

Flavor Changing Top Decays to Charm and Higgs with $\tau\tau$ at the LHC

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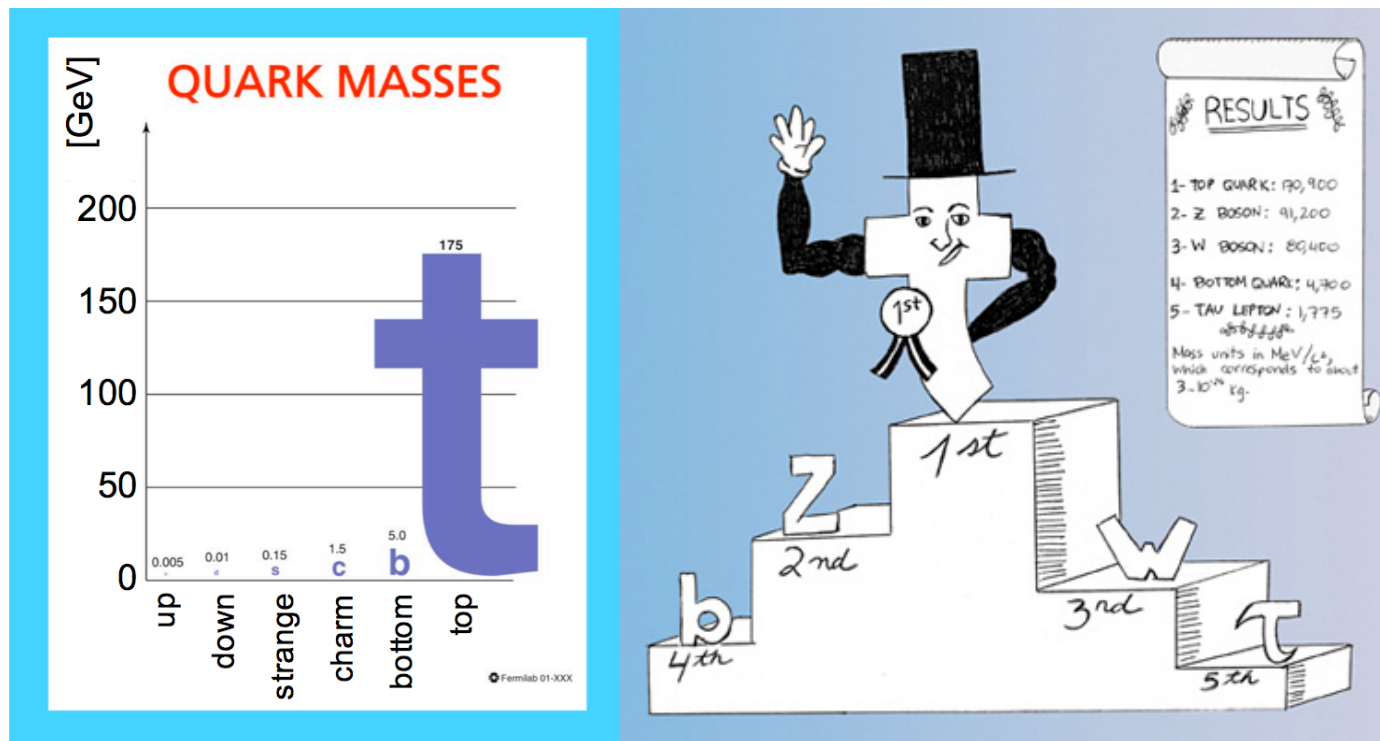


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Flavor Changing Top Decays

- 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.

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 ($v_2 \gg v_1$).

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



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Das and Kao (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.

A General Two Higgs Doublet Model

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

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



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Davidson and Haber (2005)

Mahmoudi and Stal (2009)

When the Higgs meets the Top

When the mass giver meets the most massive particle, they might lead to complementary new physics:

- (a) $t \rightarrow ch^0$, $\lambda_{tch} = \rho_{tc} \cos(\beta - \alpha)$
- (b) $H^0, A^0 \rightarrow t\bar{c} + \bar{t}c$,
- (c) $H^0, A^0 \rightarrow \tau^+ \mu^- + \tau^- \mu^+$,
 $\lambda_{Htc} = \rho_{tc} \sin(\beta - \alpha)$, $\lambda_{Atc} = \rho_{tc}$, and $\lambda_{H\tau\mu} = \rho_{\tau\mu} \sin(\beta - \alpha)$.

