Triple Top-Quark Production at the LHC

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Based on Phys. Rev. D **100**, 055035 in collaboration with Q. H. Cao, S. L. Chen and X. P. Wang

Outline

Motivation

Result from Triple Top-Quark production

Summary

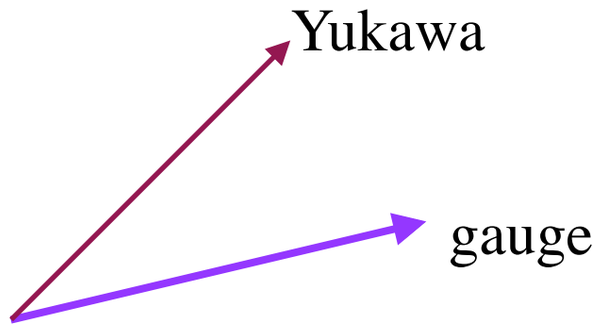
Why do we care about triple top-quark production?

FCNC is a golden signal of new physics beyond SM

In the SM: only one Higgs doublet

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}_{\text{mass}} = \frac{v}{\sqrt{2}} \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}_{\text{Yukawa}}$$

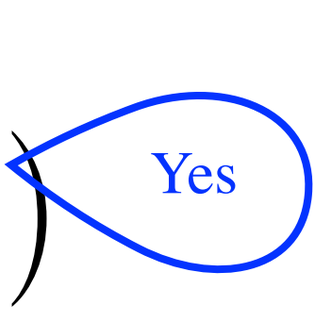
gauge interaction universality



S. L. Glashow, S. Weinberg Phys. Rev. D 15, 1958 (1977)

E. A. Pascho Phys. Rev. D 15, 1966 (1977)

At the tree level: $\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix}$



$h/g/Z/\gamma$

GIM mechanism S.L. Glashow, J. Iliopoulos, L. Maiani 1970 Phys Rev D. 2.1285

At one-loop level: $t \to u + \gamma/g/Z/h \sim 10^{-12} - 10^{-15}$

No FCNC in the SM

Top FCNC from New Physics

Glashow-Weinberg condition + interaction universality

2HDM, SUSY models

3-3-1 model, topcolor model

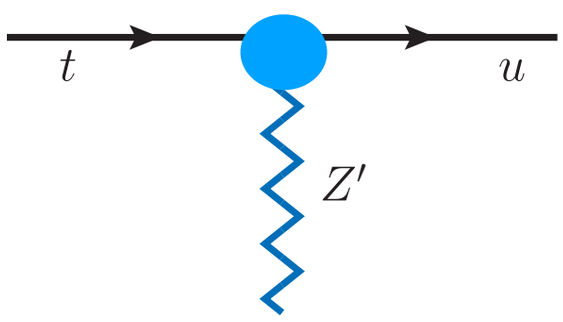
FCNC

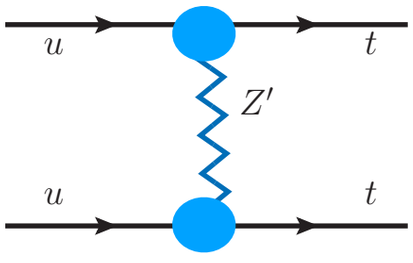
V. Barger, W. Y. Keung, B.Yencho Phys.Lett. B687 (2010) 70-74
S. Kanemura, H. Yokoya, Y. J. Zhang Nucl.Phys. B898 (2015) 286-300
R. Patric, P. Sharma, A. G. Williams Phys.Lett. B780 (2018) 603-607
M. Kohda, T. Modak, W. S. Hou Phys.Lett. B776 (2018) 379-384

C. Han, N. Liu, L. Wu, J. M. Yang Phys.Lett. B714 (2012) 295-300

Z' MxFV

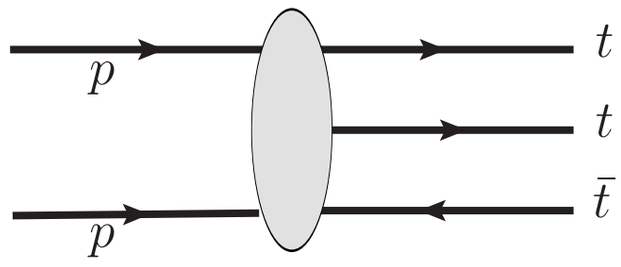
$\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix}$



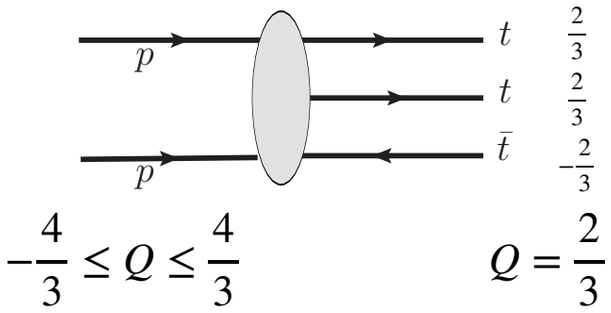


same-sign top

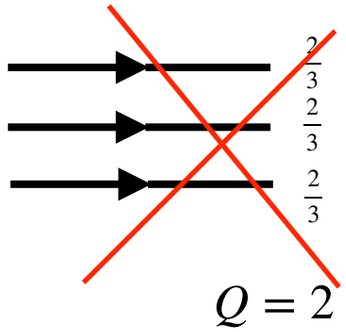
Why triple top-quark?



