Flavor physics in di- and trilepton events from single-top production at the LHC

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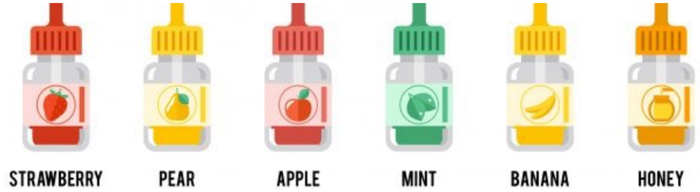
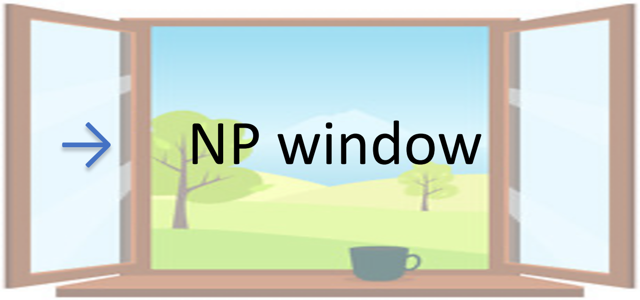
(presenter)

Flavor physics



SM: GIM suppressed (FCNC) → NP window

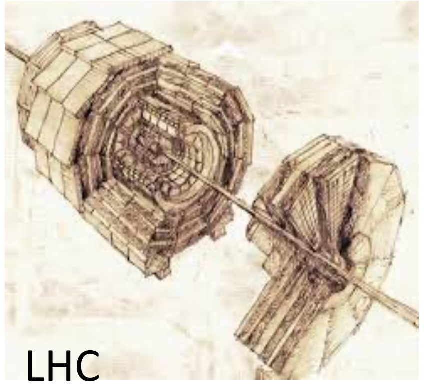


NP:

