VECTOR-LIKE TOP PARTNERS

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LFC17, ECT*, Trento, 15/9/2017

MOTIVATION

- For the “believers”:
  they are introduced in many extensions of the Standard Model that try to address the hierarchy problem (e.g. extra dimensions, little/composite Higgs models, ..)

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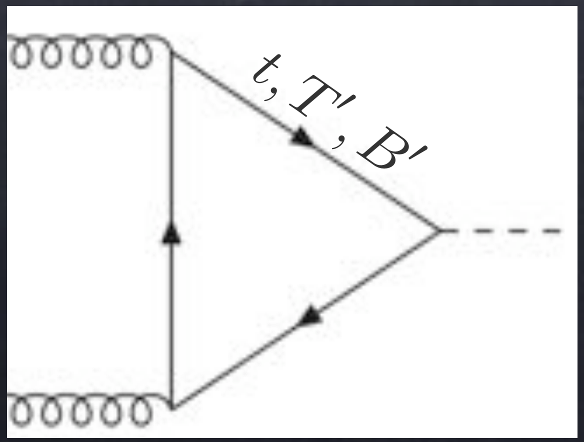
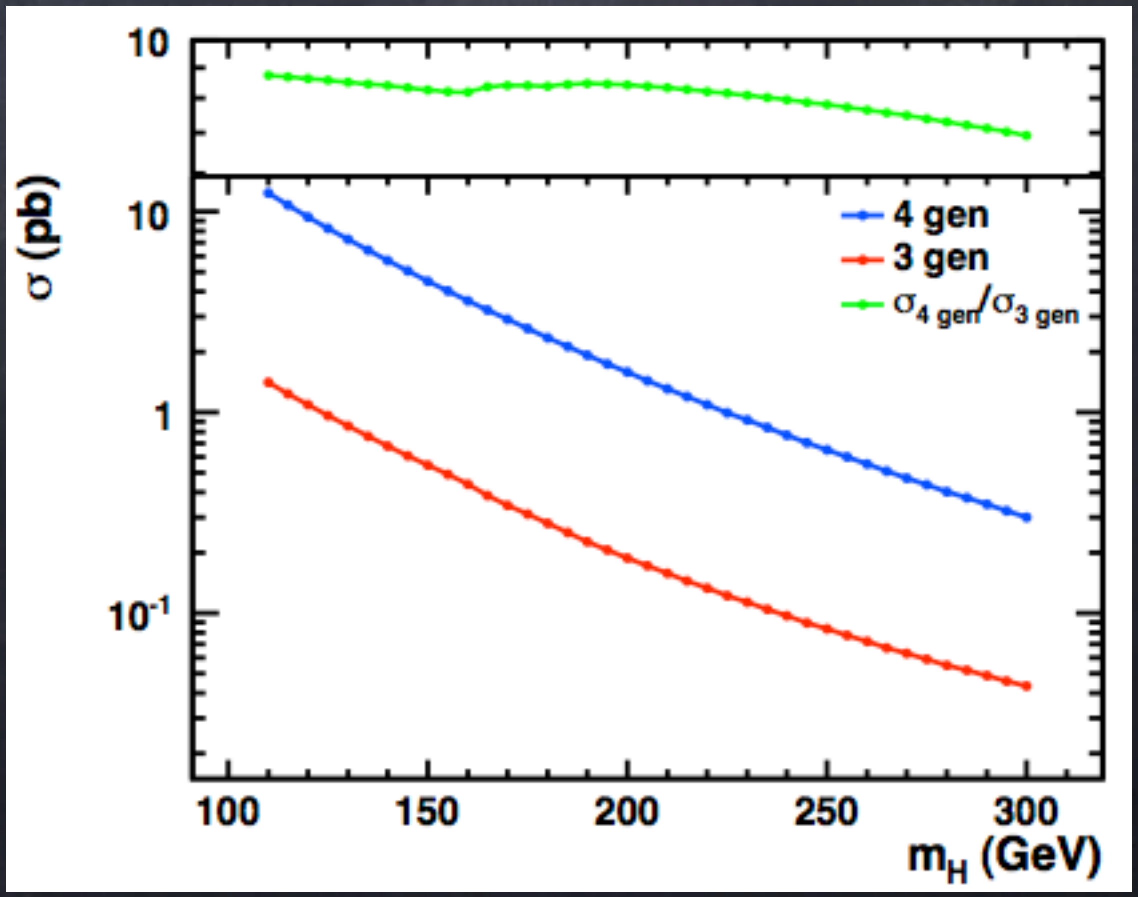
  they are introduced in many extensions of the Standard Model that try to address the hierarchy problem (e.g. extra dimensions, little/composite Higgs models, ..)
- For the “pragmatists”:
  LHC is a exploration machine and the existence of new vector-like quarks is a possibility worth exploring

MOTIVATION

- Why vector-like?
  - ➡ (heavy) chiral quarks would have large Yukawa couplings, and therefore enhance the Higgs production cross section
  - ➡ example: "four-generation Standard Model"





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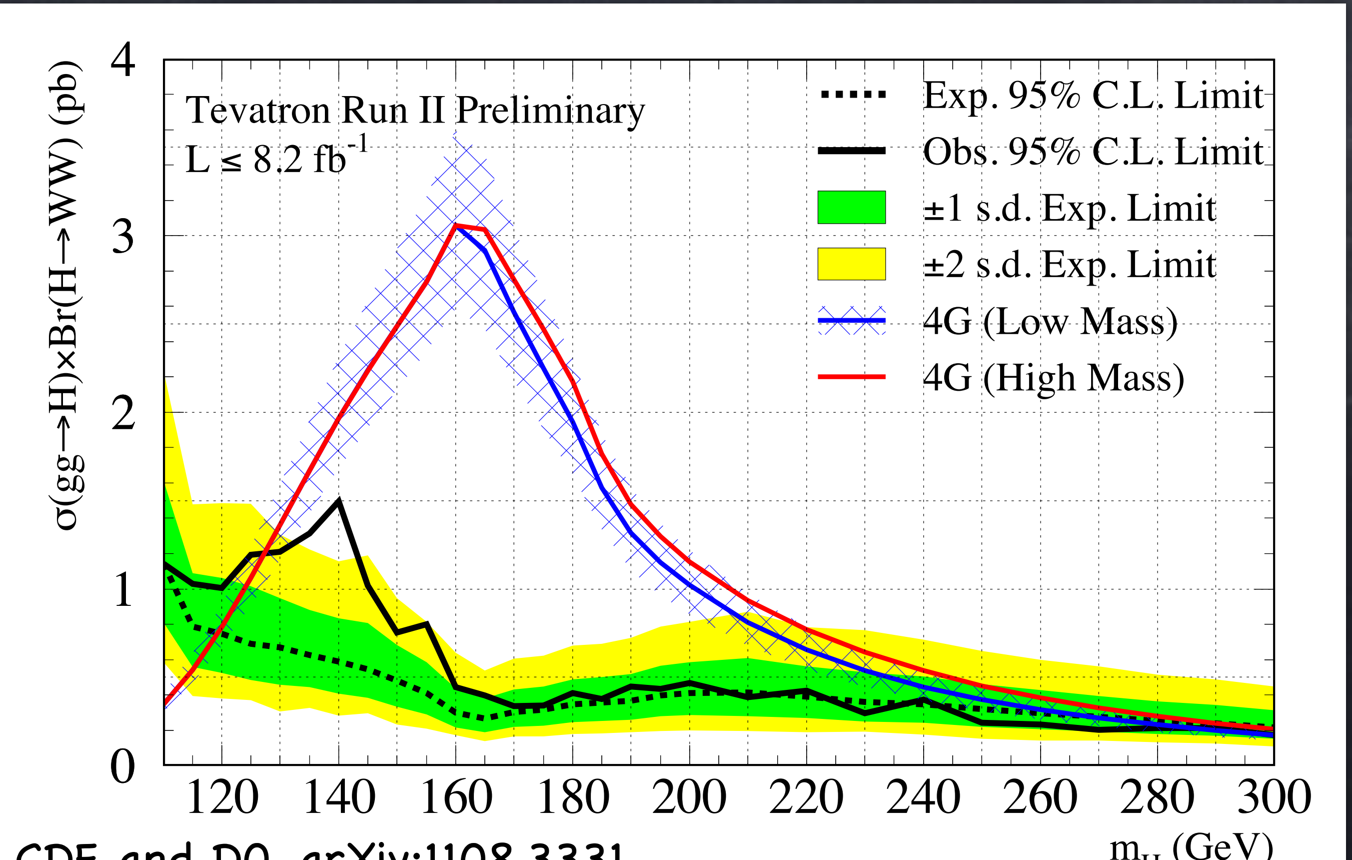
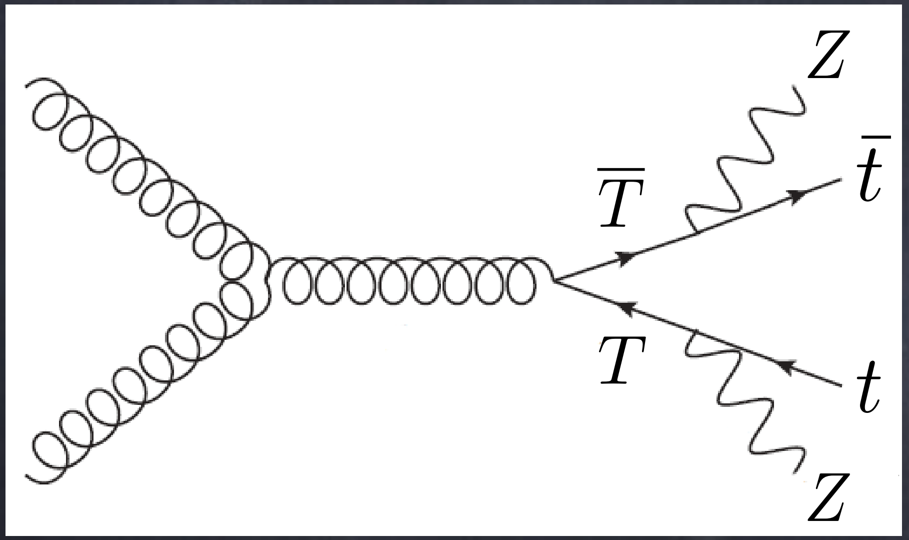
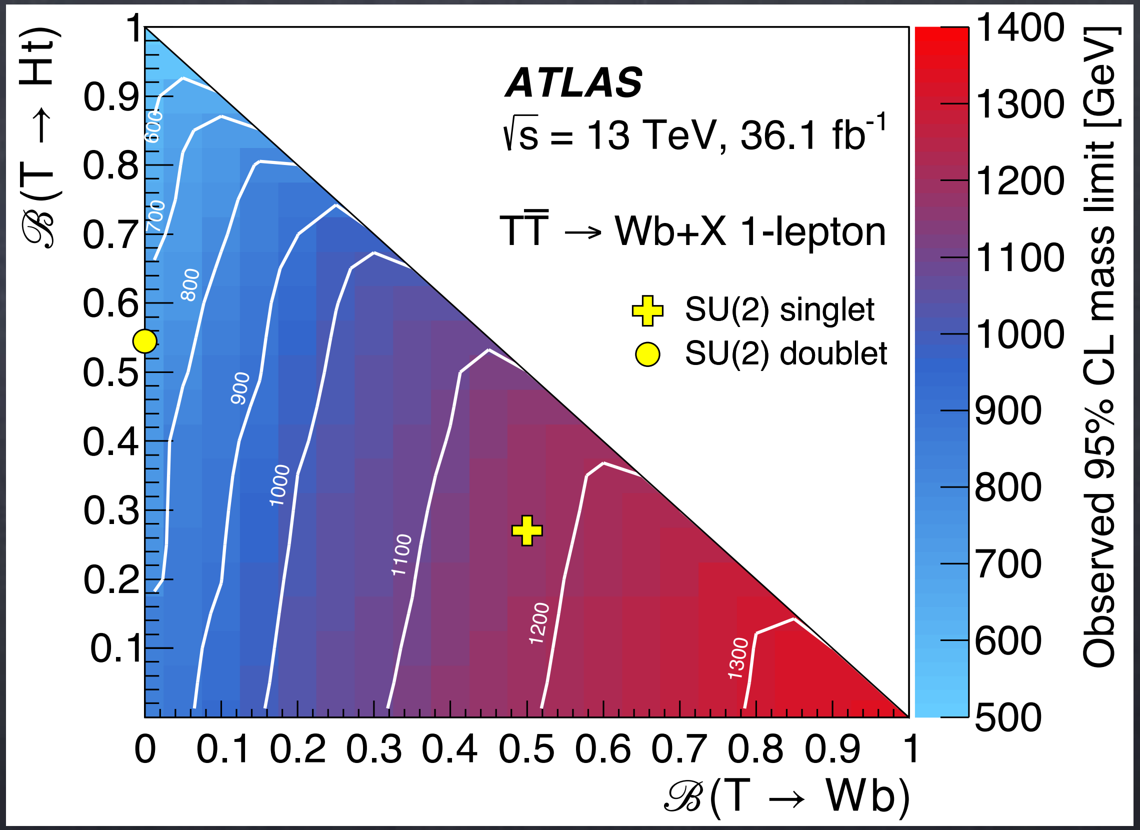