Triple Top-Quark Production at the LHC

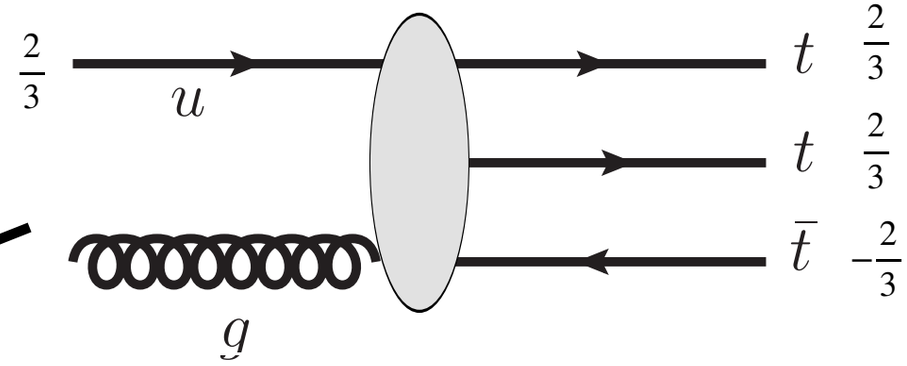


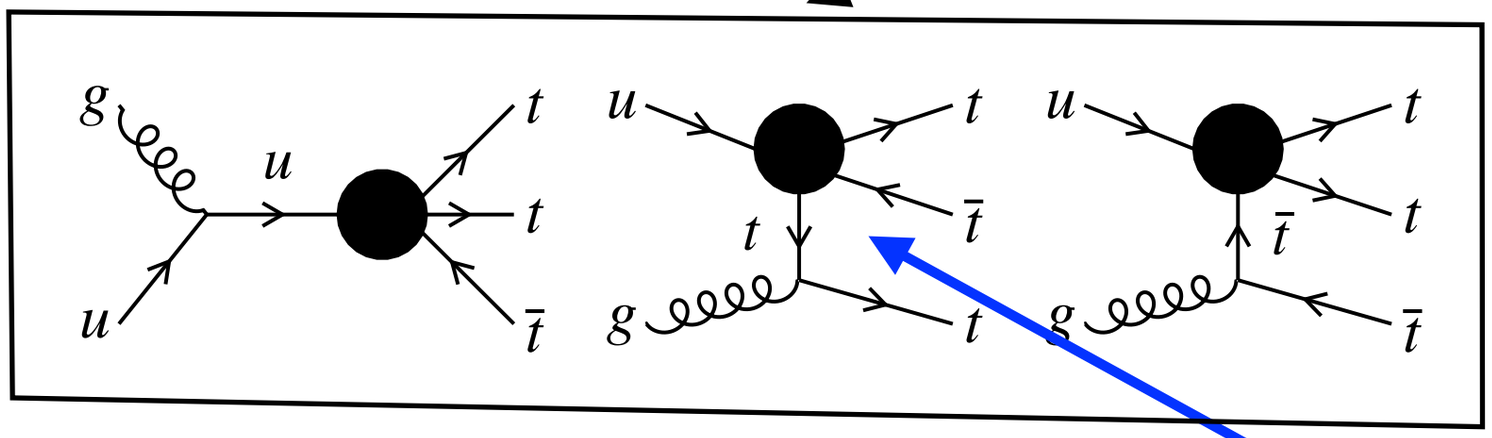
$$-\frac{4}{3} \le Q \le \frac{4}{3}$$



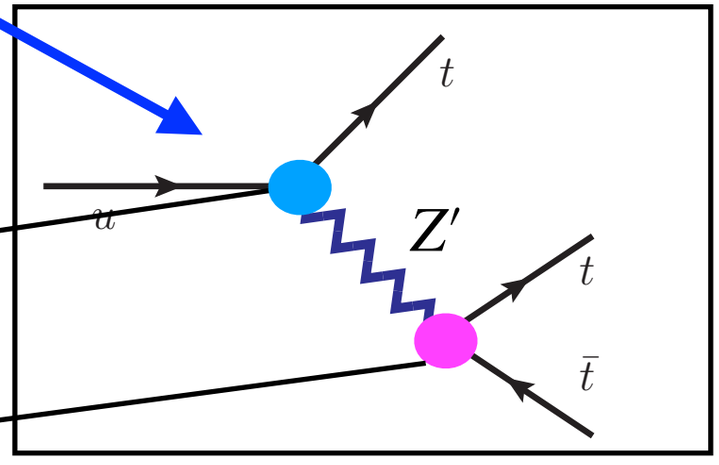
$$Q = \frac{2}{3}$$

$$Q = 2$$





Top FCNC



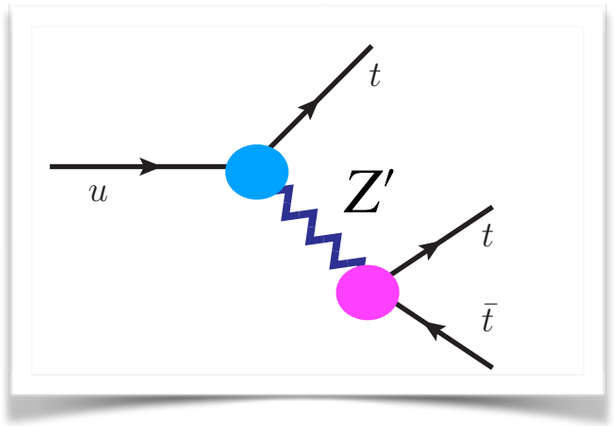
Top FCNC

coexistence

Top flavor conserving

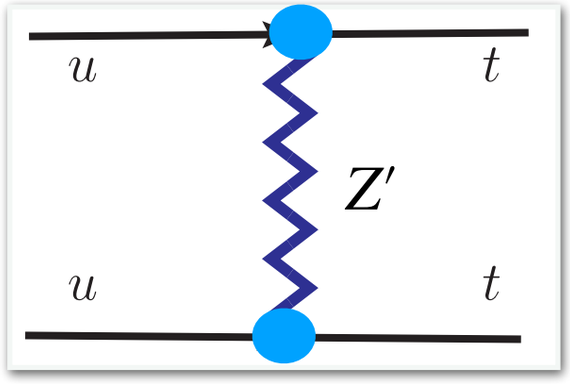
$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\mathrm{FVNI}} f^{\mathcal{V}}_{\mathrm{FCNI}}}{\Lambda^2} (\bar{t}\gamma^{\mu} P_R t)(\bar{t}\gamma_{\mu} P_R u)$$

NP-EFT

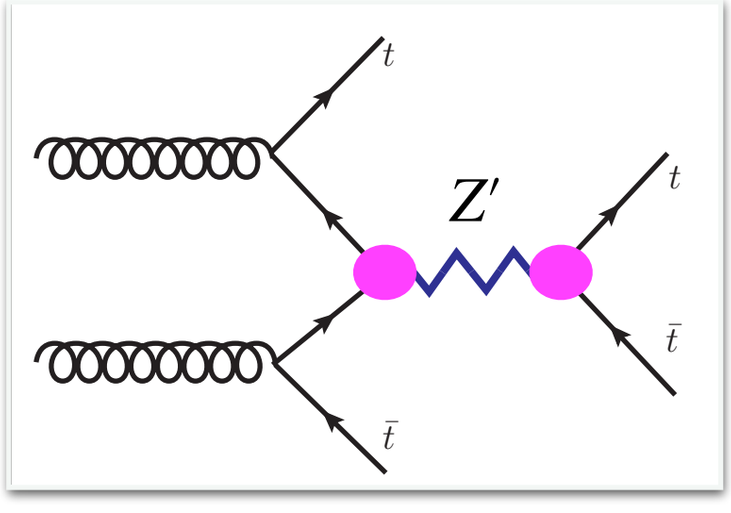


$$\mathcal{O}^{\mathscr{V}}_{uttt} = \frac{f^{\mathscr{V}}_{\mathrm{FVNI}} f^{\mathscr{V}}_{\mathrm{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$

$$\mathcal{O}^{\mathscr{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathscr{V}}_{\mathrm{FVNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R u)(\bar{t}\gamma_{\mu}P_R u)$$

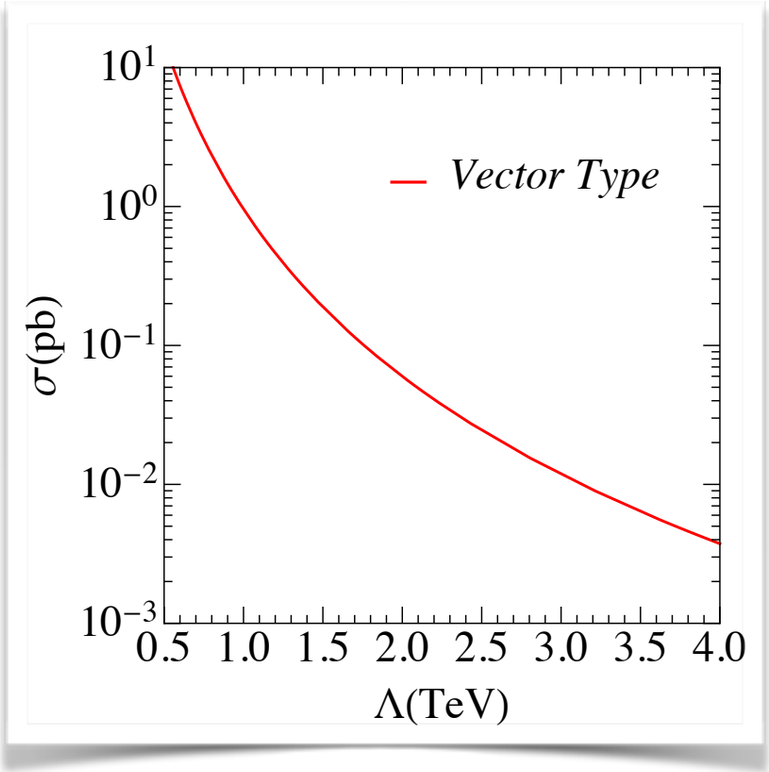


$$\mathcal{O}^{\mathscr{V}}_{tttt} = \frac{1}{2}\frac{(f^{\mathscr{V}}_{\mathrm{FCNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R t)$$



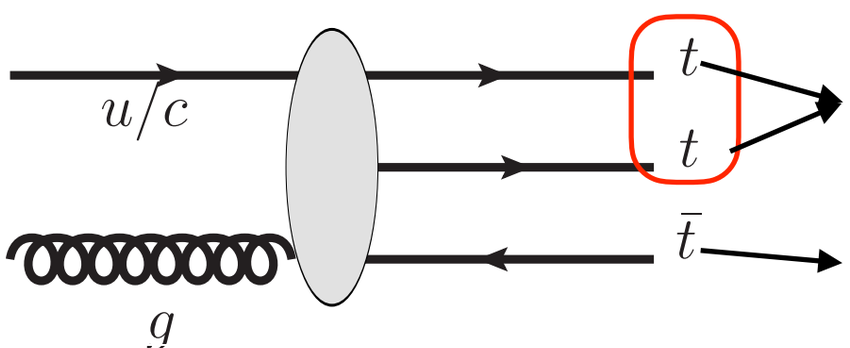
Simulation on Triple Top-Quark Production

13 TeV LHC



$$\mathcal{O}^{\mathscr{V}}_{uttt} = \frac{f^{\mathscr{V}}_{\mathrm{FVNI}} f^{\mathscr{V}}_{\mathrm{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$

$$\sigma^{\mathscr{V}}_{ttt} = 0.9582 \times \left(f^{\mathscr{V}}_{\mathrm{FCNI}} f^{\mathscr{V}}_{\mathrm{FVNI}}\right)^2 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \ \mathrm{pb}$$



$$b\ W^+ \rightarrow b\ l^+\ \nu_l \quad (l = e, \mu)$$

$$\bar{b}\ W^- \rightarrow b\ \bar{u}(\bar{c})\ d(s)$$

same-sign lepton + multiple (b-)jets + missing energy

Simulation on Triple Top-Quark Production

signal: same-sign lepton + multiple (b-)jets + missing energy

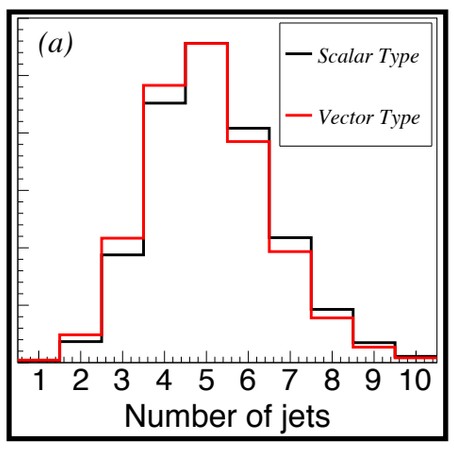
background: $t\bar{t}W^{\pm}$, $t\bar{t}Z$, $t\bar{t}h$, $t\bar{t}$, etc.

