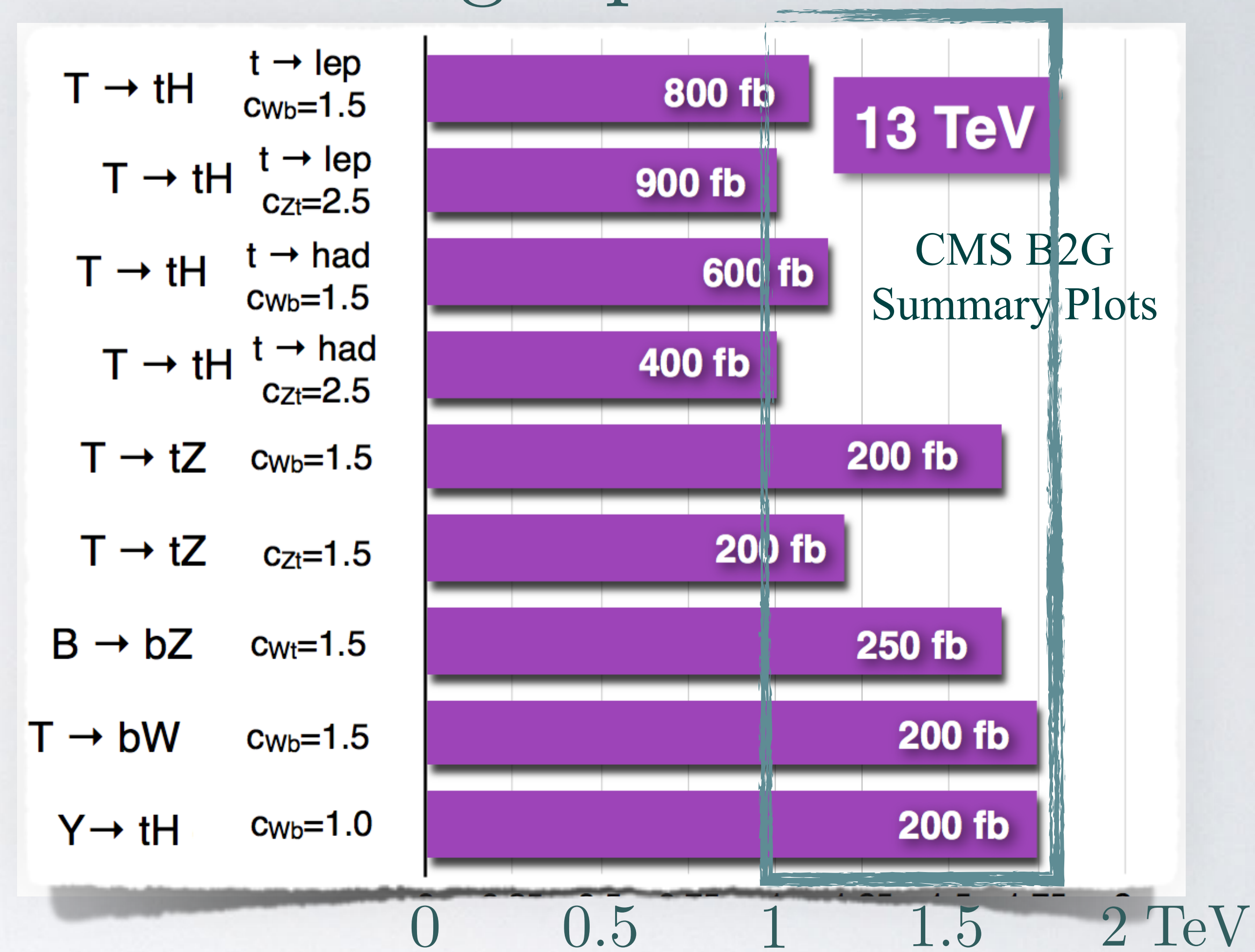
Current Bounds on T

Pair production



$m_T \gtrsim 1.3$ TeV

EW single production



$m_T > 1 \sim 1.8$ TeV

- Recent bounds on T from the pair and single productions.
- The bounds keep increasing every year.
- A considerable amount of searches are still going in the same direction with the classic assumption on T decays.

Nothing

- Under the searches based on the classic channels, no sign of T has been seen.
- To tackle this current challenge and to prepare for all eventualities ahead, we must think every possible scenario.
- And we believe that the null result may hint at T hiding in new places.
- We introduce a simple model predicting new signatures of maverick top partners, providing a roadmap to hunt them down.

The Model

- We consider a simplified model with a $SU(2)_L$ singlet T and an additional gauge singlet scalar S.

- A minimal set of interactions we identify consists of :

$$\mathcal{L}_{\rm NP} = \bar{T} i \not{D} T - m_2 \bar{T} T + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + \left(-\lambda_2 S \bar{T}_L T_R + \text{h.c.} \right)$$

$$\mathcal{L}_{\rm mix} = -\left(\lambda_t \bar{Q}_L \tilde{\Phi} T_R + \lambda_1 S \bar{T}_L t_R + \text{h.c.} \right)$$

Mixing

$$\mathcal{L}_m = -\begin{bmatrix} \bar{t}_L & \bar{T}_L \end{bmatrix} \begin{bmatrix} \frac{y_t v}{\sqrt{2}} & \frac{\lambda_t}{\sqrt{2}} v \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} t_R \\ T_R \end{bmatrix} + \text{h.c.}$$

$$\not{D} = \not{\partial} - i g' \frac{2}{3} \not{B} - i g_s \not{G}$$

$$\Phi = \begin{pmatrix} -i G_p \\ \frac{1}{\sqrt{2}}(v + h + i G_0) \end{pmatrix}$$

$$Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

- Allowing T to mix with a top quark.

Minimal set of parameters

- In this simplified model, we have 5 independent parameters.

$$\lambda_1 \quad \lambda_2 \quad \sin\theta_L \quad m_T \quad m_S$$

$$\lambda_1 S \bar{T}_L t_R + \text{h.c.} \qquad -\lambda_2 S \bar{T}_L T_R + \text{h.c.}$$

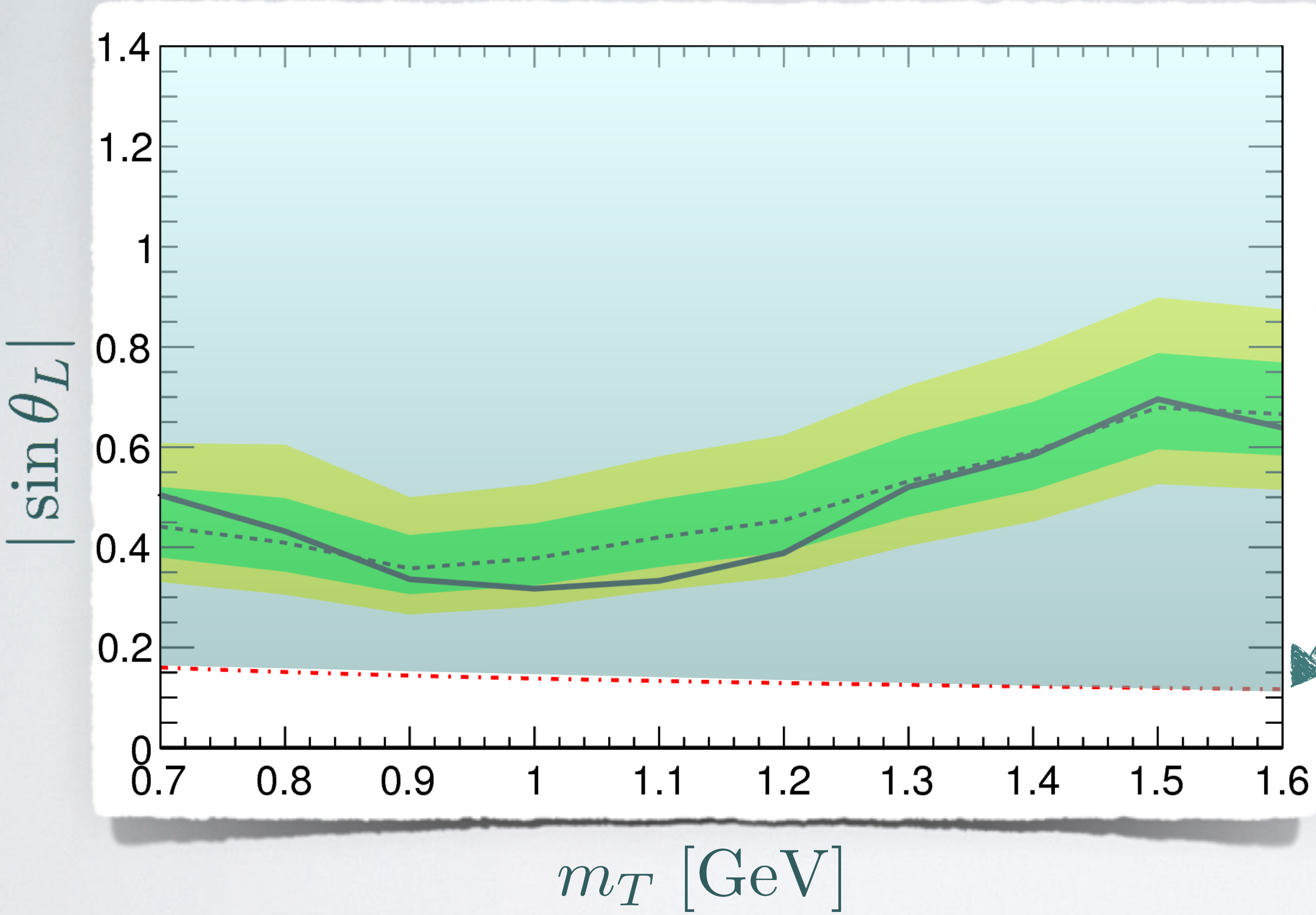
- All other parameters can be expressed in terms of $\sin\theta_L$, m_T and m_S.

- It will be interesting to introduce another mixing between *S* and the Higgs…

- For simplicity, we set the scalar mixing to zero, and leave it to a future study.

Limits on the mixing angle

ATLAS-CONF-2016-072 $\sqrt{s} = 13$ TeV $3.2\ \mathrm{fb}^{-1}$ singlet T



by oblique parameters

Chien-Yi Chen, S. Dawson, I. M. Lewis [2014]

J. A. A. Saavedra, R. Benbrik, S. Heinemeyer, M. P. Victoria [2013]

S. Dawson, E. Furlan [2012]

H. J. He, N. Polonsky, S.F. Su [2001]

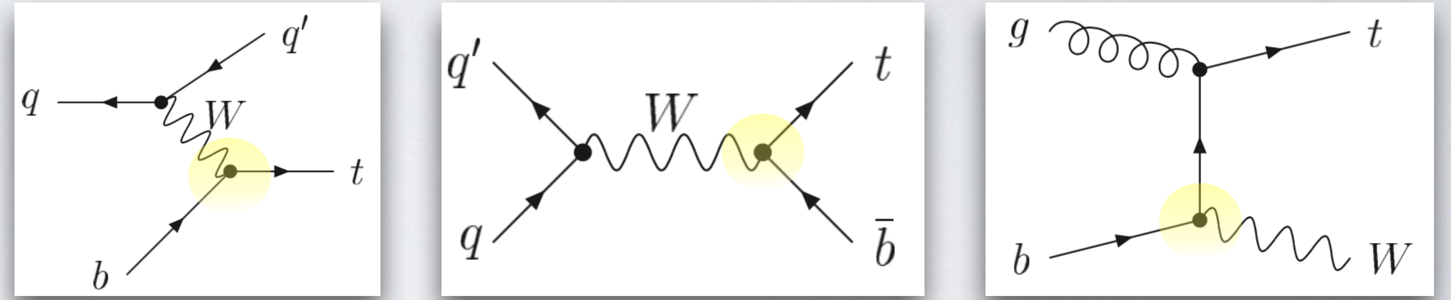
- The mixing angle is higly constrained by oblique parameters.

$$|\sin\theta_L| < 0.11 \sim 0.16 \quad (\text{for } m_T < 1 \sim 2 \text{ TeV})$$

Limits on the mixing angle

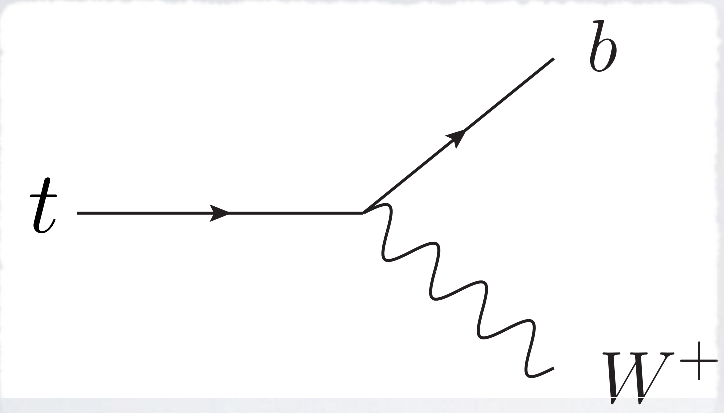
- Also the measurement of the CKM element from the single top.

$$|V_{tb}| = 1.019 \pm 0.025$$



(7, 8, and 13 TeV data combined)

- In our model, the *t-W-b* coupling picks up $\cos\theta_L$



$$= i\frac{g}{\sqrt{2}} \boxed{\cos\theta_L} \gamma^\mu P_L$$

- from which we can obtain a bound on the mixing angle.

$$|\sin\theta_L| < 0.11 \quad (\text{ independent of } m_T)$$

Can we ever distinguish a sign? (e.g. via interferences…)

Getting out of touch…

- The *T* and top are getting out of touch with each other.
- Therefore, *T* is less likely to inherit the properties of the top.
- But the messanger *S* plays an important role connecting two parties.
- And it will give rise to new properties of *T*.

Getting out of touch…

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- Therefore, T is less likely to inherit the properties of the top.
- But the messanger S plays an important role connecting two parties.
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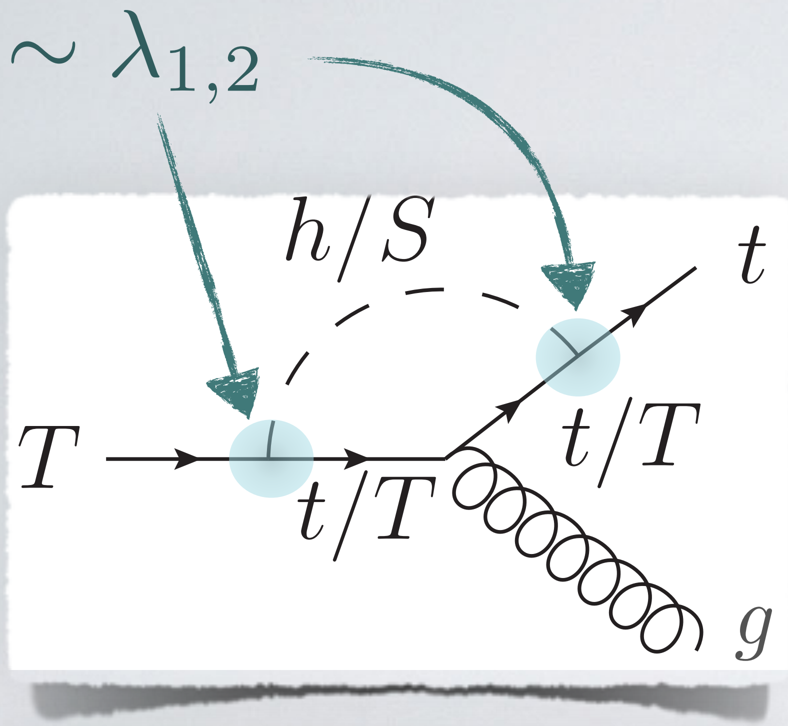
New T decays

J. H. Kim, I. M. Lewis [2018]

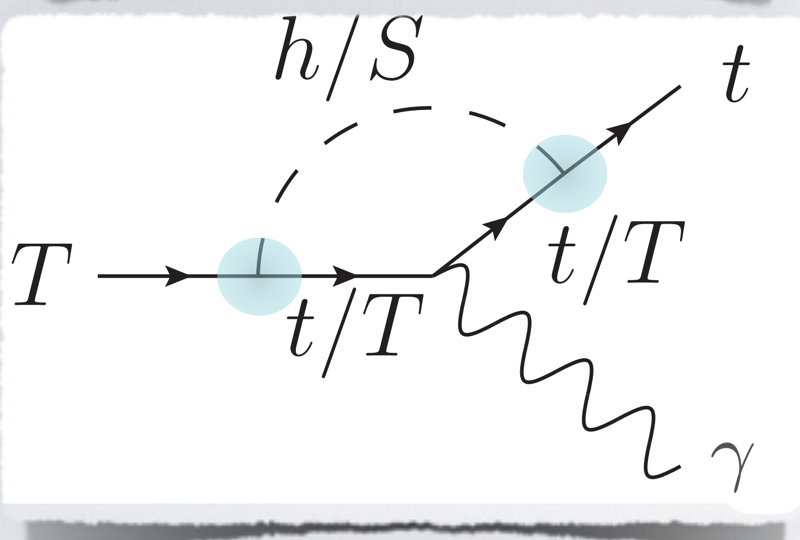


+ Counter terms

External self-energies

W and Z bosons loops

Goldstone bosons loops



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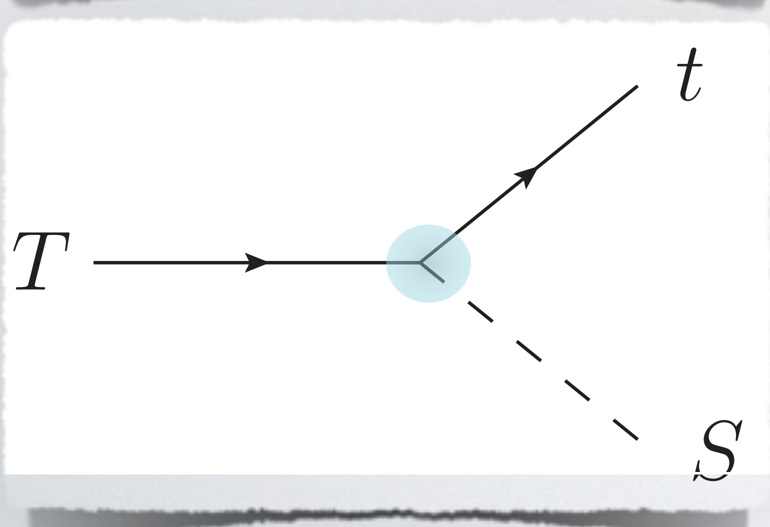


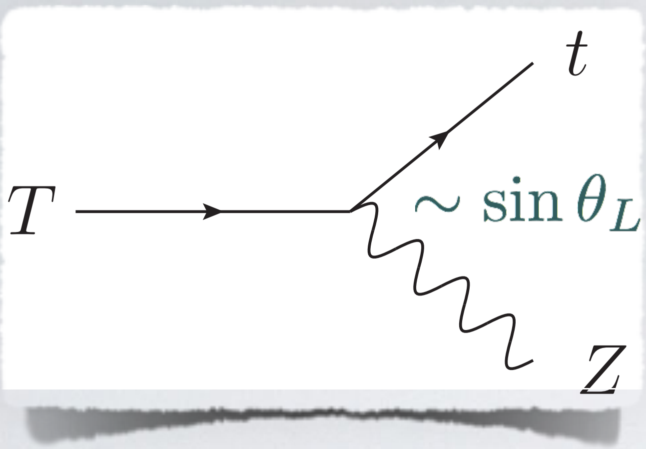
If $m_T > m_S + m_t$

- The scalar S can mediate loop-level decays of T.
- The partial width is proportional to λ^4.
- Non-vanishing if $\sin\theta_L = 0$, simply because it isn't a result of the inheritance.
- And If the scalar mass is light, there is a new tree-level decay of T:

$$T \to t\, S$$

Classic T decay modes

J. H. Kim, I. M. Lewis [2018]



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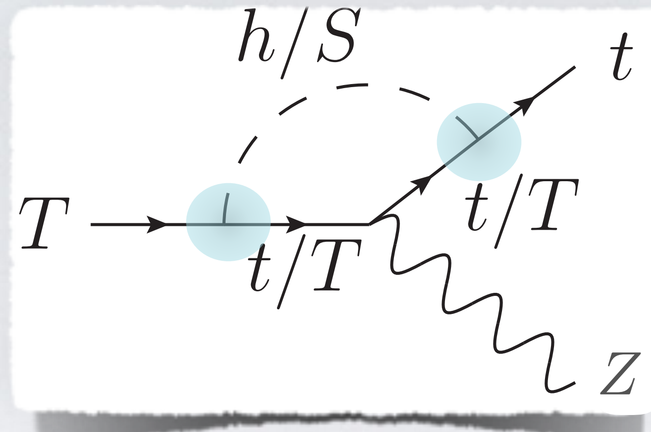