Altunkaynak, Hou, Kao, Kohda, McCoy (2015)

Hou, Jain, Kao, Kohda, McCoy, and Soni (2019)

CMS JHEP 03 (2020)



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Charming Top Decay with the Higgs boson

$$\text{FCNH} \quad \Gamma(t \rightarrow ch^0) = \frac{|\lambda_{tc}|^2}{16\pi} \times (m_t) \times [(1 + \rho_c)^2 - \rho_h^2] \\ \times \sqrt{1 - (\rho_h + \rho_c)^2} \sqrt{1 - (\rho_h - \rho_c)^2}, \quad \rho_c = m_c/m_t \\ \rho_h = M_h/m_t$$

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

Simple Relation (ATLAS):

$$\lambda_{tc} \sim 1.92 \times \sqrt{B(t \rightarrow ch^0)}$$

Hou (1991)
Aguilar-Saavedra and Branco (2000)
Kao, Cheng, Hou, and Sayre (2012)
Chen, Hou, Kao, and Kohda (2013)
Atwood, Gupta, and Soni (2014)
Jain and Kao (2019)



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Constraints on FCNH Couplings

- Recent ATLAS data have placed constraints on λ_{tc} and λ_{ct} :
 - ▶ the top decay should have $\mathcal{B}(t \rightarrow ch^0) < 0.0011$,
 - ▶ or $\sqrt{\lambda_{tc}^2 + \lambda_{ct}^2} < 0.064$, with $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$.
- A new CMS analysis with t to ch to $c\gamma\gamma$ set a new limit $\mathcal{B}(t \text{ to } ch) < 7.3 \times 10^{-4}$, or $\lambda_{tc} < 0.052$.
- If the ρ -matrix is not Hermitian, then we must have $|\rho_{ct}| < 0.1$, while $|\rho_{tc}|$ can be close to 1.