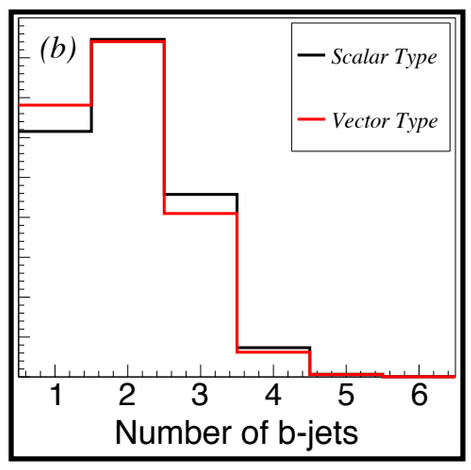
multiple top-quark search at the LHC

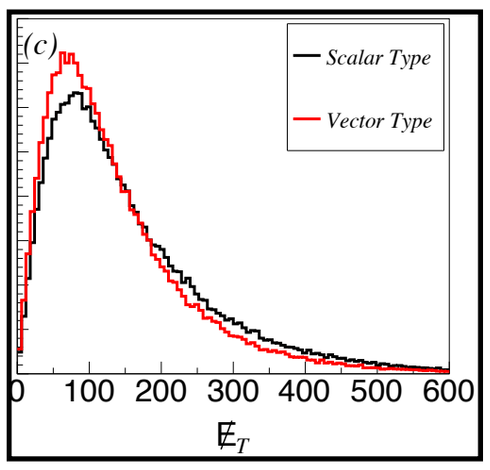
ATLAS Collaboration (Morad Aaboud (Oujda U.) *et al.*).
Jun 12, 2017. 43 pp. JHEP 1709 (2017) 084

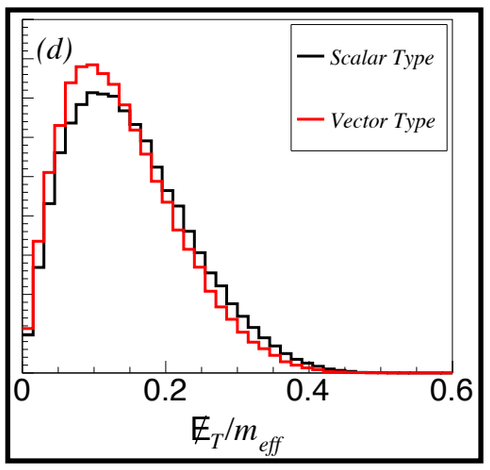
$$N_{\ell^+(\ell^-)} = 2, \quad N_b \geq 1, \quad N_{\text{jets}} \geq 6,$$
$$\not{E}_T > 250 \text{ GeV}, \quad \not{E}_T/m_{\text{eff}} > 0.2 \ ,$$

cut validation:







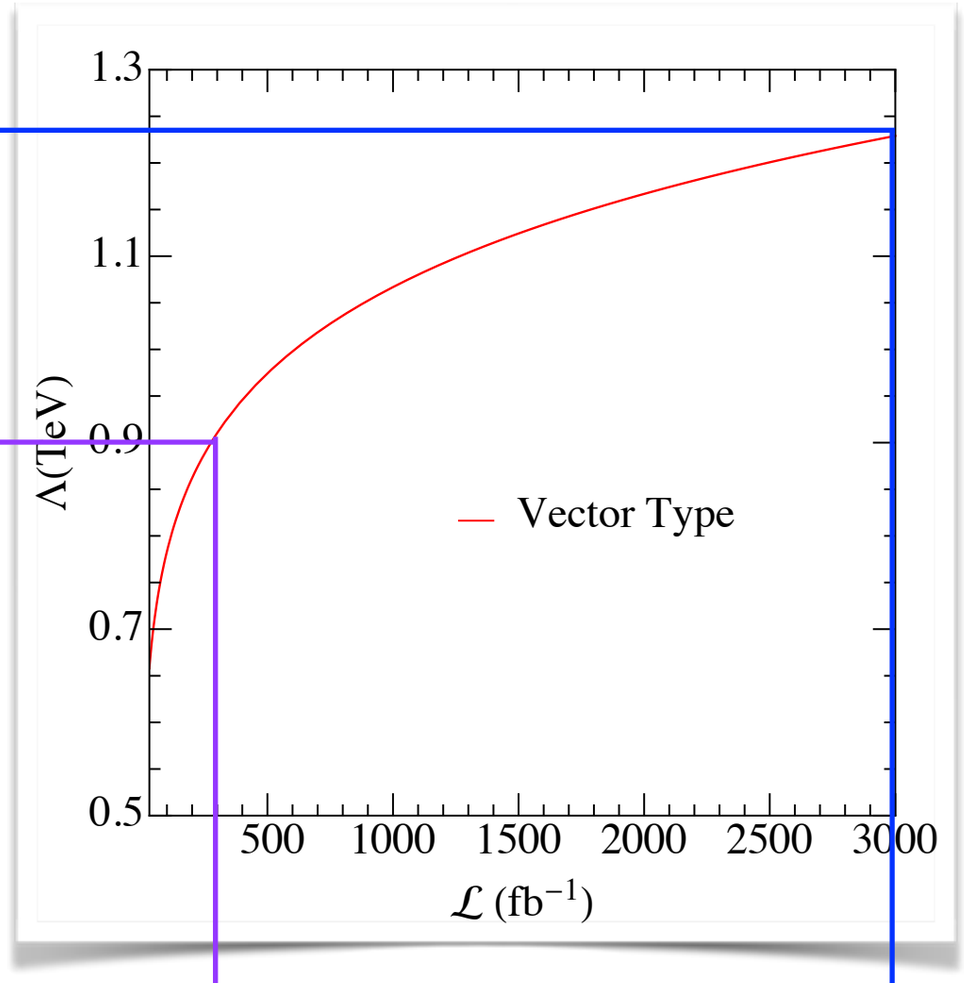


Result from Simulation

2σ exclusion potential

1.23 TeV

0.91 TeV



300 fb^{-1}

3000 fb^{-1}

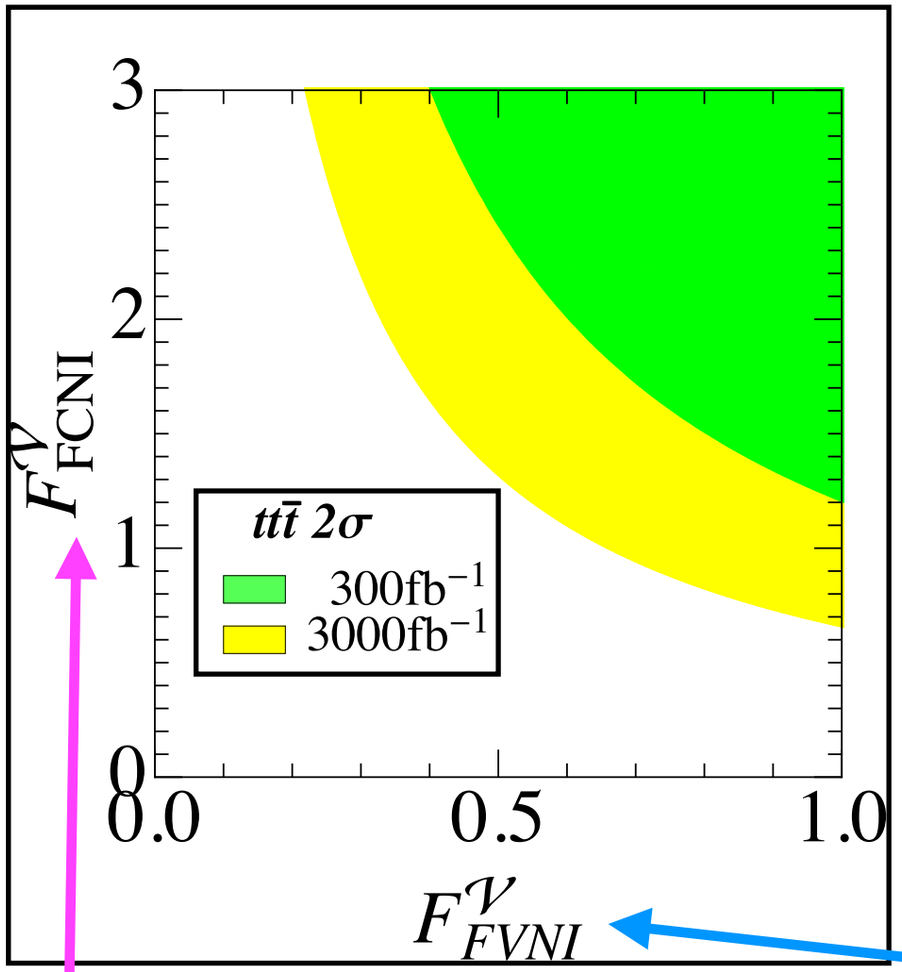
$$\mathcal{O}^{\mathscr{V}}_{uttt} = \frac{f^{\mathscr{V}}_{\text{FVNI}} f^{\mathscr{V}}_{\text{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$