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Counter terms

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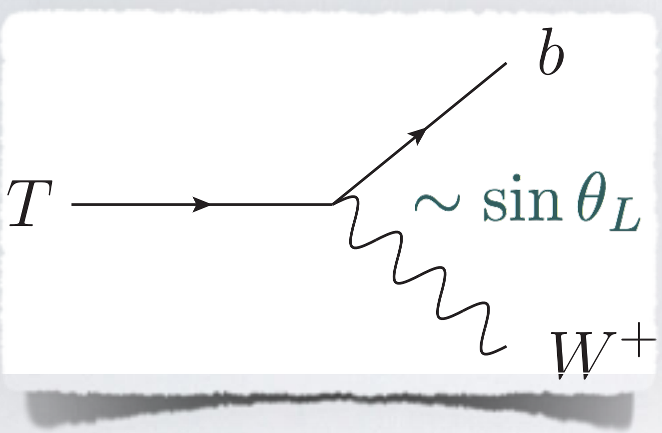
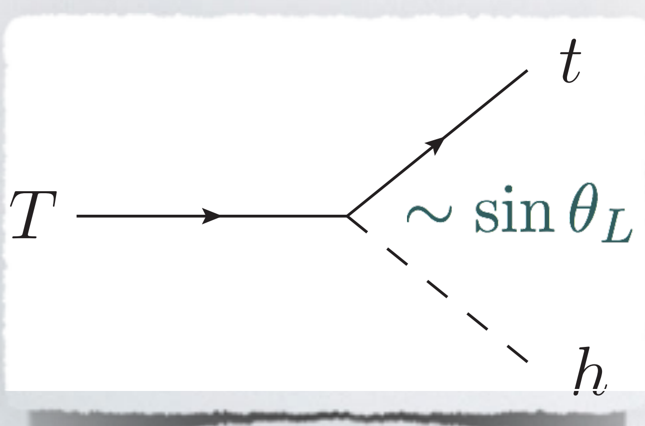
(survives in the zero-mixing limit)



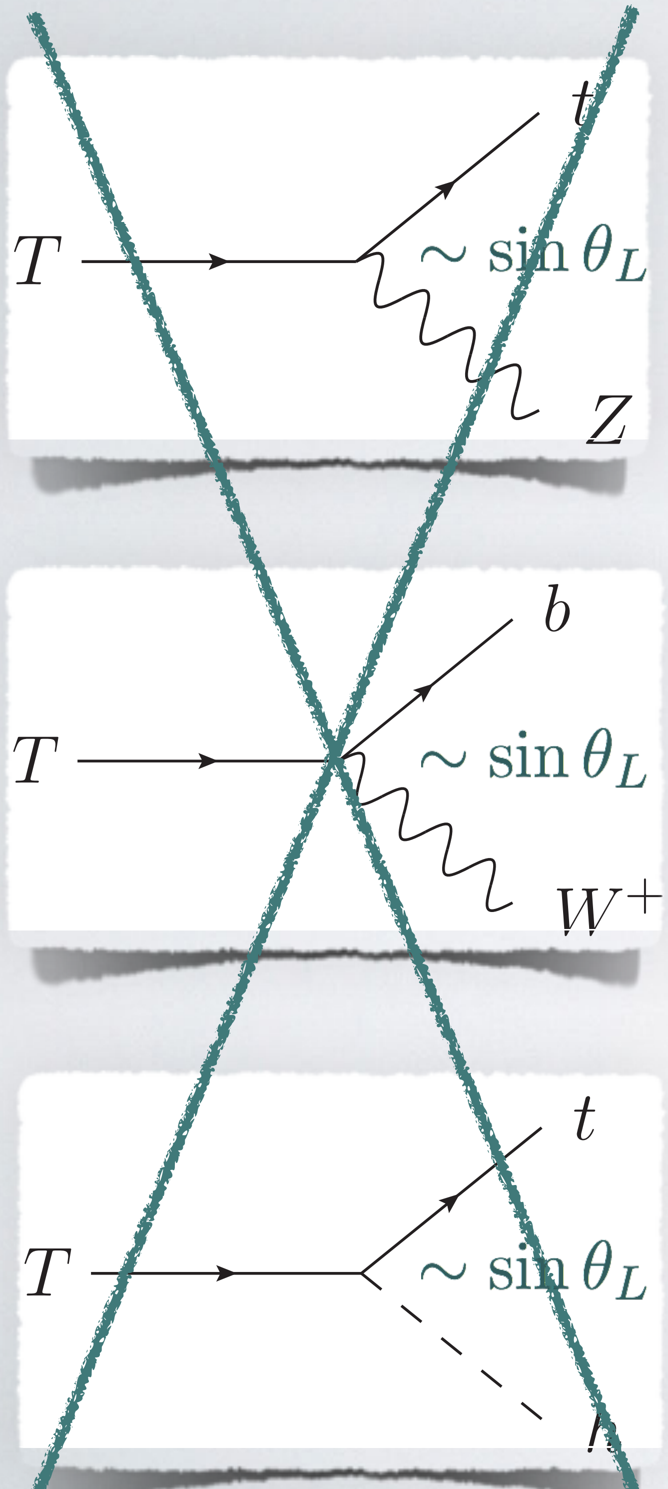


- All classic tree-level decay modes are controlled by $\sin\theta_L$ as a result of the inheritance.
- They all vanish in the $\sin\theta_L \to 0$ limit (if we neglect NLO corrections).
- And there is a similar loop-level decay $T \to t\,Z$.

Classic T decay modes

J. H. Kim, I. M. Lewis [2018]

$\sin\theta_L \to 0$



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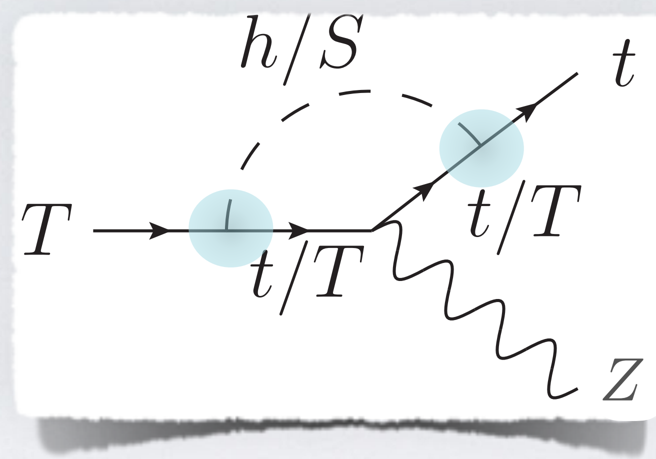

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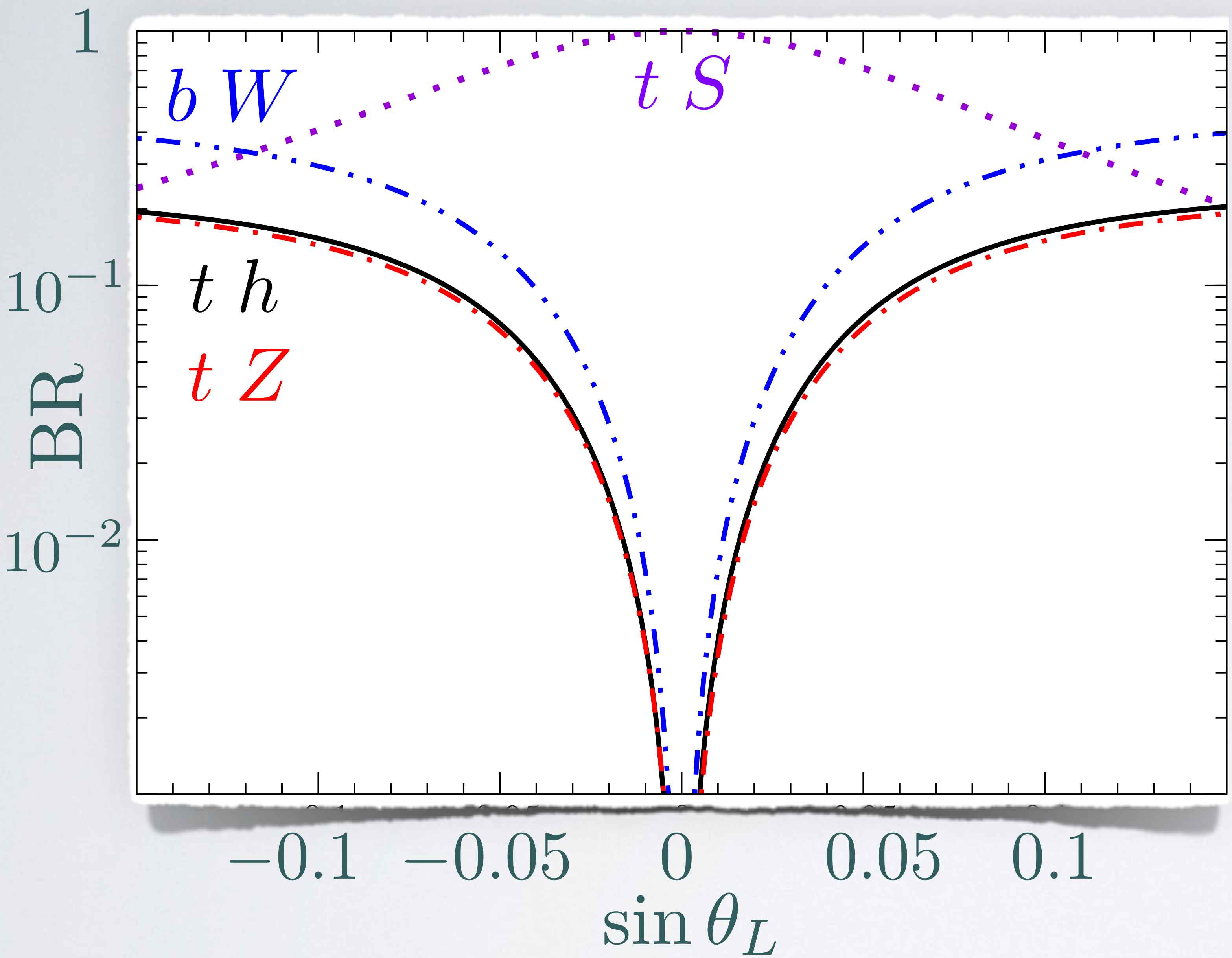
Branching ratios ($m_T > m_S$)

J. H. Kim, I. M. Lewis [2018]



$m_T = 1.5$ TeV

$m_S = 200$ GeV

$\lambda_1 = \lambda_2 = 1$

- When *T* is heavier than *S*.

- *T*→ *t S* decay is allowed with a dominant branching ratio over the wide range of the mixing angle.
- All other ther classic tree-level decays are substantially suppressed!

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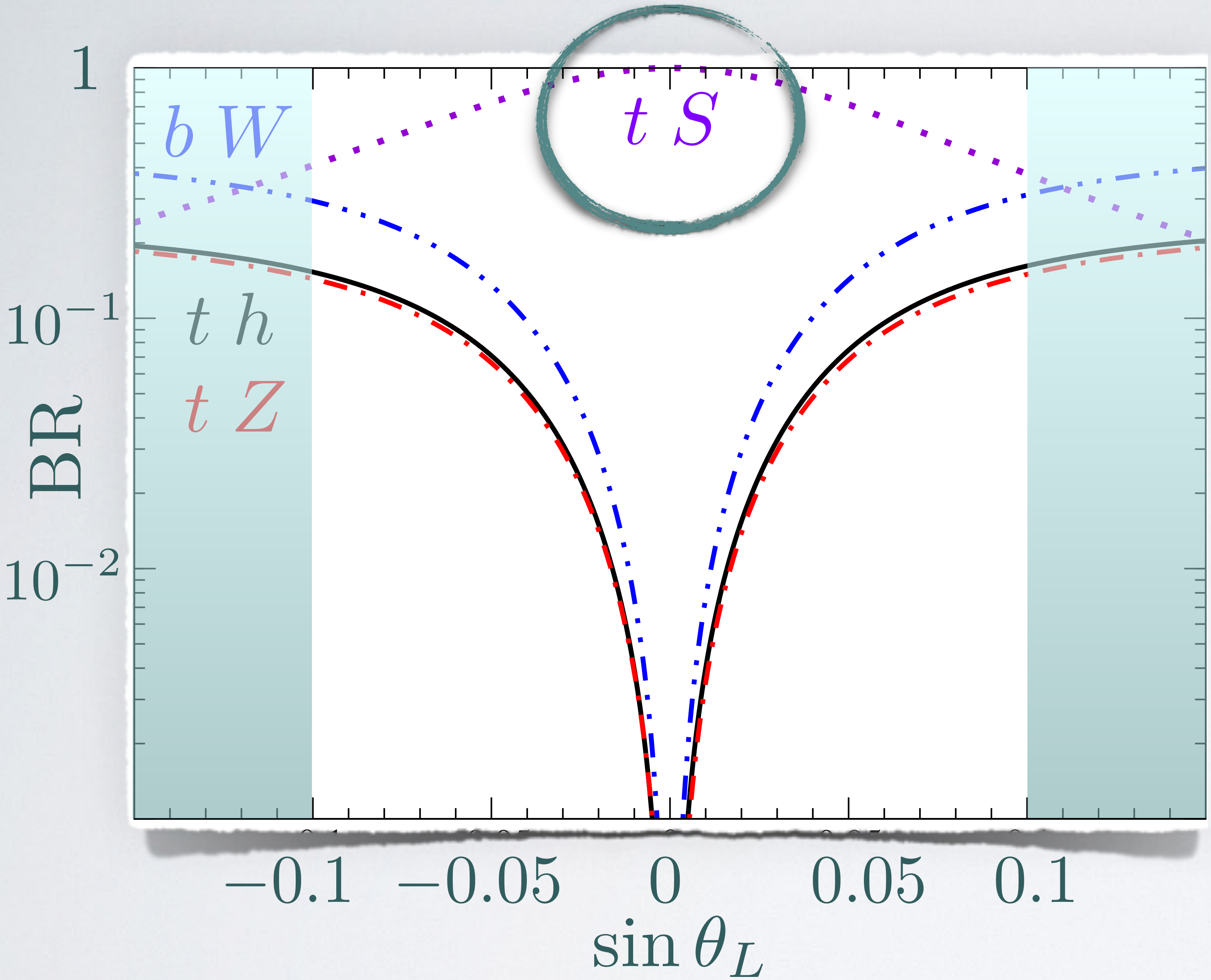

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Branching ratios ($m_S > m_T$)

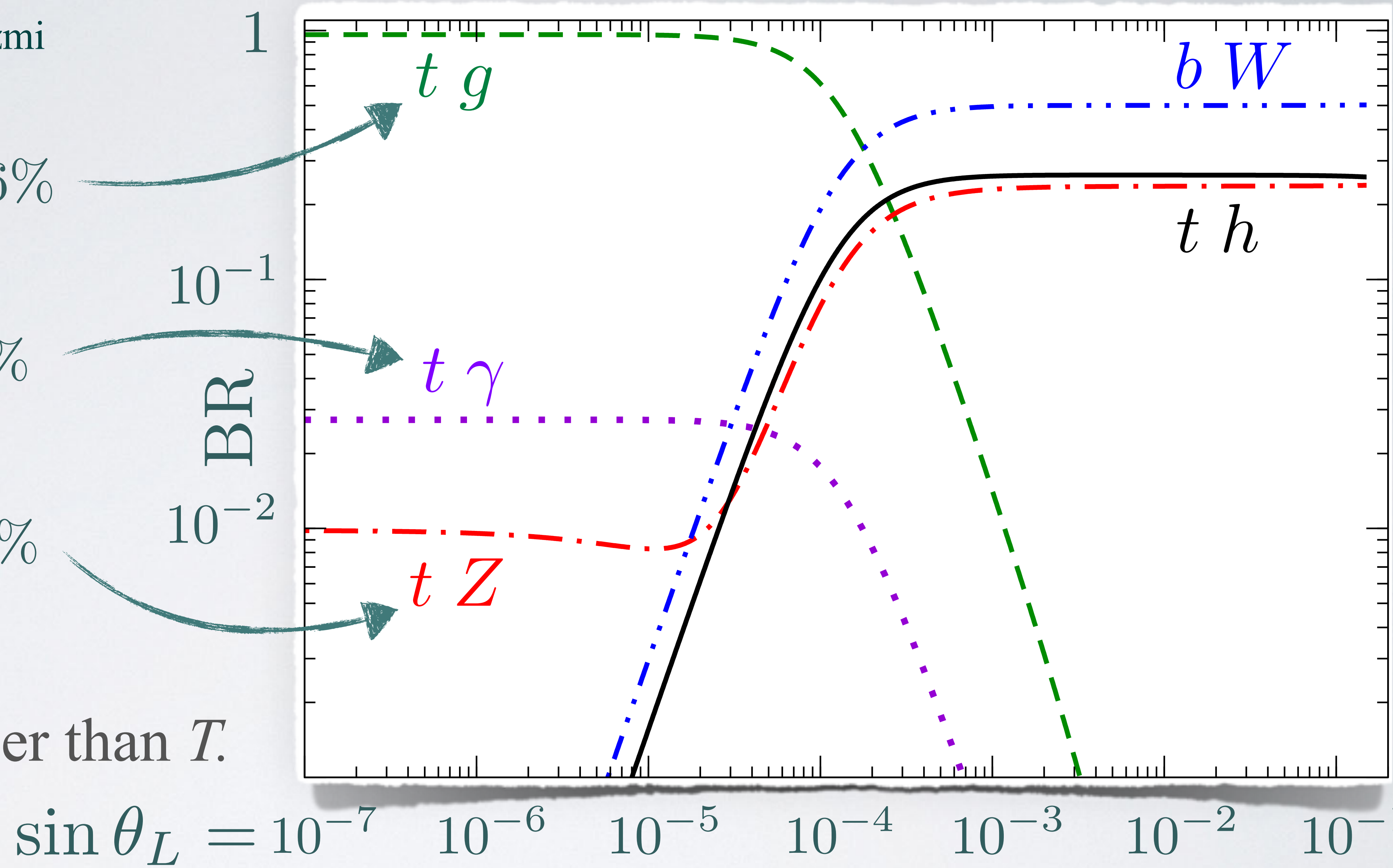
J. H. Kim, I. M. Lewis [2018]

See talk by Haider Alhazmi [next.speaker]

$\mathrm{BR}(T \to tg) \sim 96\%$

$\mathrm{BR}(T \to t\gamma) \sim 3\%$

$\mathrm{BR}(T \to tZ) \sim 1\%$



- When S is heavier than T.
- In the zero-mixing limit, all classic decays are suppressed & vanishing.
- $T \to t\,g$ is dominant due to the strong coupling.
- $T \to t\,\gamma$, $T \to t\,Z$ are sub-dominant due to the weak couplings.

