The Flavor Changing Neutral Higgs Boson Meets Top and Tau at Hadron Colliders

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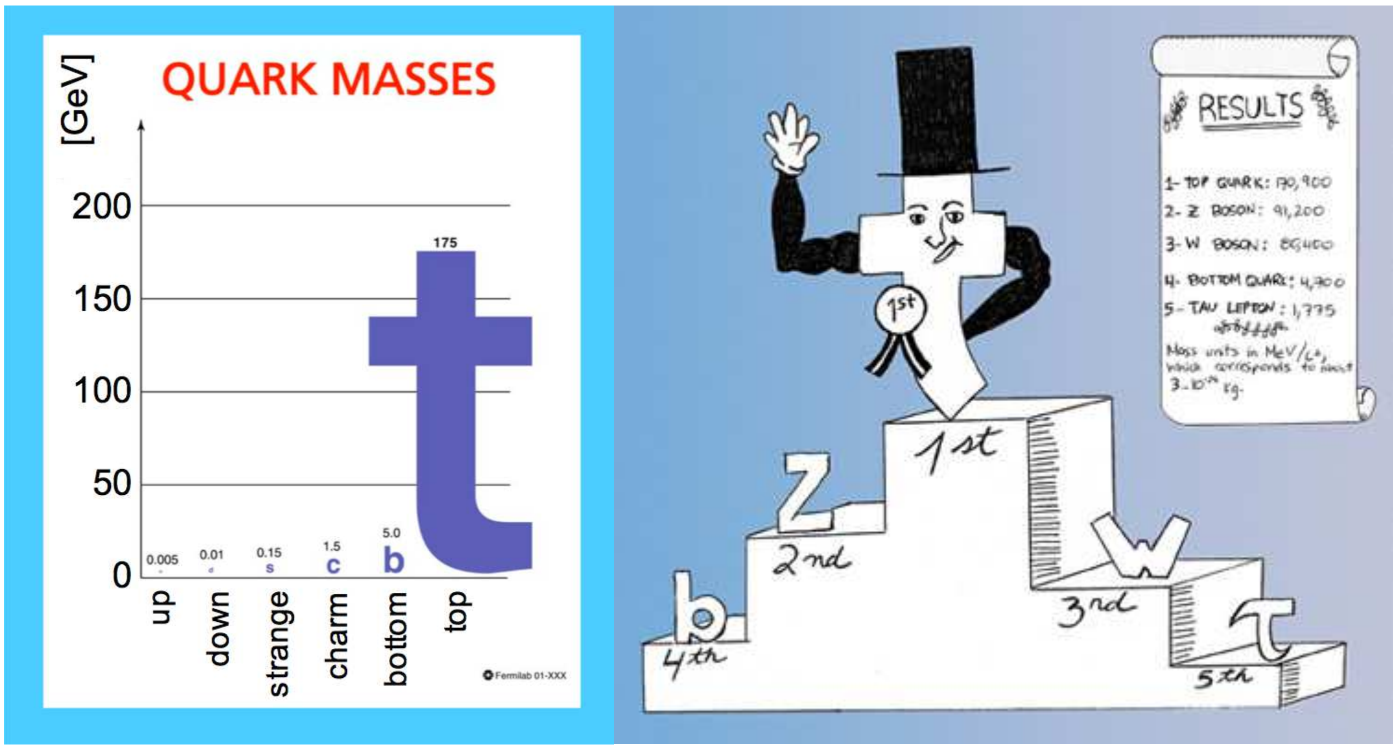
Flavor Changing Top Decays

- In the Standard Model, there is no tree level flavor changing neutral current (FCNC) mediated by the gauge bosons or the Higgs boson.
- At the one loop level, the branching fraction of t to c h^0 is 3×10^{-15} for $M_h = 125$ GeV.