$$\mathscr{L} = 300\ (3000)\ \text{fb}^{-1}$$

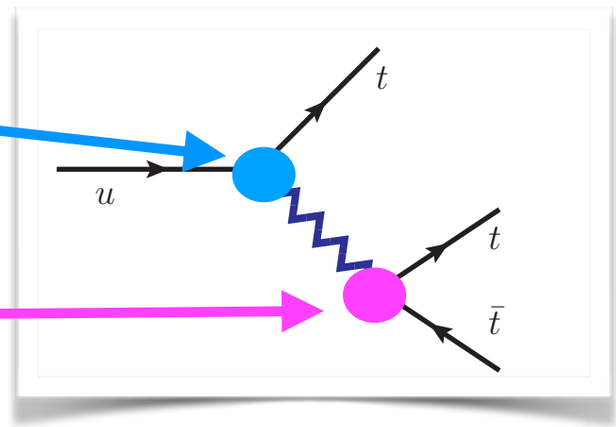
$$\Lambda \geq 0.91(1.23)\sqrt{f^{\mathscr{V}}_{\text{FVNI}} f^{\mathscr{V}}_{\text{FCNI}}}\ \text{TeV}$$

Result from Triple Top-Quark Production Simulation

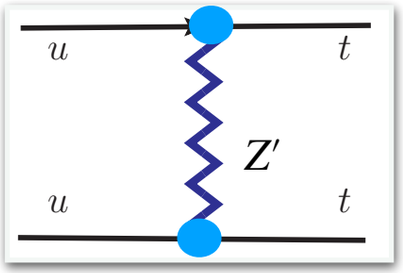
$\Lambda = 1$ TeV



$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\mathrm{FVNI}} f^{\mathcal{V}}_{\mathrm{FCNI}}}{\Lambda^2} (\bar{t}\gamma^{\mu} P_R t)(\bar{t}\gamma_{\mu} P_R u)$$



Same-Sign Top-Quark Production

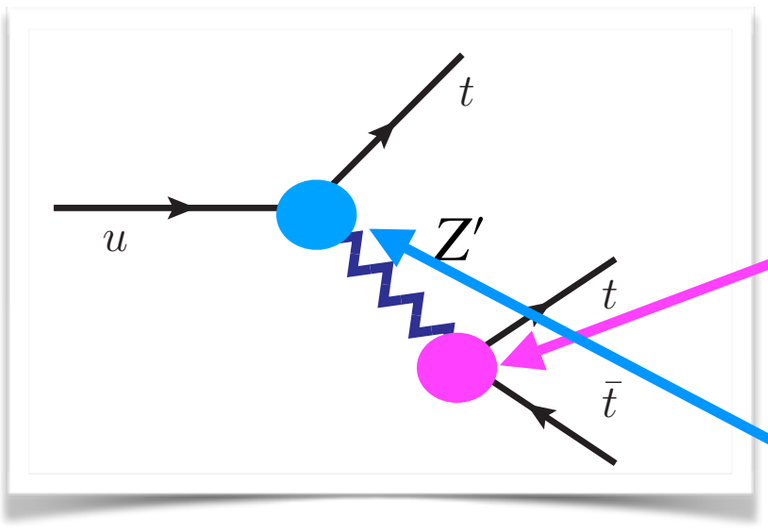


$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\mathrm{FVNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R u)(\bar{t}\gamma_{\mu}P_R u) \qquad \sigma^{\mathcal{V}}_{tt+\bar{t}\bar{t}} = 52.28 \times (f^{\mathcal{V}}_{\mathrm{FVNI}})^4 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \ \mathrm{pb}$$

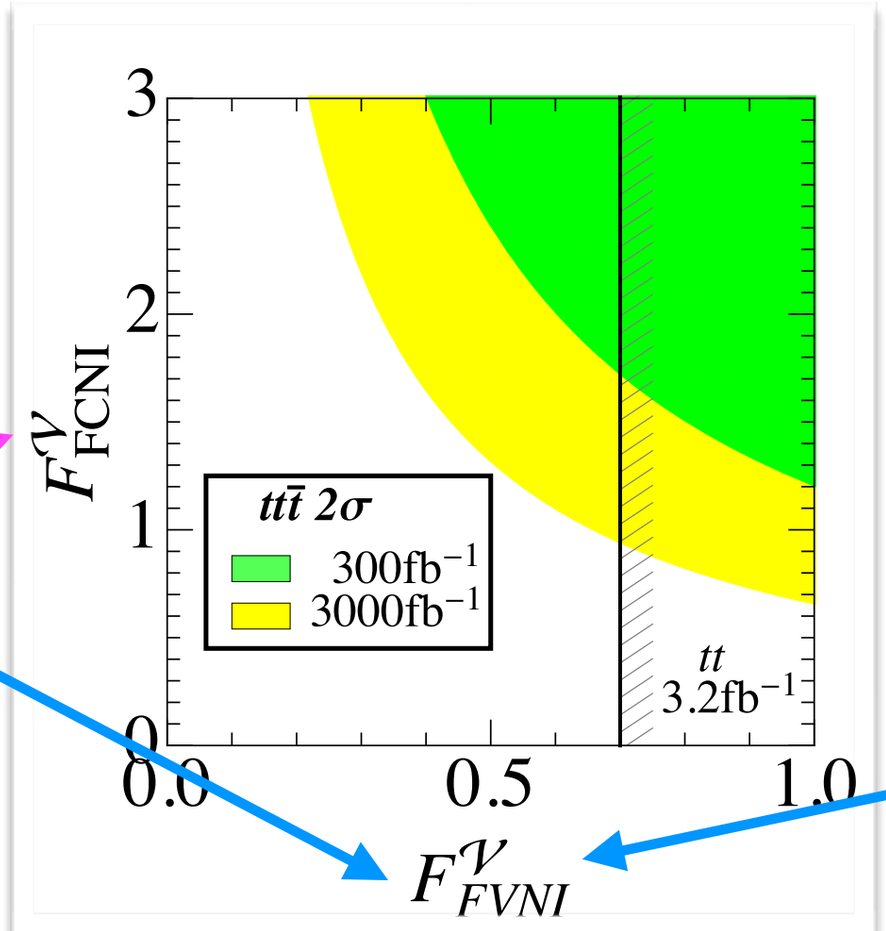
ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). JHEP 1406 (2014) 035

current: $3.2\ \mathrm{fb}^{-1}$ $\qquad f^{\mathcal{V}}_{\mathrm{FVNI}} \leq 0.70\ \frac{\Lambda}{\mathrm{TeV}}$

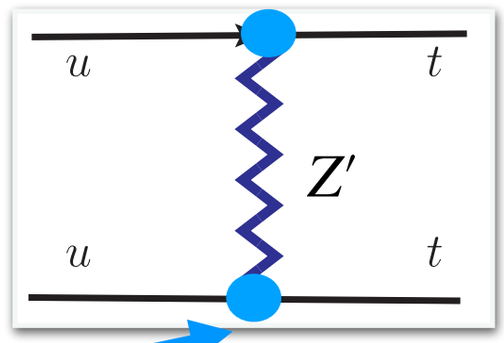
$\Lambda = 1\ \mathrm{TeV}$



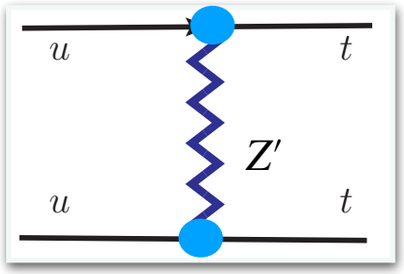
$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\mathrm{FVNI}} f^{\mathcal{V}}_{\mathrm{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$



$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\mathrm{FVNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R u)(\bar{t}\gamma_{\mu}P_R u)$$