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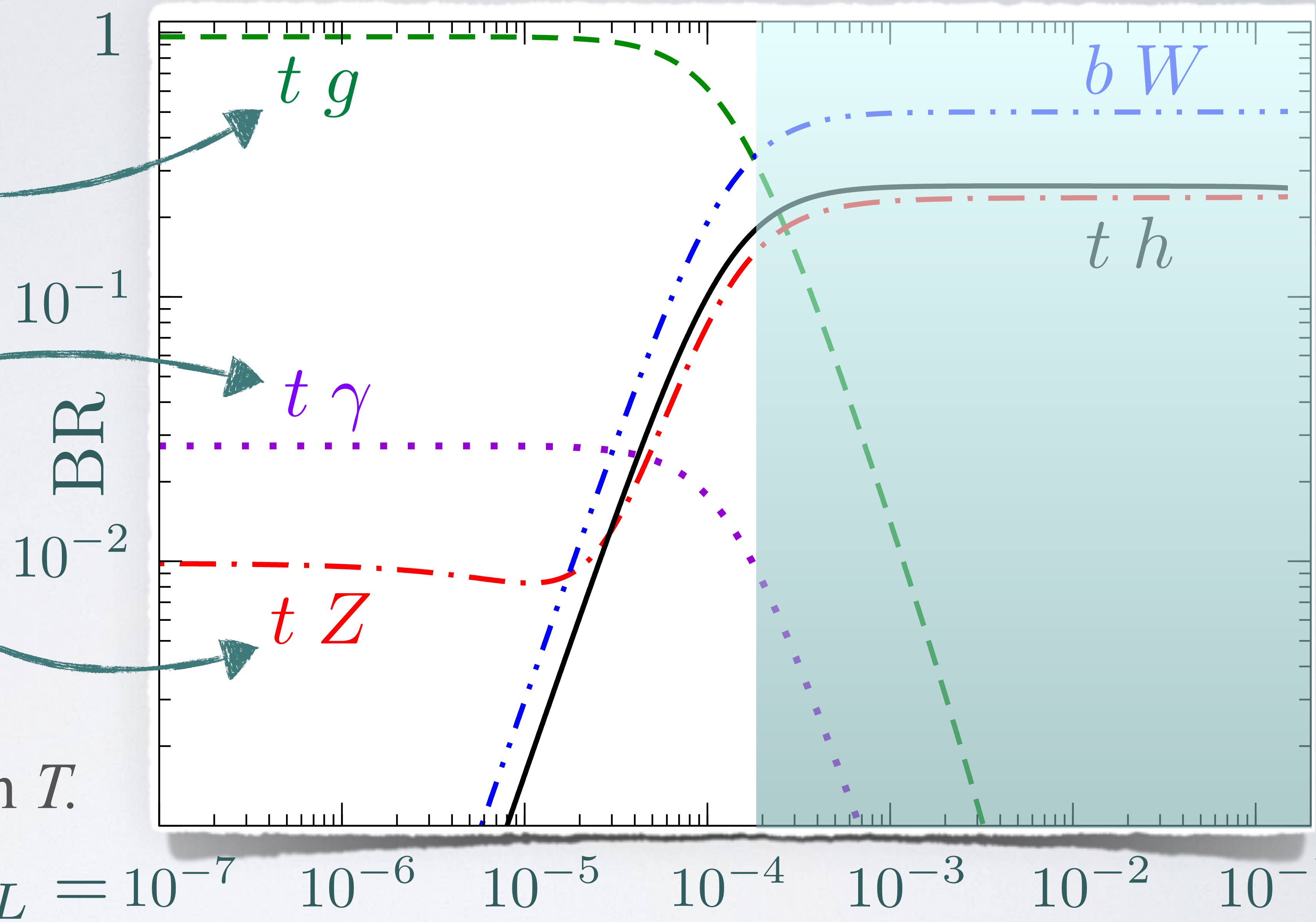

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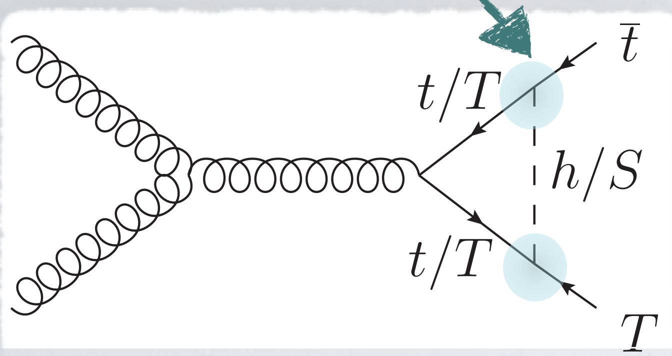
New $T\bar{t} + t\bar{T}$ productions

$\sim \lambda_{1,2}$

J. H. Kim, I. M. Lewis [2018]



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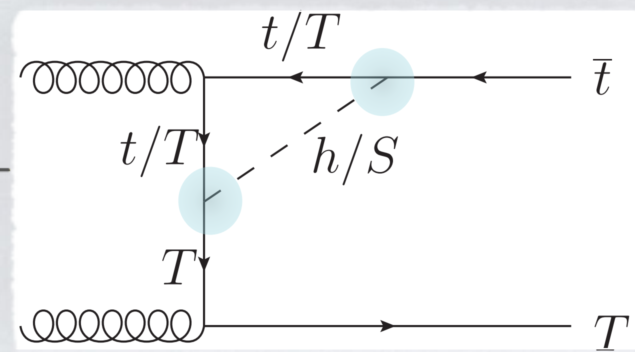

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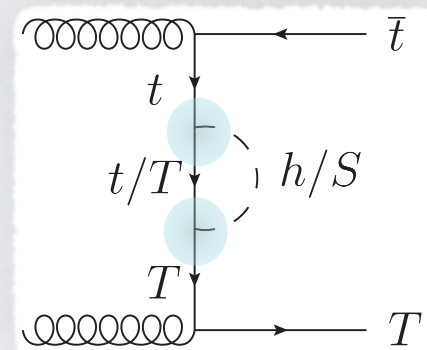

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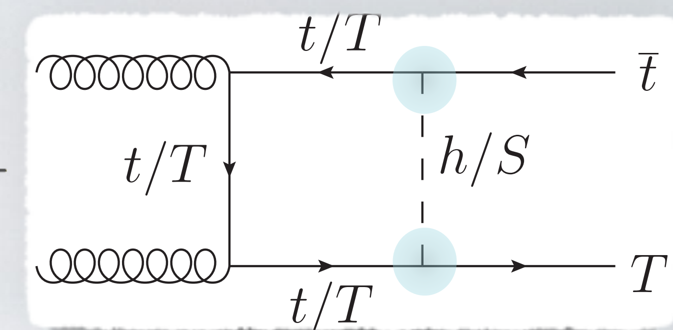

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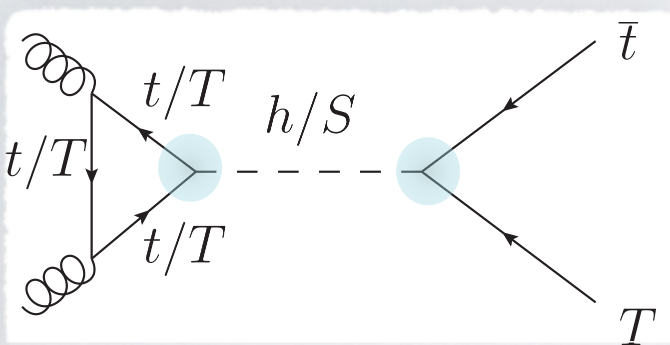

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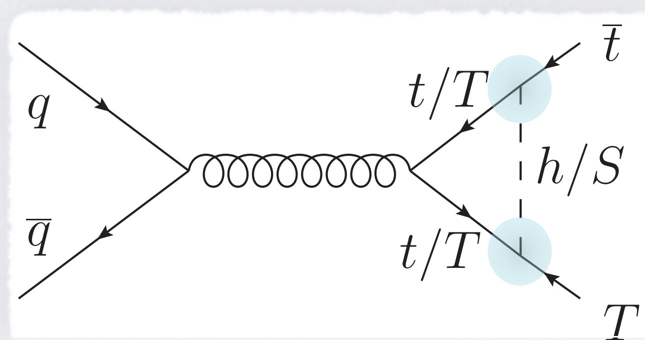


$+ \cdots +$

Counter terms

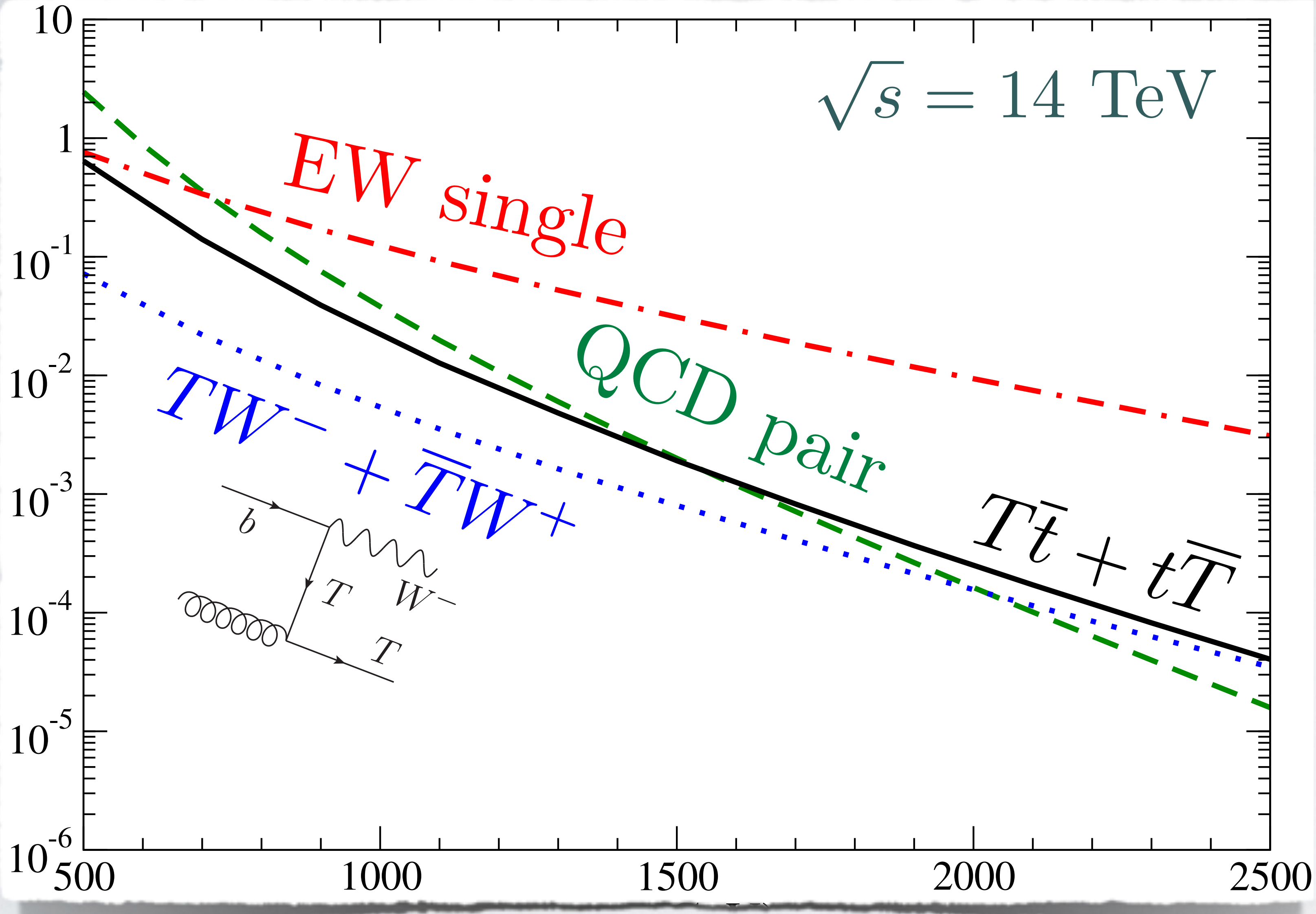
External self-energies

W and Z bosons loops

Goldstone bosons loops

- The scalar S can mediate loop-induced $g\,g \to T\,t$ productions.
- There are also loop-induced $q\,\bar{q} \to T\,t$ productions.
- Even they are loop-suppressed, we can freely dial up and down the couplings $\lambda_{1,2}$ to control a total cross section.

Production cross sections



[pb]

m_T [GeV]

J. H. Kim, I. M. Lewis [2018]

$m_S = 200$ GeV

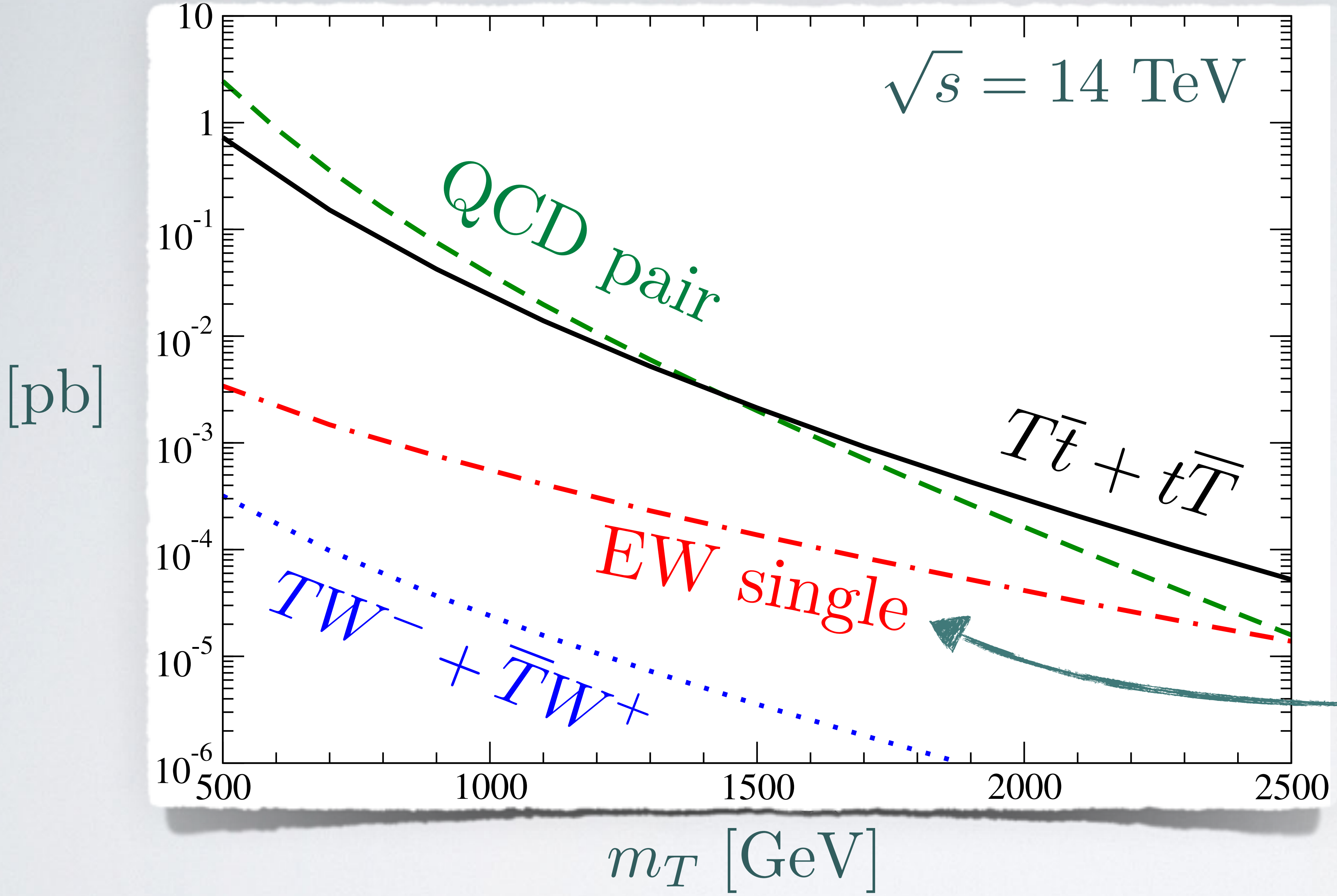
$\lambda_1 = \lambda_2 = 3$

$\sin\theta_L = 0.15$

- Production cross sections as a function of T mass.

- The EW single T production dominates if the mixing angle is large.
- The loop-induced $T\,t$ productions stay way below.

Production cross sections

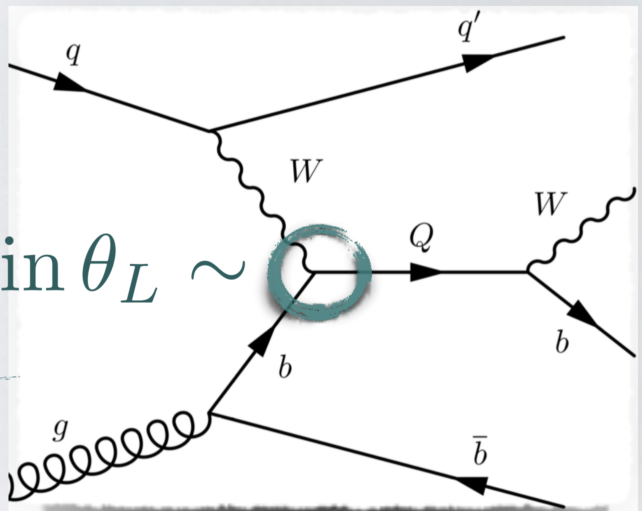


$m_S = 200$ GeV

$\lambda_1 = \lambda_2 = 3$

$\sin\theta_L = 0.01$

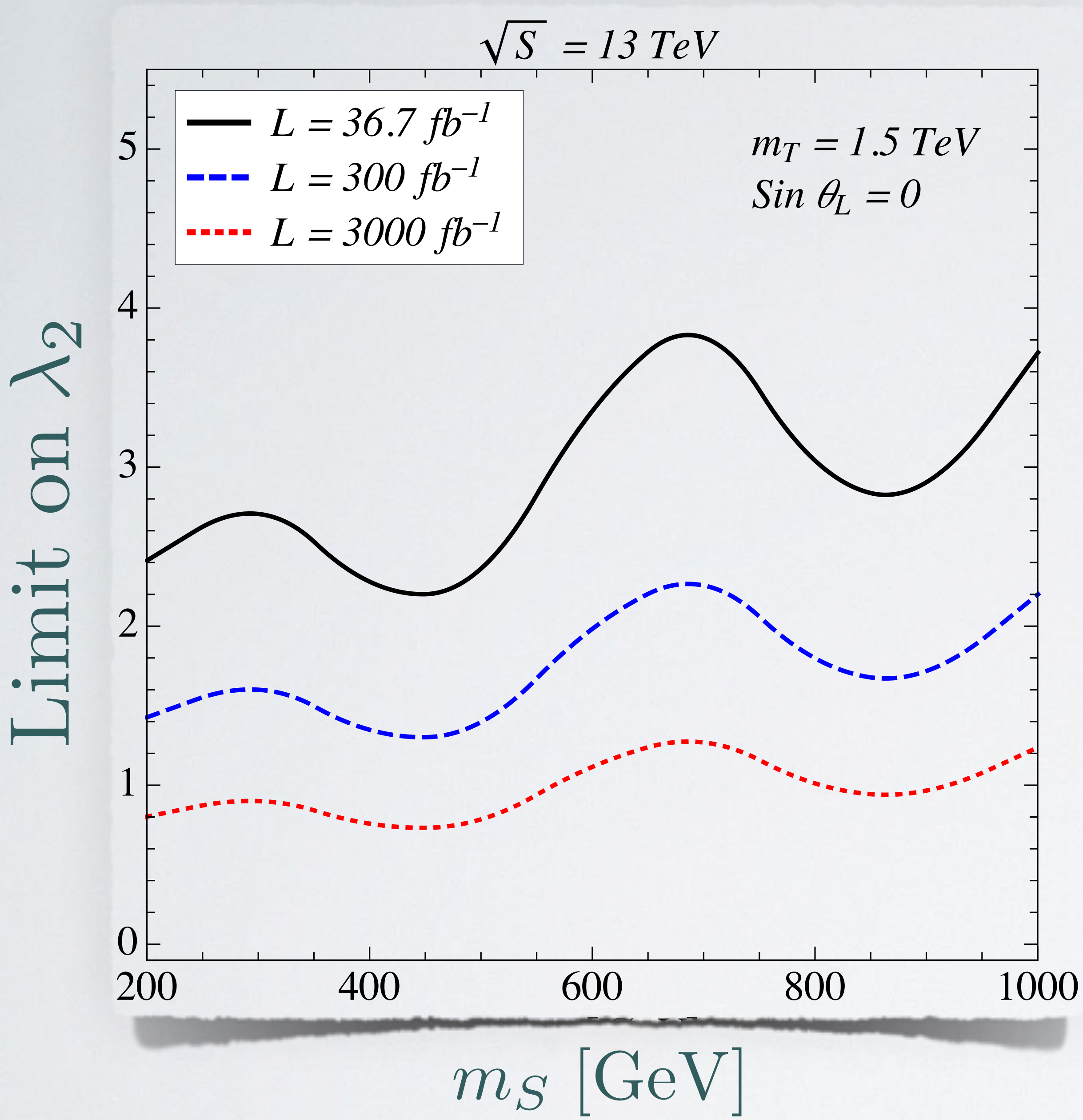
$\sin\theta_L \sim$



- But the tide changes in the small-mixing regime where the EW single *T* production loses its dominance.
- Therefore, the loop-induced *T t* productions become more important.