Aguilar-Saavedra (2004)
Mele, Petrarca, and Soddu (1998)
Eilam, Hewett, and Soni (1990)

Heavy Weight Champion



A Special Higgs Model for the Top Quark

A special two Higgs doublet model for the top quark explains why the top quark is the most massive elementary fermion by suggesting that it is the only fermion that couples to a Higgs doublet (ϕ_2) with a much larger VEV ($v_2 >> v_1$).

$$\mathcal{L}_Y = \sum_{m,n=1}^{3} \bar{L}_L^m \phi_1 E_{mn} l_R^n + \sum_{m,n=1}^{3} \bar{Q}_L^m \phi_1 F_{mn} d_R^n + \sum_{n=1}^{2} \sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_1 G_{mn} u_R^n + \sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_2 G_{mn} u_R^3 + \text{H.c.}$$

Das and Kao. PLB (1996)

A Special Higgs Model for the Top Quark

- This model leads to CP violation, and flavor changing neutral Higgs (FCNH) interactions.
- Most LHC data are consistent with the Standard Model (SM). FCNH interactions might lead to new physics beyond SM.

Higgs Potential in the Higgs Basis

$$\begin{aligned} V[\Phi_1, \Phi_2] &= \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1 - \frac{v^2}{2})^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+\lambda_3(\Phi_1^\dagger\Phi_1 - \frac{v^2}{2})\Phi_2^\dagger\Phi_2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+\lambda_5(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 - \frac{v^2}{2})(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) \\ &+(\lambda_6\Phi_1^\dagger\Phi_2 + \lambda_6^*\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1 - \Phi_2^\dagger\Phi_2 - \frac{v^2}{2}) \\ &+\frac{1}{2}\lambda_7(\Phi_1^\dagger\Phi_2)^2 + \frac{1}{2}\lambda_7^*(\Phi_2^\dagger\Phi_1)^2 + \rho(\Phi_2^\dagger\Phi_2)\,. \end{aligned}$$

$$\tan\beta = \frac{\lambda_1 - \lambda_2}{\lambda_5} + \sqrt{1 + \frac{(\lambda_1 - \lambda_2)^2}{\lambda_5^2}}\,.$$

A General Two Higgs Doublet Model

$$\mathcal{L} = \frac{-1}{\sqrt{2}} \sum_{F=U,\,D,\,E} \bar{F}\Big\{\left[\kappa^F s_{\beta-\alpha} + \rho^F c_{\beta-\alpha}\right] h^0 + \left[\kappa^F c_{\beta-\alpha} - \rho^F s_{\beta-\alpha}\right] H^0 - i\,\mathrm{sgn}(Q_F)\rho^F A^0\Big\} RF - \bar{U}\left[V\rho^D R - \rho^{U\dagger} V L\right] D H^+ - \bar{\nu}\left[\rho^E R\right] E H^+ + \mathrm{H.c.}$$

- κ matrices: diagonal, fixed by fermion mass
- ρ matrices: off diagonal elements lead to FCNH couplings

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When the Higgs meets the Top

When the mass giver (Higgs boson) meets the most massive particle (top quark), they might lead to complementary new physics.

(a) $t \to ch^0 \quad \lambda_{tch} = \rho_{tc} \cos(\beta - \alpha)$

(b) $H^0, A^0 \to t\bar{c} + \bar{t}c \quad \lambda_{Htc} = \rho_{tc} \sin(\beta - \alpha)$

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Top Decay Width

FCNH

$$\Gamma(t \to ch^0) = \frac{|\lambda_{tc}|^2}{16\pi} \times (m_t) \times \left[(1+\rho_c)^2 - \rho_h^2\right] \times \sqrt{1-(\rho_h+\rho_c)^2}\sqrt{1-(\rho_h-\rho_c)^2}\,,$$

$$\rho_c = m_c/m_t$$
$$\rho_h = M_h/m_t$$

Total

$$\Gamma_t = \Gamma(t \to bW) + \Gamma(t \to ch^0)\,.$$

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Hou (1991)

Constraints on FCNH Couplings

- Recent ATLAS data have placed tight constraints on λ_{tc} and λ_{ct} with $t \to ch^0 \to c\tau^+\tau^-$:
  - the top decay should have $\mathcal{B}(t \to ch^0) < 0.0011$,
  - or $\sqrt{\lambda_{tc}^2 + \lambda_{ct}^2} < 0.064$, with $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$.
- If we choose ρ-matrix to be Hermitian, then $b \to s\gamma$ and $B - \bar{B}$ mixing imply $|\rho_{ct}| < 0.1$.
- If the ρ-matrix is not Hermitian, then we must have $|\rho_{ct}| < 0.1$, while $|\rho_{tc}|$ can be close to 1.