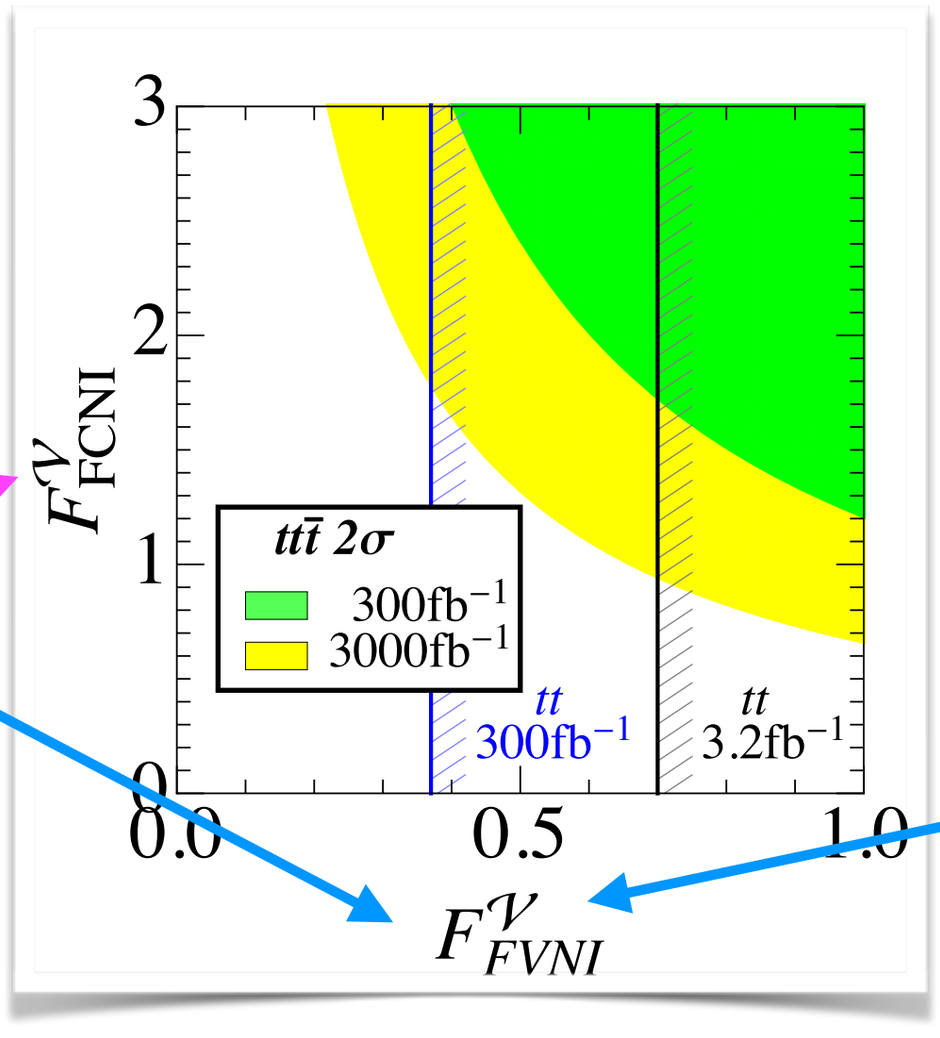
Same-Sign Top-Quark Production

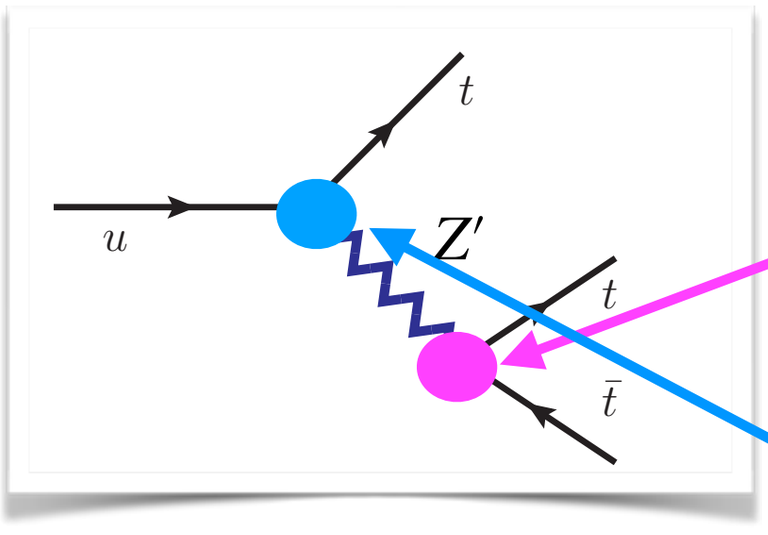


$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\rm FVNI})^2}{\Lambda^2}(\bar{t}\gamma^\mu P_R u)(\bar{t}\gamma_\mu P_R u) \qquad \sigma^{\mathcal{V}}_{tt+\bar{t}\bar{t}} = 52.28 \times (f^{\mathcal{V}}_{\rm FVNI})^4 \left(\frac{\rm TeV}{\Lambda}\right)^4 \ {\rm pb}$$

$\mathscr{L} = 300\ {\rm fb}^{-1}$ $\qquad f^{\mathcal{V}}_{\rm FVNI} \leq 0.37\ \dfrac{\Lambda}{\rm TeV}$ $\qquad 2\sigma$

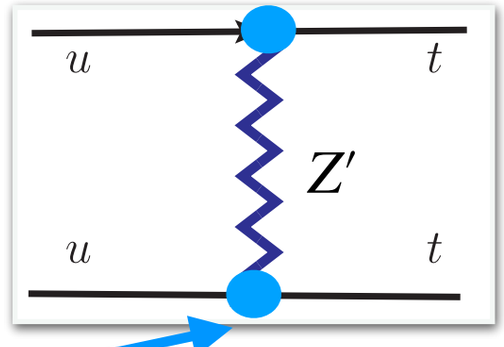
$\Lambda = 1$ TeV



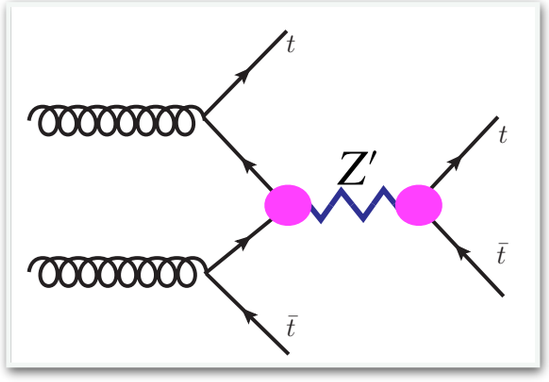


$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\rm FVNI} f^{\mathcal{V}}_{\rm FCNI}}{\Lambda^2}(\bar{t}\gamma^\mu P_R t)(\bar{t}\gamma_\mu P_R u)$$

$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\rm FVNI})^2}{\Lambda^2}(\bar{t}\gamma^\mu P_R u)(\bar{t}\gamma_\mu P_R u)$$



Four Top-Quark Production

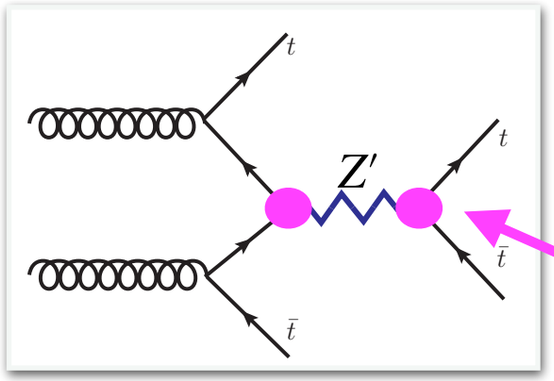


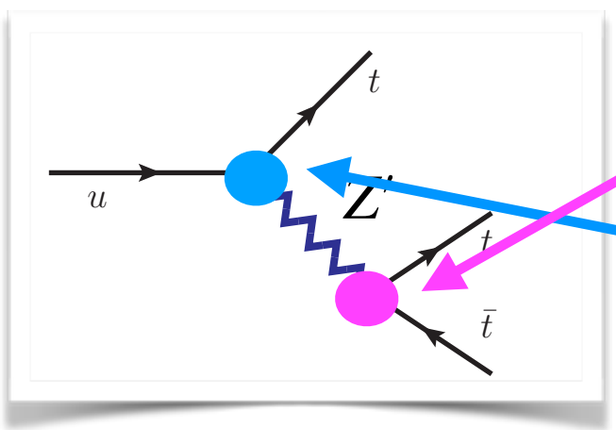
$$\mathcal{O}^{\mathcal{S}}_{tttt} = \frac{1}{2}\frac{(f^{\mathcal{S}}_{\mathrm{FCNI}})^2}{\Lambda^2}(\bar{t}t)(\bar{t}t) \qquad \sigma^{\mathcal{V}}_{tt\bar{t}\bar{t}} = 1.166 \times (f^{\mathcal{V}}_{\mathrm{FCNI}})^4 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \ \mathrm{fb}$$