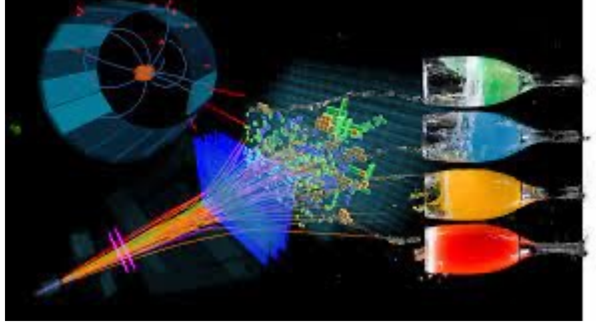
Top quark

? $$\Gamma \sim \frac{m_t}{8\pi} \times \mathcal{O}(m_t/\Lambda)^4$$

✓ $$\sigma \propto \left(s/\Lambda^2\right)^n$$



Flavor & top @ the LHC

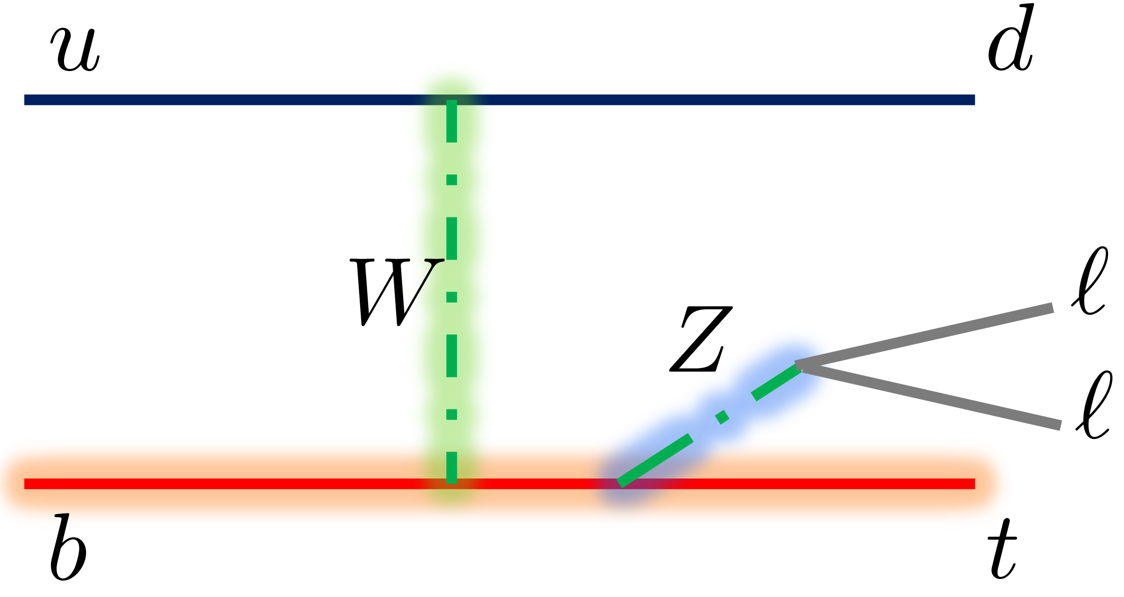


No significant irreducible SM background

$$pp \to \left\{ \begin{array}{l} \ell^+\ell^- + t \\ \ell^+\ell^- + t + j \end{array} \right\} \longrightarrow \left\{ \begin{array}{l} \ell'\ell^+\ell^- + X \\ \ell^+\ell^- + j_b + X \end{array} \right.$$

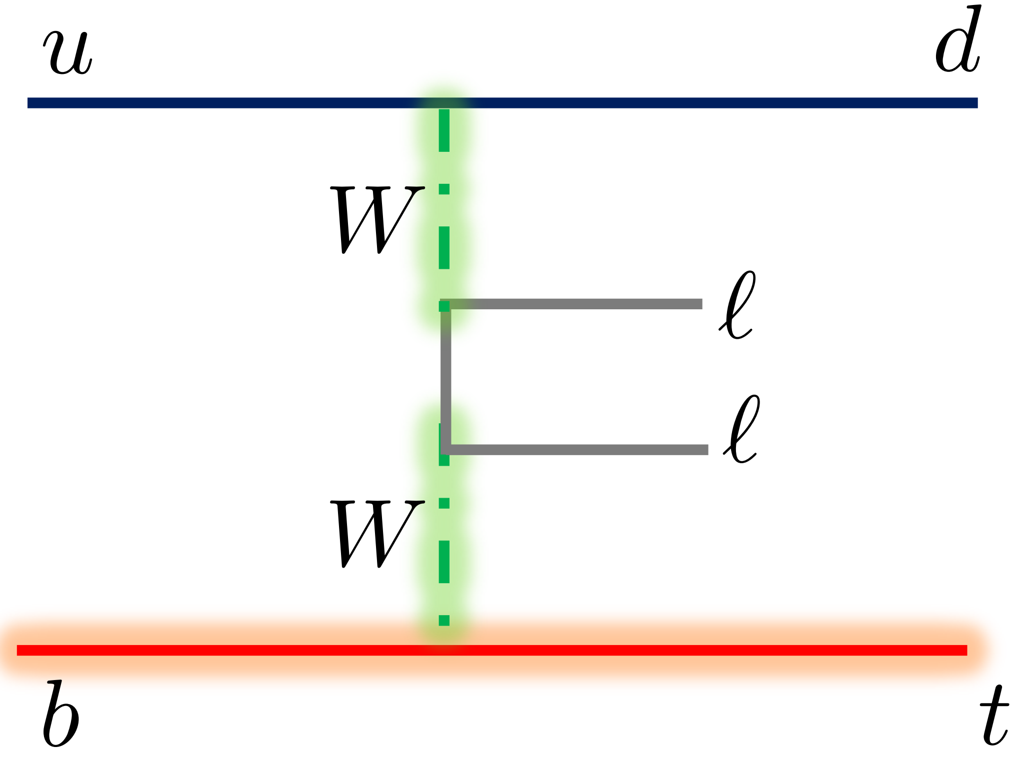
Significant irreducible SM background

SM background for $tj\ell\ell$



'resonant'

Non-resonant



New Physics (NP)

Will assume that the NP

- Is not directly produced (seen through virtual effects only)
- It is weakly coupled
- It is decoupling
- It is described by a gauge theory with scalars, vectors & fermions
- It has a typical scale Λ > v ~ 246 GeV

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i O_i^{(n)}$$

Tree level generated operators dominate

For this process: no dimension 5 operator

Lower dimension operators dominate

A few observations

- Leading operators have dimension 6: $\mathcal{L}_{\tt eff} \sim {\tt SM} + 1/\Lambda^2$
- The basis of operators is not unique – the S-matrix is

  I'll use the Warsaw basis

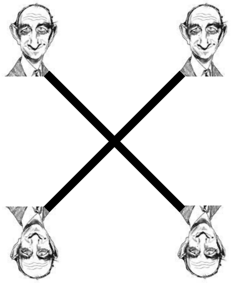
- Loop-generated (LG) operators are known
- Non-LG operators may be tree-generated … but may not: depends on the NP

  → I'll call them Potentially Tree Generated (PTG) operators

- For this calculation: PTG operators with *t* → *u* flavor-changing couplings

  (will not be sensitive to flavor changing *W* and *Z* couplings: Λ too large)