The single S production

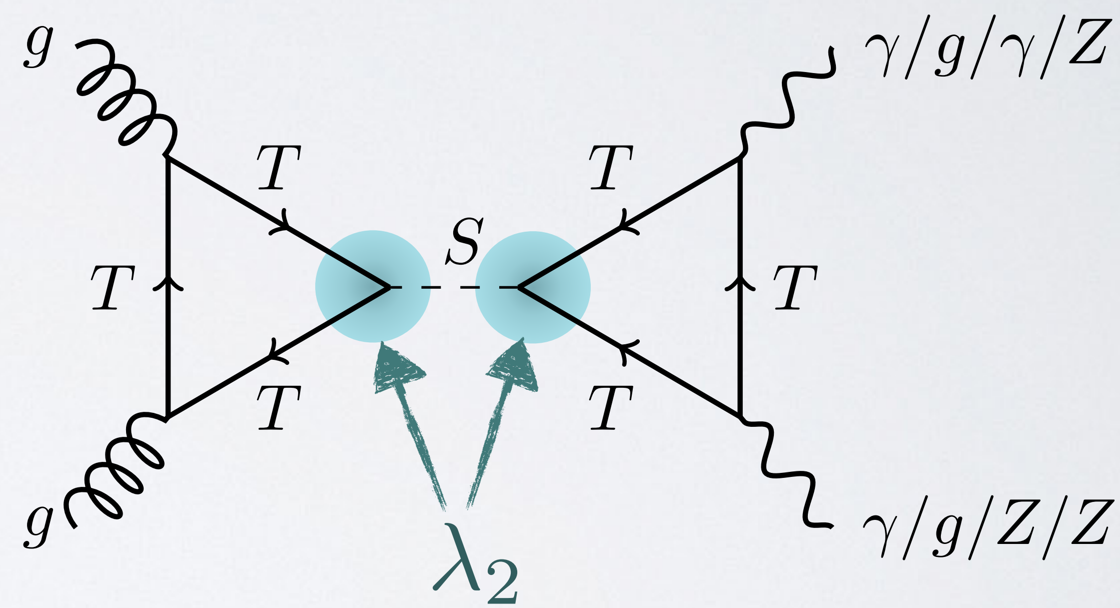
CMS-PAS-HIG-17-013 **J. H. Kim**, I. M. Lewis [2018]



high mass region

$$\lambda_1 S\bar{T}_L t_R + \text{h.c.} \quad -\lambda_2 S\bar{T}_L T_R + \text{h.c.}$$

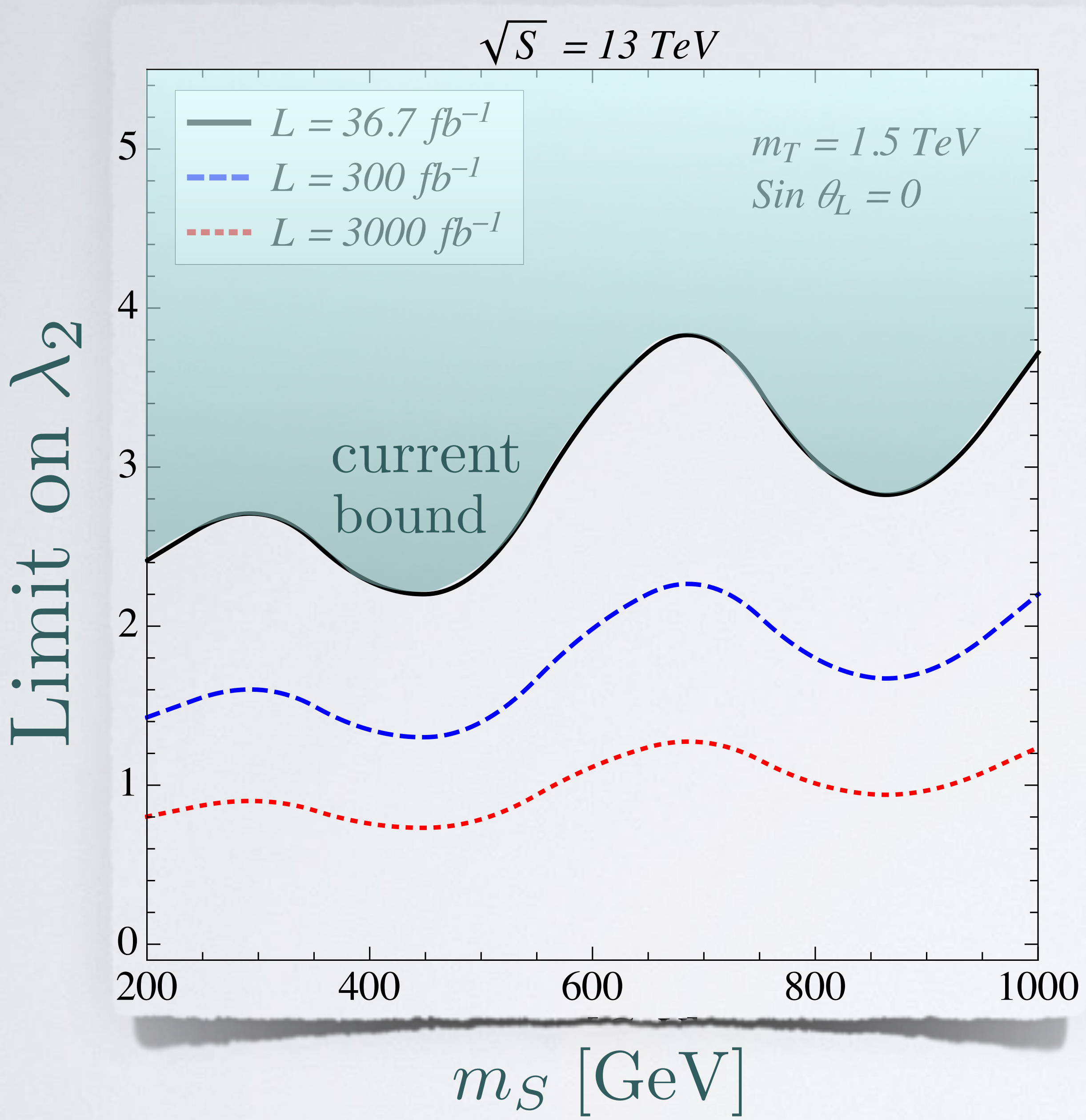
- The S can be also produced via gluon fusion with T loop.
- The S can decay into $\gamma\gamma$, gg, γZ and ZZ in the $\sin\theta_L \to 0$ limit.



- As we haven't seen anything, diphoton searches set the most stringent limit.

The single S production

CMS-PAS-HIG-17-013 **J. H. Kim**, I. M. Lewis [2018]



high mass region

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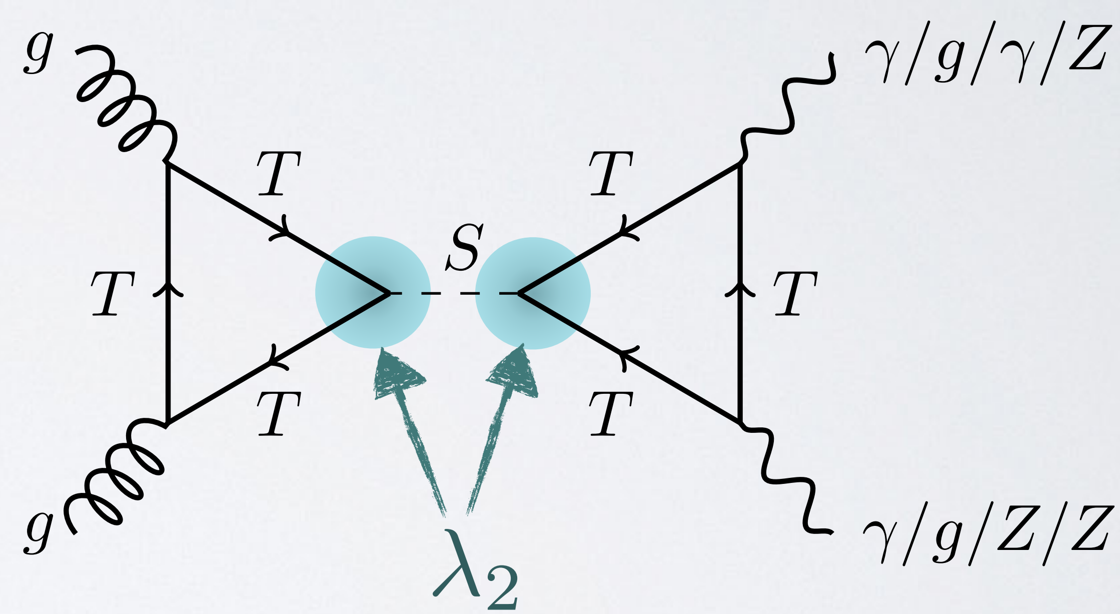
- The S can be also produced via gluon fusion with T loop.
- The S can decay into $\gamma\gamma$, gg, γZ and ZZ in the sin $\theta_L \to 0$ limit.



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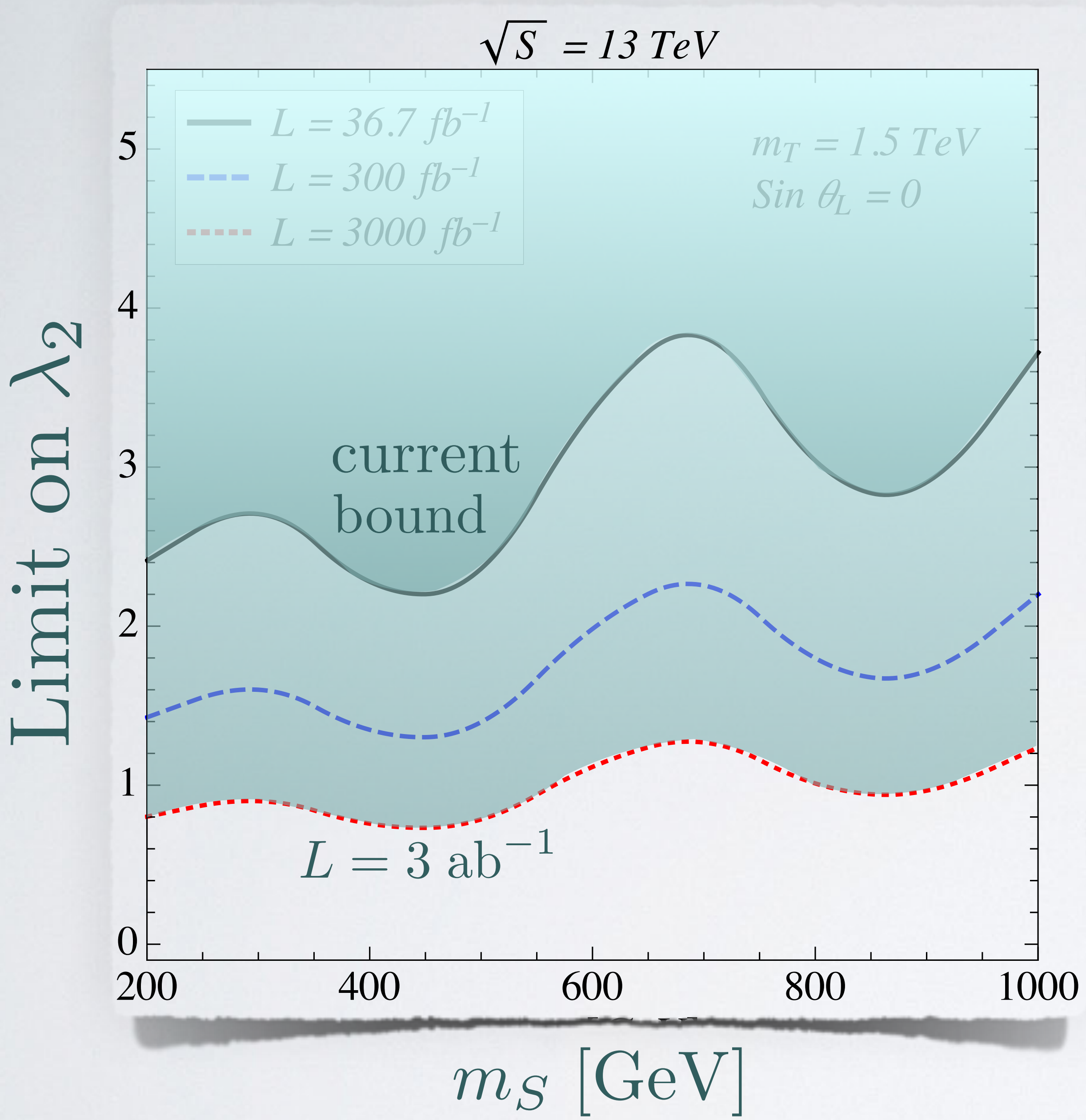

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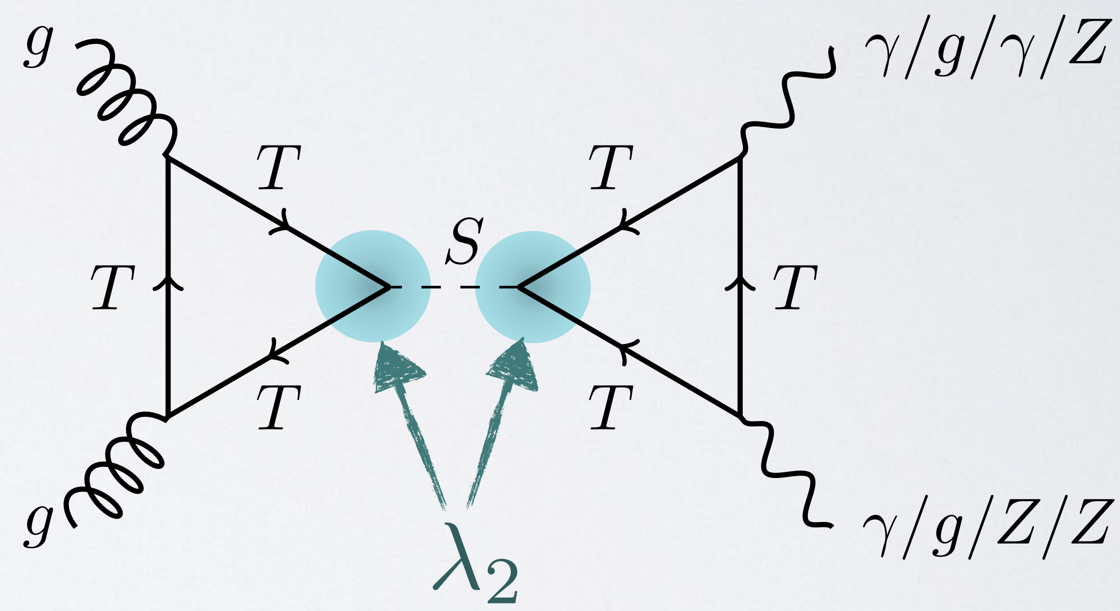

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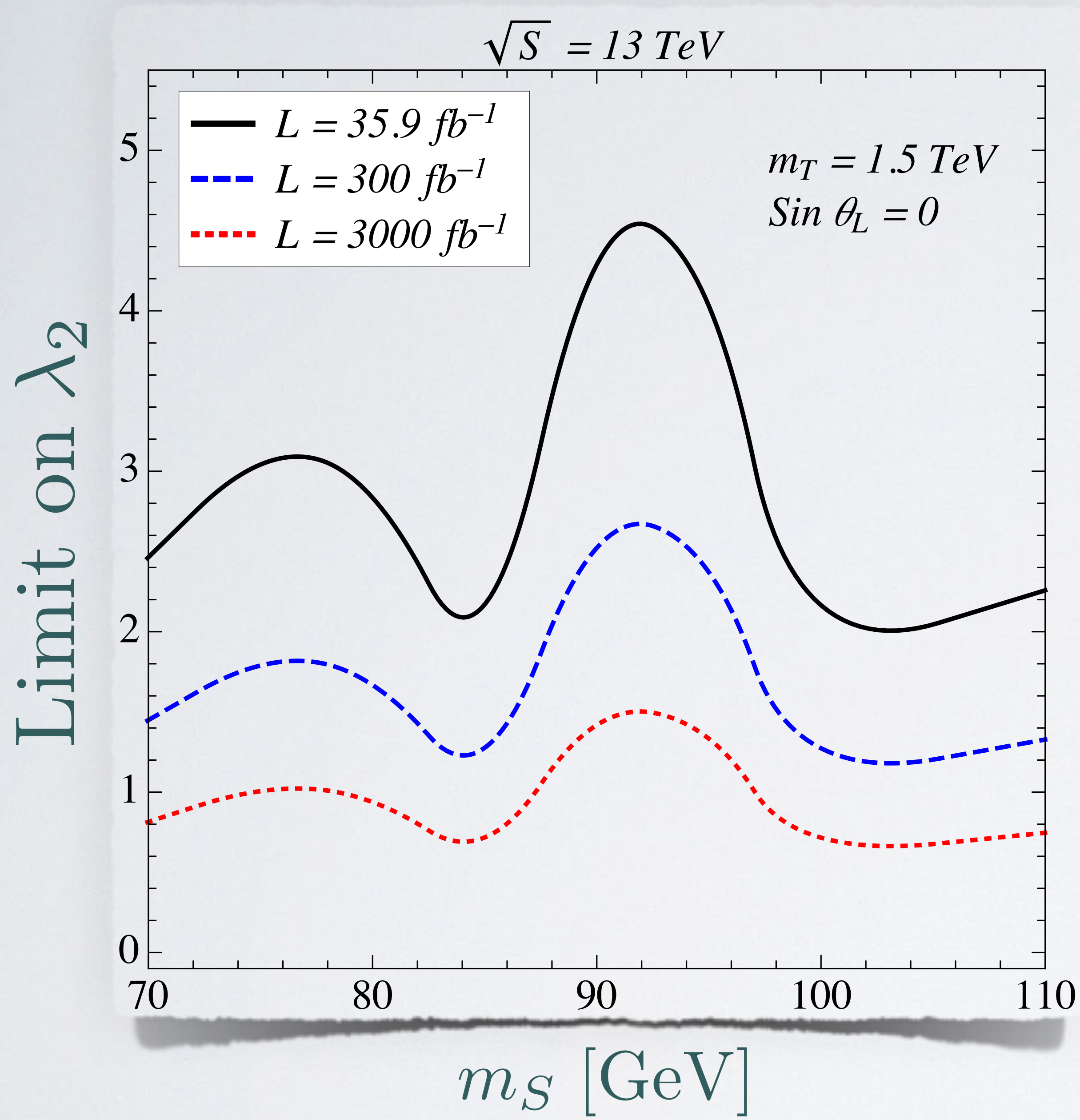
The single S production

ATLAS collab. [1707.04147] **J. H. Kim**, I. M. Lewis [2018]



low mass region

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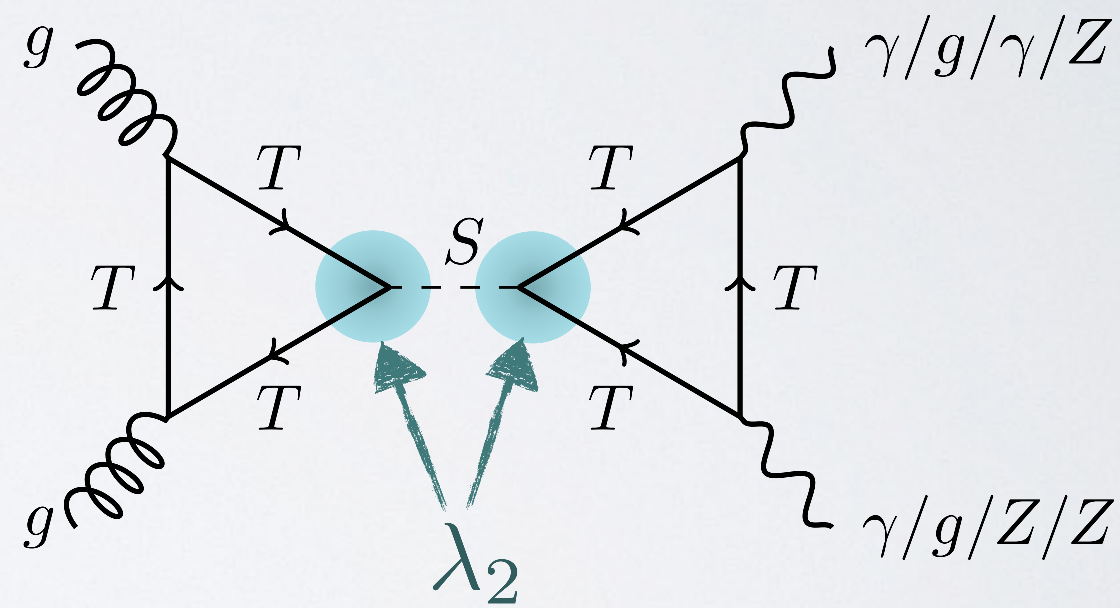