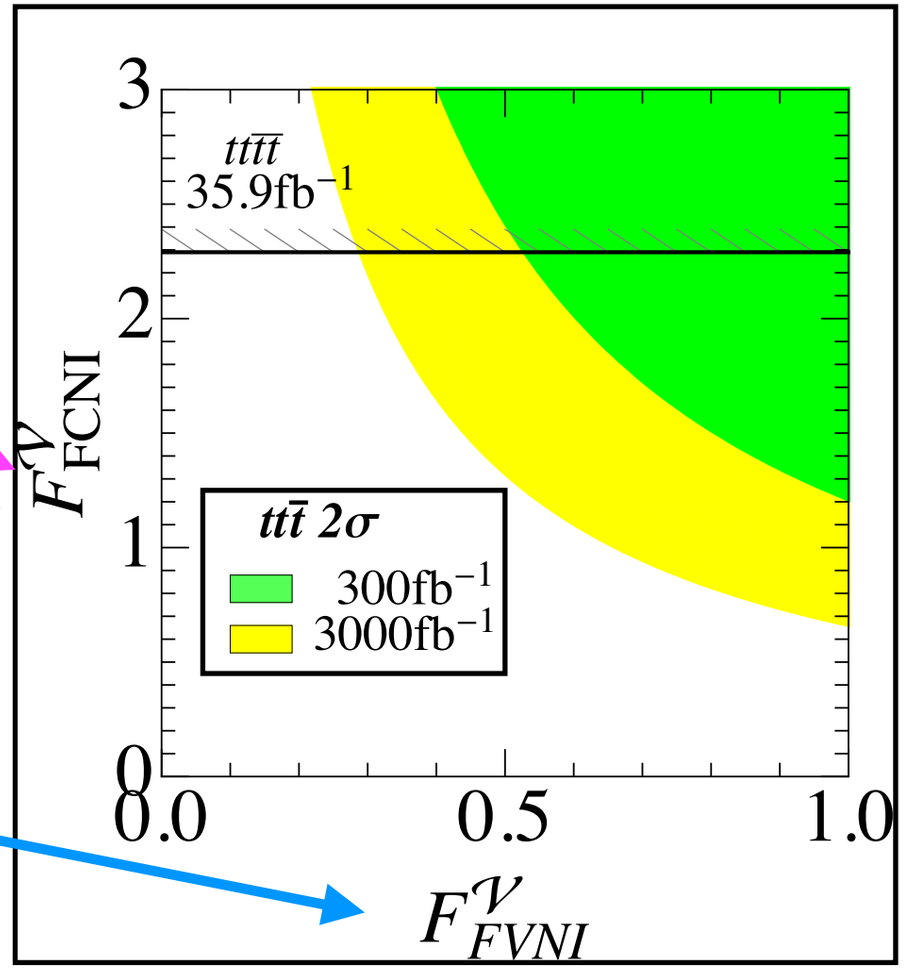
CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Eur.Phys.J. C78 (2018) no.2, 140

$\sigma(t\bar{t}t\bar{t}) \leq 41.7 \ \ 2\sigma \quad 13\ \mathrm{TeV\ LHC}\ 35.9\ \mathrm{fb}^{-1}$ $\qquad f^{\mathcal{V}}_{\mathrm{FCNI}} \leq 2.29\frac{\Lambda}{\mathrm{TeV}}$

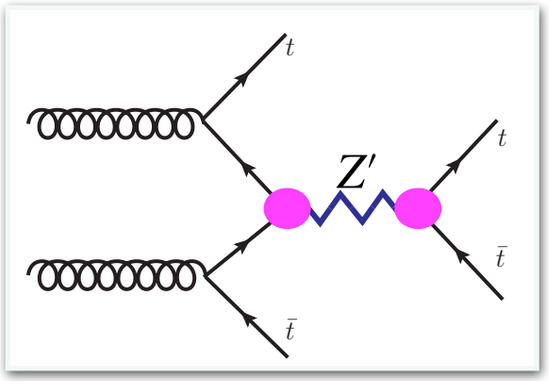
$\Lambda = 1$ TeV







Four Top-Quark Production

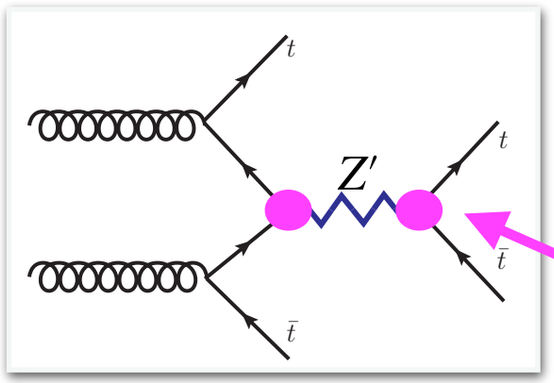


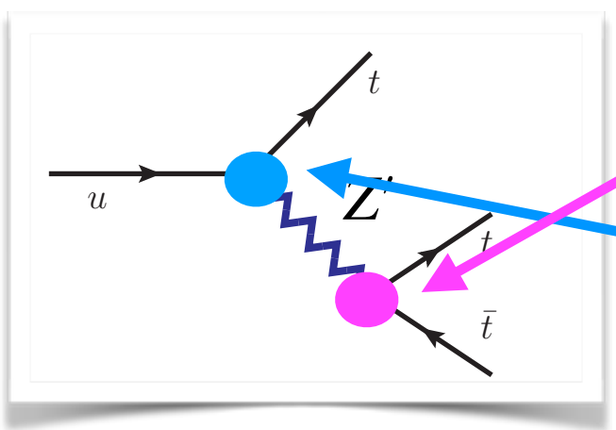
$$\mathcal{O}^{\mathcal{S}}_{tttt} = \frac{1}{2}\frac{(f^{\mathcal{S}}_{\mathrm{FCNI}})^2}{\Lambda^2}(\bar{t}t)(\bar{t}t) \qquad \sigma^{\mathcal{V}}_{tt\bar{t}\bar{t}} = 1.166 \times (f^{\mathcal{V}}_{\mathrm{FCNI}})^4 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \ \mathrm{fb}$$

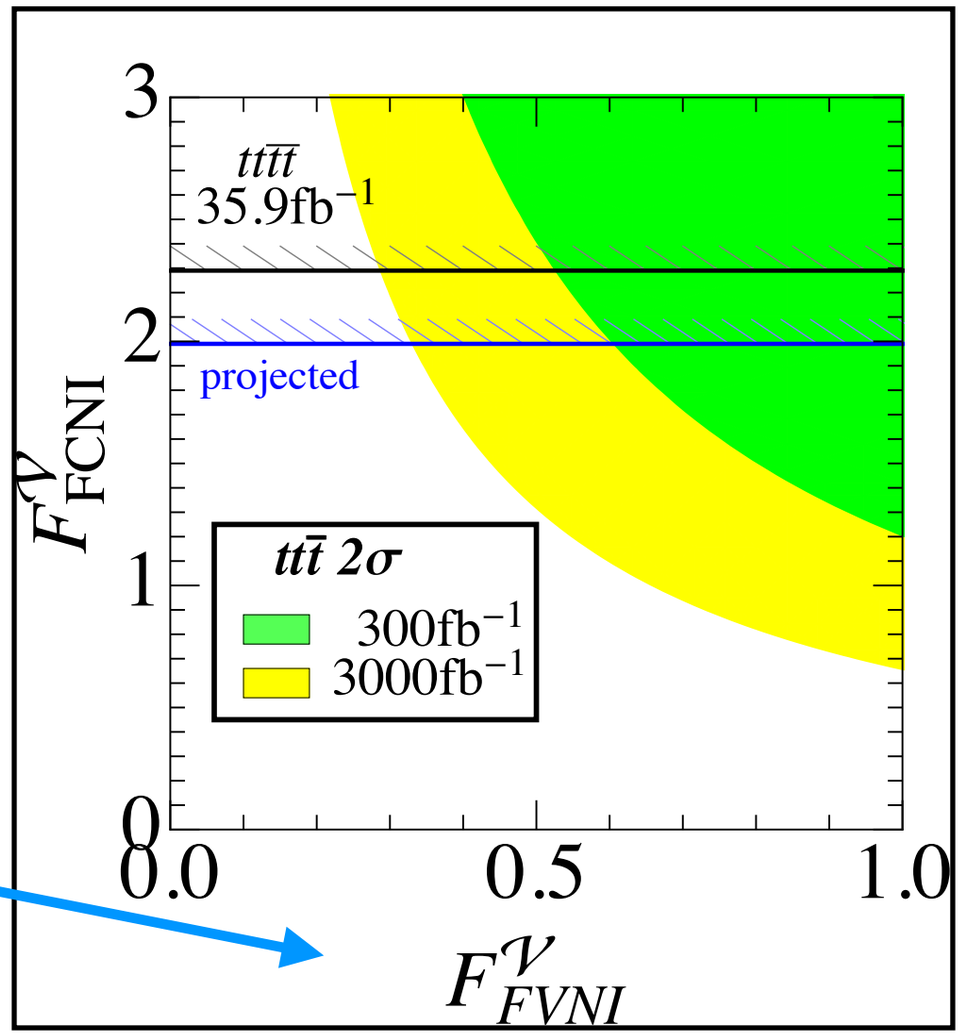
CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Eur.Phys.J. C78 (2018) no.2, 140

$$\mathscr{L} = 300\ \mathrm{fb}^{-1} \qquad f^{\mathcal{V}}_{\mathrm{FCNI}} \leq 1.99\frac{\Lambda}{\mathrm{TeV}}$$