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Discovery Potential of $t \to ch^0 \to \tau^+\tau^-$

- The discovery channel has relatively low background.
- We have studied the final states of (i) a pair of leptons and (ii) a lepton plus a tau jet.
- Collinear approximation offers the possibility of reconstruction Higgs mass and Top quark mass.
- Requiring momentum fractions of tau decays $0 < x < 1$, effectively removes irreducible background.

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Gutierrez, Jain, and Kao (2020)

Recent Studies of $pp \to t\bar{t} \to tch^0 \to tc\tau^+\tau^- + X$

- X. Chen and L. Xia, Phys. Rev. D **93**, no.11, 113010 (2016).
- M. Aaboud *et al.* [ATLAS], JHEP **05**, 123 (2019).
  ATLAS limit: $\lambda_{tc} < 0.064$.
- We have done parton level, event level, and BDT analysis.
- We have improved the significance by a cut on E_{charm}(top).

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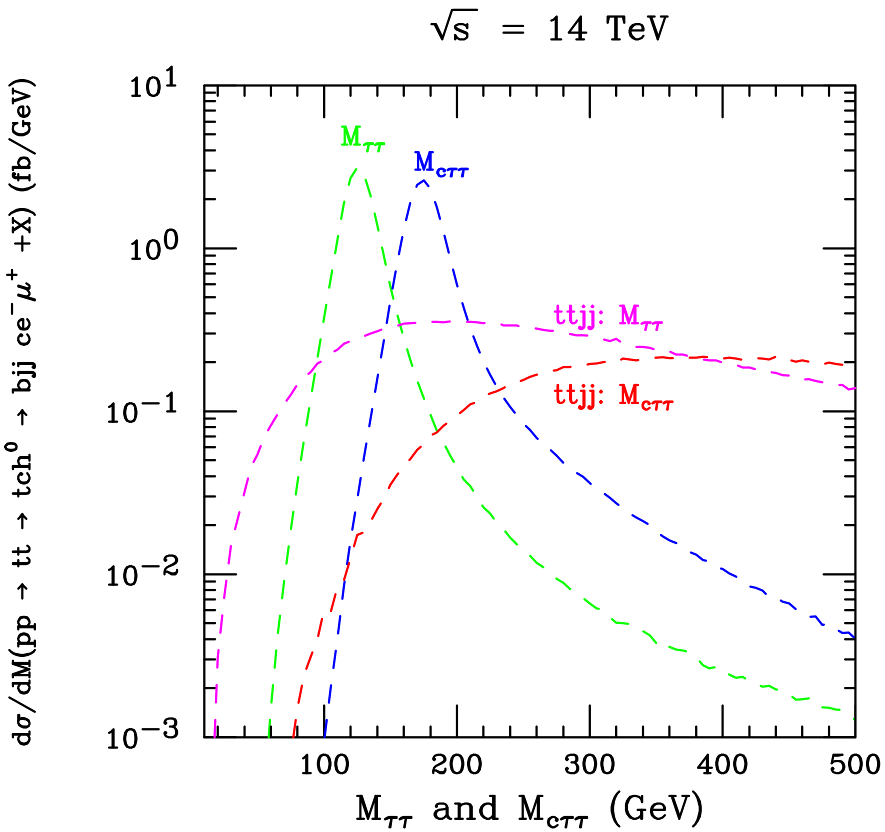
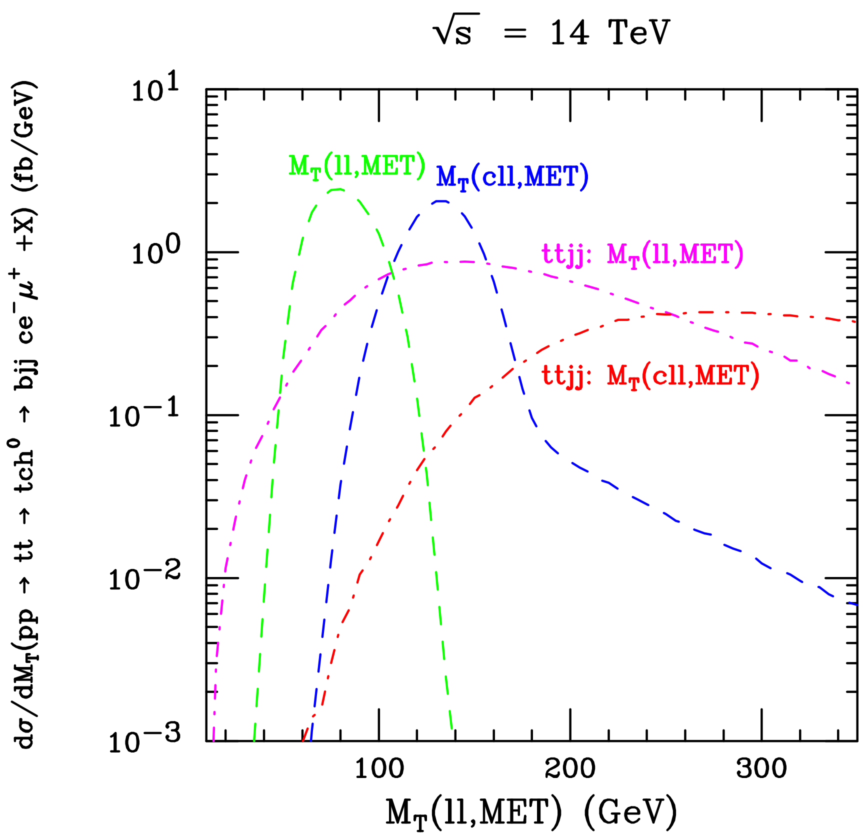
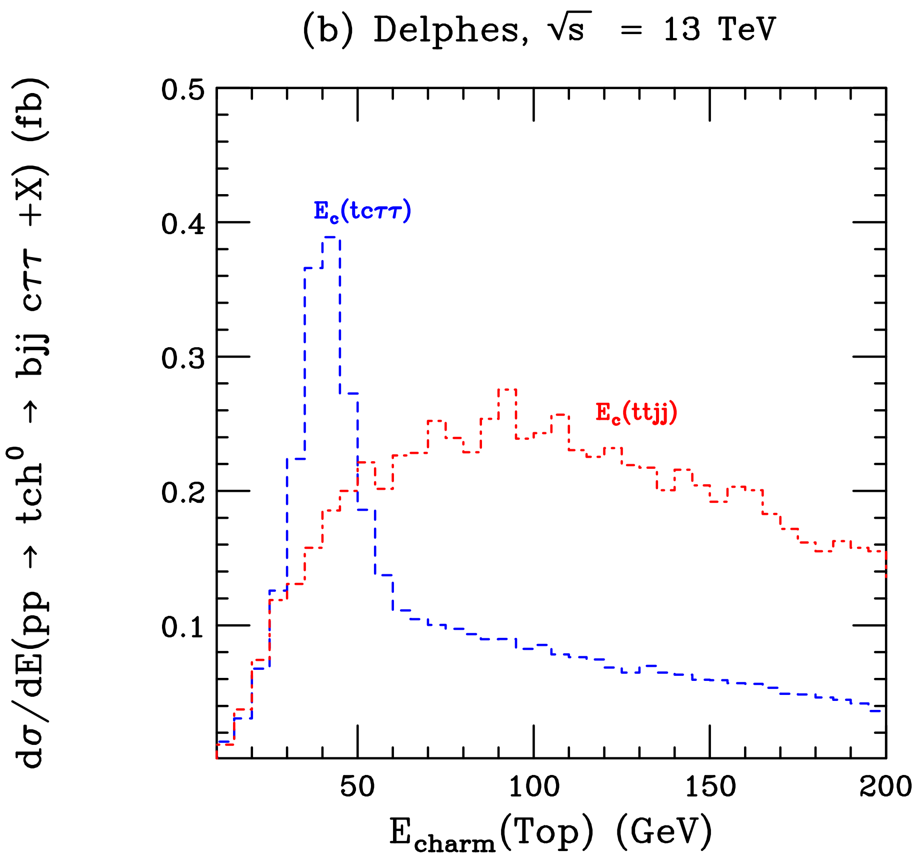
Reconstruction of the Higgs Mass