The NP: 4-fermi interactions



$$\mathcal{O}^{(1)}_{\mathtt{lq}} = (\bar{l}\gamma_\mu l')(\bar{q}_{\mathtt{u}}\gamma^\mu q_{\mathtt{t}})$$

$$\mathcal{O}^{(3)}_{\mathtt{lq}} = (\bar{l}\,\tau^I\,\gamma_\mu l')(\bar{q}_{\mathtt{u}}\,\tau^I\,\gamma^\mu q_{\mathtt{t}})$$

$$\mathcal{O}^{(1)}_{\mathtt{eu}} = (\bar{e}\gamma_\mu e')(\bar{u}\gamma^\mu t)$$

$$\mathcal{O}^{(1)}_{\mathtt{lu}} = (\bar{l}\gamma_\mu l')(\bar{u}\gamma^\mu t)$$

$$\mathcal{O}^{(1)}_{\mathtt{eq}} = (\bar{e}\gamma_\mu e')(\bar{q}_{\mathtt{u}}\gamma^\mu q_{\mathtt{t}})$$

$$\mathcal{O}^{(1)}_{\mathtt{lequ}} = (\bar{l}e')\varepsilon(\bar{q}_{\mathtt{u}}t)$$

$$\mathcal{O}^{(3)}_{\mathtt{lequ}} = (\bar{l}\sigma_{\mu\nu}e')\varepsilon(\bar{q}_{\mathtt{u}}\sigma^{\mu\nu}t)$$

Dictionary:

l	:	LH e, μ lepton doublets (will not use τ)
$q_{\mathtt{u}}$	:	LH $u-d$ quark doublet
$q_{\mathtt{t}}$	:	LH $t-b$ quark doublet
e	:	RH e, μ lepton singlets (will not use τ)
$q_{\mathtt{u}}$	:	RH u quark singlet
t	:	RH t quark singlet

Equivalently:

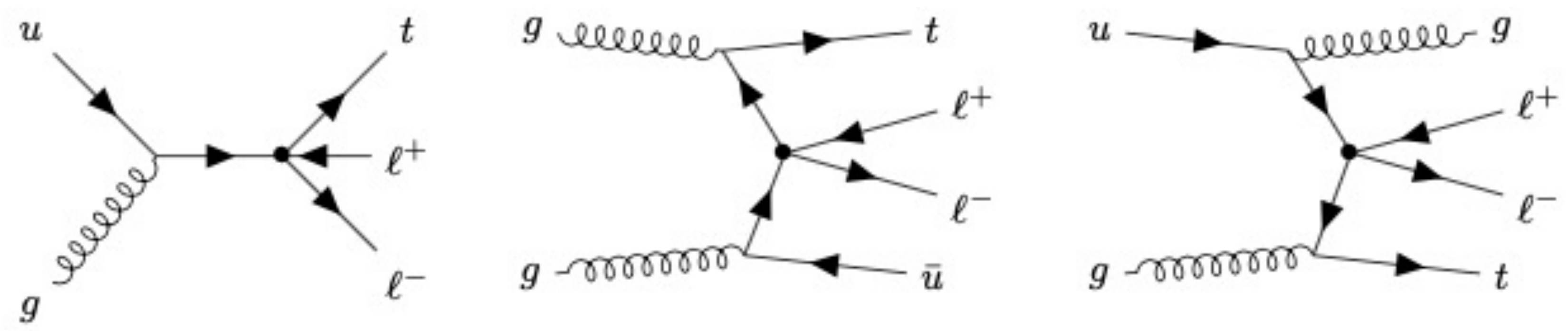
$$\mathcal{L}_{\mathtt{tu}\ell\ell} = \frac{1}{\Lambda^2} \sum_{i,j=L,R} \left[V_{ij}^{\ell} \left(\bar{\ell}\gamma_\mu P_i \ell\right) \left(\bar{t}\gamma^\mu P_j u\right) + S_{ij}^{\ell} \left(\bar{\ell} P_i \ell\right) \left(\bar{t} P_j u\right) + T_{ij}^{\ell} \left(\bar{\ell}\sigma_{\mu\nu} P_i \ell\right) \left(\bar{t}\sigma_{\mu\nu} P_j u\right) \right]$$

Correspondence:

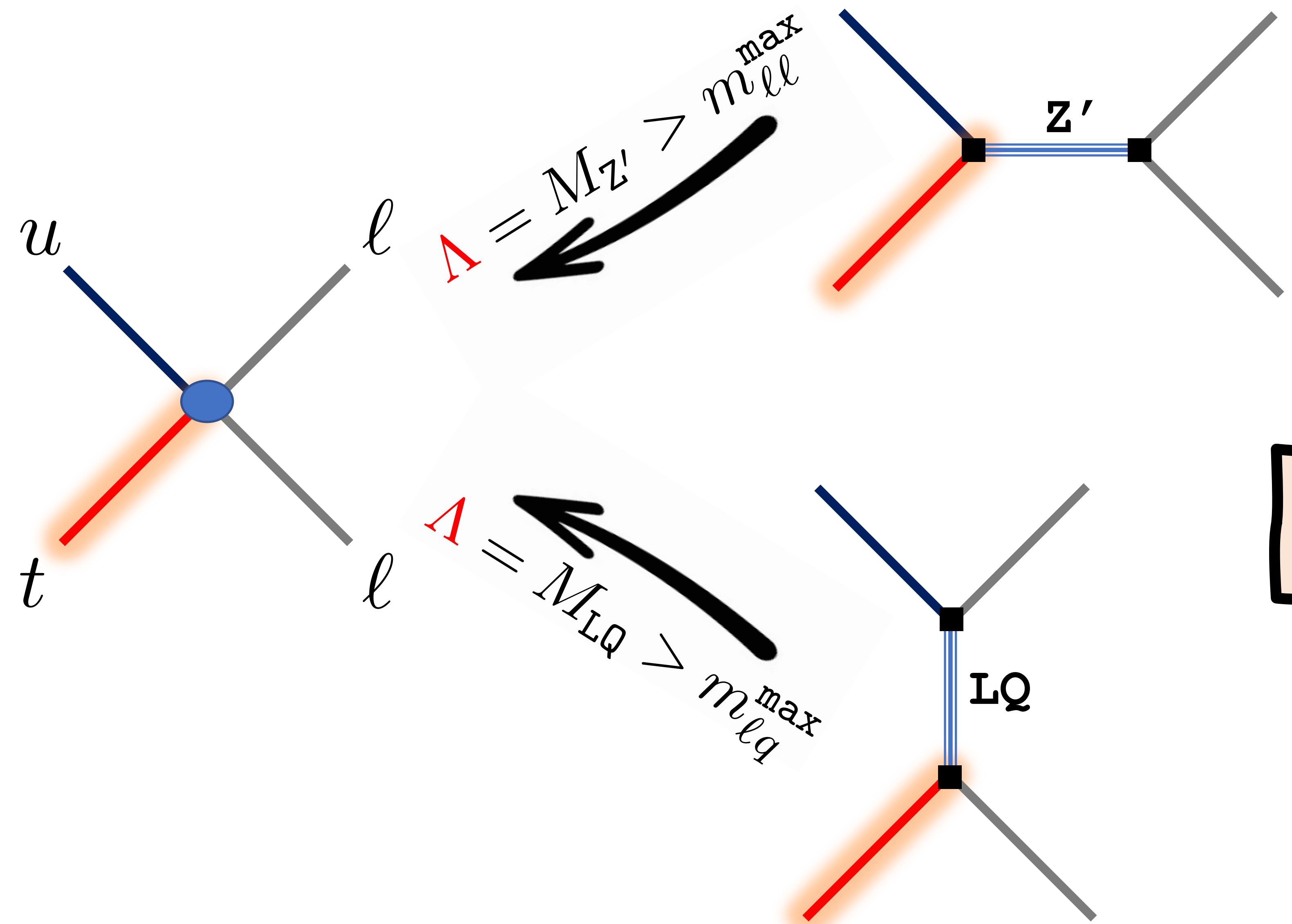
$$V_{LL} = \alpha_{\ell q}^{(1)} - \alpha_{\ell q}^{(3)} \ , \ V_{LR} = \alpha_{\ell u} \ , \ V_{RR} = \alpha_{eu} \ , \ V_{RL} = \alpha_{qe}$$

$$S_{RR} = -\alpha_{\ell equ}^{(1)} \ , \ S_{LL} = S_{LR} = S_{RL} = 0 \ ,$$

$$T_{RR} = -\alpha_{\ell equ}^{(3)} \ , \ T_{LL} = T_{LR} = T_{RL} = 0$$



Applicability of the EFT



✓ EFT: $\Lambda > m_{\ell\ell}^{\mathtt{max}}$ or $m_{\ell q}^{\mathtt{max}}$

Effects

signal	$\ell\,\ell\,t\,u/c$ 4-fermi type					
	S_{RR}	T_{RR}	V_{RR}	V_{LL}	V_{RL}	V_{LR}
$pp \to t\ell\ell/t\ell\ell + j$	✓	✓	✓	✓	✓	✓
$pp \to t\ell + \not{E}_T/t\ell + j + \not{E}_T$	✓	✓		✓		
$pp \to t + \not{E}_T/t + j + \not{E}_T$				✓		✓
b/B-physics	✓	✓		✓	✓	