$\Lambda = 1$ TeV

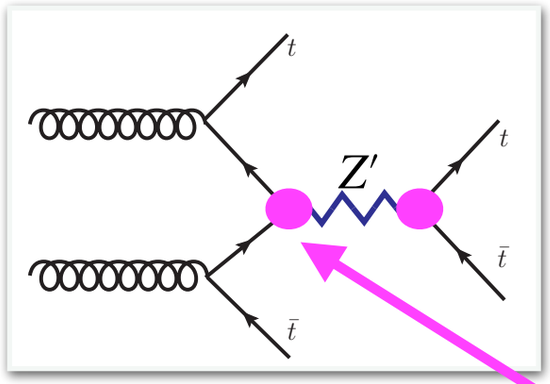


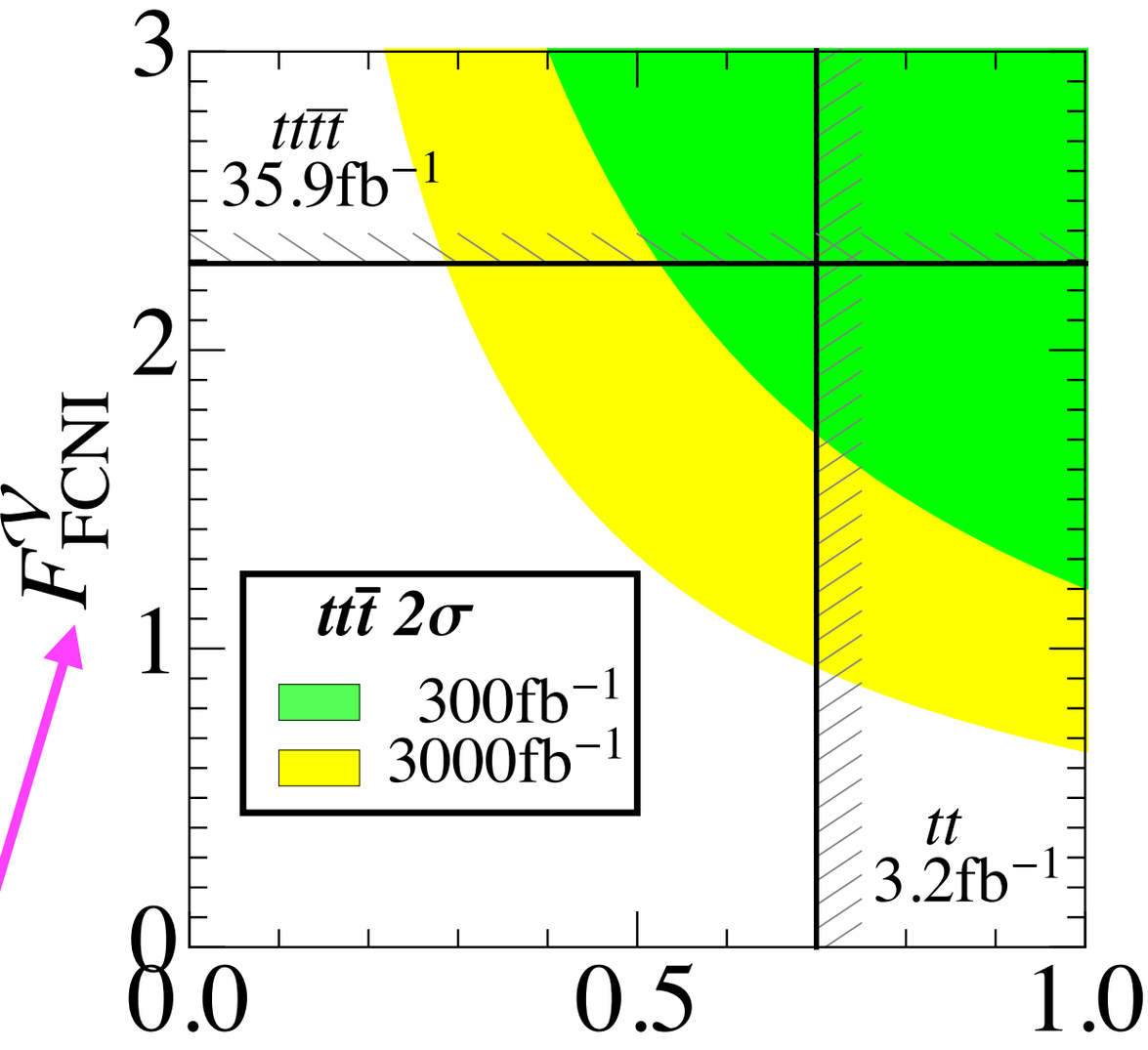




Combined Result and Correlation

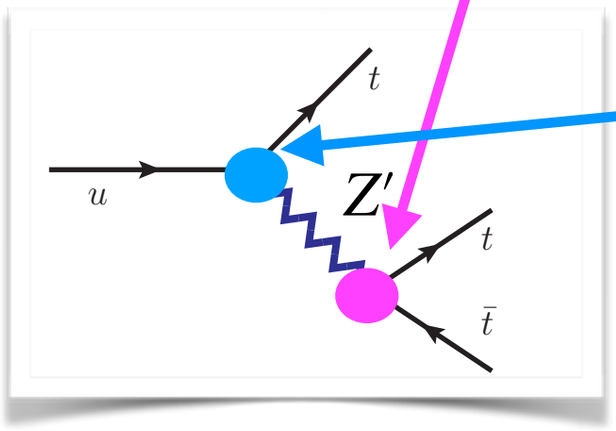
$$\mathcal{O}^{\mathcal{S}}_{tttt} = \frac{1}{2}\frac{(f^{\mathcal{S}}_{\mathrm{FCNI}})^2}{\Lambda^2}(\bar{t}t)(\bar{t}t)$$



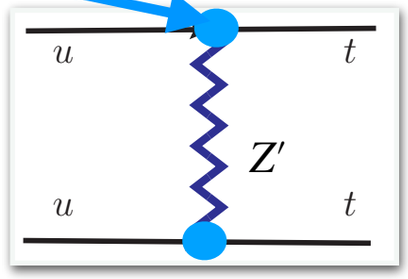


$\Lambda = 1$ TeV

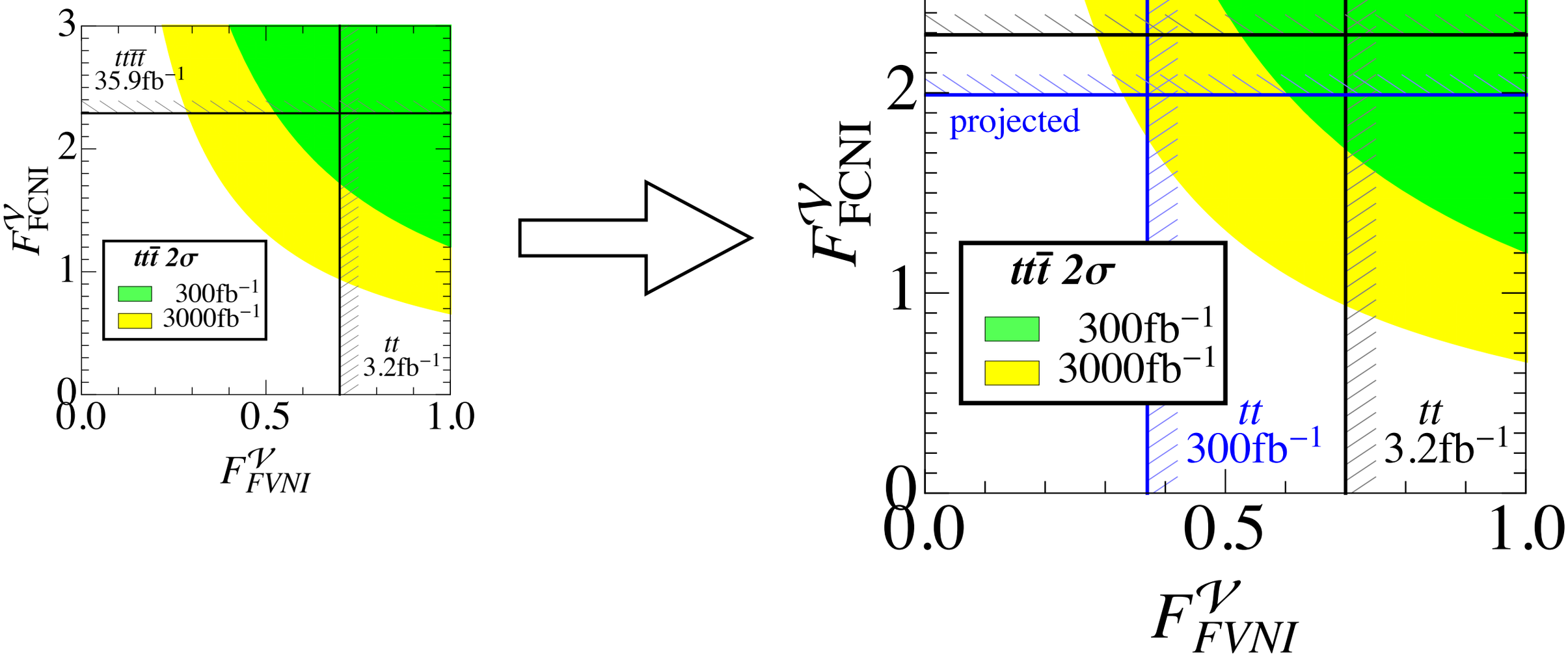
$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\mathrm{FVNI}} f^{\mathcal{V}}_{\mathrm{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$