CDF and D0, arXiv:1108.3331

BOUNDS

- Lower bounds on the mass of new quarks are set by direct searches





ATLAS-CONF-2016-102

$$M_T > (1170 - 1350)\text{GeV}$$ (singlet/doublet with 100% BR to Wb)

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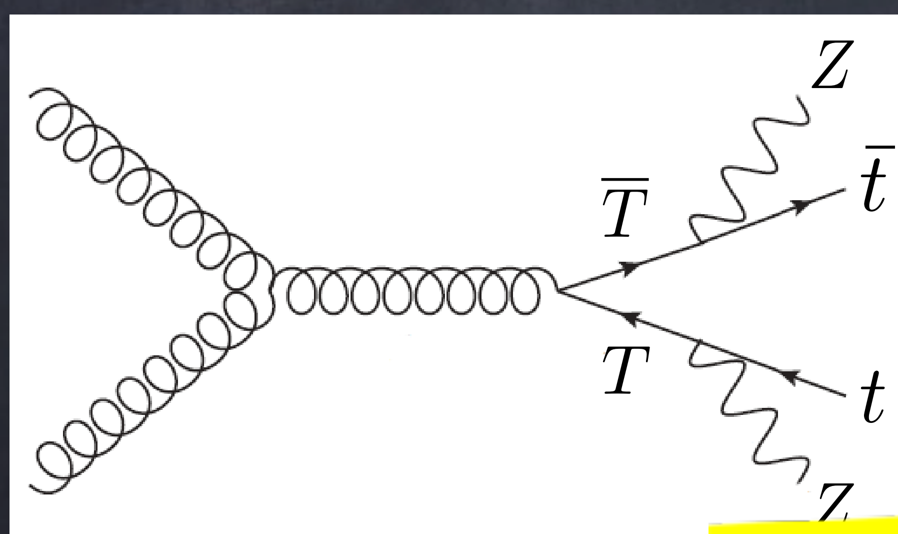
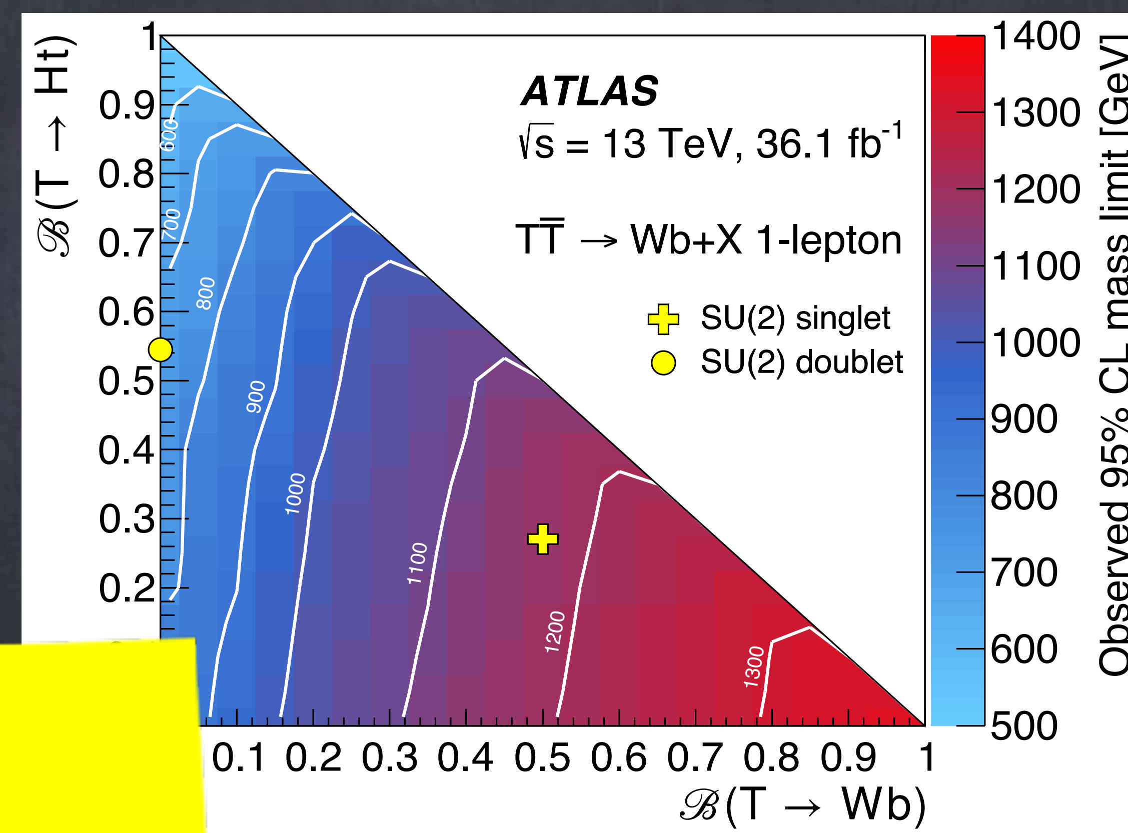




ATLAS-CONF-2016-102

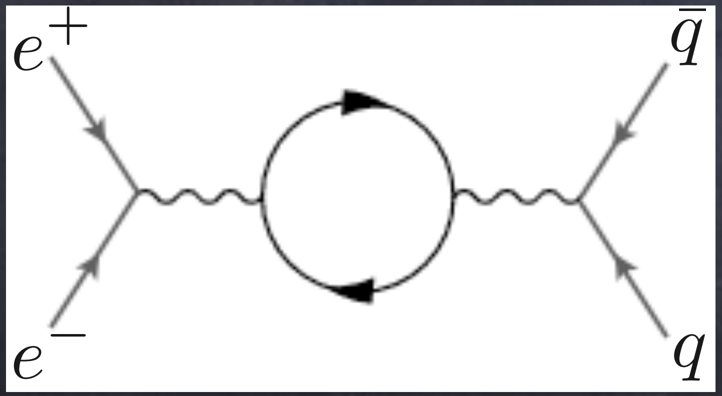
see Meenakshi's talk

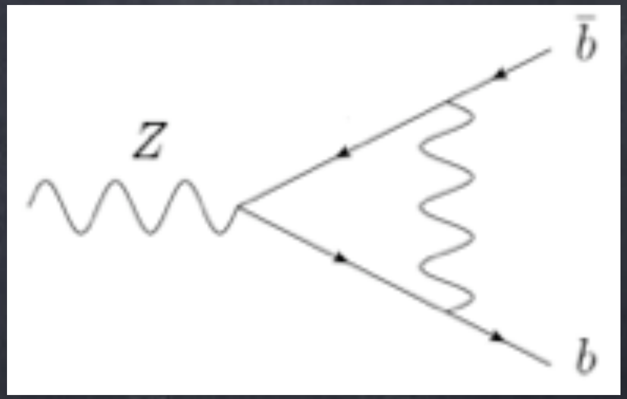
M_T … GeV (singlet/doublet with 100% BR to Wb)

BOUNDS

➡ the new quarks could be too heavy to be observed directly...
... but they could affect loop-mediated processes:

- electroweak precision parameters (*S, T, U,* $Z \to b\bar{b}$)





- Higgs rates

$$\frac{\sigma}{\sigma^{SM}} = \begin{cases} 1.16\,^{+0.15}_{-0.14} & \text{(CMS)} \\ 0.99 \pm 0.14 & \text{(ATLAS)} \end{cases}$$

$$\frac{\sigma_{H\to\gamma\gamma}}{\sigma^{SM}_{H\to\gamma\gamma}} = \begin{cases} [1 - 1.2] & \text{CMS-PAS-HIG-16-040} \\ [0.8 - 1.1] & \text{ATLAS-CONF-2017-045} \end{cases}$$

Can indirect effects be useful in the search for new quarks?

SET-UP

- Consider vector-like quarks in the lower representations of $SU(2)_L$, that can mix with the Standard Model top and bottom
  - ➡ vector-like singlets T^0 B^0
  - ➡ vector-like doublets (X^0, T^0) (T^0, B^0) (B^0, Y^0)
  - ➡ vector-like triplets (X^0, T^0, B^0) (T^0, B^0, Y^0)

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"exotic" quarks of charge

5/3 -4/3

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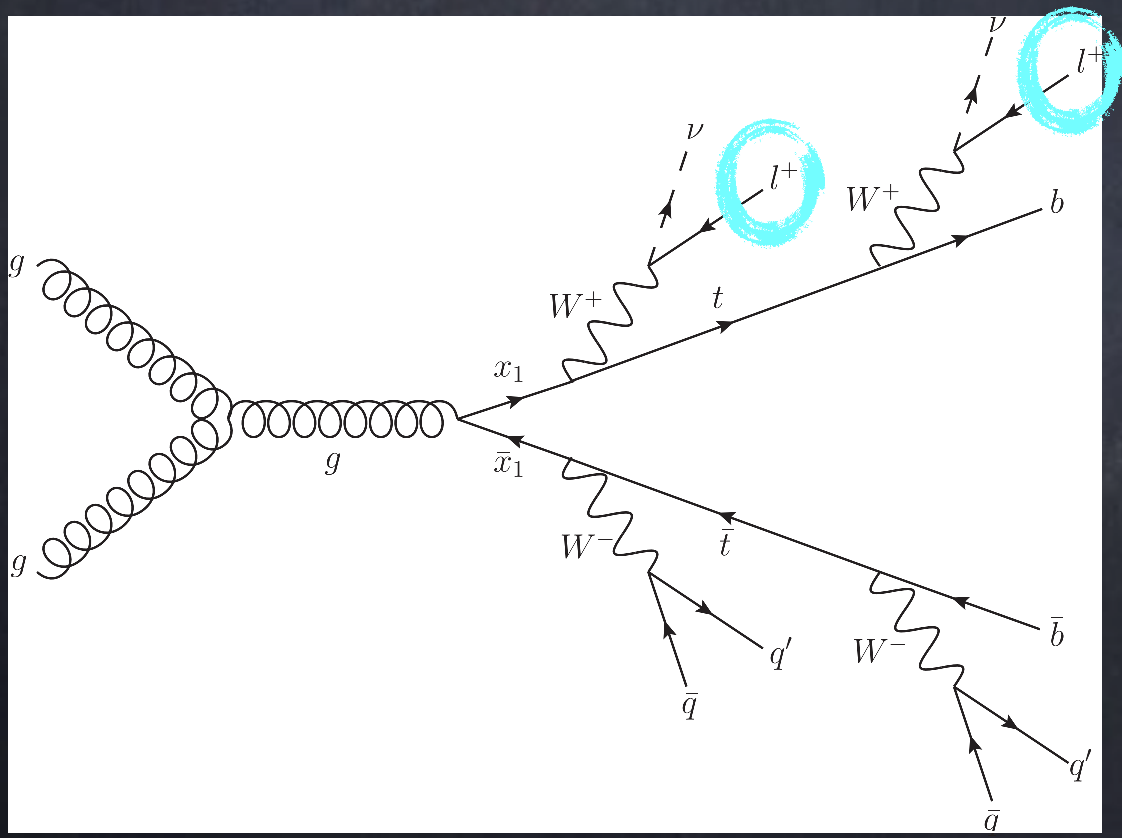

- The “exotic” quarks could give interesting collider signatures

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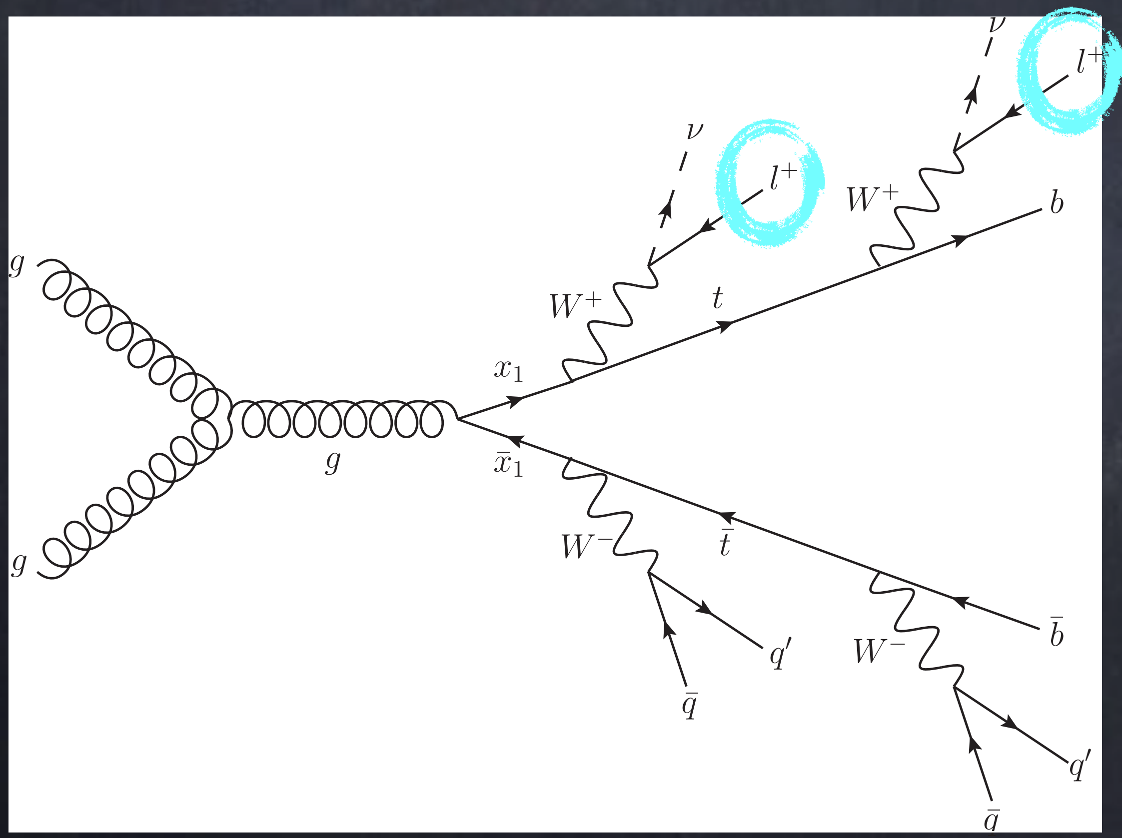