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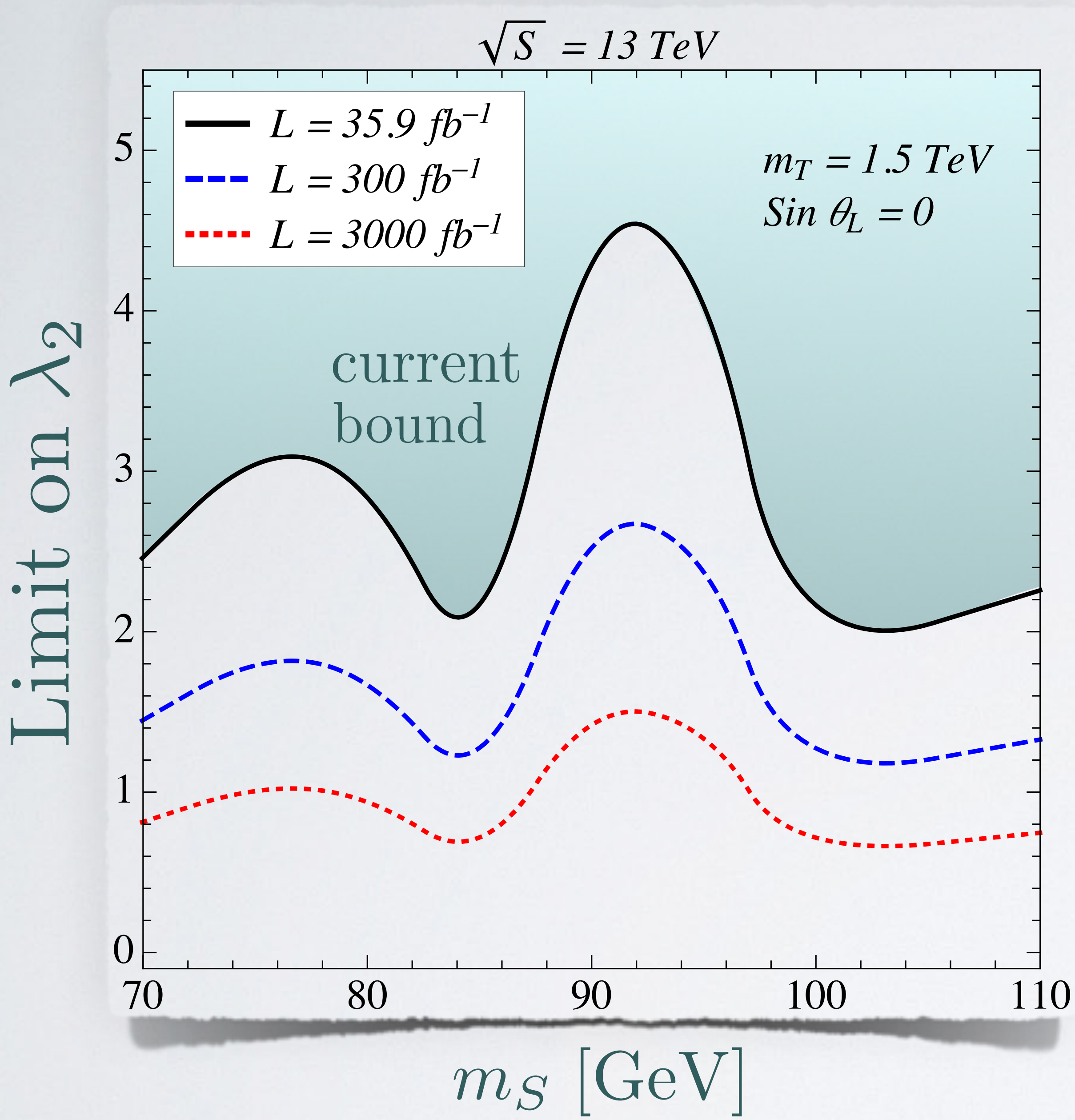

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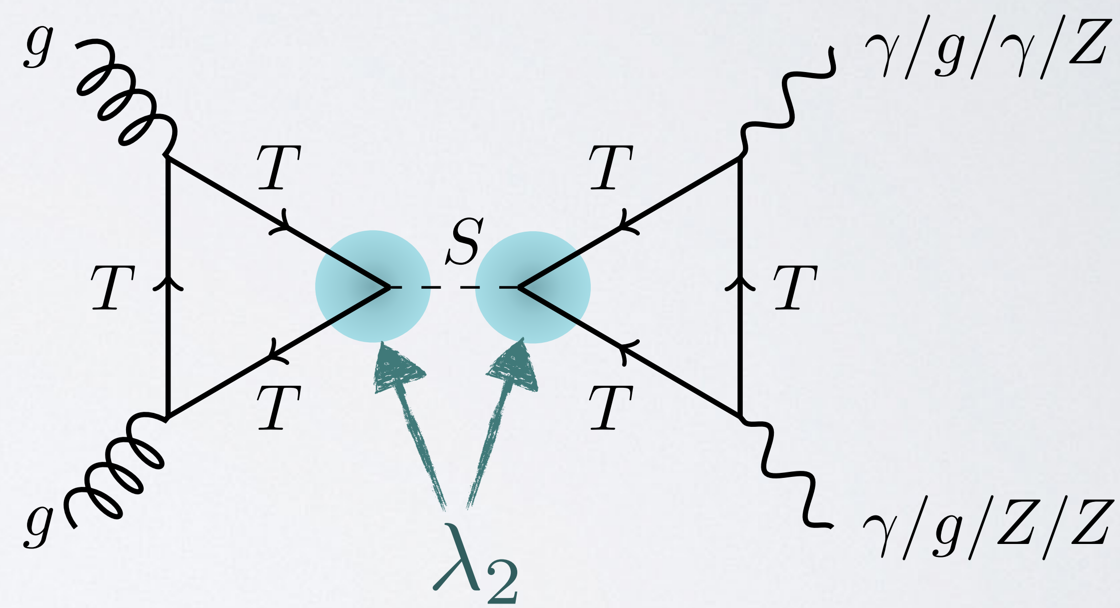
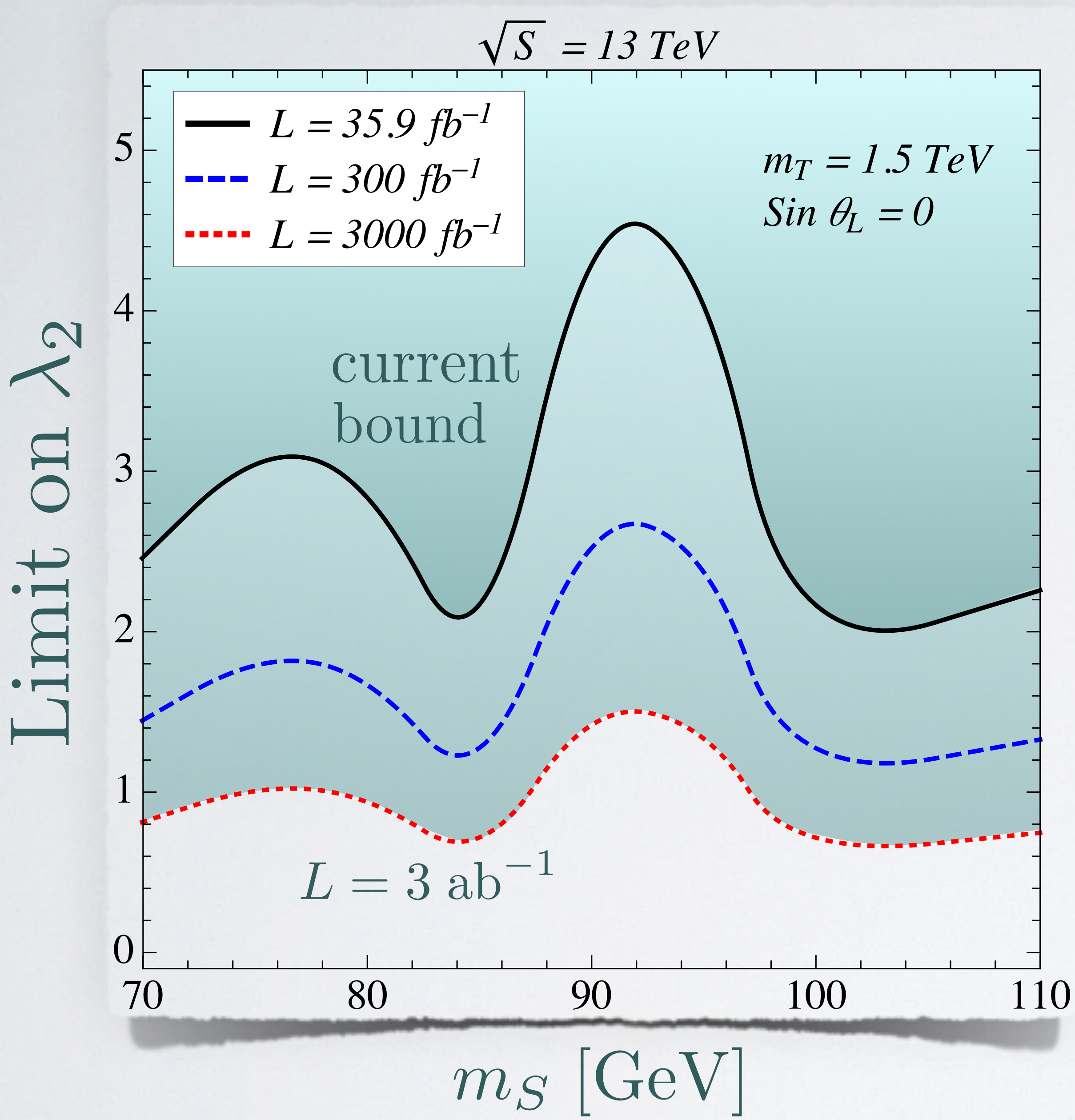


- As we haven't seen anything, diphoton searches set the most stringent limit.

$$\lambda_1 S\bar{T}_L t_R + \text{h.c.} \quad -\lambda_2 S\bar{T}_L T_R + \text{h.c.}$$

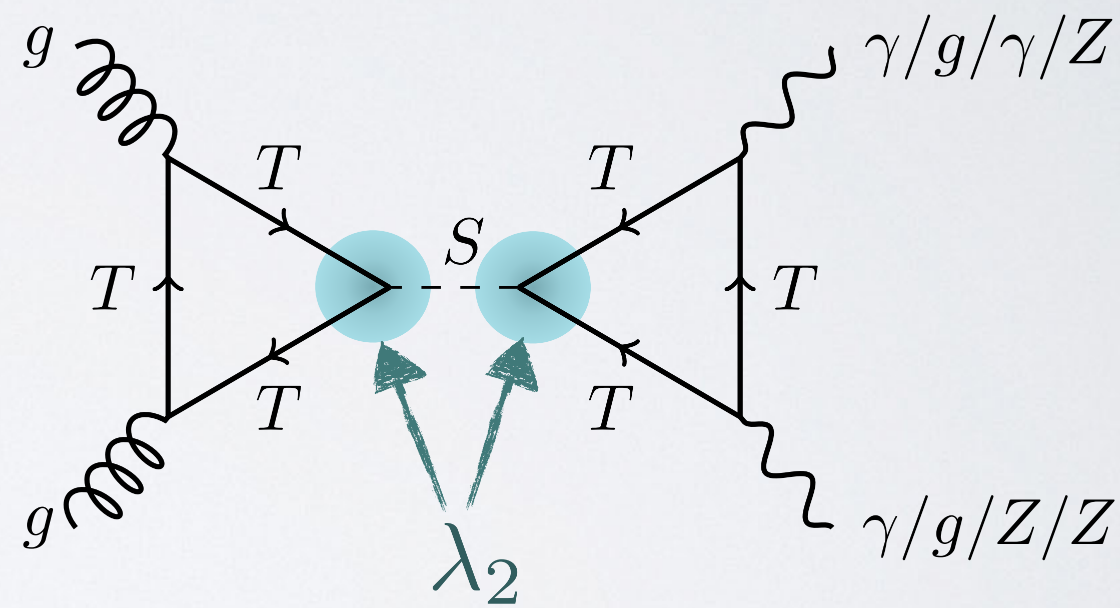
The single S production

ATLAS collab. [1707.04147] **J. H. Kim**, I. M. Lewis [2018]



low mass region

- The S can be also produced via gluon fusion with T loop.
- The S can decay into $\gamma\gamma$, gg, γZ and ZZ in the $\sin\theta_L \to 0$ limit.



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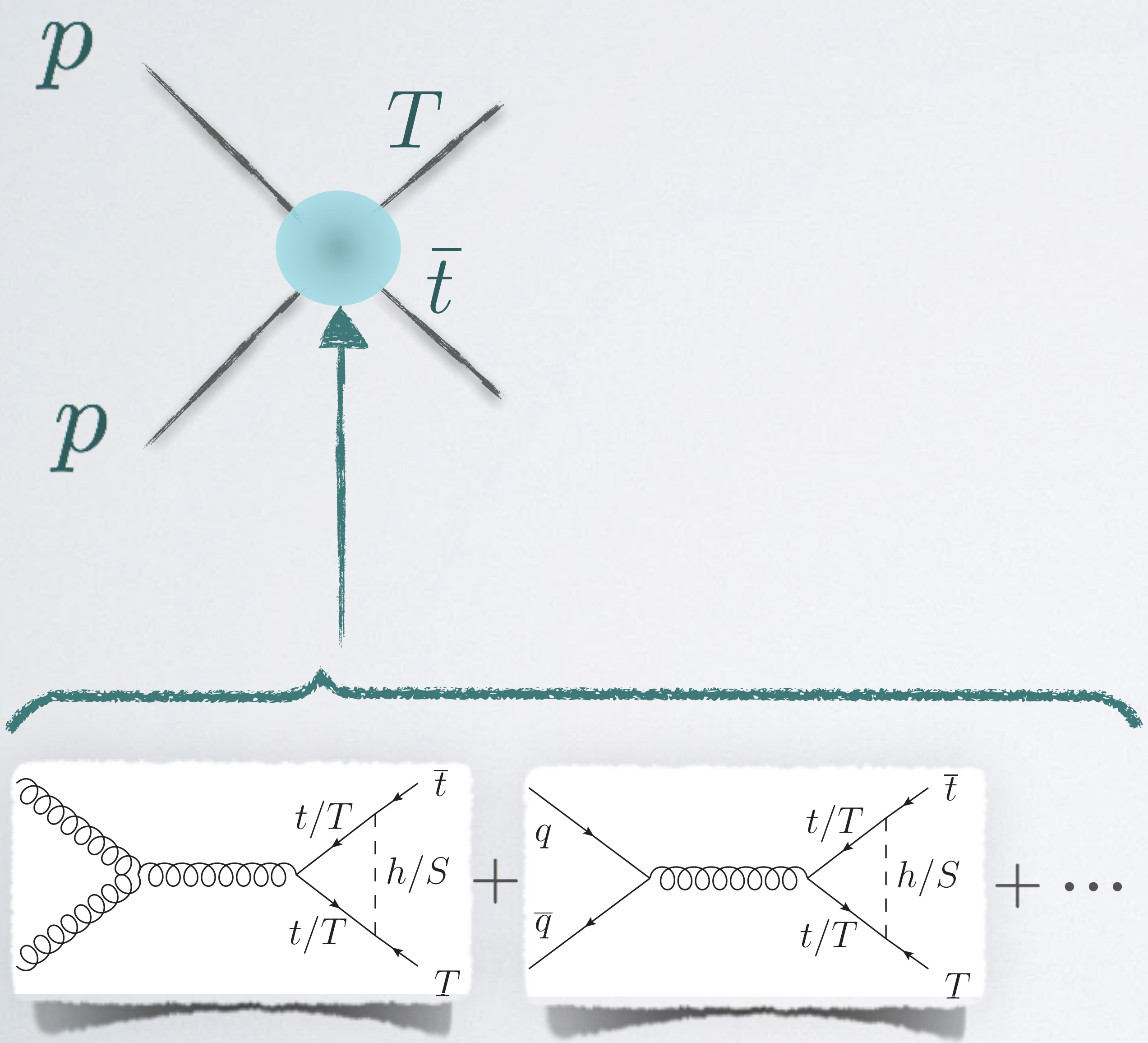
On the LHC sensitivity

J. H. Kim, I. M. Lewis [2018]

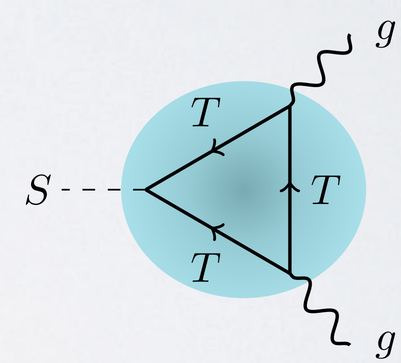
$\sqrt{s} = 14\ \text{TeV}$

$m_S = 110\ \text{GeV}$

$\sin\theta_L = 0$



- Now we talk about a sensitivity of the $T\,t$ production at the LHC.
- T decays to $t\,S$ nearly 100 % in the zero mixing case ($\sin\theta_L = 0$).
- S exclusively decays into gg nearly 100 %



- Both tops decay semi-leptonically.
- The production vertex includes all loop contributions.

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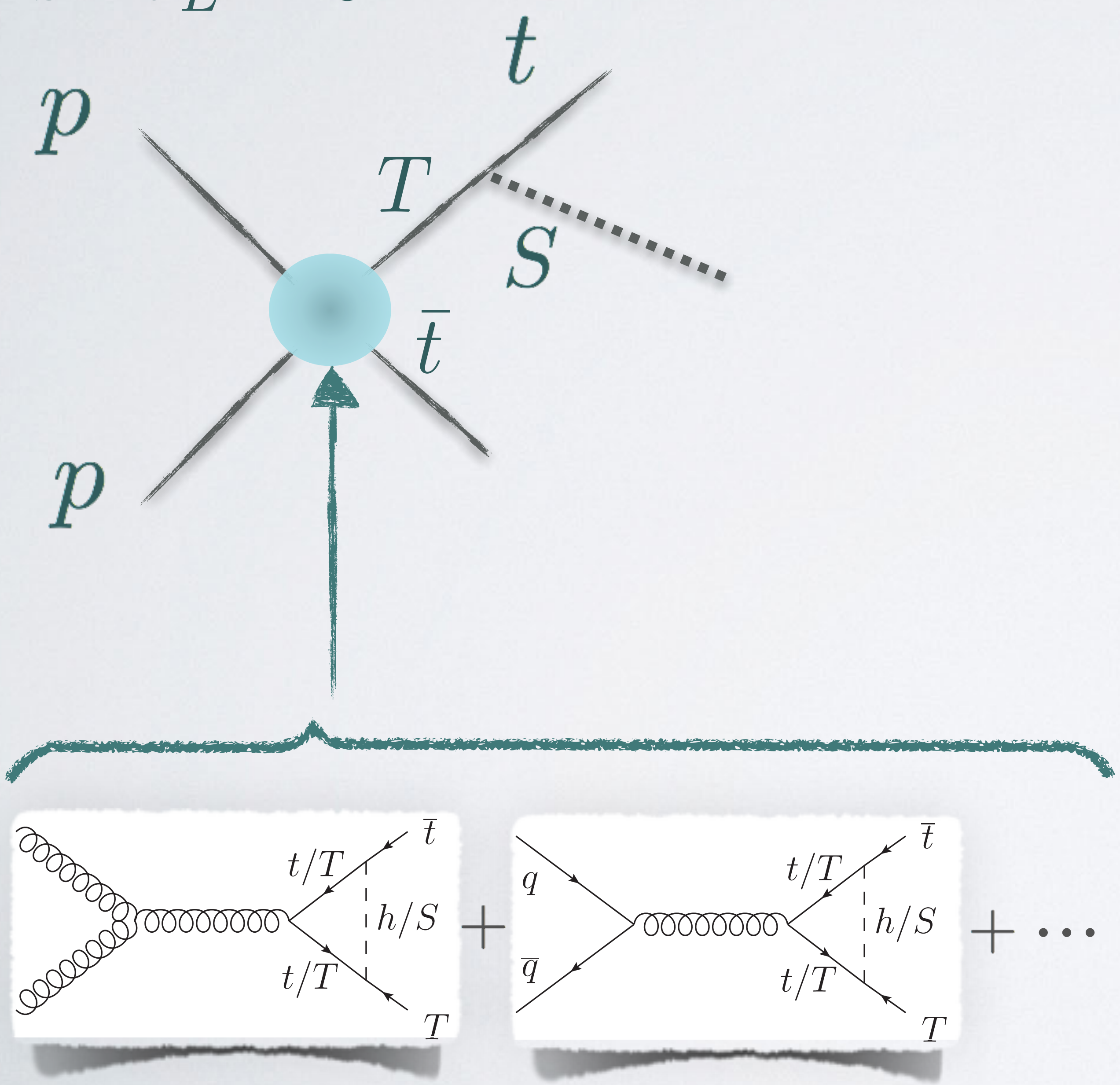

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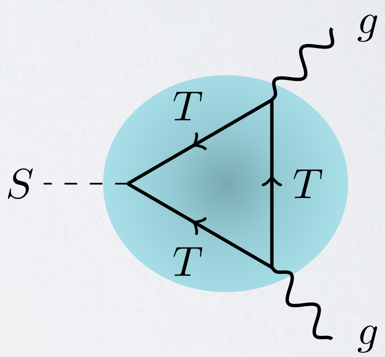