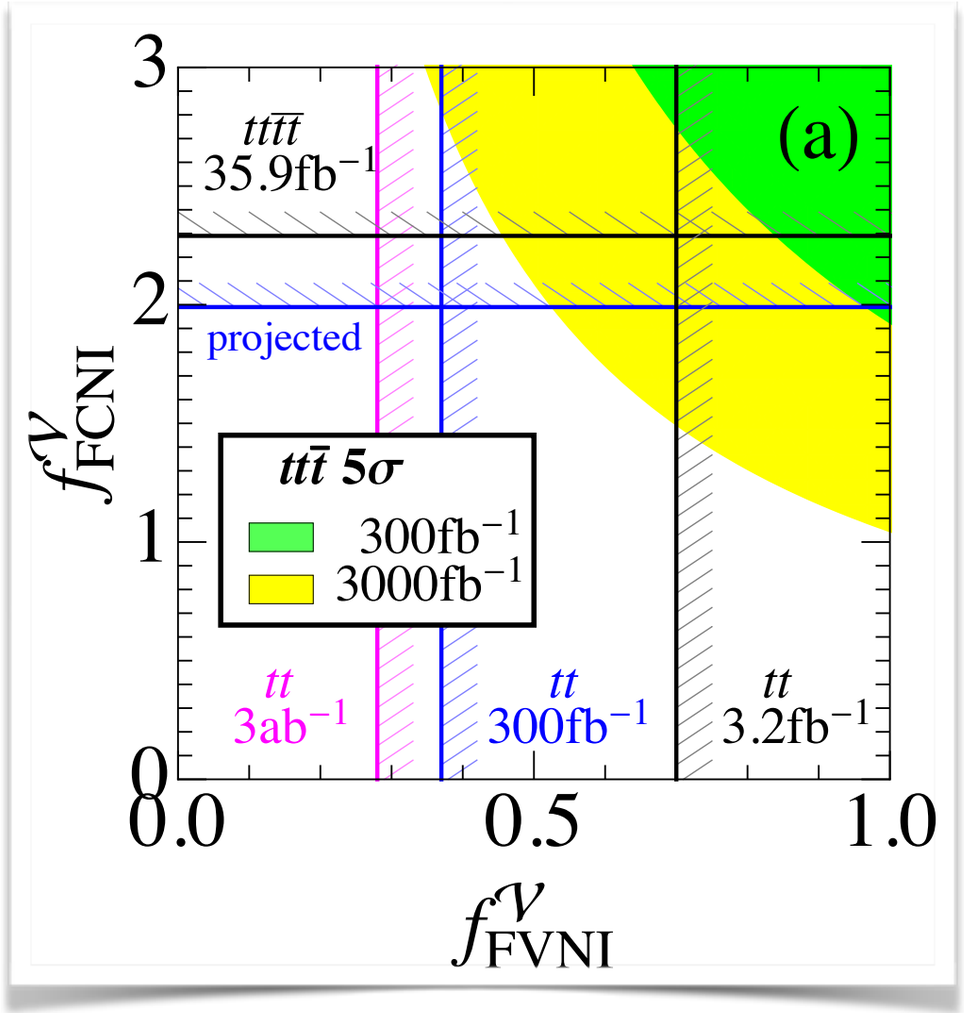
$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\mathrm{FVNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R u)(\bar{t}\gamma_{\mu}P_R u)$$

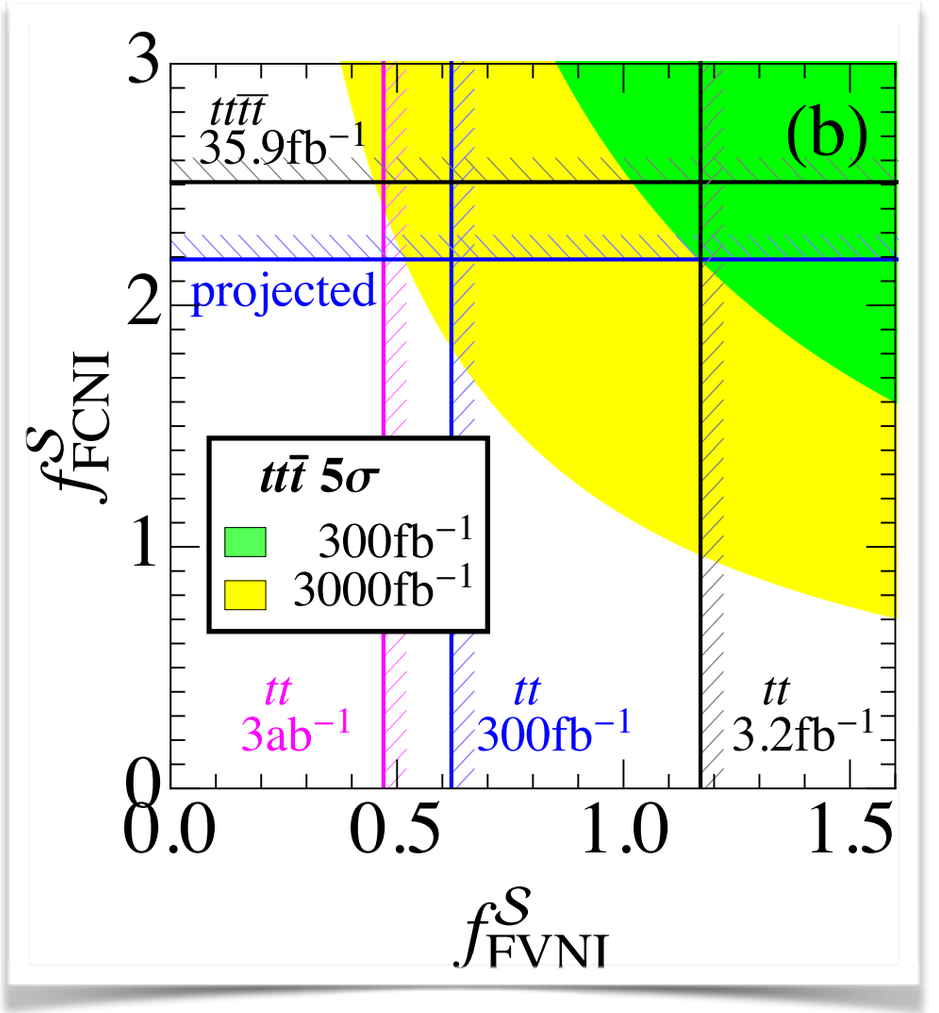


Combined Result and Correlation



More Result


(a)
$tt\bar{t}\bar{t}$
35.9fb^{-1}
projected
$tt\bar{t}$ 5σ
300fb^{-1}
3000fb^{-1}
tt
3ab^{-1}
tt
300fb^{-1}
tt
3.2fb^{-1}
$f_{\mathrm{FCNI}}^{\mathcal{V}}$
$f_{\mathrm{FVNI}}^{\mathcal{V}}$
0.0
0.5
1.0
0
1
2
3


(b)
$tt\bar{t}\bar{t}$
35.9fb^{-1}
projected
$tt\bar{t}$ 5σ
300fb^{-1}
3000fb^{-1}
tt
3ab^{-1}
tt
300fb^{-1}
tt
3.2fb^{-1}
$f_{\mathrm{FCNI}}^{\mathcal{S}}$
$f_{\mathrm{FVNI}}^{\mathcal{S}}$
0.0
0.5
1.0
1.5
0
1
2
3

Summary

- Triple top-quark production is unique for probing top-quark FCNC, as it unambiguously requires top-quark FCNC
- Except for FCNC, top flavor conserving vertex must coexist in the triple top-quark production
- Processes are correlated, e.g., triple top-quark, same-sign top and four top-quark productions

Thanks