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

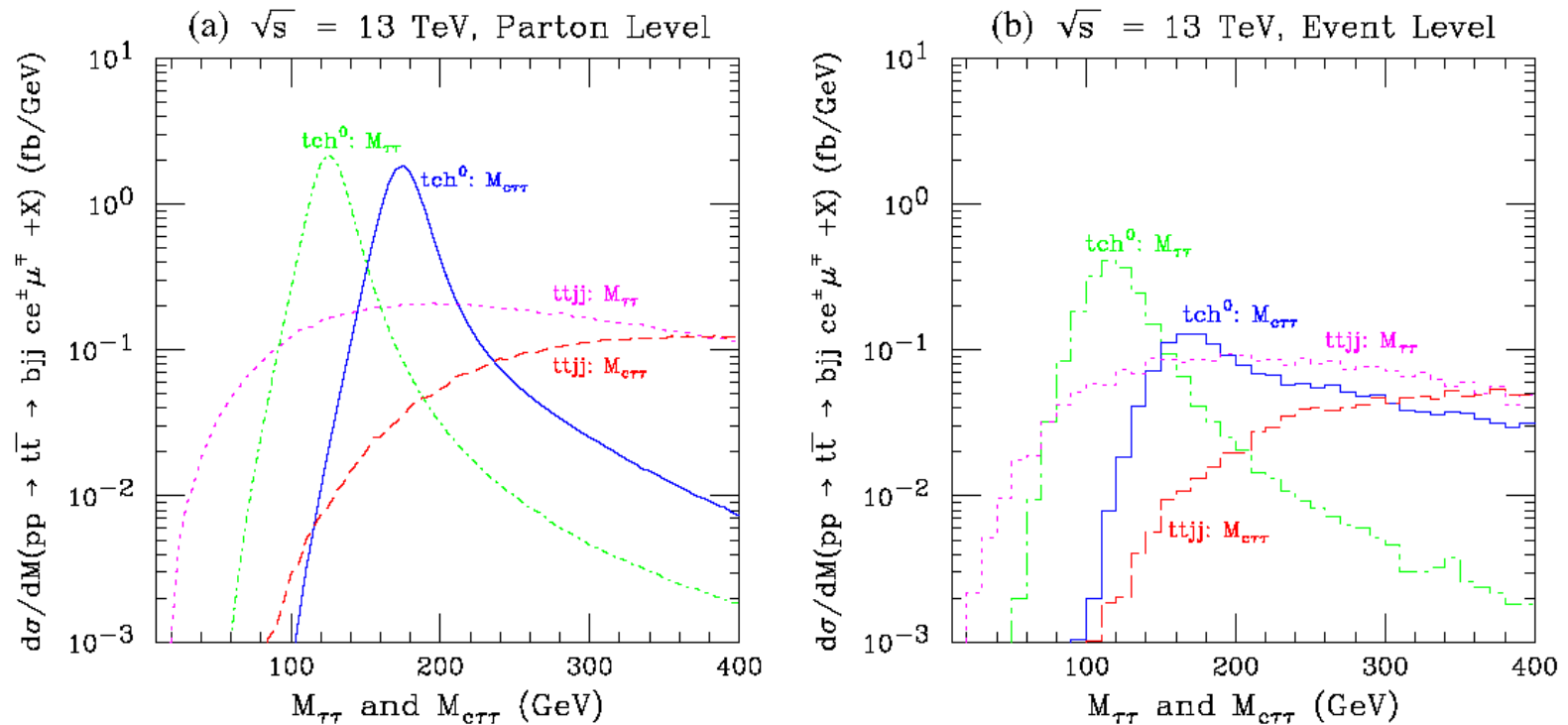
- The discovery channel has relatively low background.
- We have studied the final states of (i) a pair of leptons and (ii) a lepton plus a tau jet.
- Collinear approximation offers the possibility of reconstruction Higgs mass and Top quark mass.
- Requiring momentum fractions of tau decays $0 < x <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



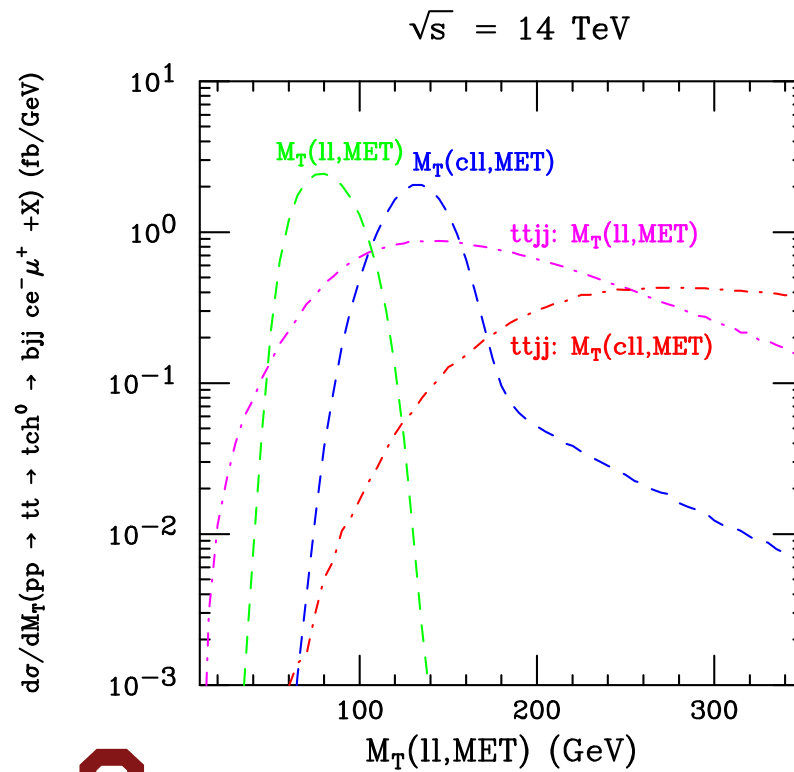
Recent Studies of $pp \rightarrow t\bar{t} \rightarrow tch^0 \rightarrow tc\tau^+\tau^- + X$

- 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 $E_{\text{charm}}(\text{top})$.