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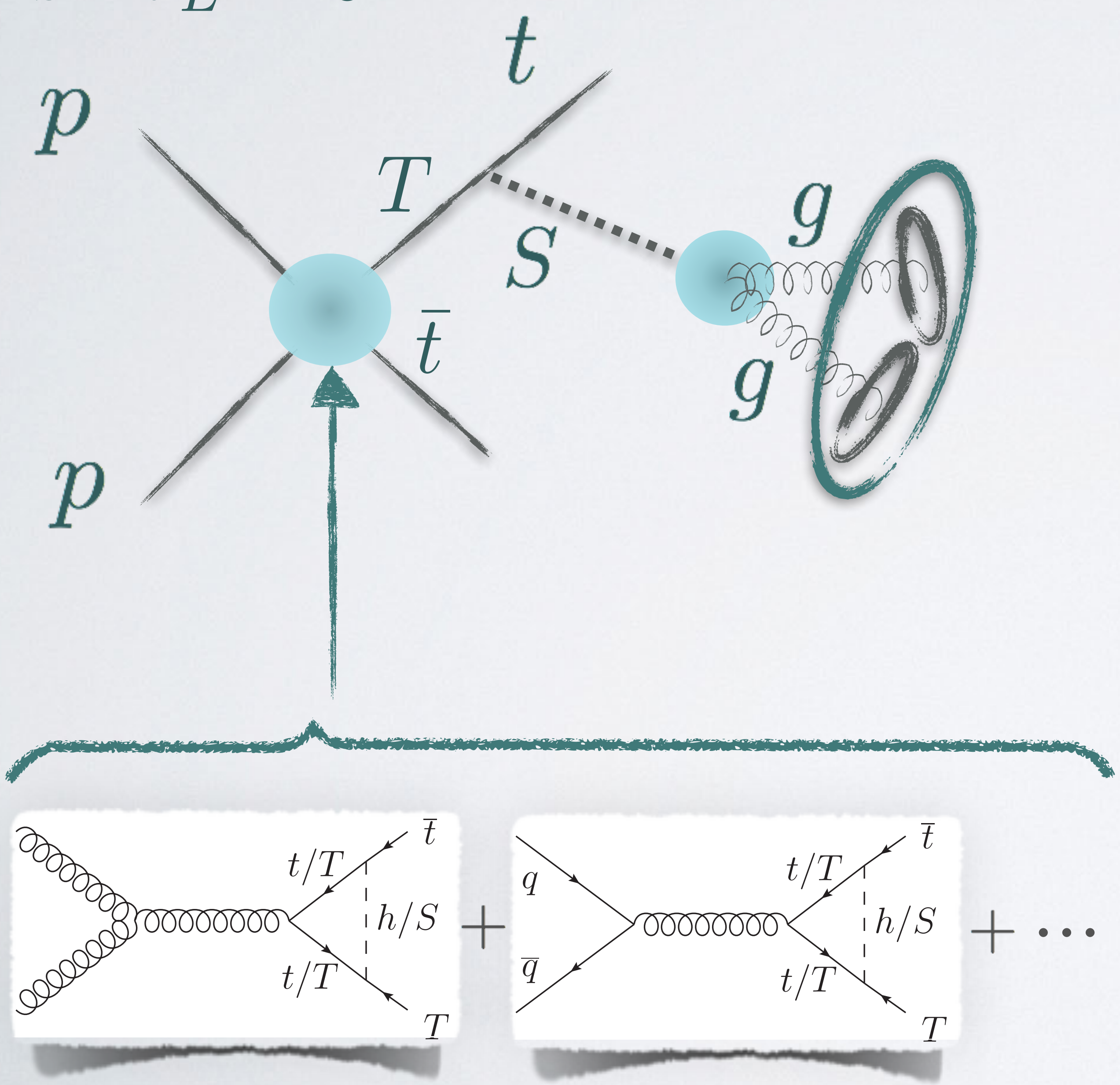

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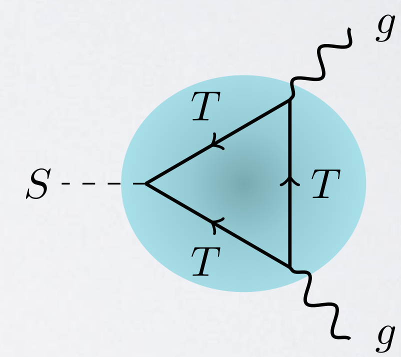

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On the LHC sensitivity

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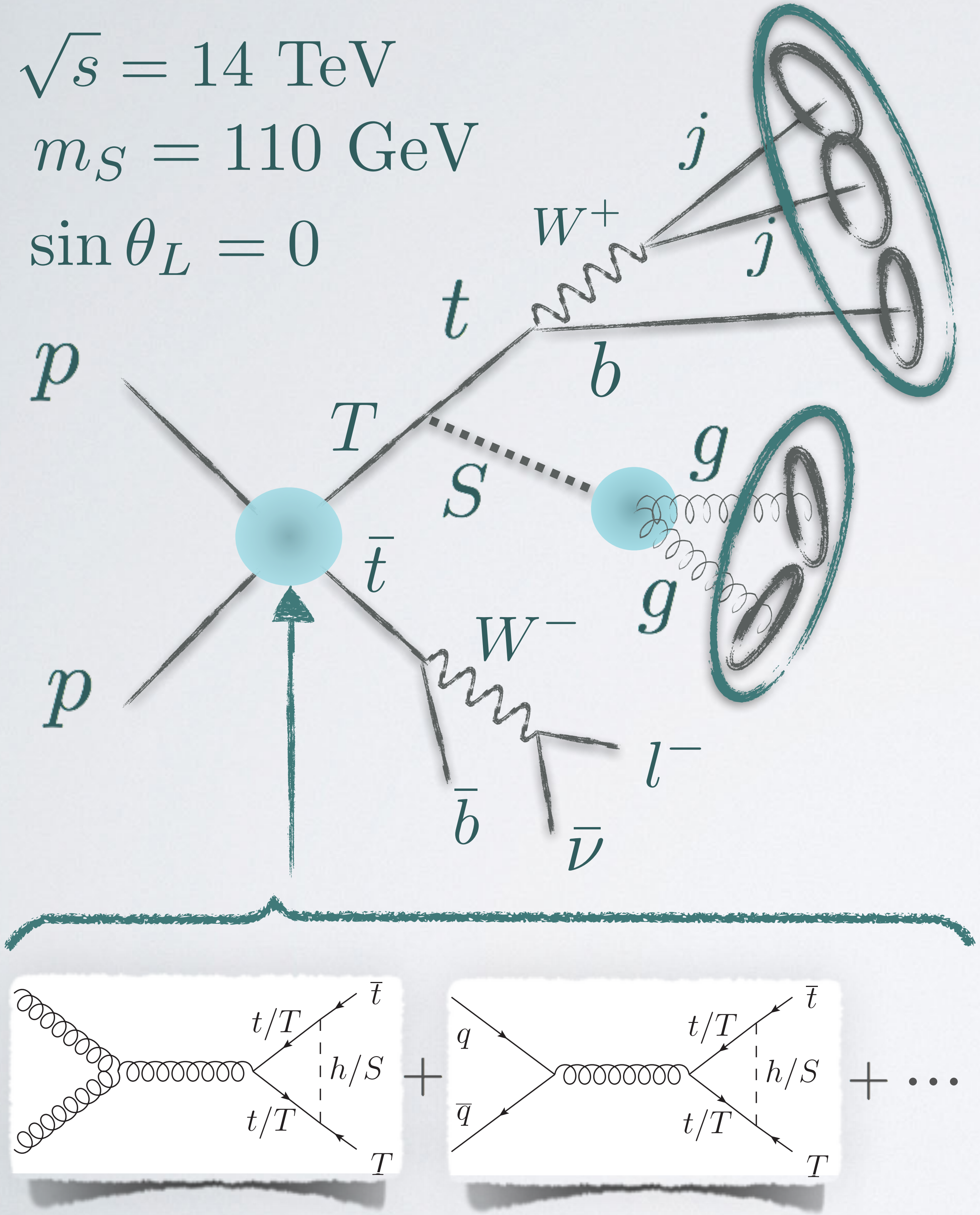

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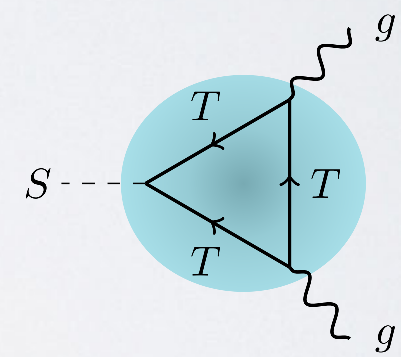

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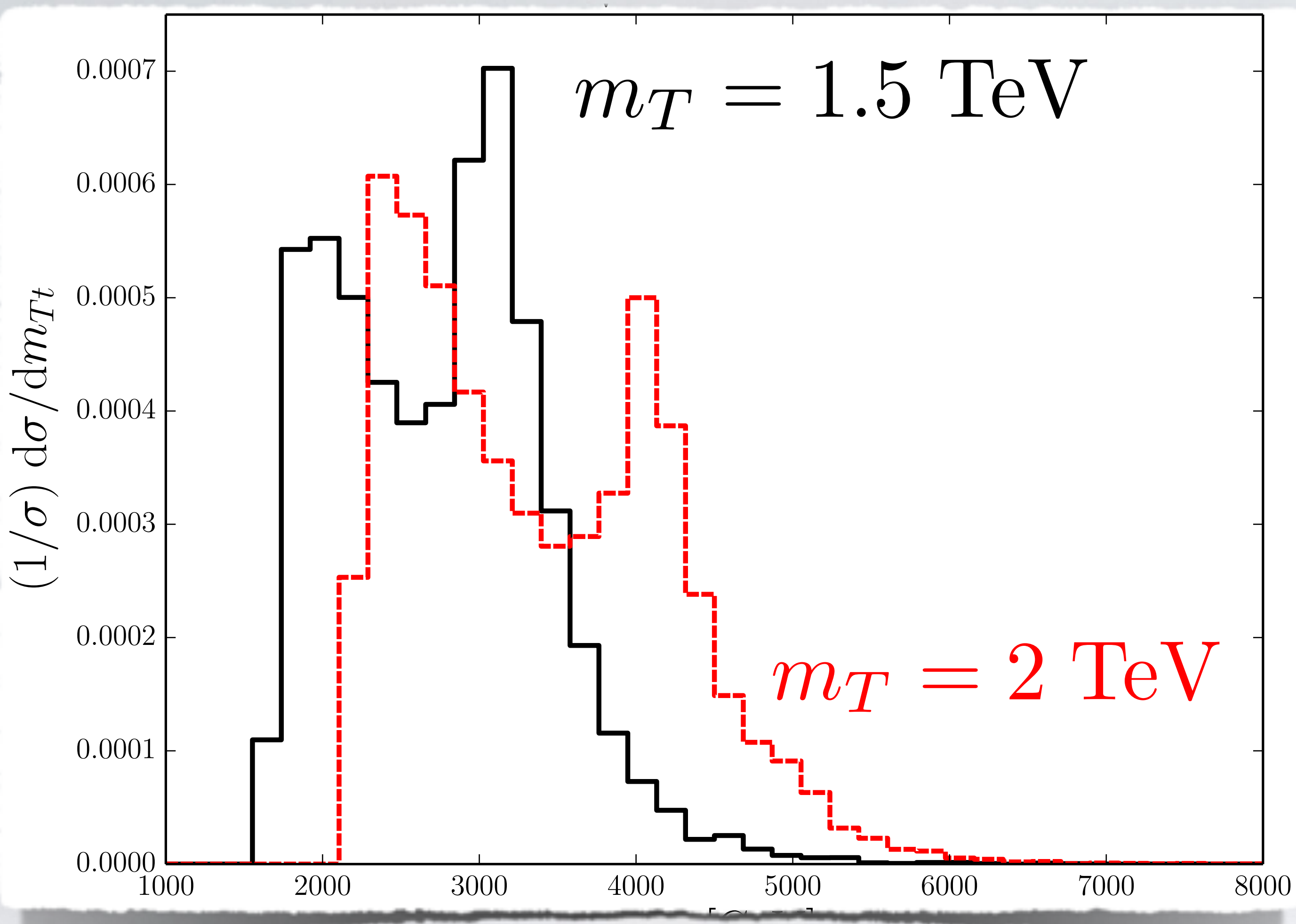
- The production vertex includes all loop contributions.

What's in the loops?

See also S. Dawson, A. Ismail, Ian Low [2015]

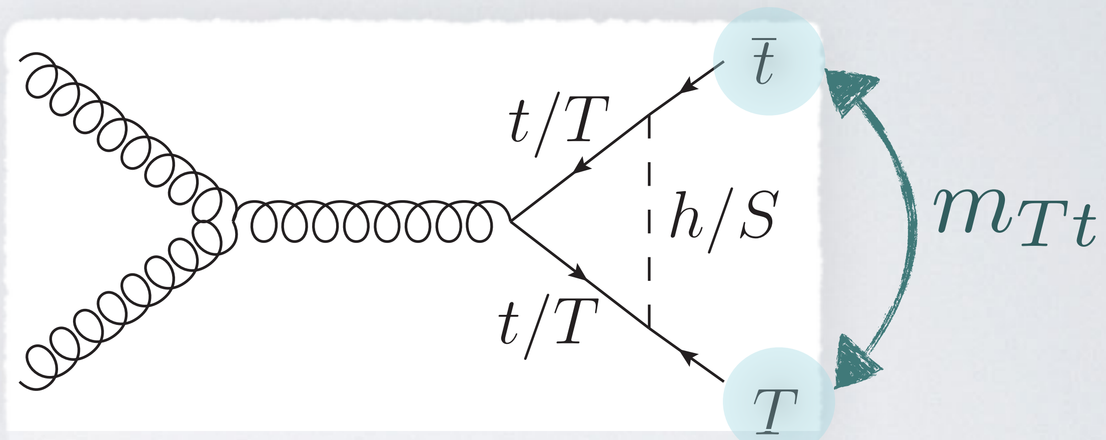
J. H. Kim, I. M. Lewis [2018]

$\sqrt{s} = 14$ TeV parton-level



m_{Tt} [GeV]

- When $m_{Tt} \sim 2m_T$, the internal top partners in the loop can go on-shell.



- It gives rise to the peaks in m_{Tt} distributions.
- It enhances the overall p_T distribution of the top, causing shoulder features.

What's in the loops?

See also S. Dawson, A. Ismail, Ian Low [2015]

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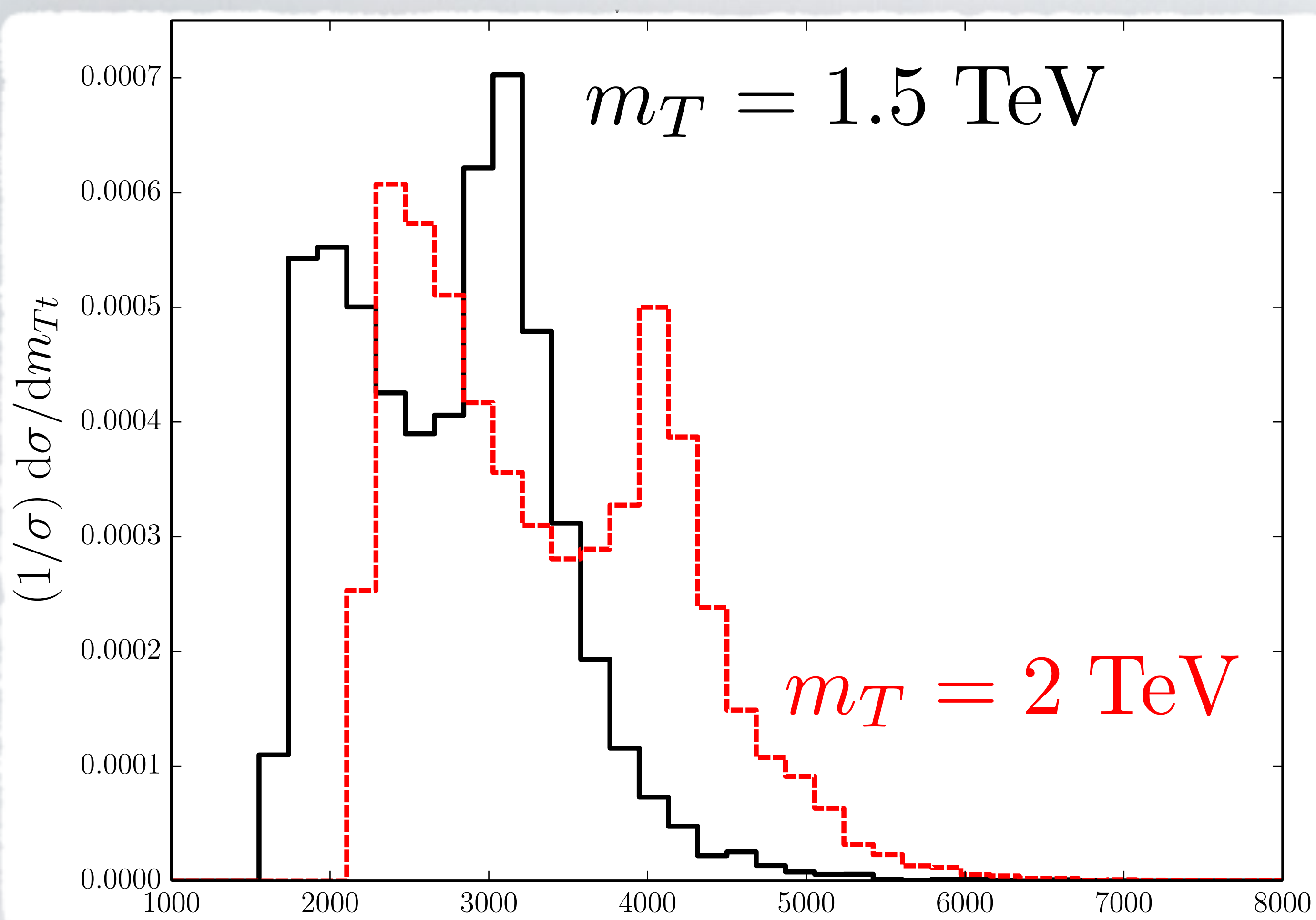
$\sqrt{s} = 14$ TeV

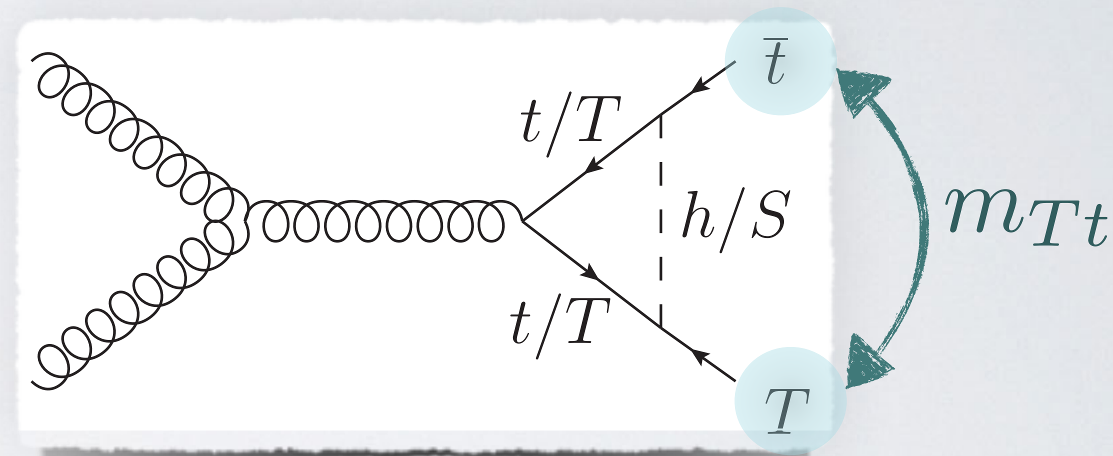
parton-level



m_{Tt} [GeV]

$m_{Tt} \sim 3$ TeV

- When $m_{Tt} \sim 2m_T$, the internal top partners in the loop can go on-shell.