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see Meenakshi's talk

SET-UP

- Write the most general Lagrangian for the interactions among the new quarks and their mixing with the Standard Model third family

  ✦ singlet T^0

$$-\mathcal{L} = M_{T_s} \overline{T}^0_L T^0_R + \lambda_1 \overline{\psi}^0_L \tilde{H} T^0_R + h.c.$$

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SM left-handed doublet

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✦ doublet $\chi^0 = (T^0, B^0)$

$$-\mathcal{L} = M_{TB} \overline{\chi}^0_L \chi^0_R + \lambda_4 \overline{\chi}^0_L \tilde{H} t^0_R + \lambda_5 \overline{\chi}^0_L H b^0_R + h.c.$$

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SM right-handed singlets

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(mixings of SM fermions and VLQs with same quantum numbers rotated away by a redefinition of the fields)

SET-UP

- From the Lagrangian we can read off the mass matrices for the top-like, bottom-like and "exotic" quarks

$$-\mathcal{L}_M = \overline{\mathcal{T}}^0_L M^t_0 \mathcal{T}^0_R + \overline{\mathcal{B}}^0_L M^b_0 \mathcal{B}^0_R + M_Y \overline{Y}_L Y_R + M_X \overline{X}_L X_R$$

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$$\overline{\mathcal{T}}^0_L \rightarrow \begin{pmatrix} t^0_L \\ T^0_L \end{pmatrix}$$

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- The physical quarks are obtained through unitary rotations. For example

$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} \cos\theta^t_L & -\sin\theta^t_L \\ \sin\theta^t_L & \cos\theta^t_L \end{pmatrix} \begin{pmatrix} t^0_L \\ T^0_L \end{pmatrix}$$

COUPLINGS

- Because of these mixings
  - the heavy mass eigenstate acquires a coupling with the Higgs boson
  - the Yukawa coupling of the light “top” quark is suppressed
  - off-diagonal couplings with the electroweak gauge bosons arise

PARAMETERS

- In each model, there are a number of parameters (physical masses and mixing angles). However, not all of them are independent!
- Example: (T^0, B^0) doublet

parameters: $m_t, m_b, M_T, M_B, \theta_L^t, \theta_R^t, \theta_L^b, \theta_R^b$

relations:

$$M_T^2 (c_R^t)^2 + m_t^2 (s_R^t)^2 = M_B^2 (c_R^b)^2 + m_b^2 (s_R^b)^2$$

$$M_{T,B} \tan\theta_L^{t,b} = m_{t,b} \tan\theta_R^{t,b}$$

➡ only three independent parameters

PARAMETERS

- In each model, there are a number of parameters (physical masses and mixing angles). However, not all of them are independent!
  - ➡ as independent parameters we take

$$
\begin{aligned}
B \text{ singlet}: &\quad s_L^b, M_B \\
T \text{ singlet}: &\quad s_L^t, M_T \\
(XT) \text{ doublet}: &\quad s_R^t, M_T \\
(TB) \text{ doublet}: &\quad s_R^t, s_R^b, M_T \\
(BY) \text{ doublet}: &\quad s_R^b, M_B \\
(XTB) \text{ triplet}: &\quad s_L^t, M_T \\
(TBY) \text{ triplet}: &\quad s_L^t, M_T
\end{aligned}
$$

ELECTROWEAK PRECISION TESTS

- They are affected due to the presence of the new quarks and the change in the couplings of the "Standard Model" quarks to electroweak gauge bosons

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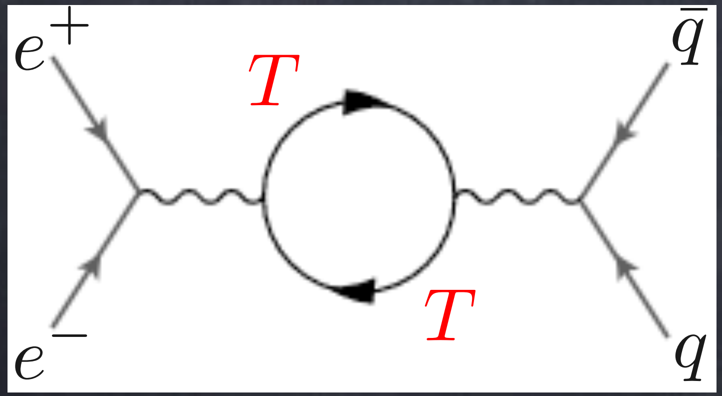

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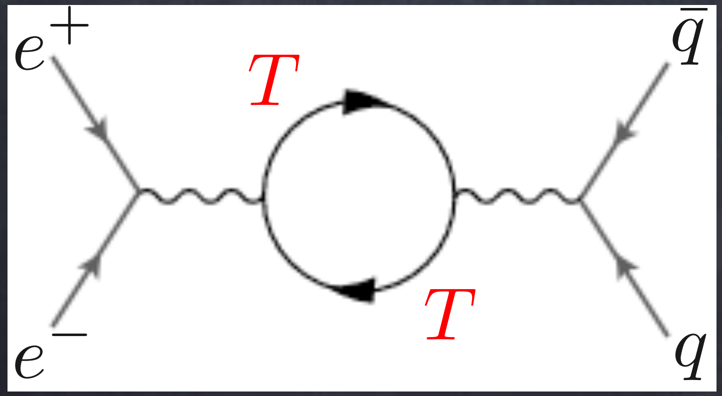

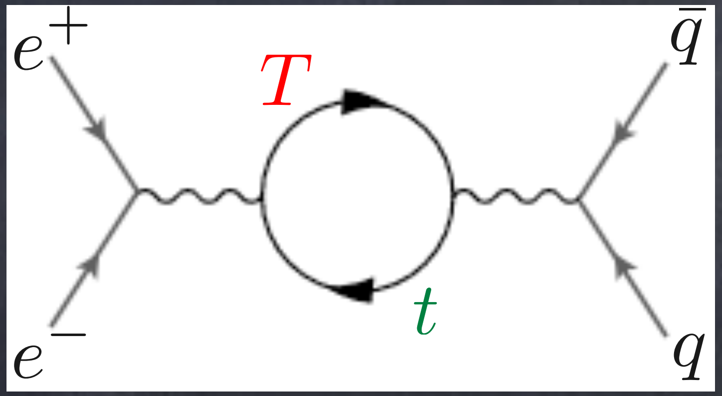

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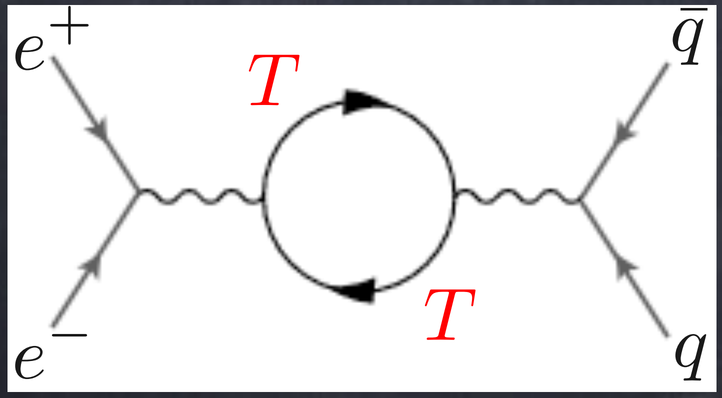

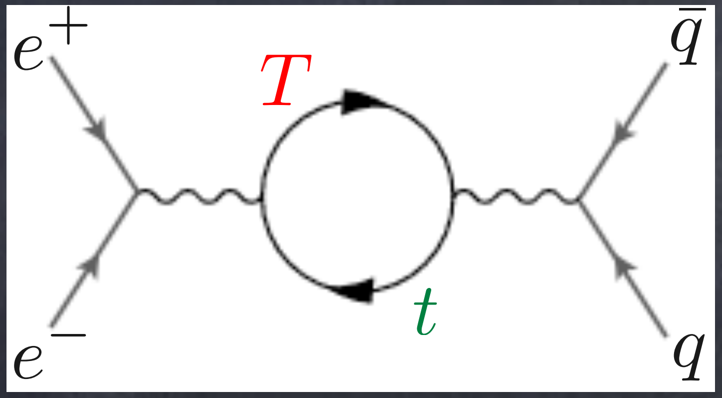

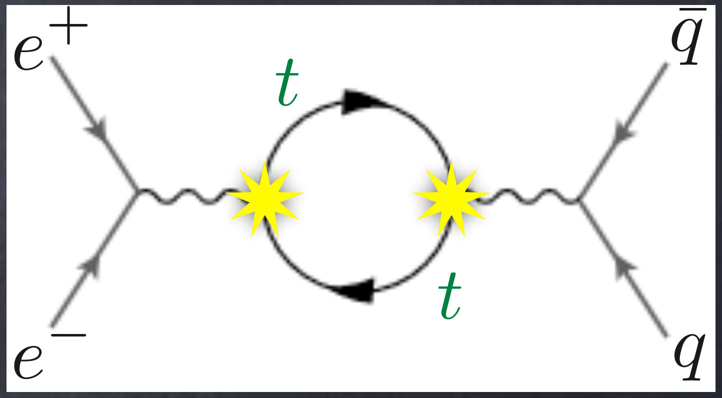

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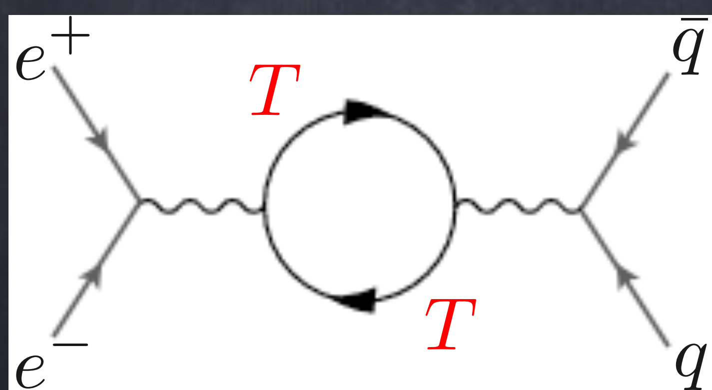
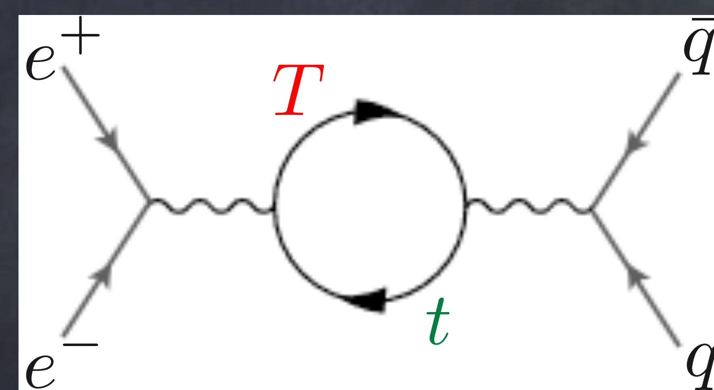
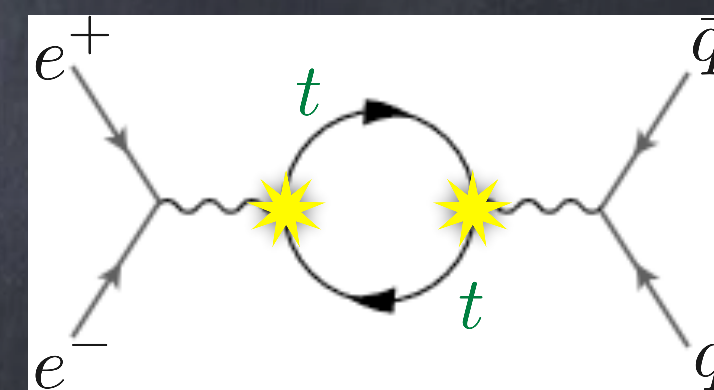
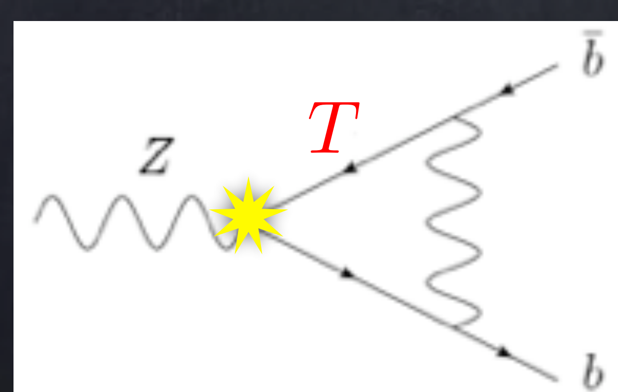
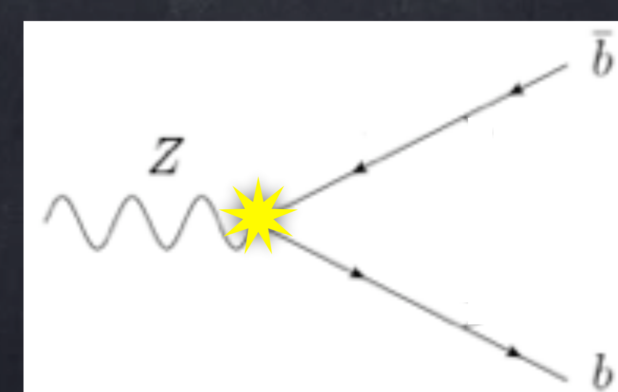