Reconstruction of the Higgs Mass

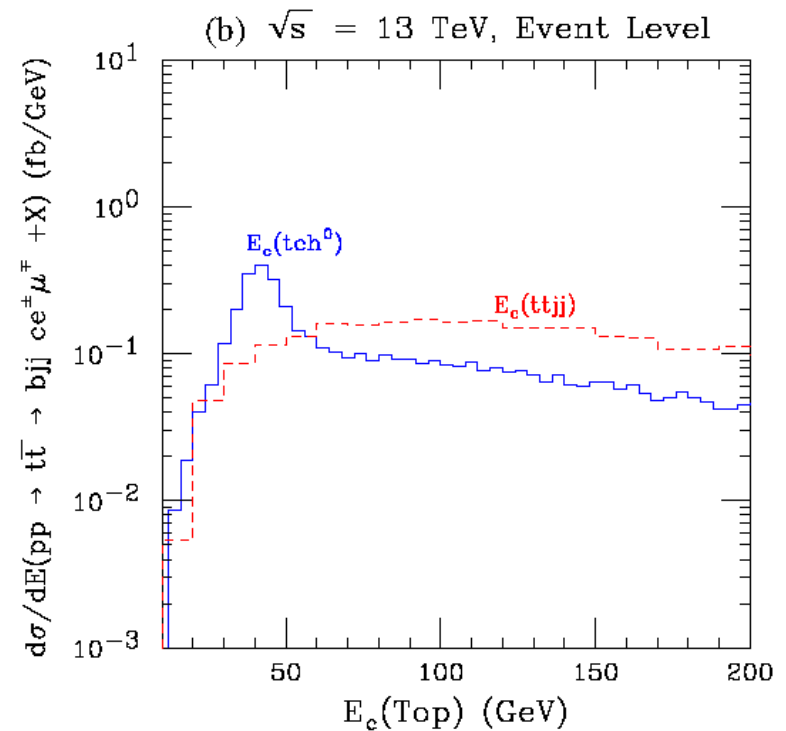
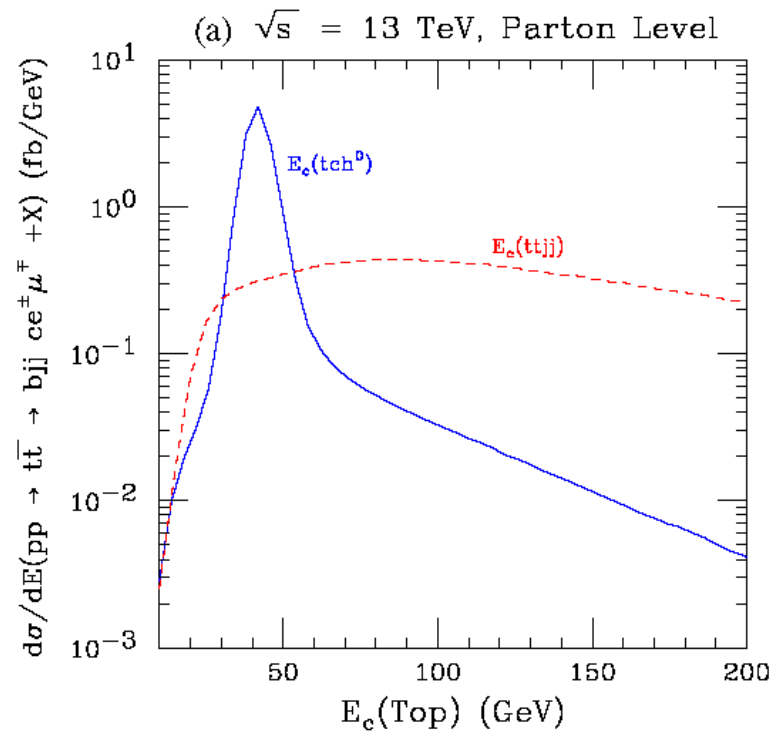