Due to gauge invariance. Example: B anomalies require

$$\alpha_{\mathtt{lq}}^{(1)} \simeq \alpha_{\mathtt{lq}}^{(3)} \quad \text{or} \quad \Lambda \simeq 40\,\mathrm{TeV}$$

Examples of underlying physics

Du-jour favorites: leptoquarks. For example:

R_2 and/or U_1 that can address the R_K, R_D and g-2 anomalies, and

$$R_2^i \left(z^* \bar{q}^i e - y \bar{u} \varepsilon_{ij} \ell^j \right) \left\{ \begin{array}{l} \alpha_{\mathtt{eq}} = -\frac{1}{2}|z|^2 \;,\; \alpha_{\ell\mathtt{u}} = \frac{1}{2}|y|^2 \\ \alpha_{\mathtt{lequ}}^{(1)} = 4\alpha_{\mathtt{lequ}}^{(3)} = -\frac{1}{2} yz \end{array} \right. \qquad (\Lambda = M_{\mathtt{LQ}})$$

$$x \bar{q} \gamma_\mu U_1^\mu \ell \left\{ \alpha_{\mathtt{lq}}^{(1)} = \alpha_{\mathtt{lq}}^{(3)} = -\frac{1}{2}|x|^2 \right.$$

Signal & background

Will use the integrated cross section …

$$\sigma(m_{\ell\ell}^{\tt min}) = \int_{m_{\ell\ell} \ge m_{\ell\ell}^{\tt min}} dm_{\ell\ell} \frac{d\sigma}{dm_{\ell\ell}}$$

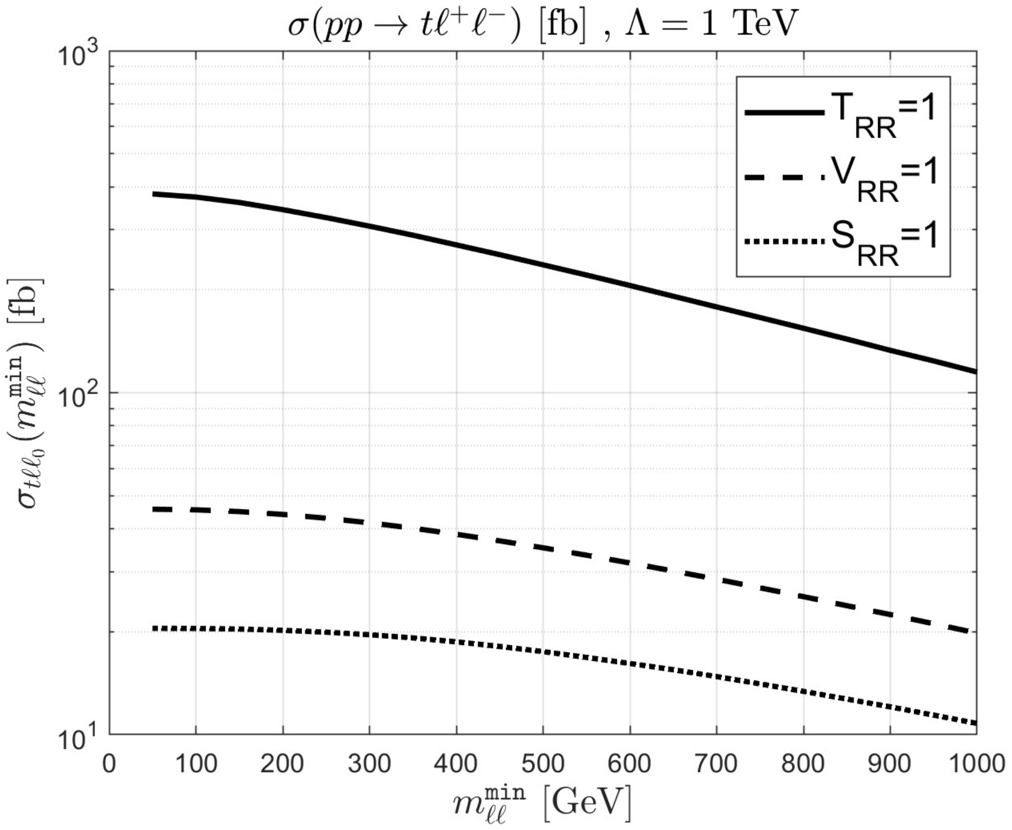
… where, since there is no SM-NP interference (different initial states),