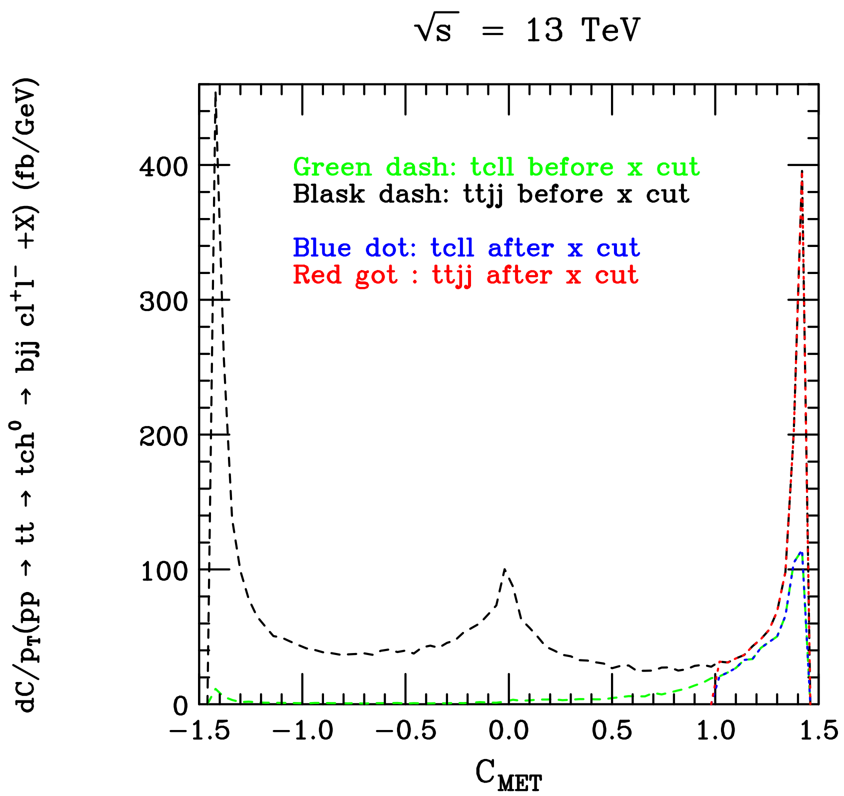
Cluster Transverse Mass



E_{charm} in the Top Frame



Centrality



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Cross section in fb at parton level

$\sqrt{s}$ (TeV)	$\lambda_{tc} = 0.01$	$\lambda_{tc} = 0.064$
13	0.0096	0.39
14	0.012	0.46
27	0.043	1.72

Higgs signal

$\sqrt{s}$ (TeV)	$t\bar{t}jj$	$b\bar{b}jj\tau\tau$	$b\bar{b}jjWW$	$t\bar{t}$W	Total
13	0.96	0.06	4.03×10^{-4}	0.006	1.03
14	1.16	0.07	5.04×10^{-4}	0.008	1.24
27	4.19	0.22	1.84×10^{-3}	0.020	4.43

Background

Statistical Significance

- We evaluate the statistical significance with a simple approximation for Poisson distributions:

$$N_{SS} = \sqrt{2 \times (N_S + N_B) \ln(1 + N_S/N_B) - 2 \times N_S}$$

- For $N_B >> N_S$, it becomes the well known Gaussian significance : $N_{SS} = N_S/\sqrt{N_B}$.