Cluster Transverse Mass



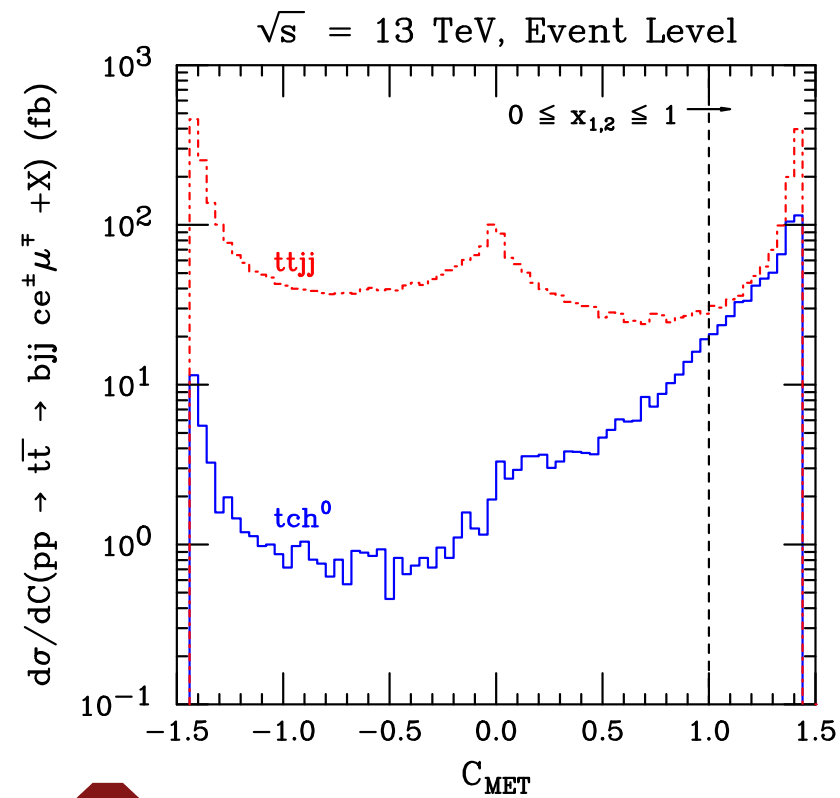
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E_{charm} in the Top Frame



Han, Jlang, and Sher (2001)
 Kao, Cheng, Hou, and Sayre (2012)
 Gutierrez, Jain and Kao (2020)