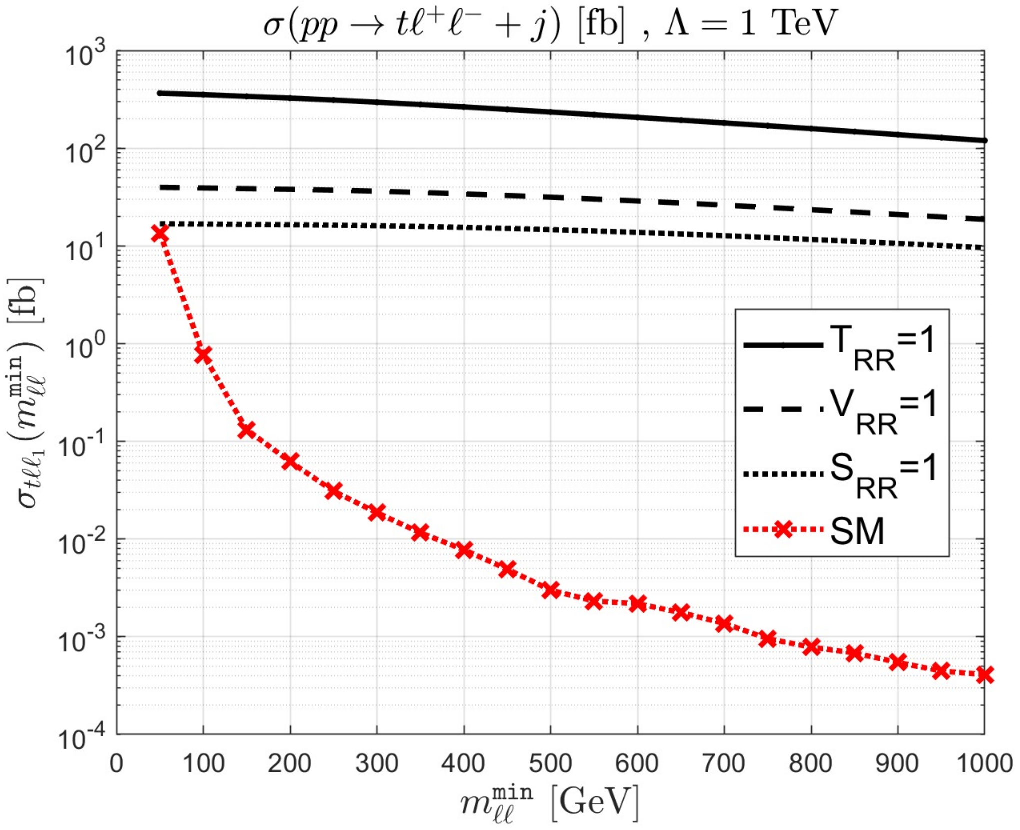
$$\sigma_{t\ell\ell_j}(m_{\ell\ell}^{\tt min}) = \sigma_{t\ell\ell_j}^{\tt SM}(m_{\ell\ell}^{\tt min}) + \frac{f^2}{\left(\Lambda/\left[{\tt TeV}\right]\right)^4} \cdot \sigma_{t\ell\ell_j}^{\tt NP}(m_{\ell\ell}^{\tt min})$$

$f = S, V, T$

j = # of light jets in the final state, in particular

$\sigma_{t\ell\ell_0}^{\tt SM} \simeq 0$





Different values:
rescale by f^2/Λ^4

Used MadGraph5_aMC@NLO, FeynRules and LO MSTW 2008 PDF's (5-flavor scheme)

We use tri and di-lepton signals

labels

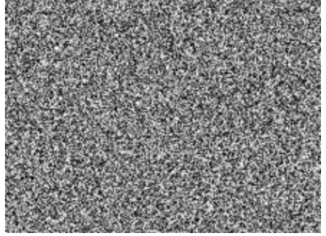
$$pp \to \left\{ \begin{array}{l} \ell^+\ell^- + t + j \\ \\ \ell^+\ell^- + t \end{array} \right\} \longrightarrow \left\{ \begin{array}{ll} \ell^+\ell^- + j_b + X & (\ell\ell 1b) \\ \\ \ell'\ell^+\ell^- + X & (\ell'\ell\ell) \end{array} \right.$$

$$\ell'\ell\ell : t \to bW \to b\ell'\nu_{\ell'}$$

For this talk:

$$\begin{array}{ll} \ell\ell 1b : & \mu^+\mu^- + j_b + X \\ \ell'\ell\ell : & e^\pm\mu^+\mu^- + X \end{array}$$