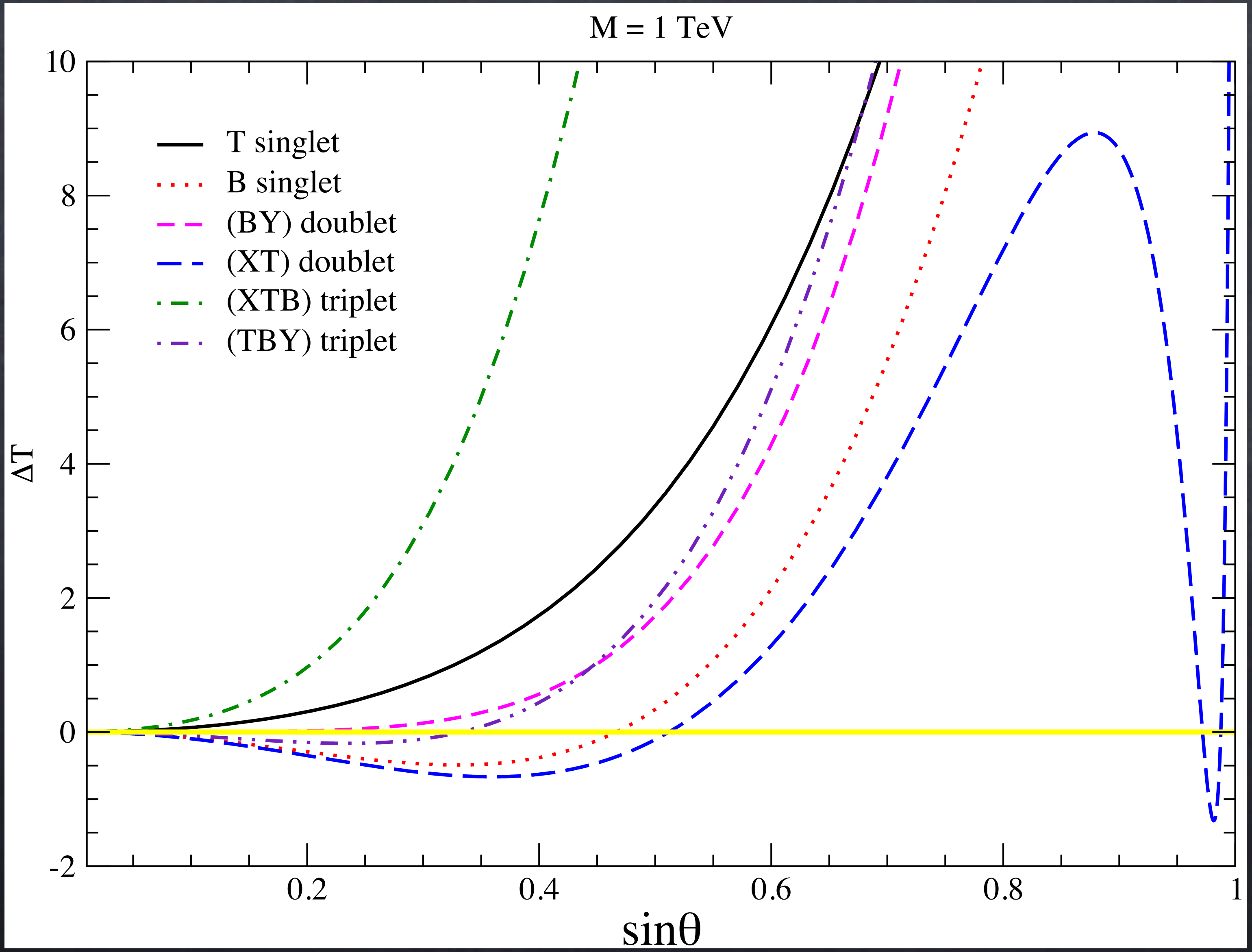






ELECTROWEAK PRECISION TESTS

- In general, only very small mixings are allowed (remember that for example $\Delta T \sim 0.1$)



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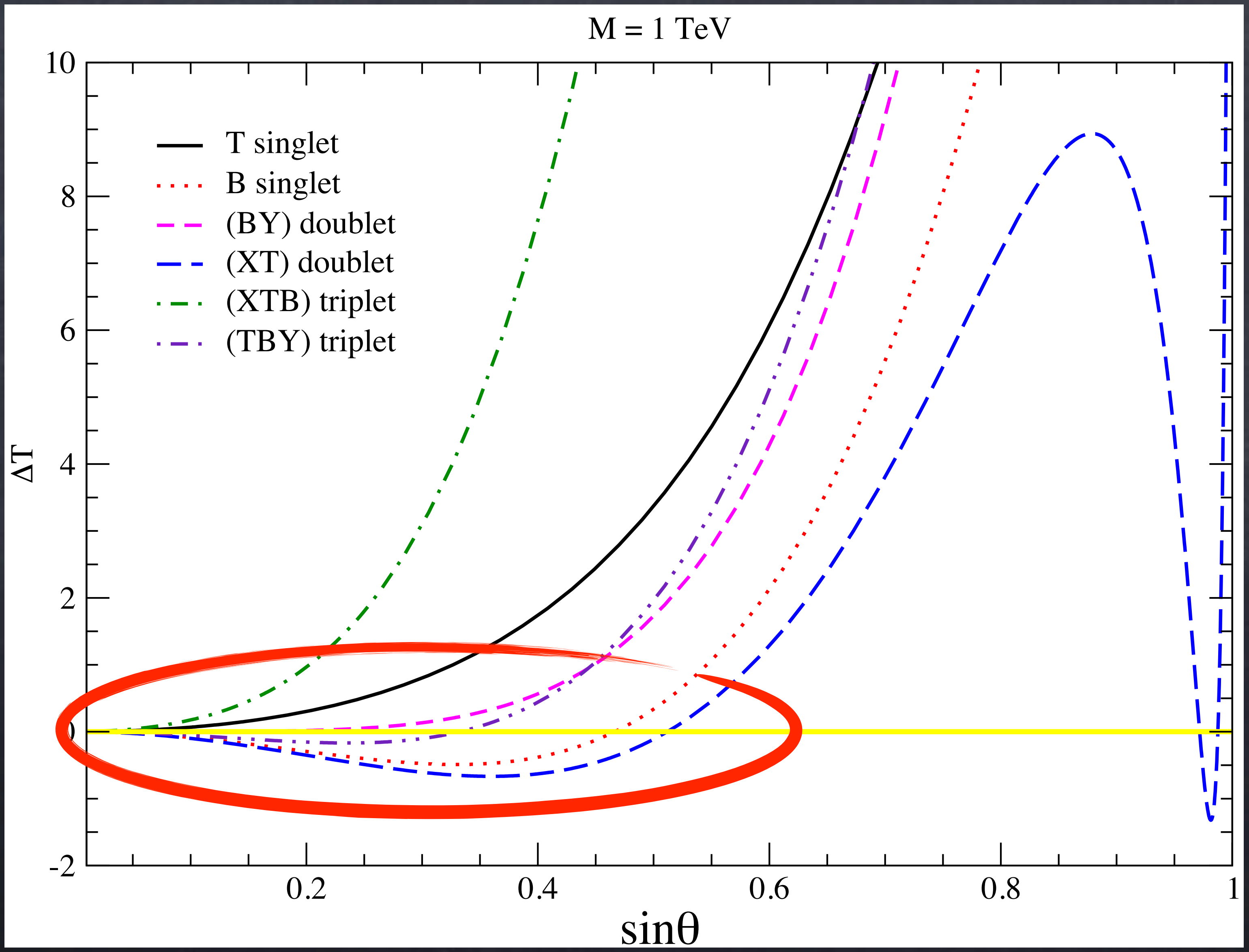

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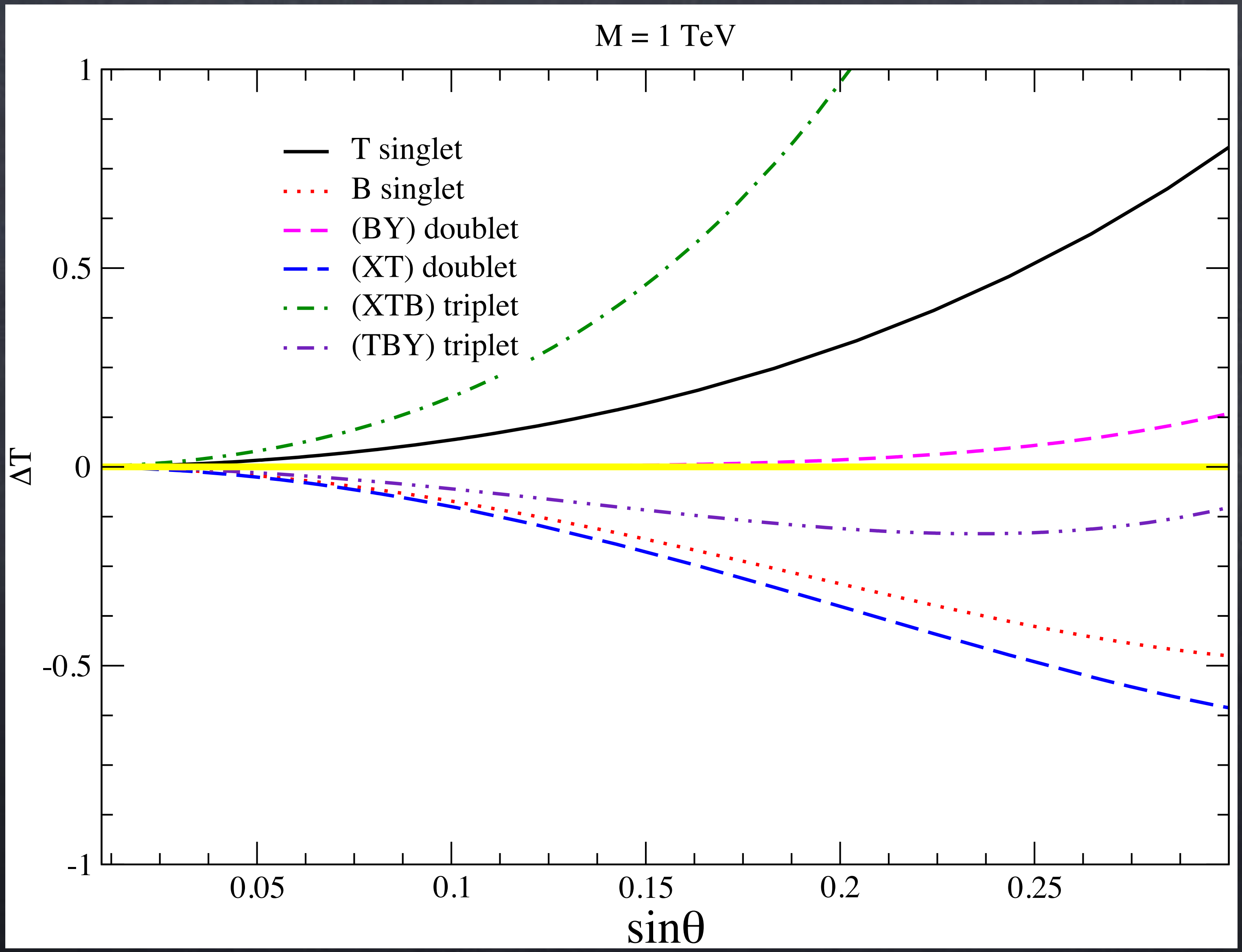