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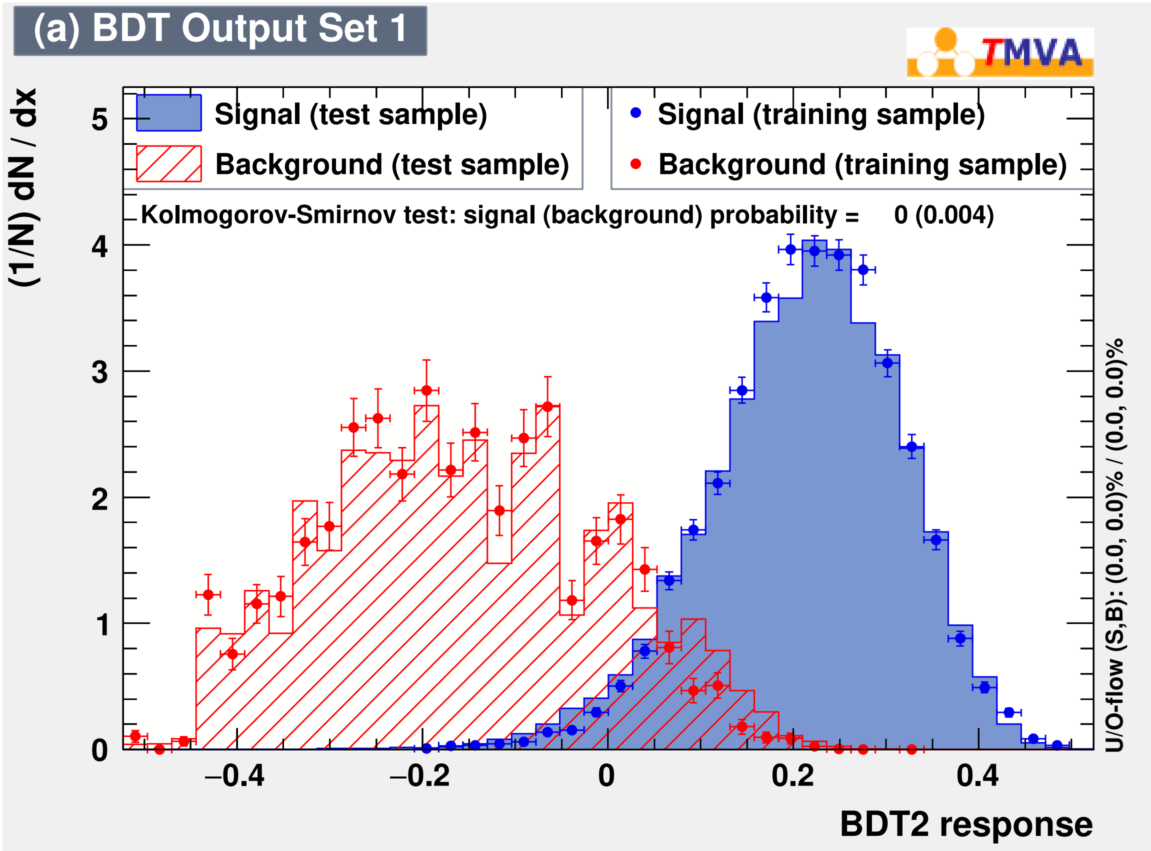
Cowan *et al.* Eur. Phys. J. (2011)

BDT Analysis for $t \to ch^0 \to \tau^+\tau^-$



Discovery Potential of $t \to ch^0 \to c\tau^+\tau^-$ at the LHC and Future Hadron Colliders

$\sqrt{s}$ (TeV)	L (fb^{-1})	$\mathcal{B}(t \to ch^0)$	λ_{tch}
13	139	1.4×10^{-3}	0.073
13	3000	3.0×10^{-4}	0.033
14	3000	2.6×10^{-4}	0.031
27	3000	1.4×10^{-4}	0.023