Backgrounds



Main

$$t\bar{t}: \quad pp \to t\bar{t} \to \mu^+\mu^- + 2j_b + \not{E}_T$$

$$Z + \texttt{jets}: \quad pp \to \mu^+\mu^- + \texttt{jets}$$

+ non-prompt/fake lepton

Subdominant

VV

- WZ: $pp \to W\mu^+\mu^-$ & $W \to e\nu_e$
- ZZ: $pp \to Z\mu^+\mu^-$ & $Z \to e^+e^-$ (one e not tracked)

Wt

- tW: $pp \to tW \to tW \to \mu^\pm\mu^\mp + j_b + 2j + \not{E}_T$ (+ non-prompt e)
- $t\bar{t}W$: $pp \to t\bar{t}\mu^\pm\nu_\mu$ & $t\bar{t} \to e^\pm\mu^\mp + 2j_b + \not{E}_T$
  $pp \to t\bar{t}e^\pm\nu_e$ & $t\bar{t} \to \mu^+\mu^- + 2j_b + \not{E}_T$
- $t\bar{t}Z$: $pp \to t\bar{t}\mu^+\mu^-$ & $t\bar{t} \to e^\pm + 2j_b + 2j + \not{E}_T$
- $t\bar{W}Z$: $pp \to tWZ$ & $Z \to \mu^+\mu^-$, $tW \to e^\pm + j_b + 2j + \not{E}_T$

Uncertainties 

<u>Theoretical:</u>

- NLO-QCD corrections
- EW corrections
- PDF choice
- Renormalization & factorization scales

(related calculations) → $\mathcal{O}(10\%)$

<u>Experimental:</u>

Unknown, esp. for $m_{\ell\ell}^{\texttt{min}} > 1\,\mathrm{TeV}$ → $\geq 20\ e\mu\mu$ events with $m_{\mu\mu}^{\texttt{min}} > 1\,\mathrm{TeV}$ ($\sim$ background free)

$$\frac{f^2}{(\Lambda/[\ \texttt{TeV}])^4} \cdot \sigma_{e\mu\mu}^{\mathrm{NP}}(m_{\mu\mu}^{\texttt{min}}) \cdot \mathcal{L} \geq 20$$

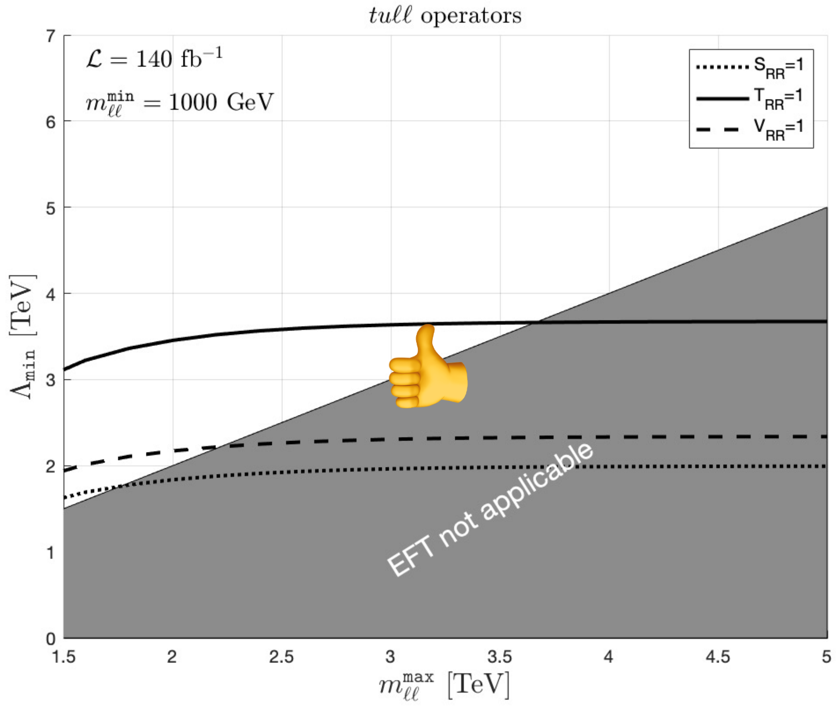
$$\left[\sigma_{t\mu\mu_0}^{\mathrm{NP}}(m_{\mu\mu}^{\texttt{min}}) + \sigma_{t\mu\mu_1}^{\mathrm{NP}}(m_{\mu\mu}^{\texttt{min}})\right] \cdot \mathrm{BR}(t \to be\nu_e)$$