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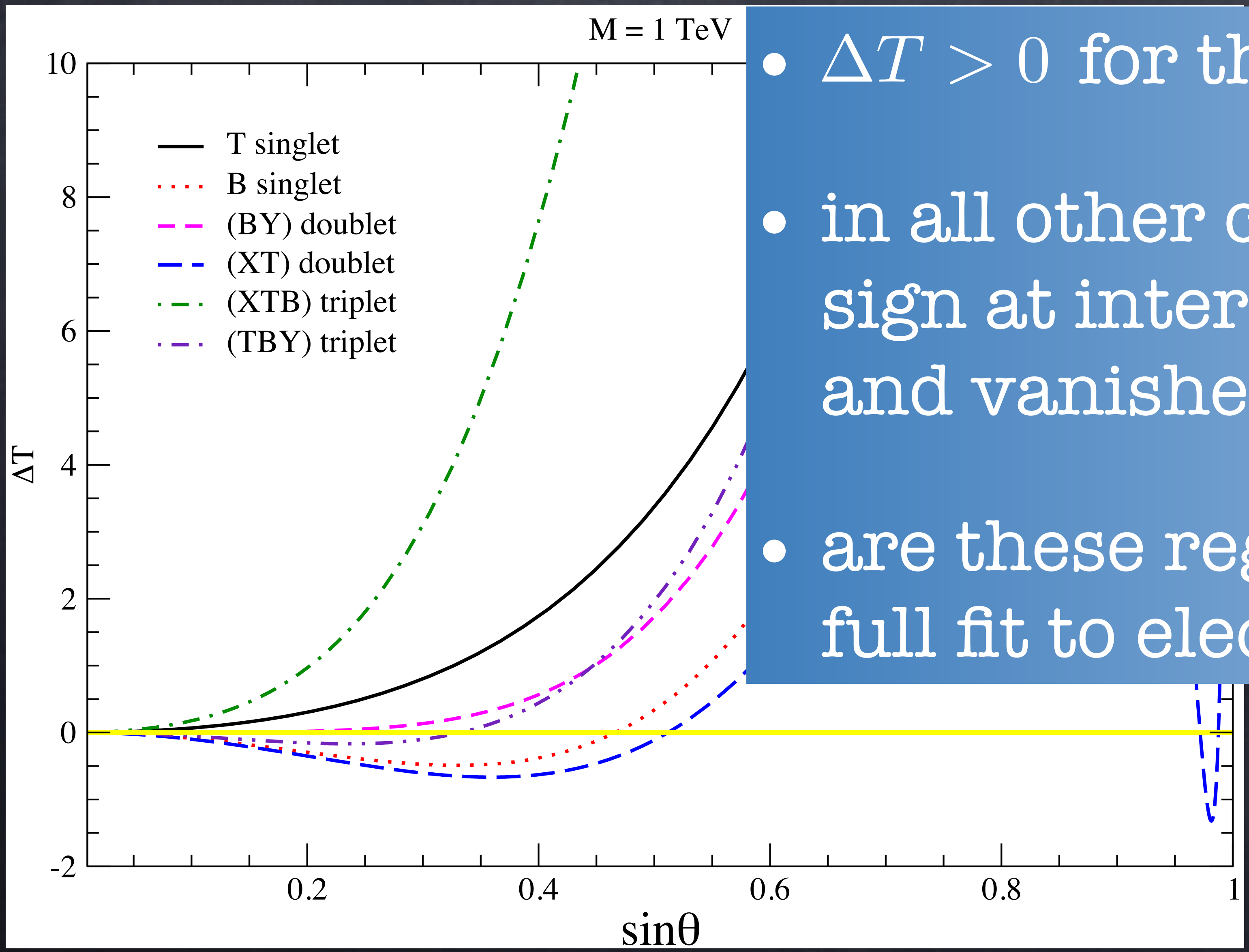


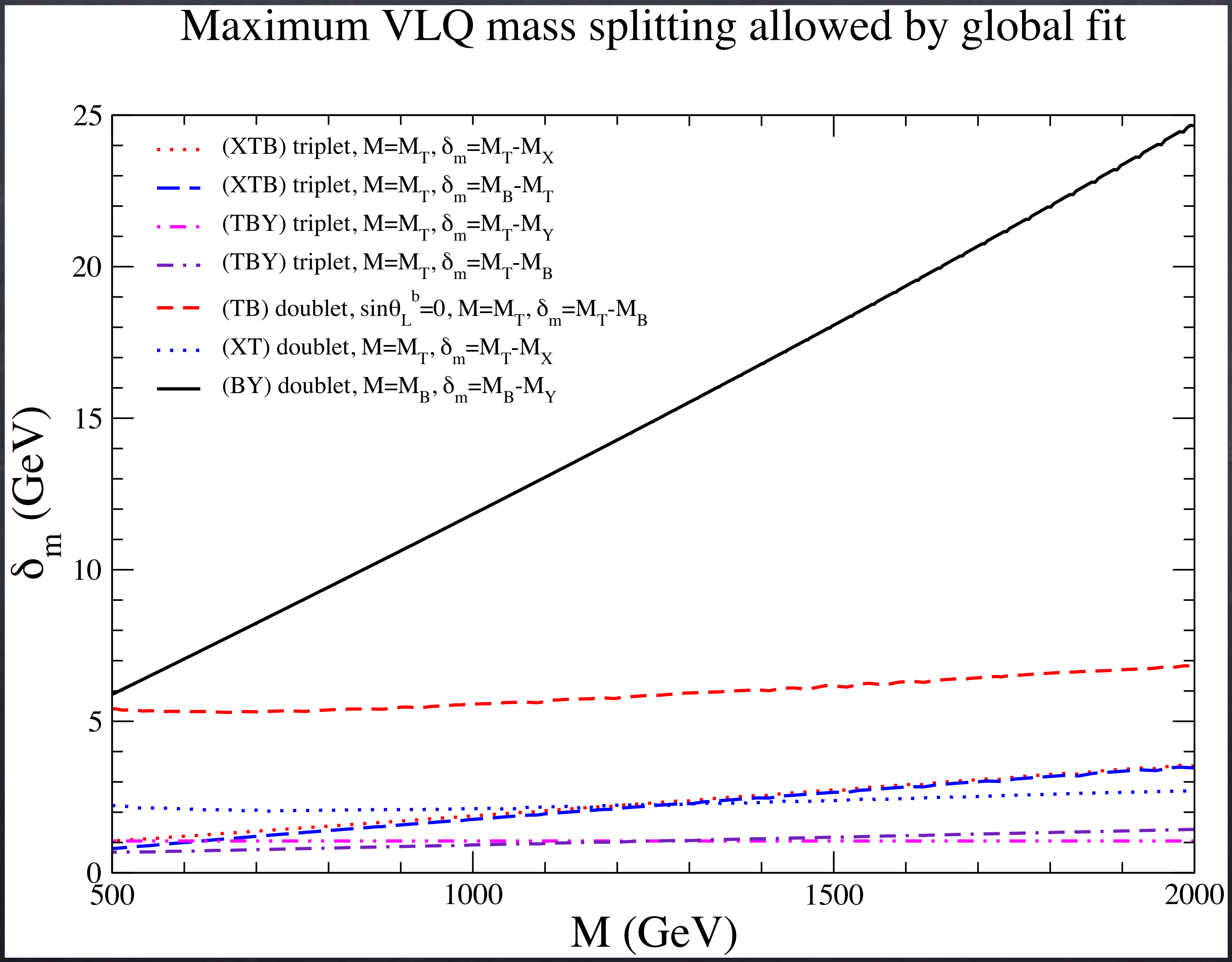
- $\Delta T > 0$ for the *T* and (*XTB*) models
- in all other cases, ΔT changes sign at intermediate values of θ and vanishes again
- are these regions allowed from the full fit to electroweak data?

ELECTROWEAK FIT

- Add constraints on the S parameter and the $Zb\bar{b}$ vertex and perform a 95% C.L. fit

ELECTROWEAK FIT

- The heavy quarks are required to be almost degenerate



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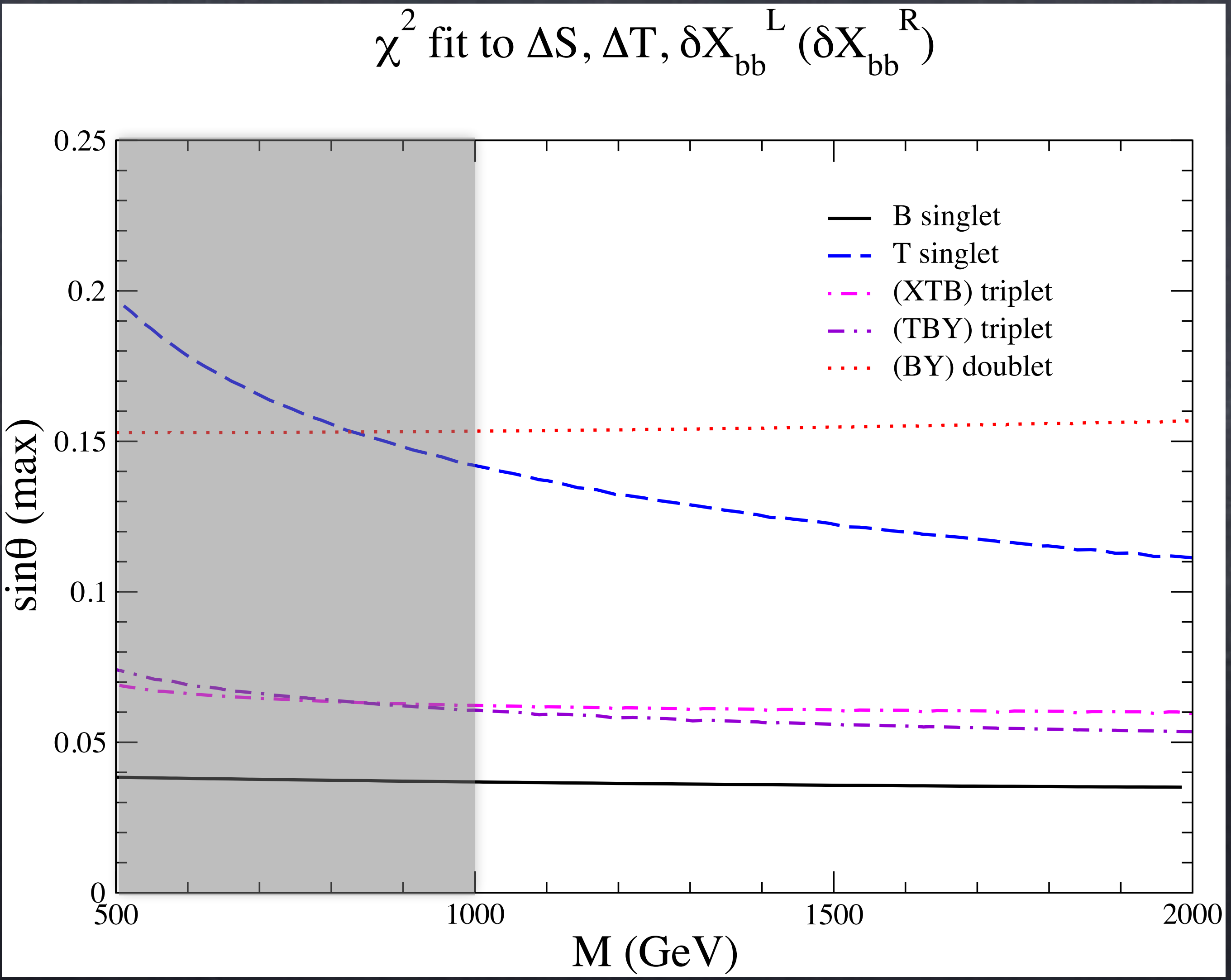

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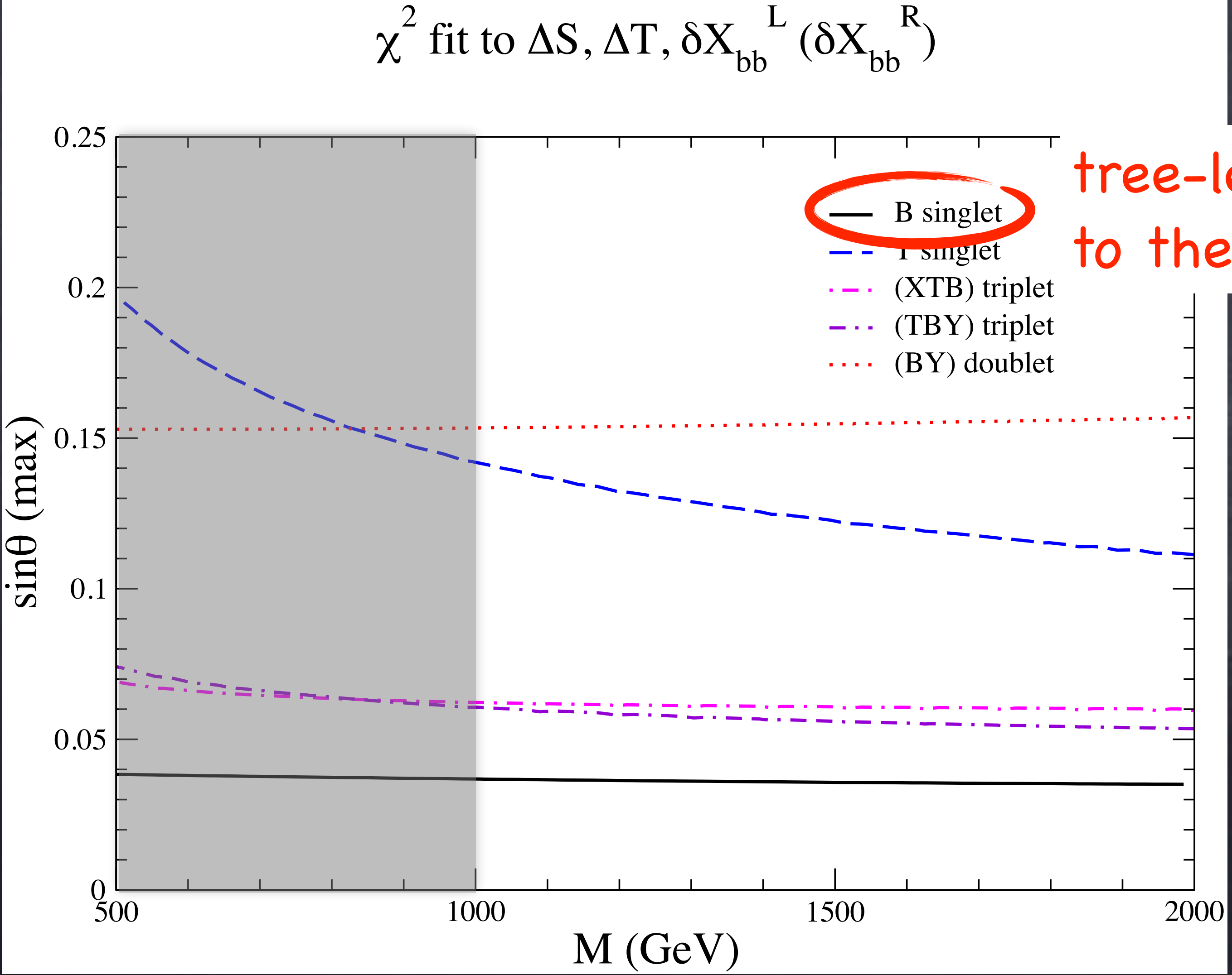