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Discovery Potential of $t \to ch^0 \to cWW^*$ at the LHC and Future Hadron Colliders

$\sqrt{s}$ (TeV)	$\mathcal{B}(t \to ch^0)$	λ_{tch}
13	1.37×10^{-3}	0.071
14	1.29×10^{-3}	0.069
27	6.2×10^{-4}	0.048
100	2.1×10^{-4}	0.028

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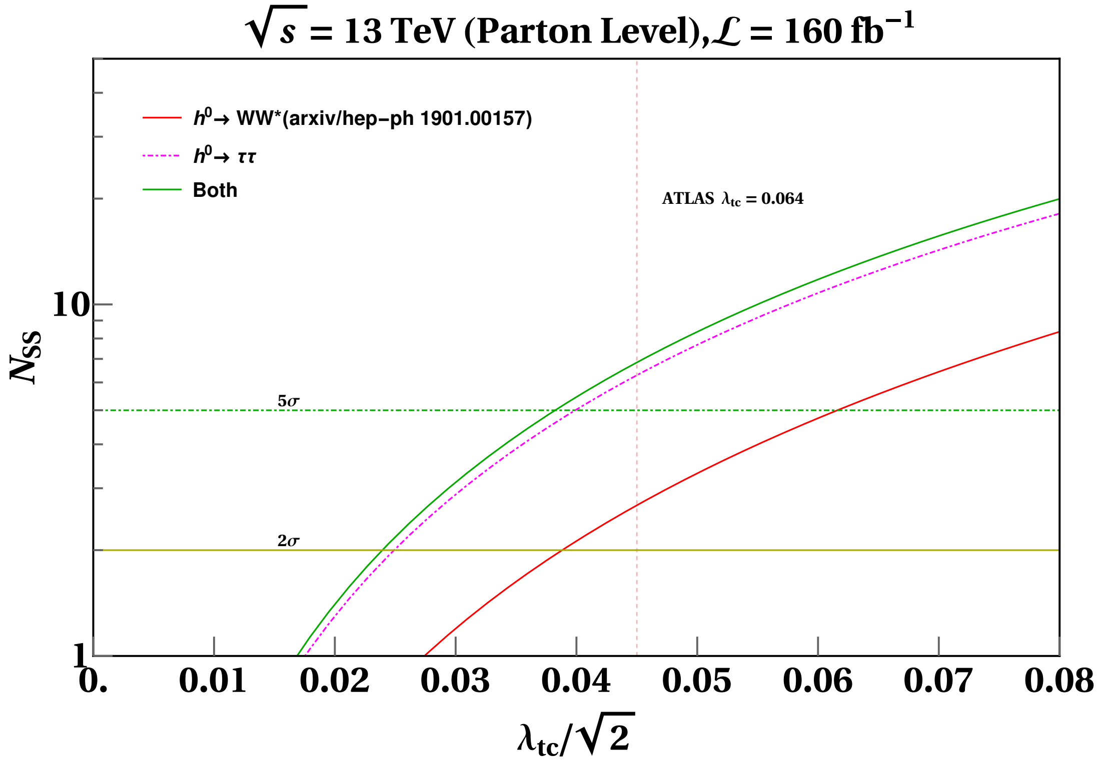
$t \longrightarrow ch^0 \longrightarrow c\tau\tau, cWW$



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Summery and Conclusions

- It is of great interest to investigate the link between the most massive particle (top) and the mass giver (Higgs).
- It is a win-win strategy to search for the FCNH top decay $t \to ch^0$ and the heavy Higgs decay $H^0, A^0 \to t\bar{c} + \bar{t}c$.
- In the alignment limit, the FCNH heavy Higgs decay $H^0, A^0 \to t\bar{c} + \bar{t}c$ can be sustained by sin(β-α) ~ 1.
- We might find out if nature chooses the same mechanism for electroweak symmetry breaking and tree level FCNC.

Collaborators: Phillip Gutierrez and Rishabh Jain

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