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



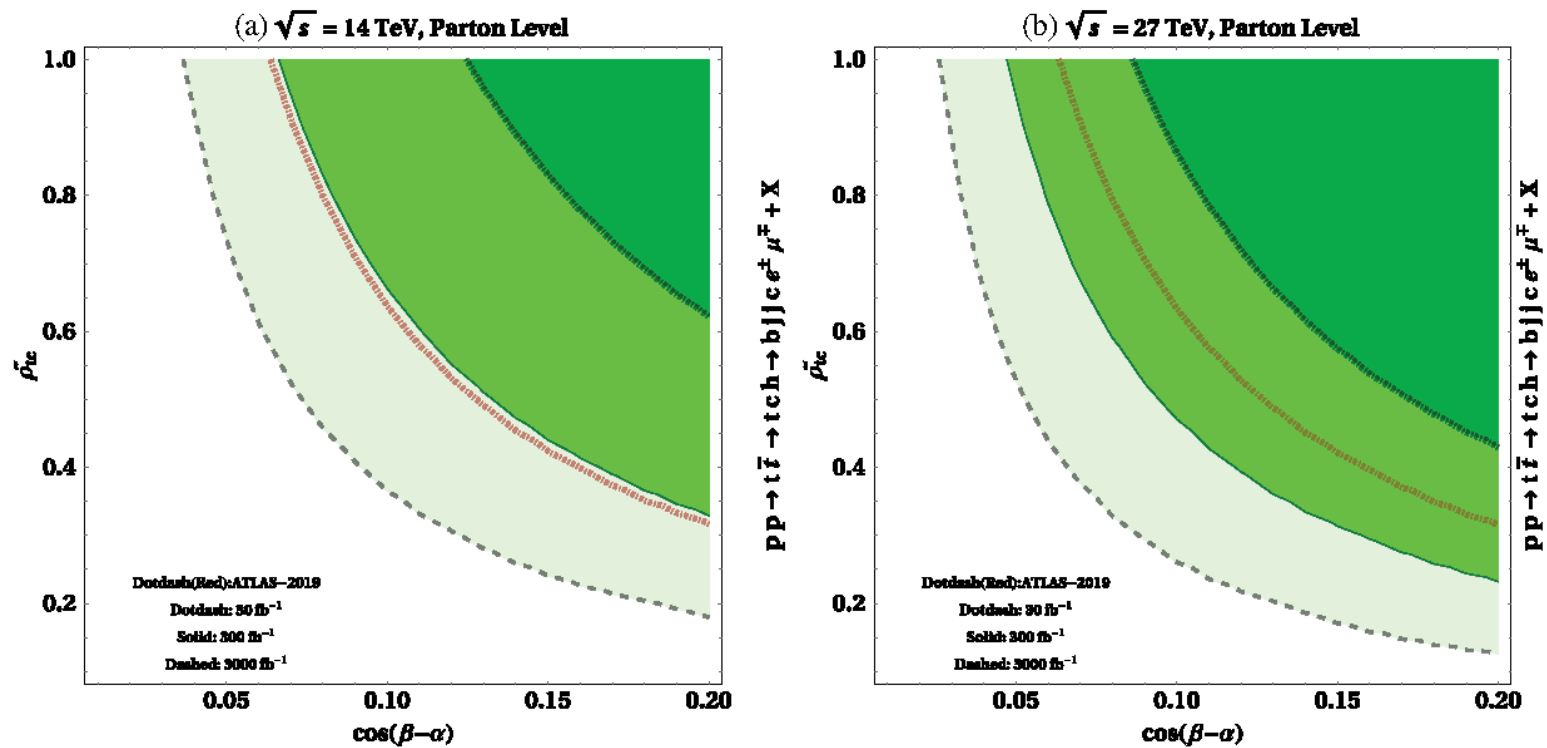
Statistical Significance

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

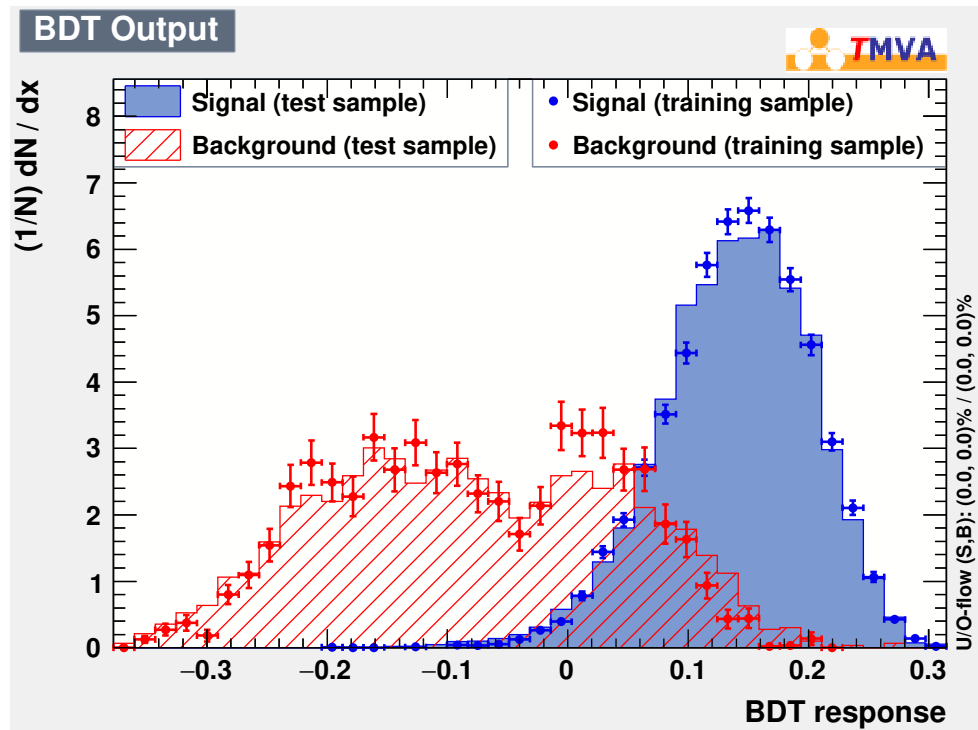
$$N_{SS} = \sqrt{2 \times (N_S + N_B) \ln(1 + N_S/N_B) - 2 \times N_S}$$