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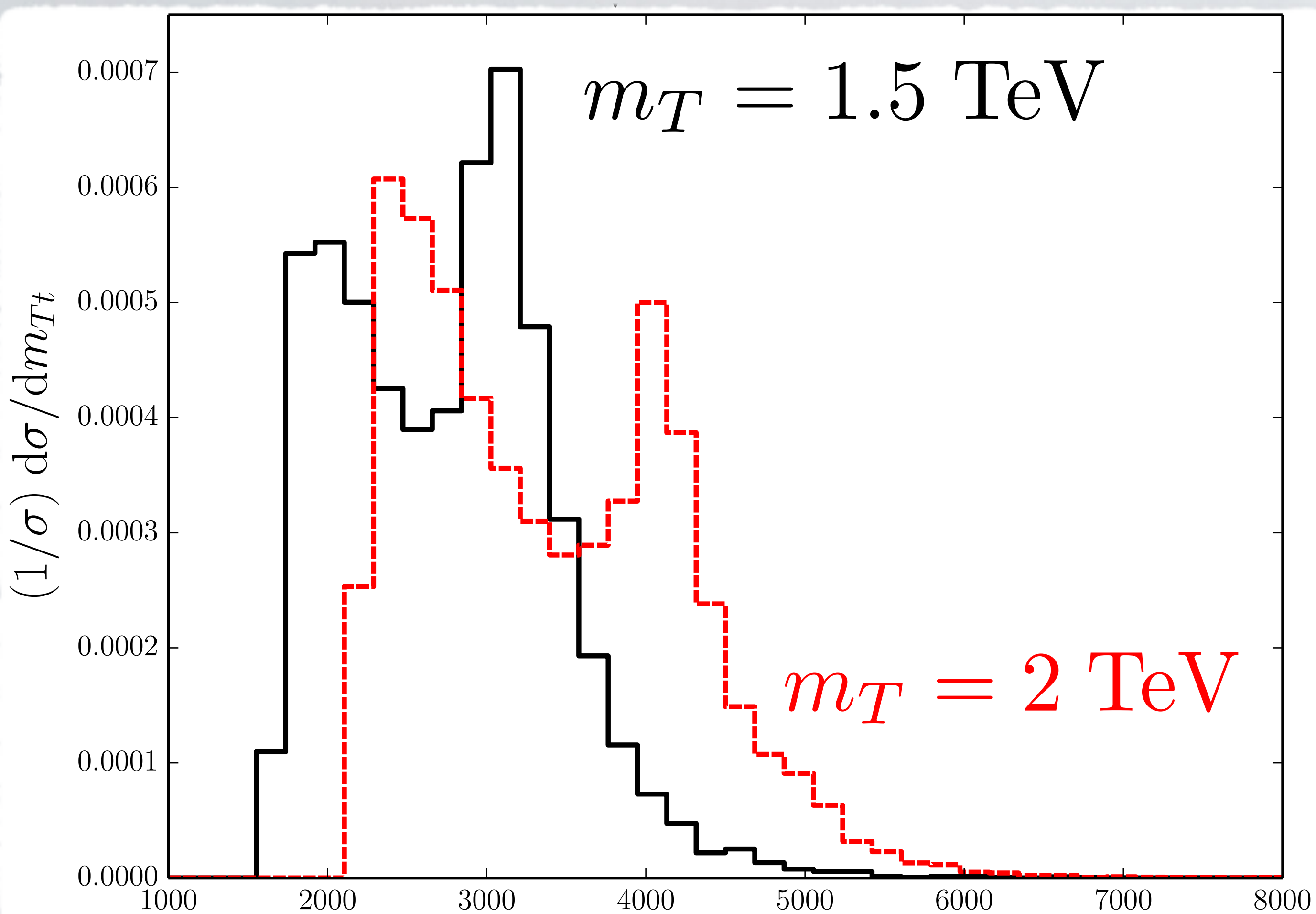
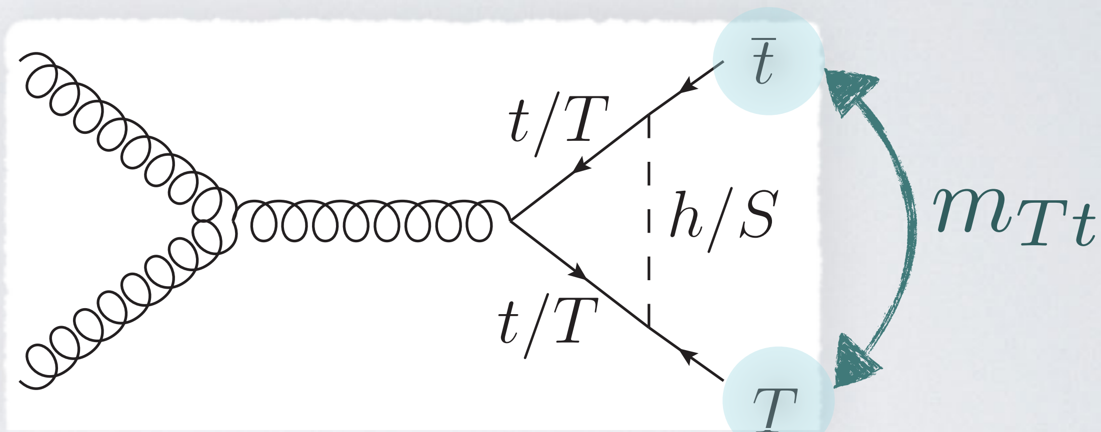


m_{Tt} [GeV]

$m_{Tt} \sim 4$ TeV

- When $m_{Tt} \sim 2m_T$, the internal top partners in the loop can go on-shell.



- It gives rise to the peaks in m_{Tt} distributions.
- It enhances the overall p_T distribution of the top, causing shoulder features.

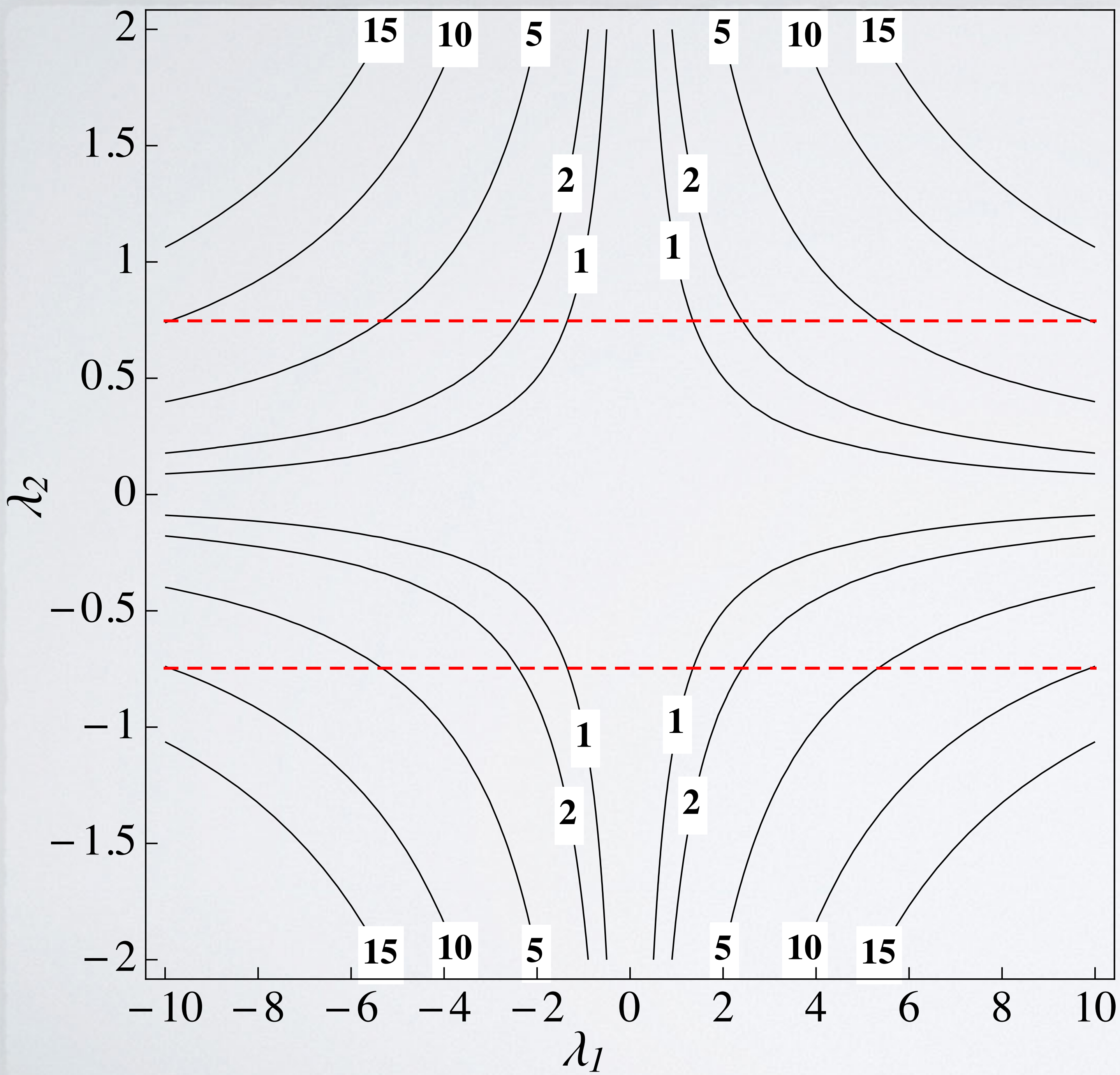
Contours of constant significance

$\sqrt{s} = 14$ TeV $m_T = 1.5$ TeV $\sin\theta_L = 0$

$L = 3$ ab^{-1} $m_S = 110$ GeV

$\lambda_1 S\bar{T}_L t_R + \text{h.c.}$

$-\lambda_2 S\bar{T}_L T_R + \text{h.c.}$



- T can be discovered in the blue region.
- T can be excluded in the cyan region.
- We have a good fraction of parameter space that can be probed by the collider search.

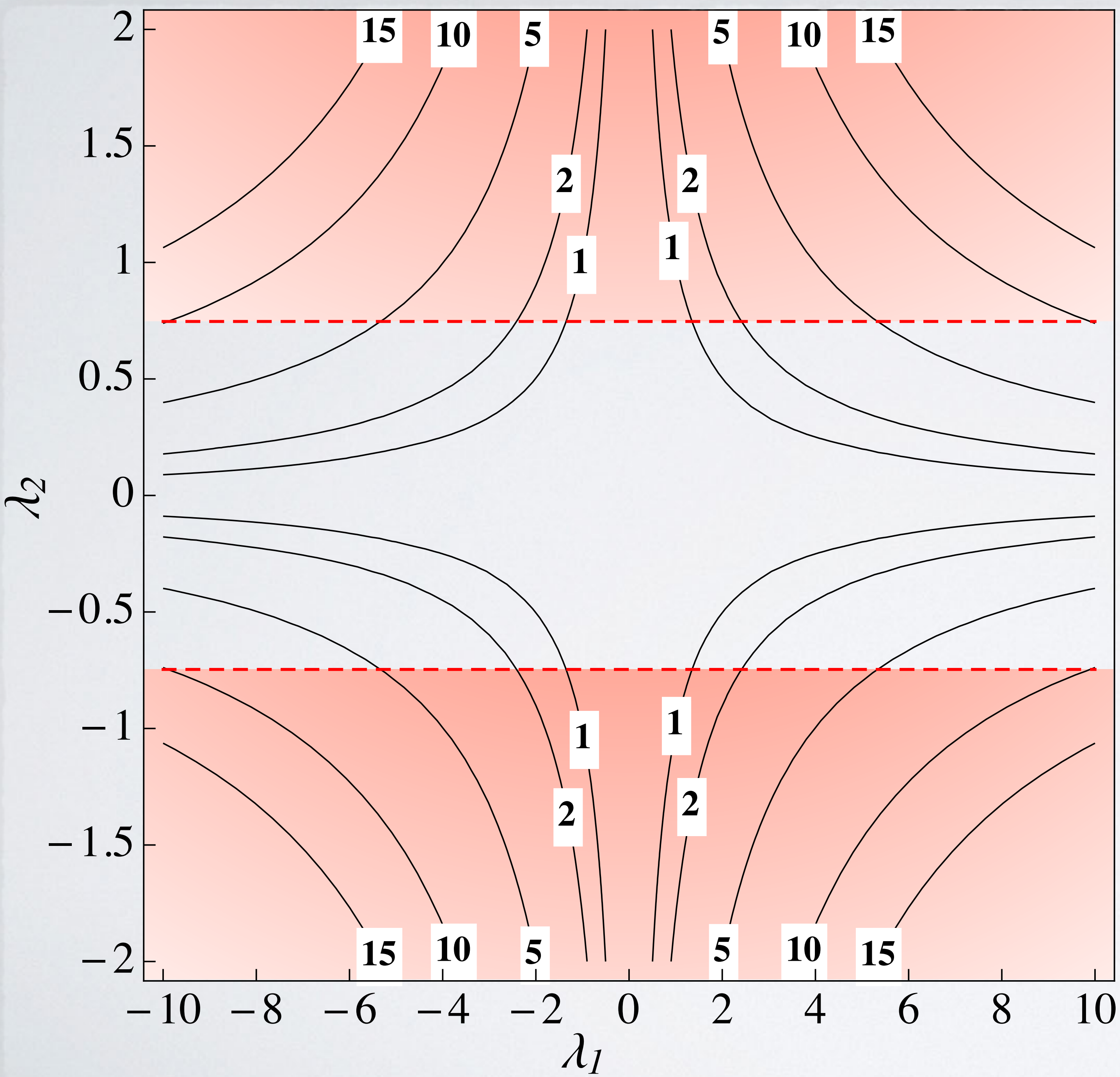
Contours of constant significance

$\sqrt{s} = 14$ TeV $\quad m_T = 1.5$ TeV $\quad \sin\theta_L = 0$

$L = 3$ ab^{-1} $\quad m_S = 110$ GeV

$\lambda_1 S \bar{T}_L t_R + \text{h.c.}$

$-\lambda_2 S \bar{T}_L T_R + \text{h.c.}$



Constraint from the scalar resonant search

- T can be discovered in the blue region.
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Contours of constant significance

$\sqrt{s} = 14$ TeV $\quad m_T = 1.5$ TeV $\quad \sin\theta_L = 0$

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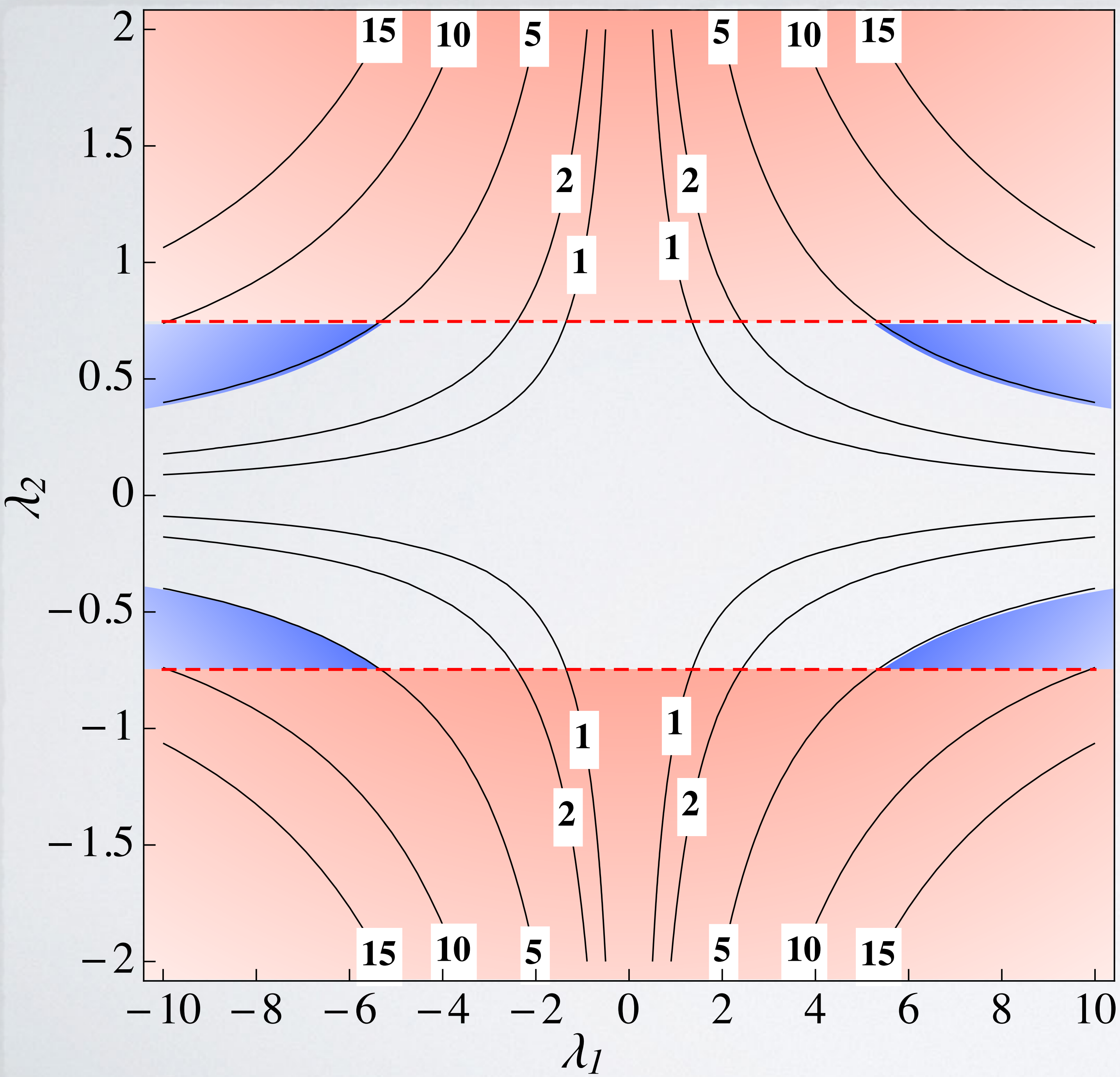

Constraint from the scalar resonant search

Can be discovered

- *T* can be discovered in the blue region.
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Contours of constant significance

$\sqrt{s} = 14$ TeV $\quad m_T = 1.5$ TeV $\quad \sin\theta_L = 0$

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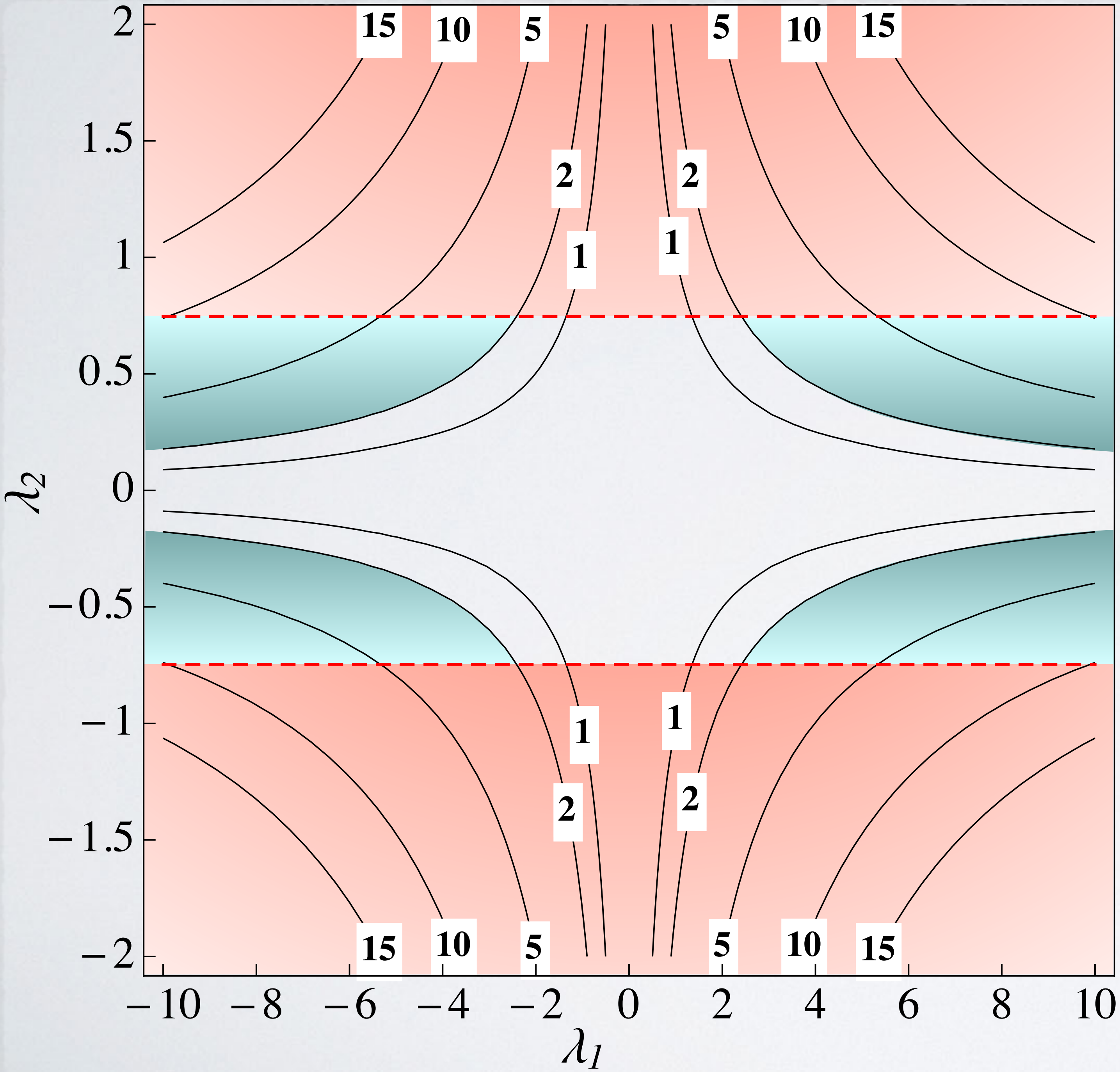