tree-level modifications to the LH *Zbb* coupling

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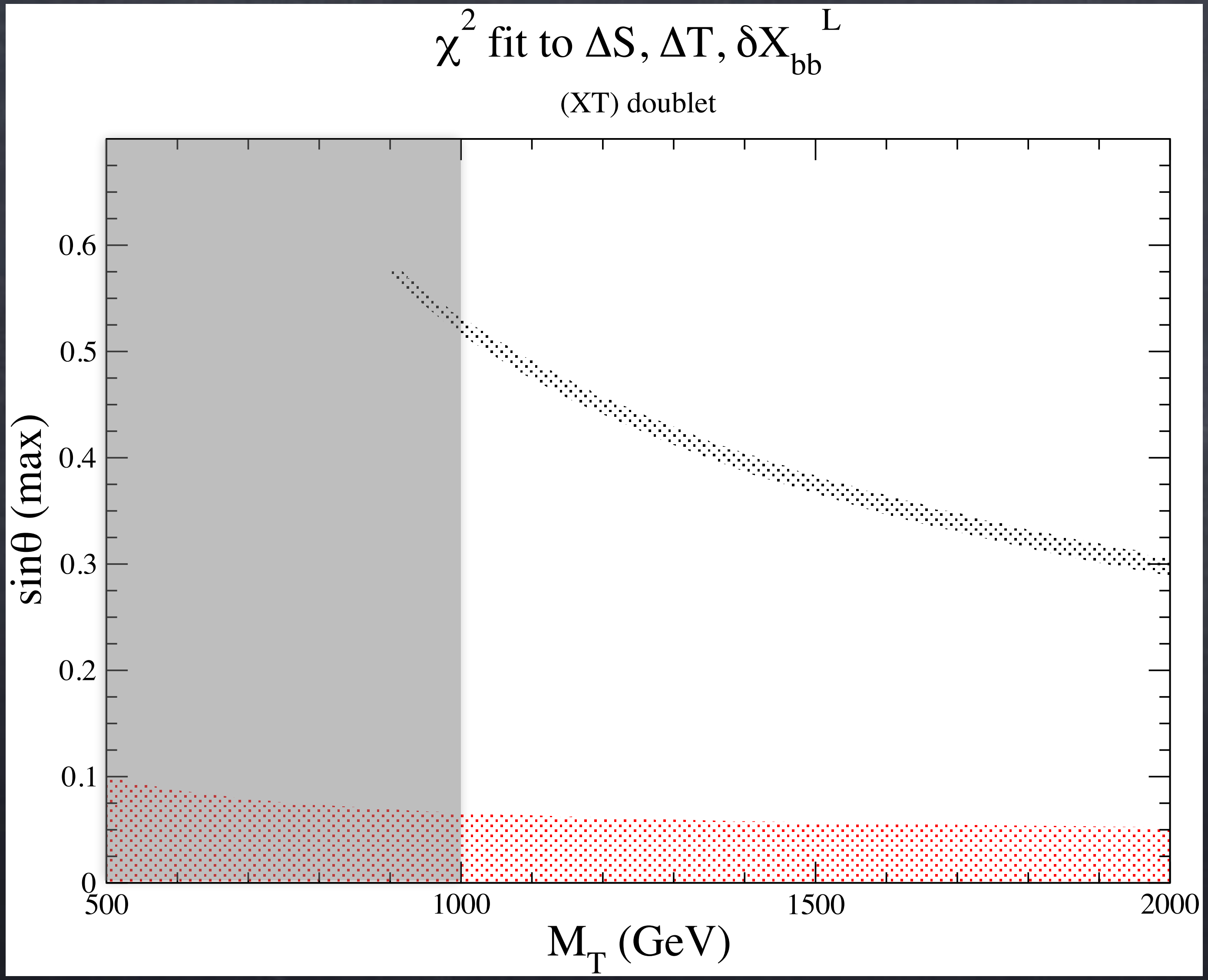

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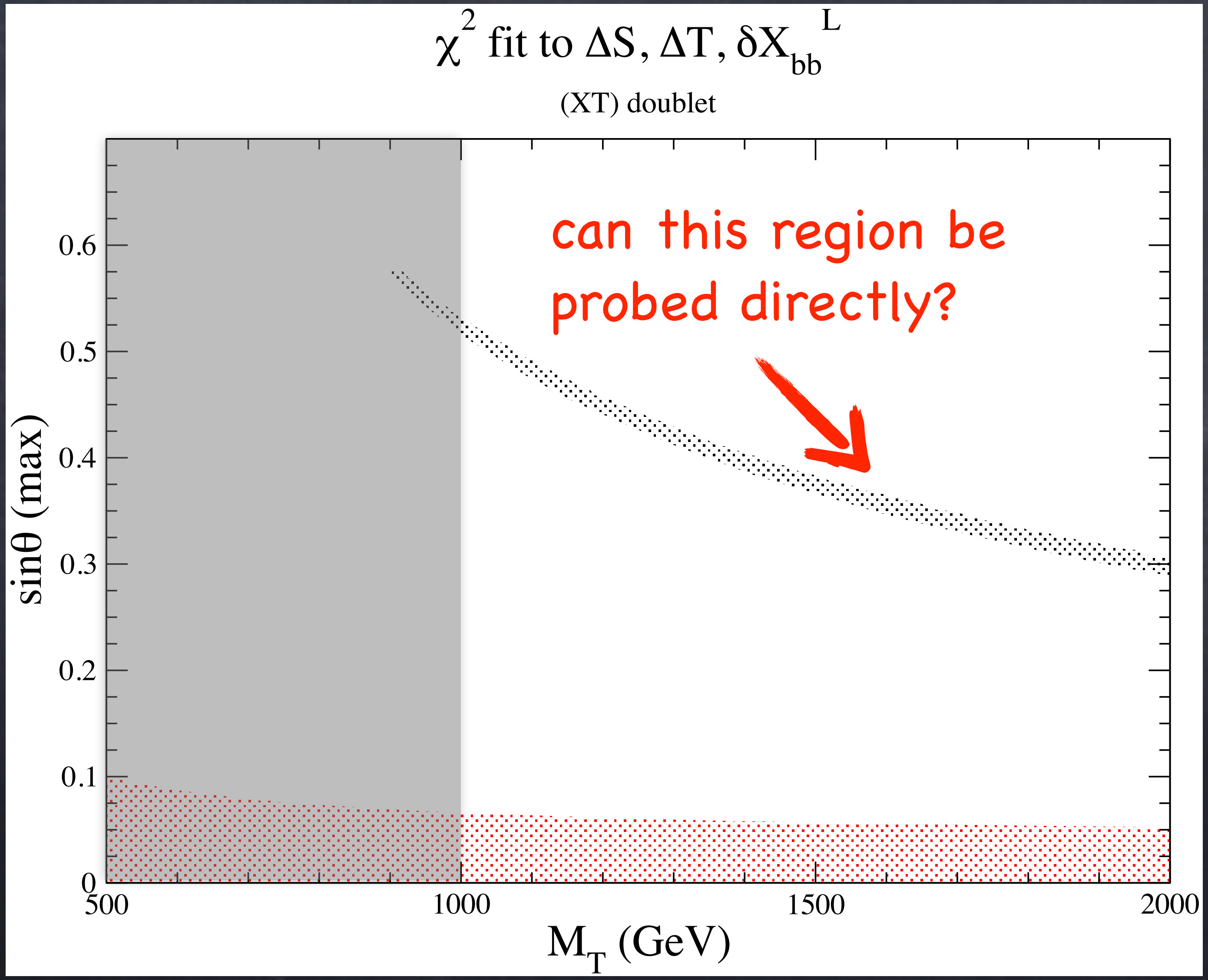

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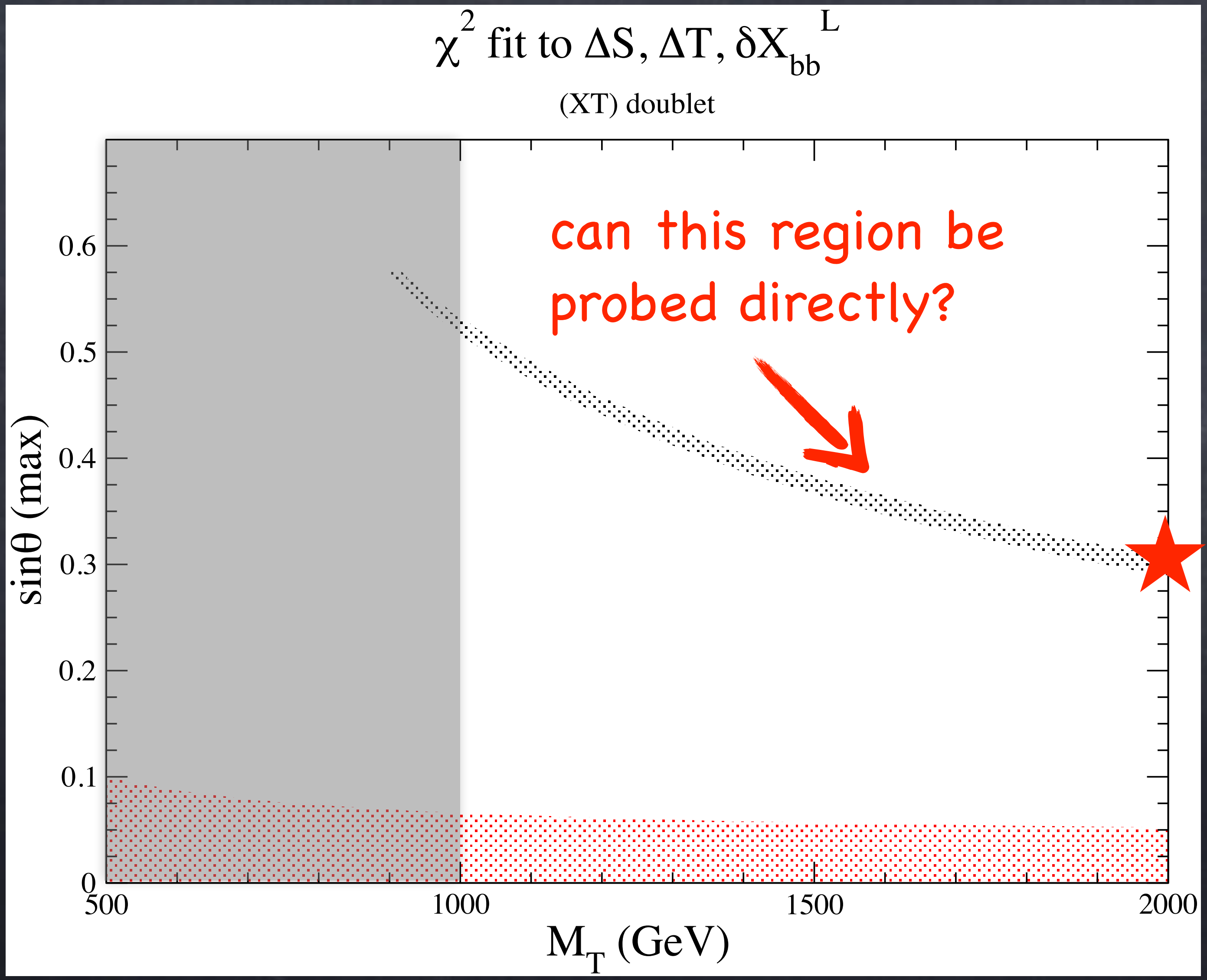
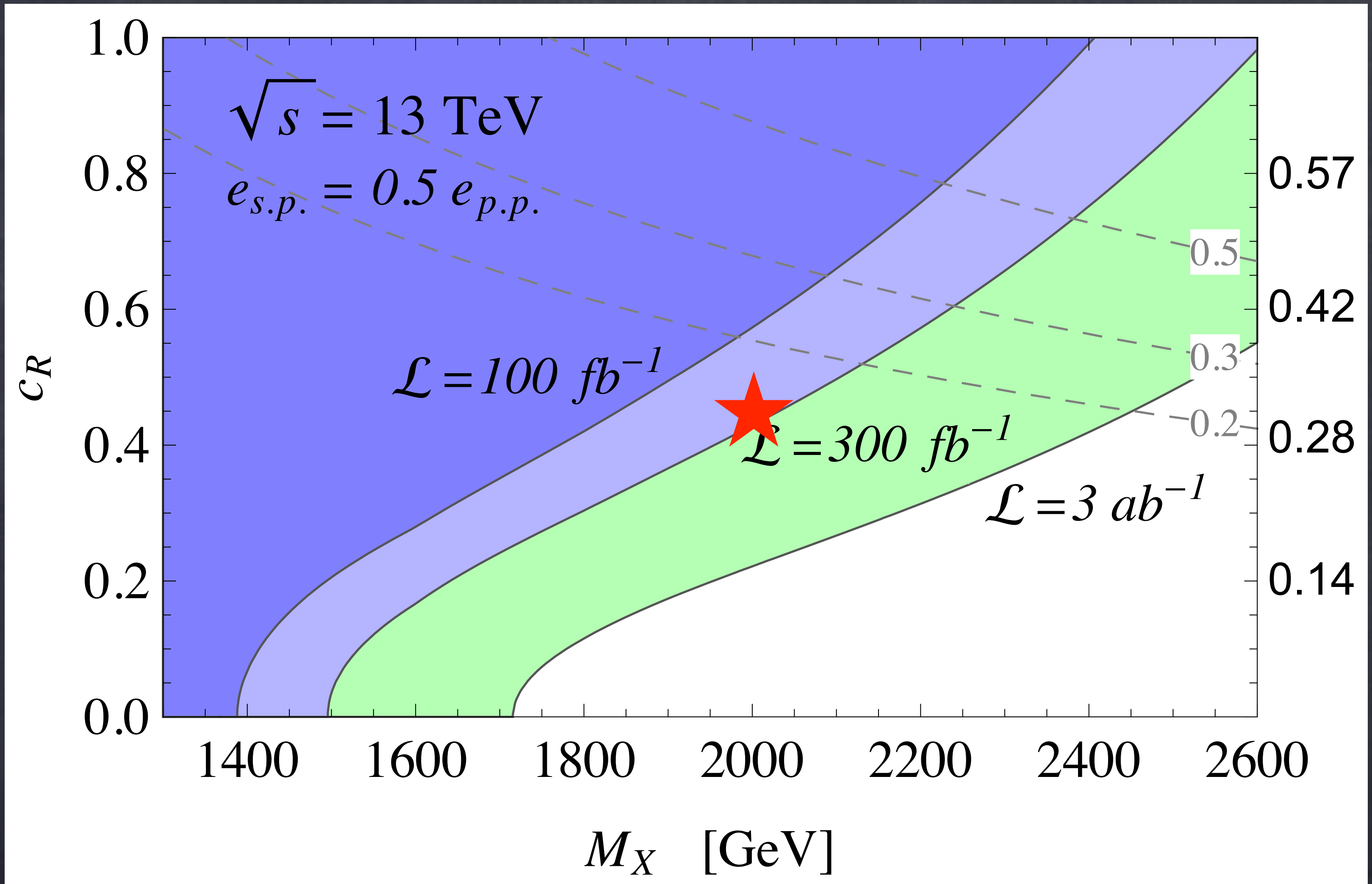