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

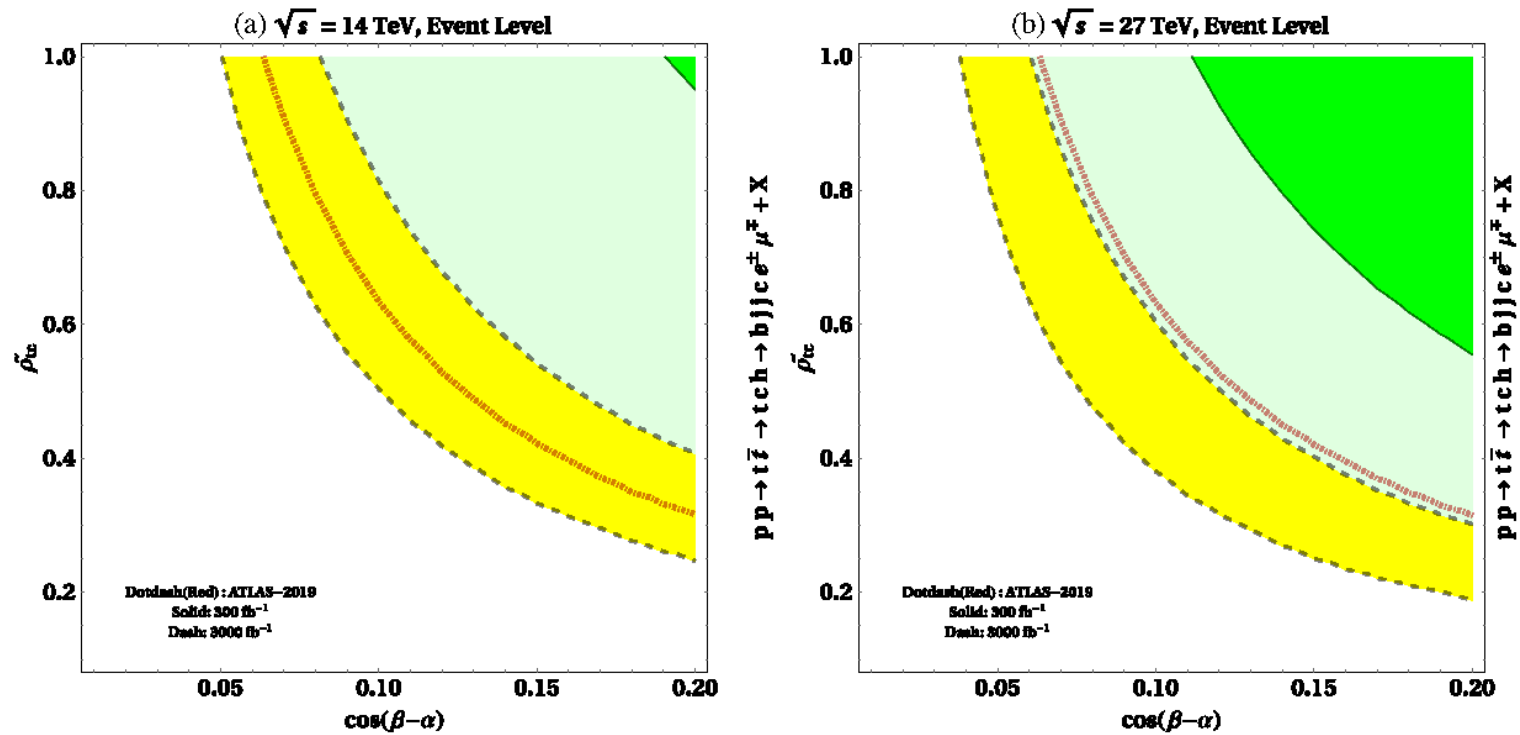
Parton Level Discovery Contours



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



Event Level Discovery Contours



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

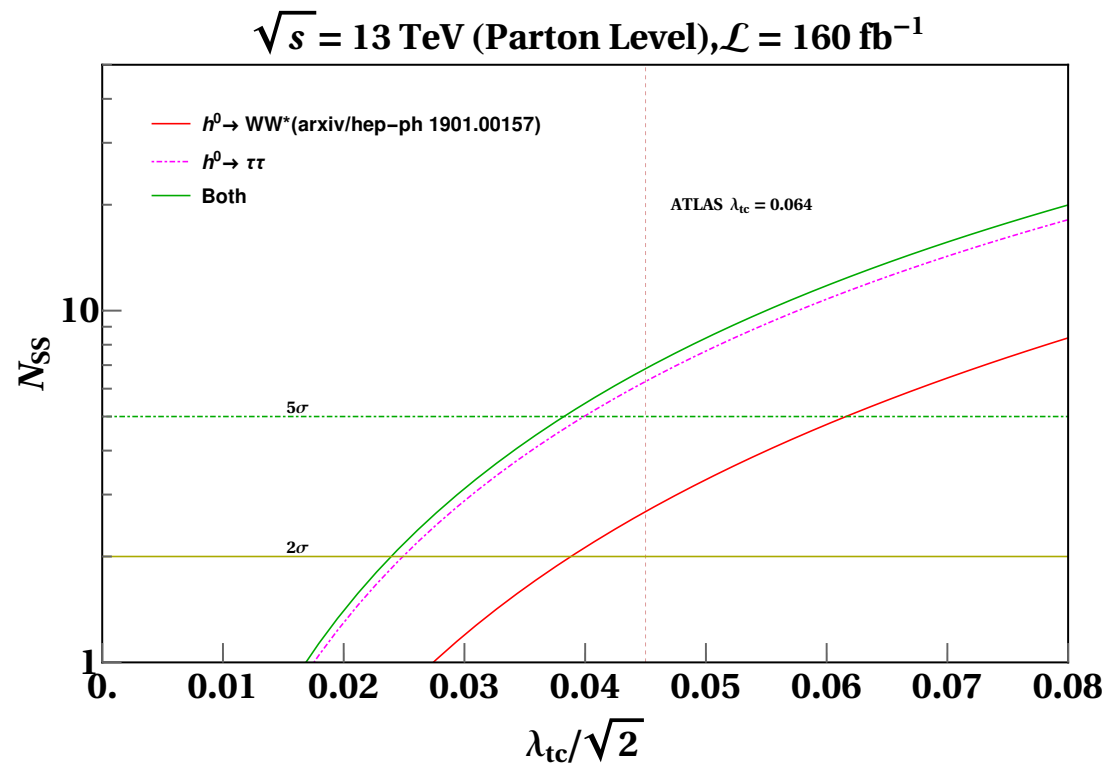
\sqrt{s} (TeV)	L (fb $^{-1}$)	$\mathcal{B}(t \rightarrow ch^0)$	λ_{tch}
13	139	1.4×10^{-3}	0.073
13	3000	3.0×10^{-4}	0.033
14	3000	2.6×10^{-4}	0.031
27	3000	1.4×10^{-4}	0.023



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

\sqrt{s} (TeV)	$\mathcal{B}(t \rightarrow ch^0)$	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

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



Summary 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 $t \rightarrow ch^0$ and the heavy Higgs decay $H^0, A^0 \rightarrow t\bar{c} + \bar{t}c$.
- In the alignment limit, the FCNH heavy Higgs decay $H^0, A^0 \rightarrow t\bar{c} + \bar{t}c$ can be sustained by $\sin(\beta-\alpha) \sim 1$.
- We might find out if nature chooses the same mechanism for electroweak symmetry breaking and tree level FCNC.

Collaborators: Phillip Gutierrez and Rishabh Jain