Constraint from the scalar resonant search

Can be excluded

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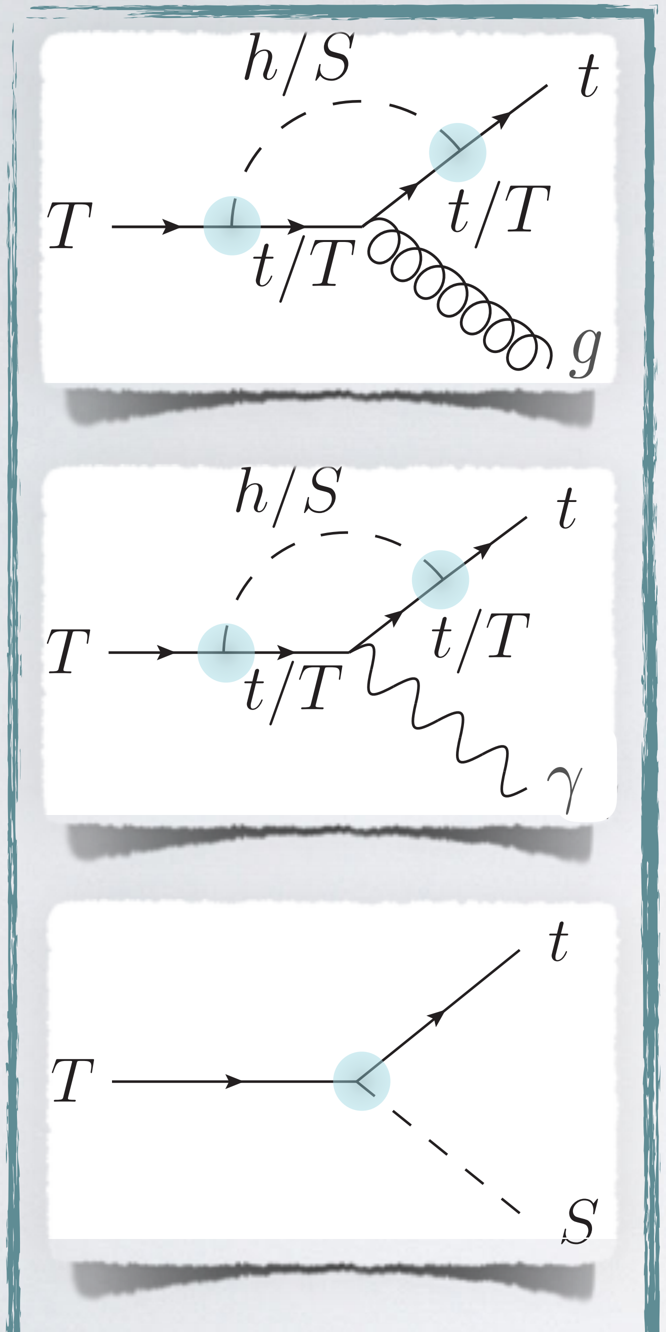
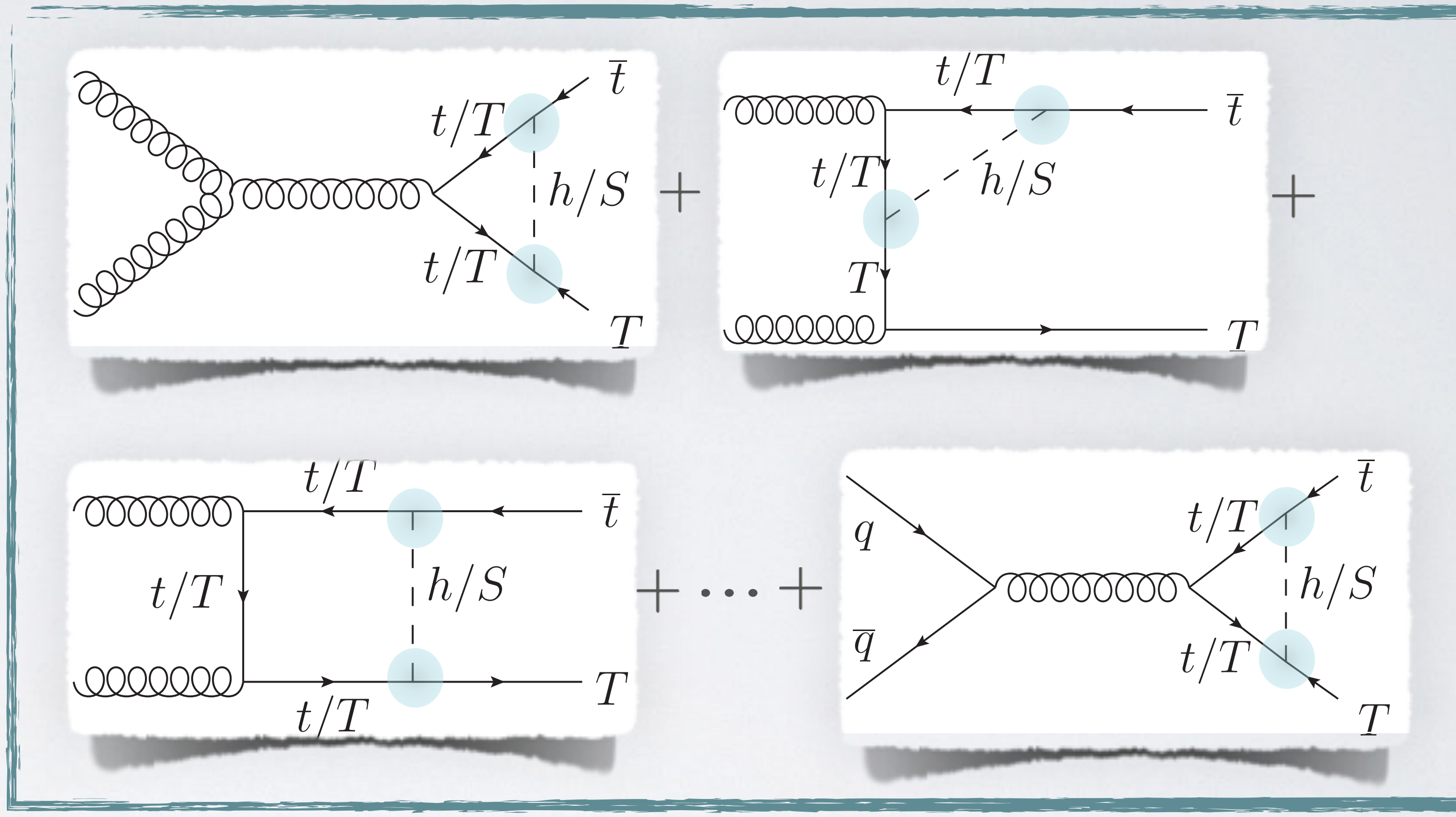
Summary

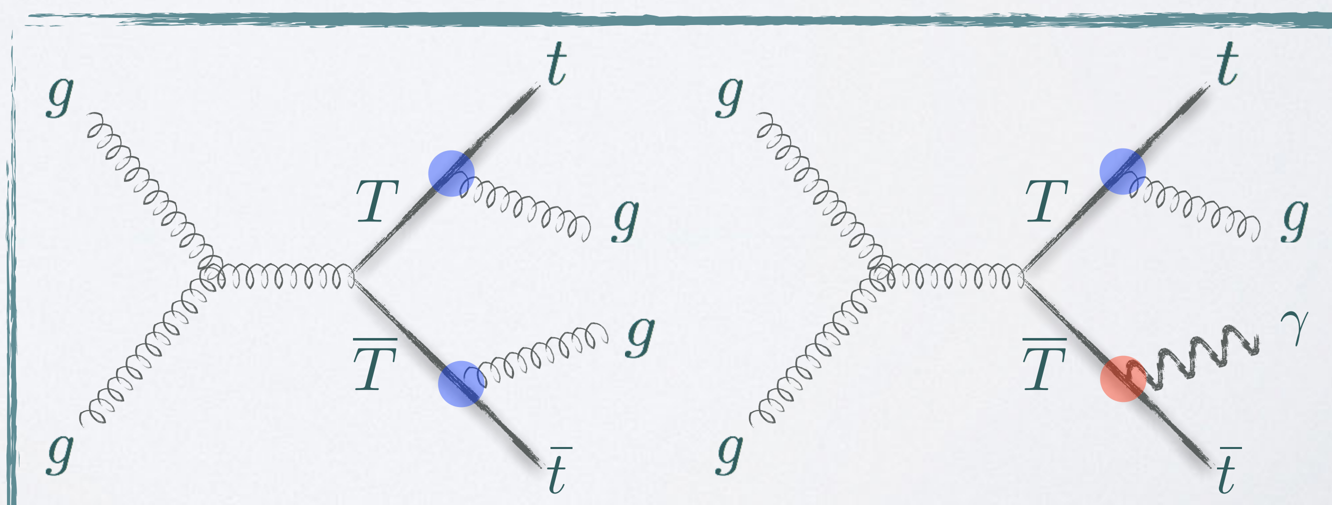
New decays



New productions



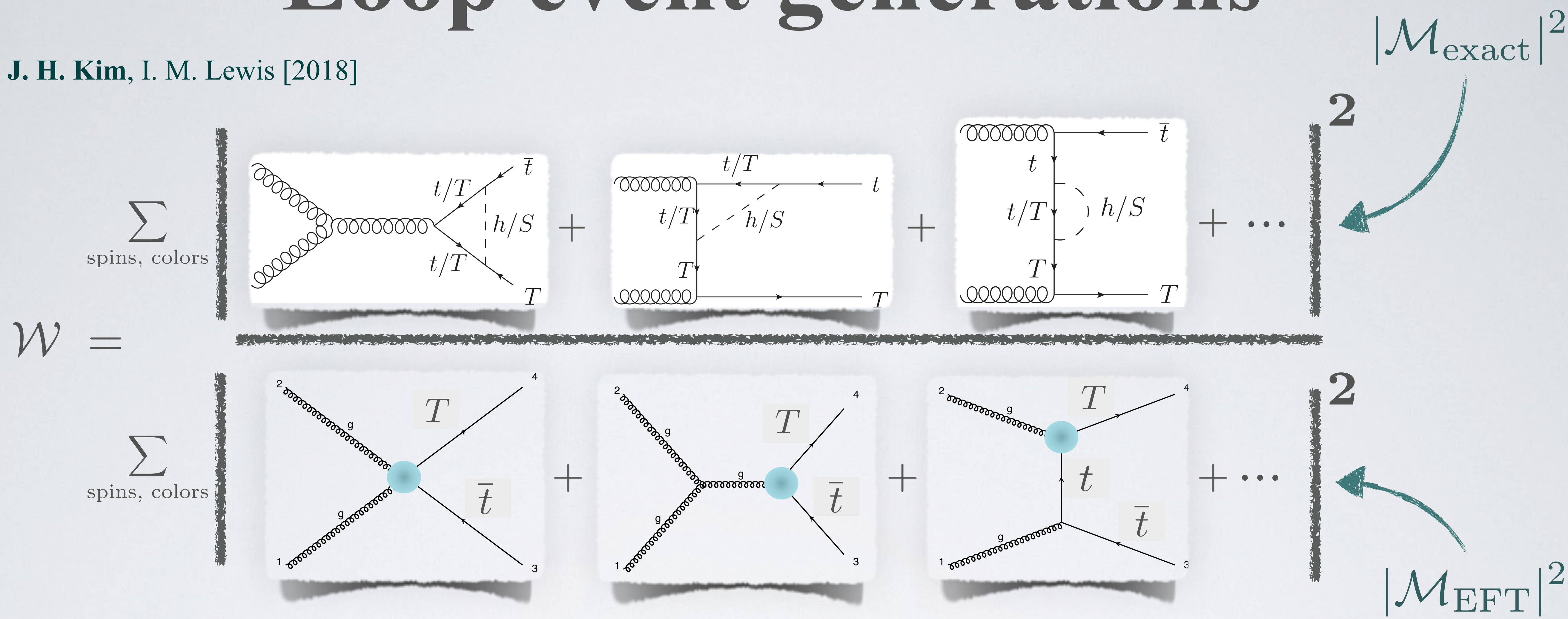
New final states



Back-up

Loop event generations

J. H. Kim, I. M. Lewis [2018]



- We first generate events based on EFT-type contact interactions using MadGraph.
- We reweight the $|\mathcal{M}|^2$ of the EFT by $|\mathcal{M}|^2$ of the exact loop calculation of the theory on an event-by-event basis.
- The reweighted events are showered and hadronized by Pythia.

Final cut-flow table

5.8% 0.08% 0.06% 0.0036% 0.0028%

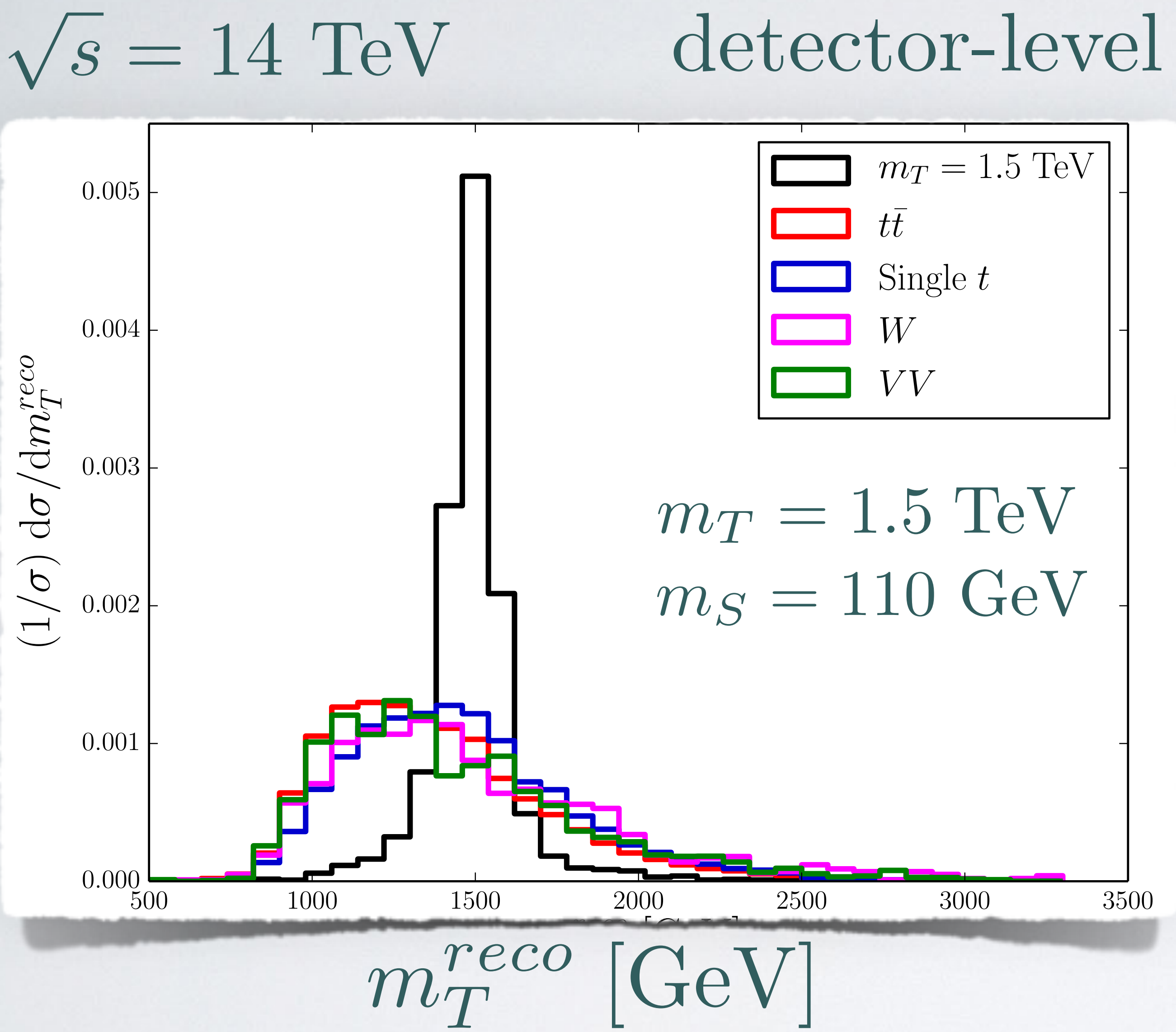
$m_T = 1.5$ TeV, $\lambda_{1,2} = 2$	Signal [fb]	$t\bar{t}$ [fb]	Single t [fb]	W [fb]	VV [fb]	σ
Basic cuts	0.055	1.3×10^3	2.8×10^3	2.7×10^3	88	0.036
$N^{1.5}_{t_{had}} = N^{1.5}_S = 1$	3.2×10^{-3}	1.11	1.6	0.098	2.5×10^{-3}	0.11
Reconstructed t_{lep}	1.2×10^{-3}	0.073	0.070	4.7×10^{-4}	$\ll \mathcal{O}(10^{-5})$	0.17
1400 GeV $< m_T^{reco} <$ 1550 GeV	9.2×10^{-4}	0.015	9.4×10^{-3}	$\ll \mathcal{O}(10^{-5})$	$\ll \mathcal{O}(10^{-5})$	0.32
2865 GeV $< m_{Tt}^{reco}$	6.3×10^{-4}	1.5×10^{-3}	7.2×10^{-5}	$\ll \mathcal{O}(10^{-5})$	$\ll \mathcal{O}(10^{-5})$	0.81
2050 GeV $< H_T^{reco}$ $\Delta R^{reco}_{t_{had}S} < 3.41$ $1.63 < \Delta R^{reco}_{t_{lep}S}$	5.8×10^{-4}	$\ll \mathcal{O}(10^{-5})$	$\ll \mathcal{O}(10^{-5})$	$\ll \mathcal{O}(10^{-5})$	$\ll \mathcal{O}(10^{-5})$	5.0

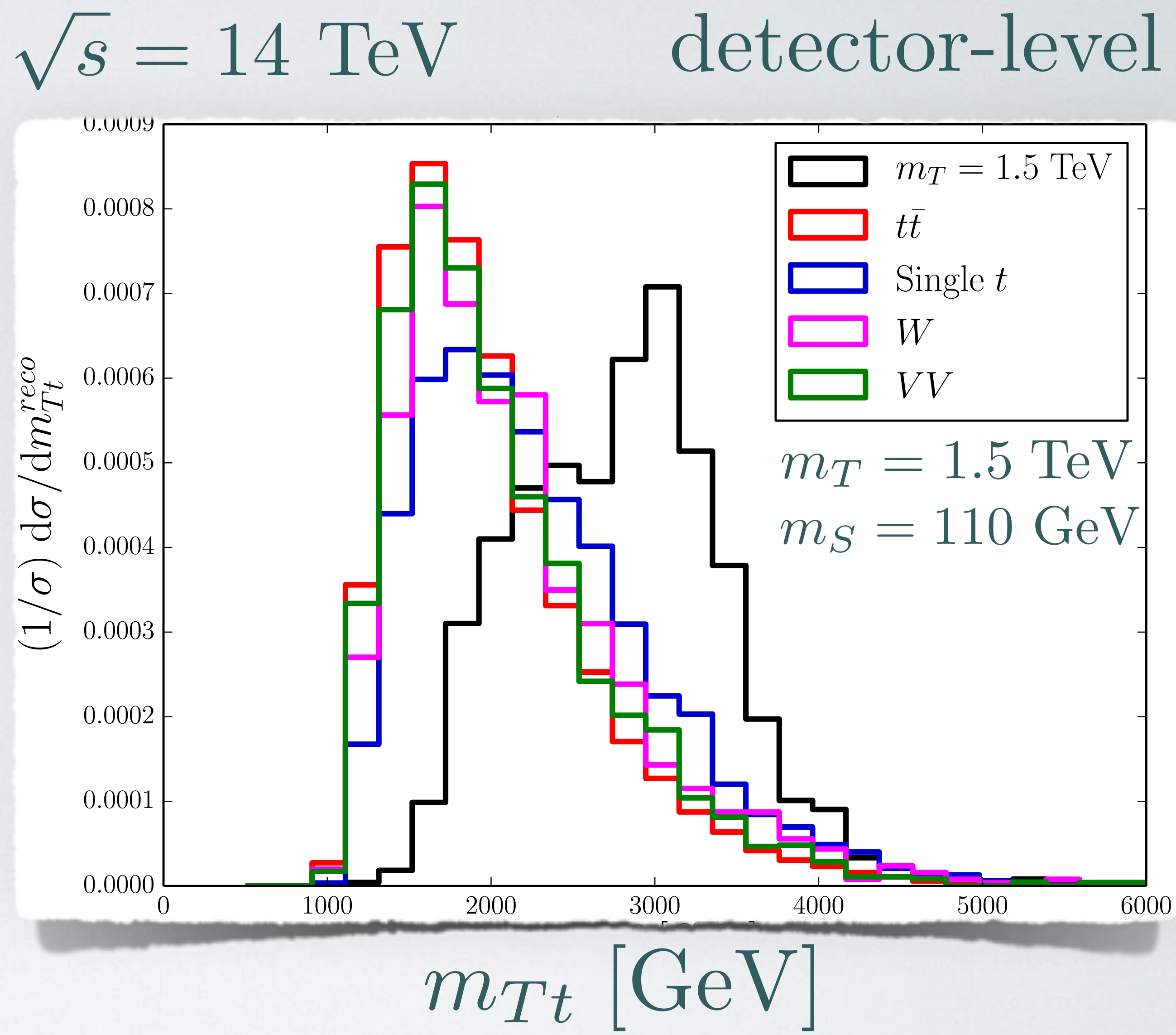
$\times 3.1$

significance

- A cut-flow table showing cross sections of each stage in fb.
- It shows that jet substructure analysis can effectively reduce the overall size of backgrounds.
- Significances calculated for a luminosity of 3 ab^{-1} show that 5σ discovery is achievable for 1.5 TeV top partner with $\lambda_{1,2} = 2$.

Reconstructed T and $T\,t$-system





- Reconstructed T invariant mass distribution with a peak at its mass.
- We see that the threshold structure at $m_{Tt} \sim 2m_T$ survives even at the detector-level (better separation against the SM backgrounds).