COMPARISON WITH DIRECT SEARCHES



Matsedonskyi et al., JHEP 1412 (2014) 097

➡ probably with $\sim 300 fb^{-1}$

COMPARISON WITH DIRECT

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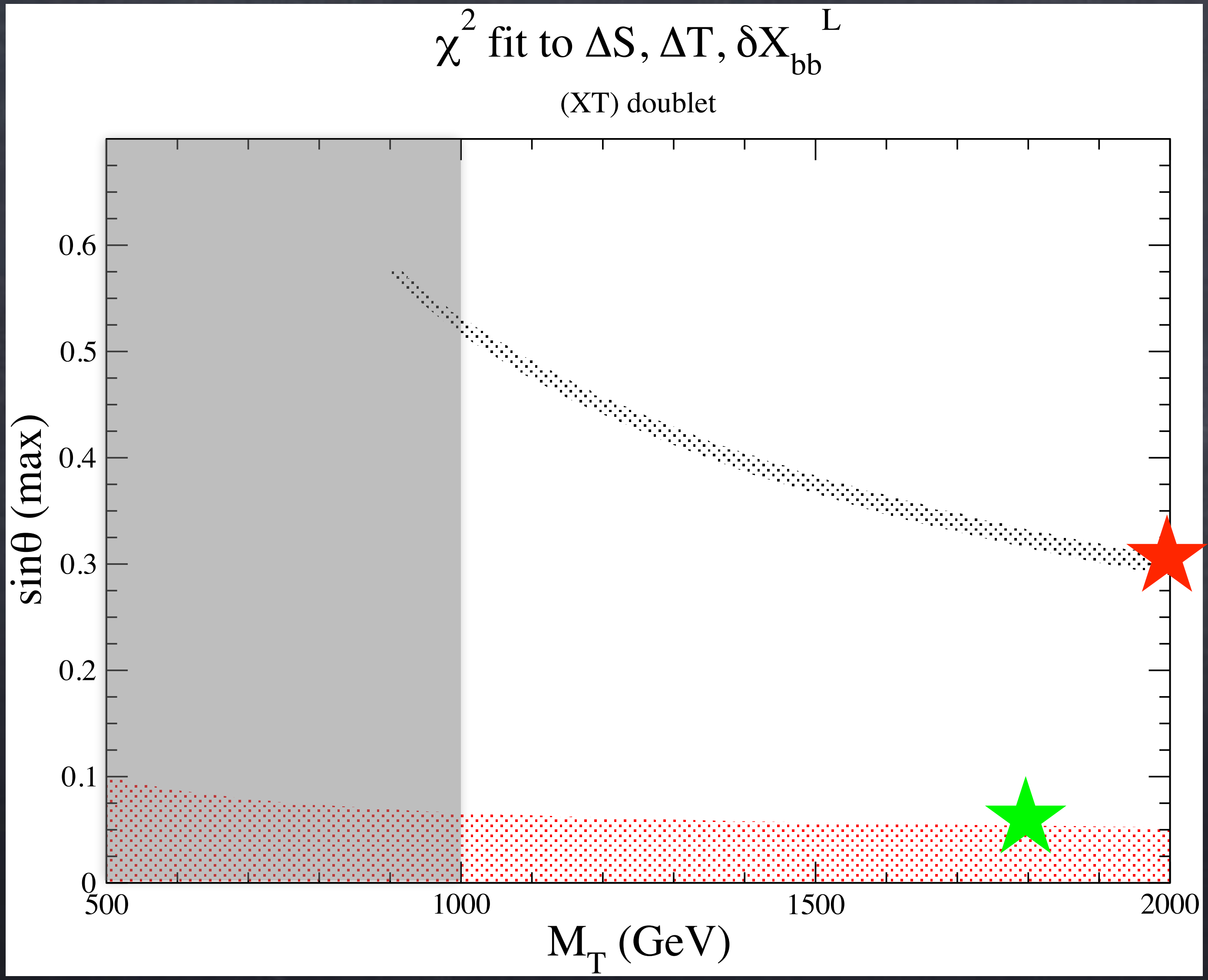

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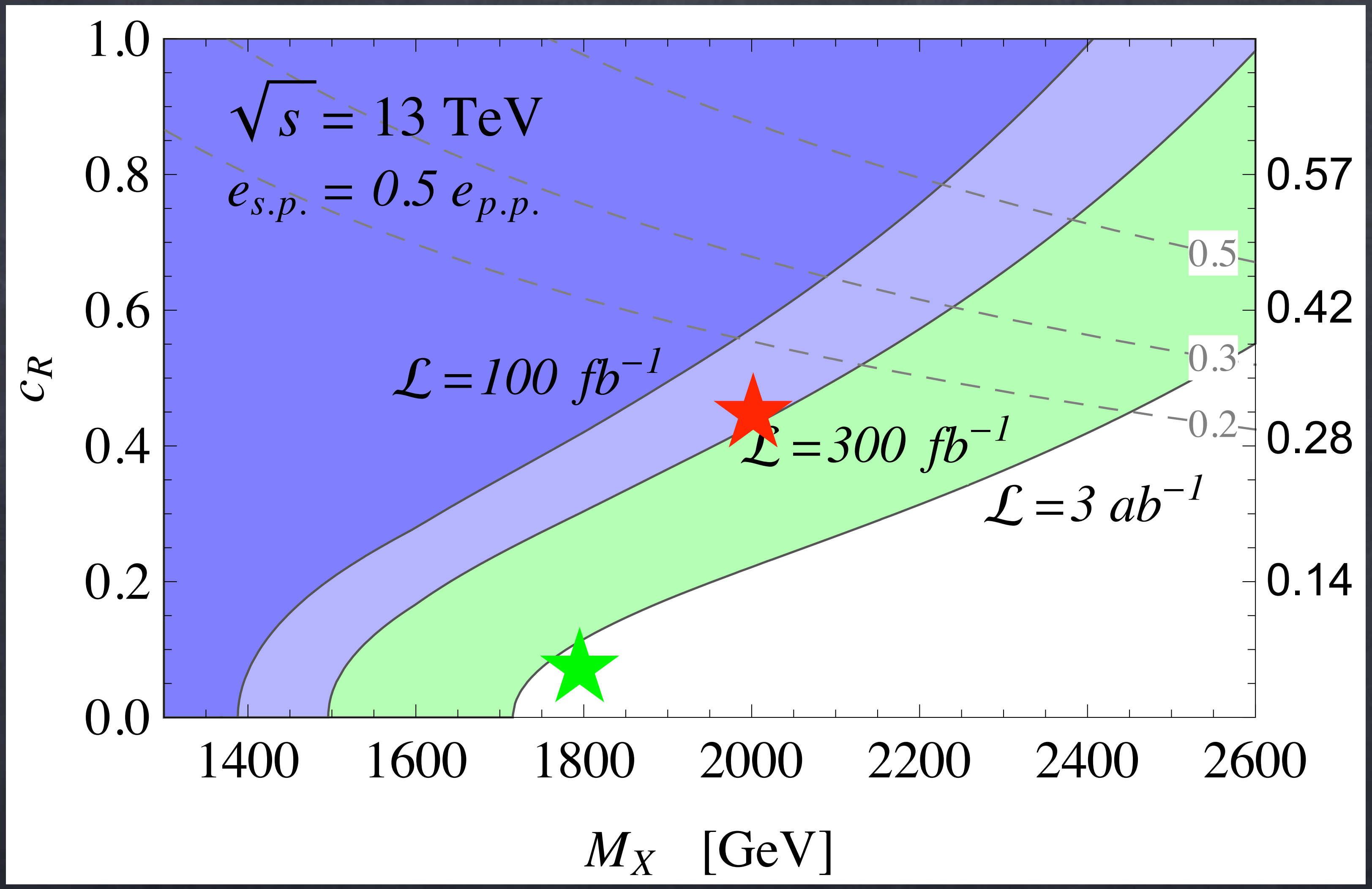
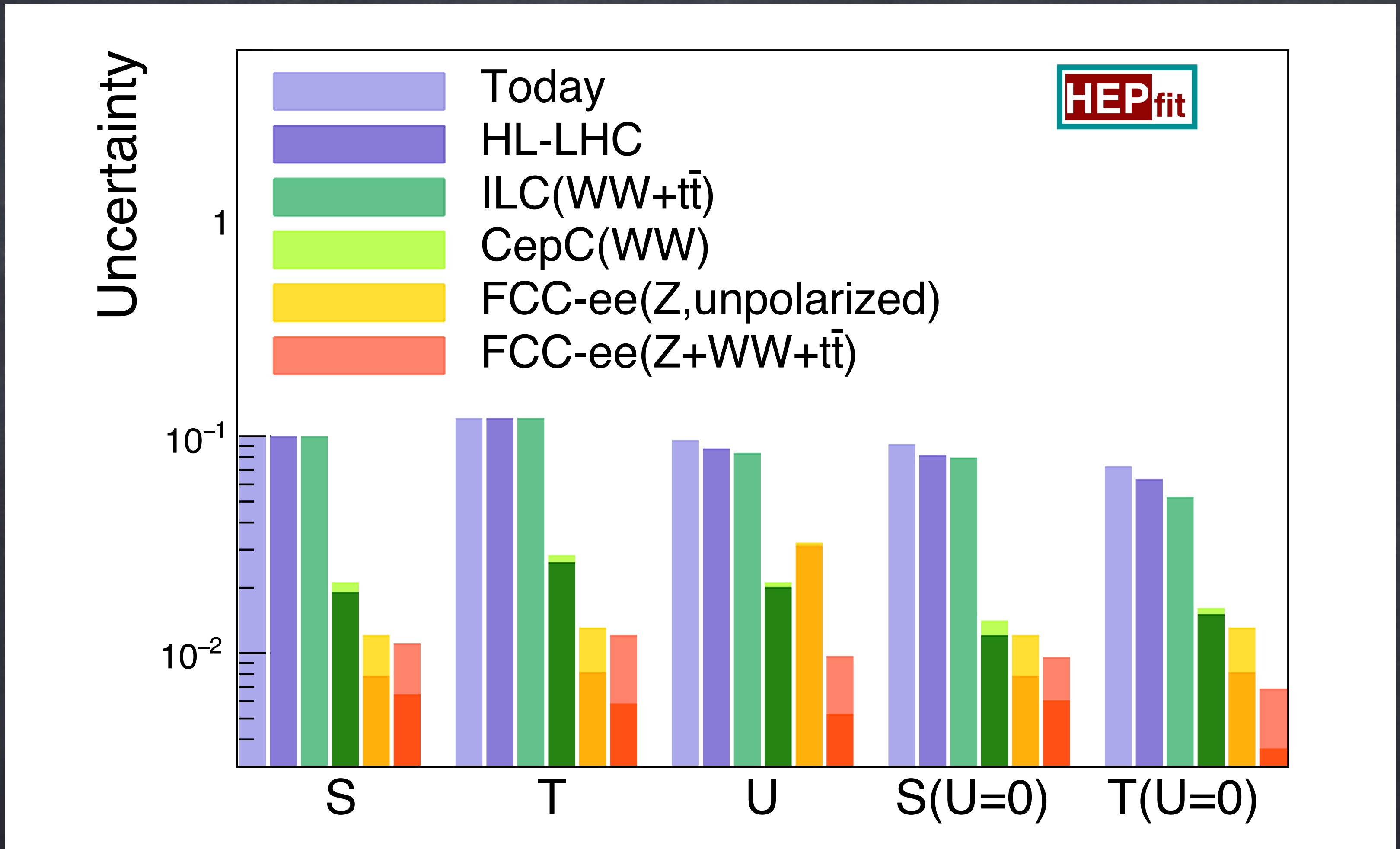


Matsedonskyi et al., JHEP 1412 (2014) 097

➡ only at an 100 TeV collider?