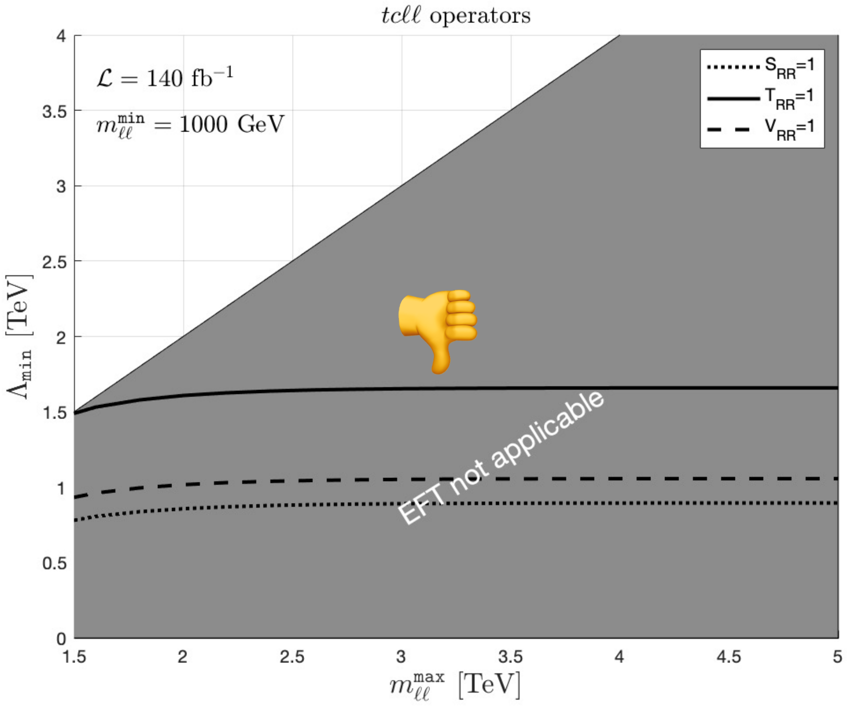
Results

Source	Coupling	Number of inclusive $pp \to e\mu^+\mu^- + X$ signal events/100 fb^{-1}, $\Lambda = 1$ TeV			
		$m^{\mathtt{min}}_{\mu^+\mu^-} = 100$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 300$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 500$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 1000$ Ge
$\boldsymbol{tu\mu\mu}$ **4-Fermi**	$S_{RR} = 1$	399	382	342	215
	$T_{RR} = 1$	7937	6568	5117	2539
	$V_{RR} = 1$	916	841	716	409
$\boldsymbol{tc\mu\mu}$ **4-Fermi**	$S_{RR} = 1$	29	25	20	9
	$T_{RR} = 1$	711	481	318	108
	$V_{RR} = 1$	75	60	44	18
$pp \to t\mu^+\mu^- j$	SM irreducible	8	0	0	0

Number of background $pp \to e\mu\mu + X$ events/140 fb^{-1}

sub-process	$m^{\mathtt{min}}_{\mu^+\mu^-} = 500$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 1000$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 1500$ GeV	$m^{\mathtt{min}}_{\mu^+\mu^-} = 2000$ GeV
$t\bar{t}$	78.2	1.6	0.1	0.0
$Z + \mathtt{jets}$	16.5	1.3	0.2	0.0
VV	7.1	1.0	0.2	0.1
Wt	9.5	0.2	0.0	0.0
Total $e\mu\mu$ Background events	111.8	4.1	0.5	0.1





High-luminosity LHC:

	Expected bounds on Λ [TeV], $m_{\mu^+\mu^-}^{min} = 1000$ GeV		
	Coupling	**$tu\mu\mu$ 4-Fermi case**	**$tc\mu\mu$ 4-Fermi case**
$\mathcal{L} = 3000$ fb^{-1}	$S_{RR} = 1$	4.3	1.8
	$T_{RR} = 1$	7.9	3.6
	$V_{RR} = 1$	5.0	2.2

Parting comments

- In a more realistic study the sensitivity to Λ is slightly reduced (5 -10 %)
- 5σ discovery limits for Λ can also be obtained

	Operator	$tu\mu\mu$ 4-Fermi case		
	Coupling	$m^{\mathtt{min}}_{\mu^+\mu^-}$ [GeV]	$\Lambda(5\sigma)$ [TeV]	$\Lambda_{\mathtt{min}}$(95% CL [TeV]
$\mathcal{L} = 140$ fb^{-1}	$S_{RR} = 1$	1500	2.1	2.8
	$T_{RR} = 1$		3.7	5.0
	$V_{RR} = 1$		2.4	3.2
$\mathcal{L} = 3000$ fb^{-1}	$S_{RR} = 1$	2000	3.1	4.1
	$T_{RR} = 1$		5.3	7.1
	$V_{RR} = 1$		3.5	4.7

- Lepton flavor universality can also be probed


THANK
YOU