COMPARISON WITH DIRECT SEARCHES

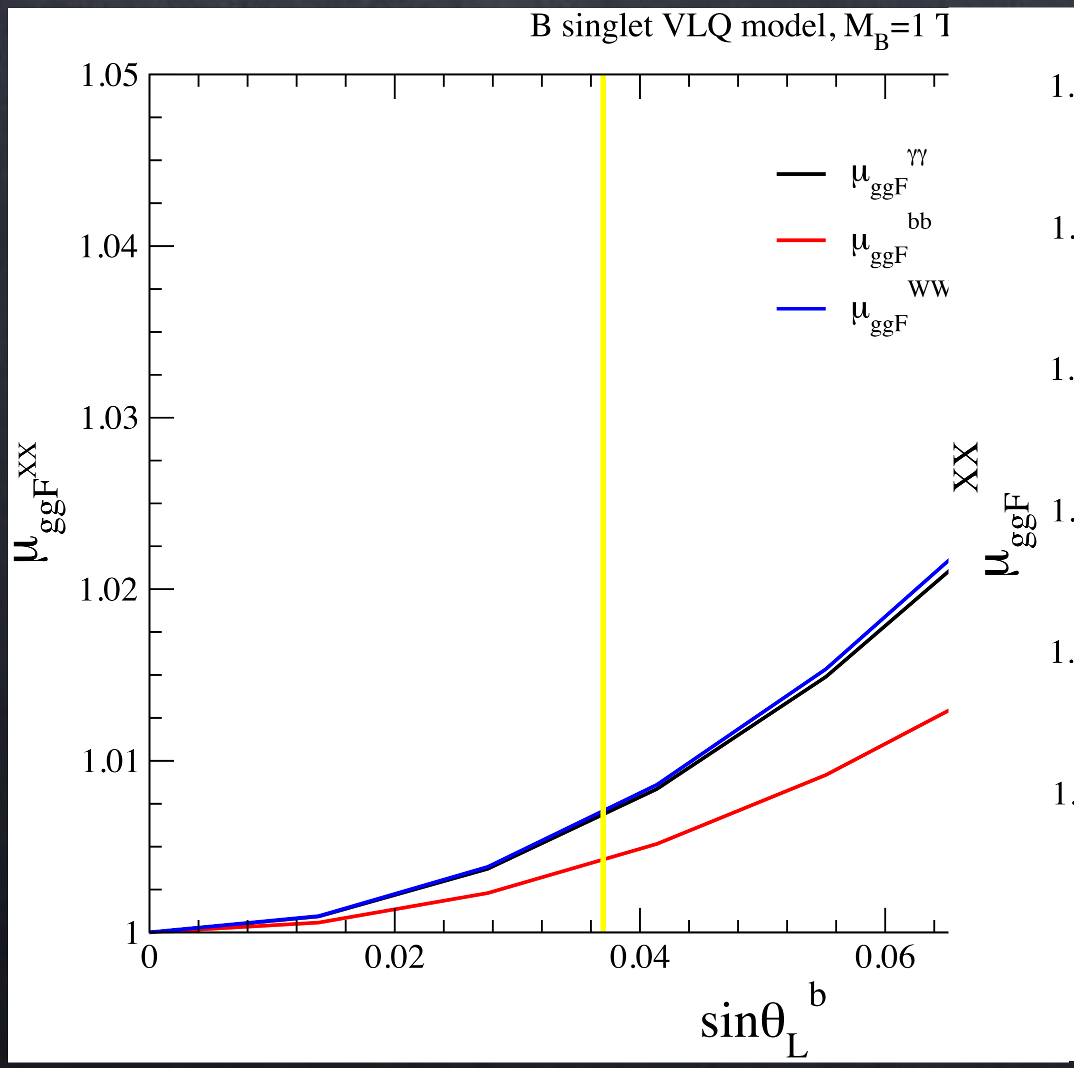


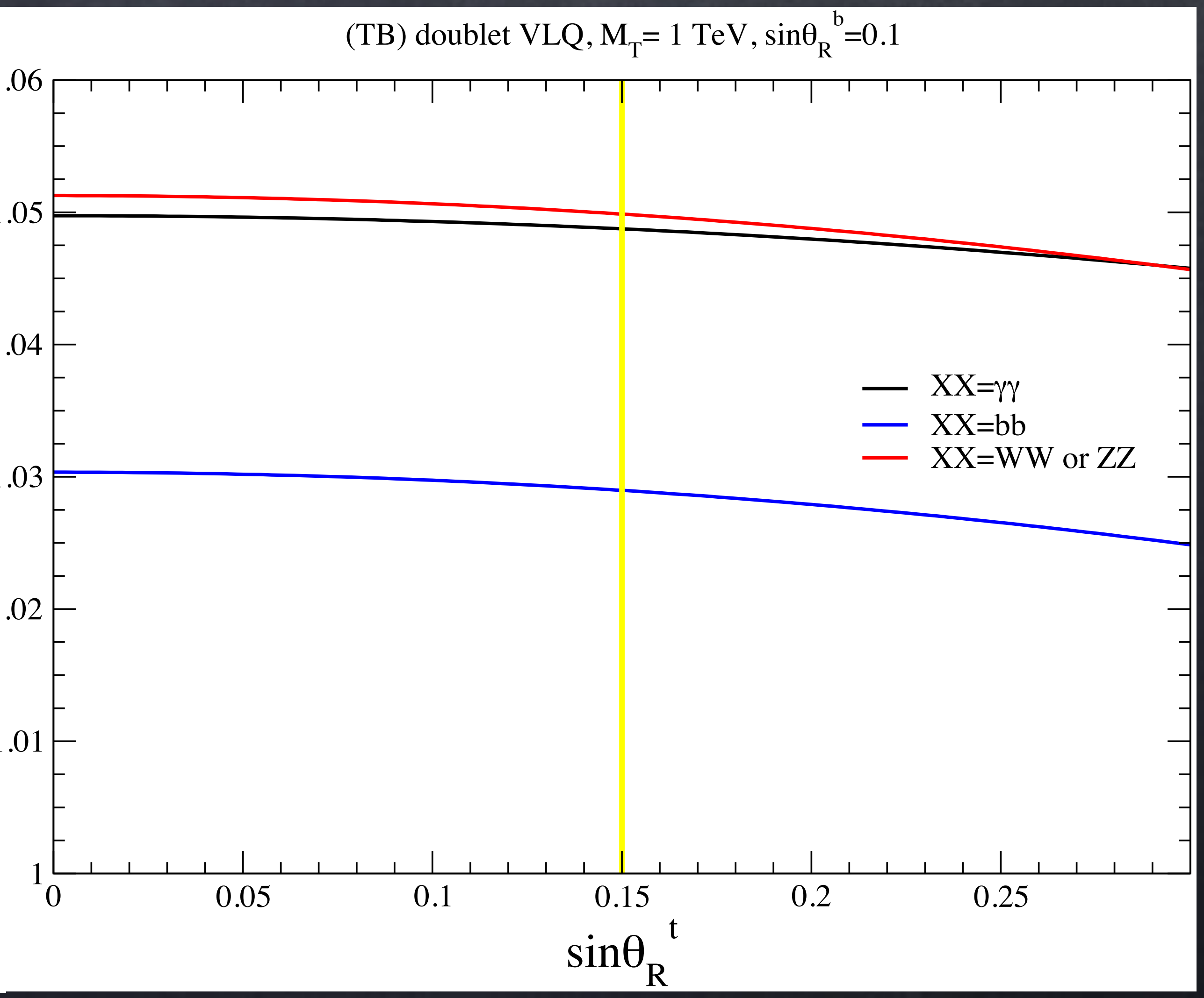
de Blas et al., JHEP 1612 (2016) 135

➡ or with precision observables at lepton colliders?

HIGGS RATES

- Since only small mixings are allowed, the effects on loop-mediated Higgs rates are typically of a few %





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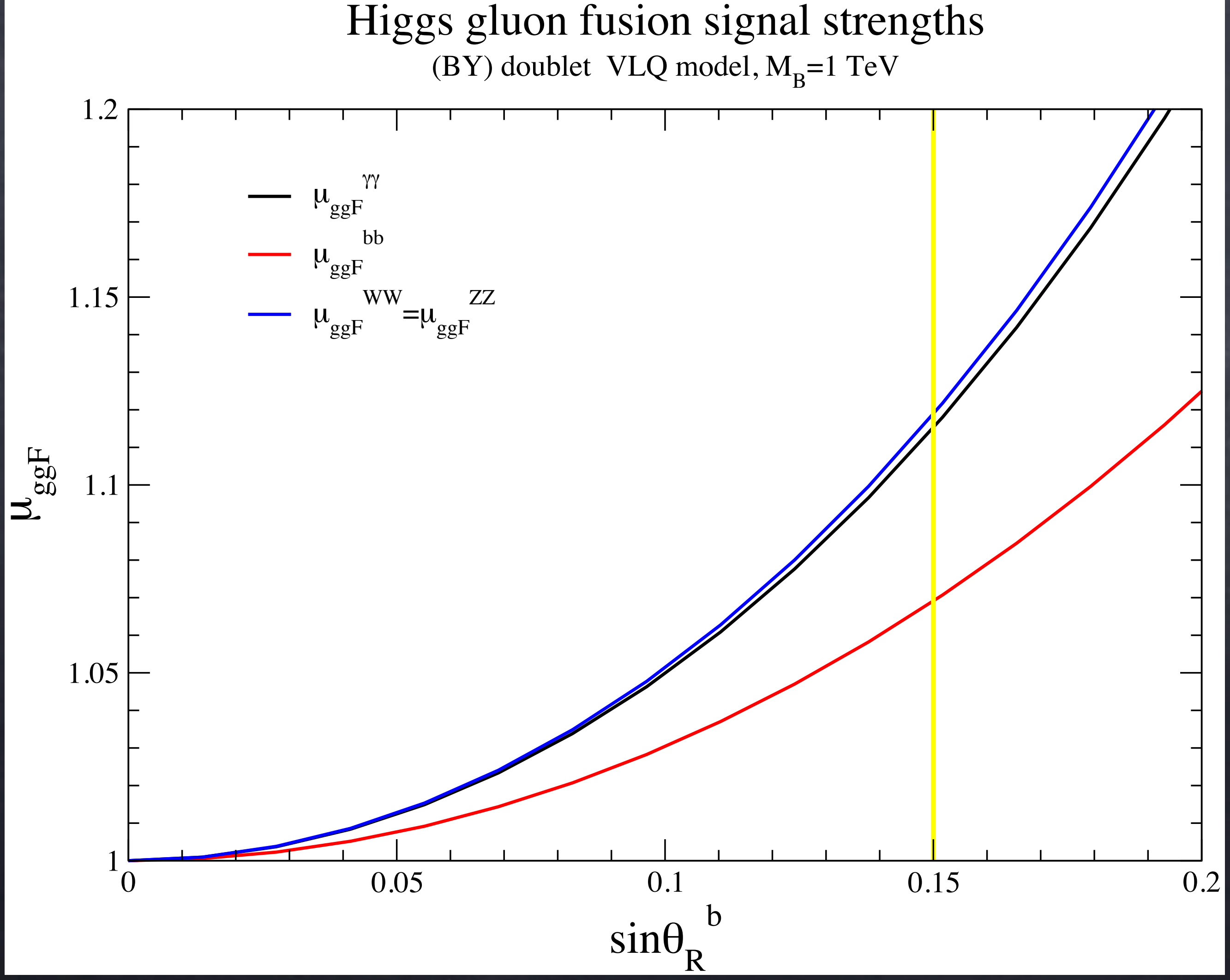

HIGGS RATES

- Since only small mixings are allowed, the effects on loop-mediated Higgs rates are typically of a few %
  - ➡ at the boundary of being probed with very precise inclusive Higgs measures

CONCLUSIONS

- Direct searches and indirect constraints from electroweak precision data can play a complementary role in probing new (vector-like) quarks
- the phase space of these models is unlikely to be probed thoroughly by direct production at the LHC; both a lepton collider or a hadron collider with an higher center of mass energy can be useful

CONCLUSIONS

- Higgs phenomenology is affected at most at a 10% level, requiring the determination of the loop-mediated Higgs rates with a precision of a few %