multi-leptons probes of NP & lepton flavor universality @ top - systems

ICHEP2022 - BSM
7/7/2022

Based on:

"Tri- and four-lepton events as a probe for new physics in ttll contact interactions"
NPB (2022), 115849, arxiv: 2111.13711, Afik(CERN), SBS(Technion), Pal(UCR), Soni(BNL), Wudka(UCR)

"New flavor physics in di- and trilepton events from single-top production at the LHC and beyond",
PRD103 (2021), 075031, arxiv: 2101.05286, Afik, SBS, Soni, Wudka

"High pT correlated tests of lepton universality in lepton(s) + jet(s) processes; An EFT analysis",
PLB811 (2020), 135908, arxiv: 2005.06457, Afik, SBS, Cohen (Technion), Soni, Wudka

Shaouly Bar-Shalom
shaouly@physics.technion.ac.il

multi-leptons signals – a window to NP

$$(1\ell) : pp \to \ell^\pm + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(2\ell) : pp \to \ell'^+ \ell''^- + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(3\ell) : pp \to \ell'^\pm \ell^+ \ell^- + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(4\ell) : pp \to \ell'^\pm \ell''^\mp \ell^+ \ell^- + n \cdot j_b + m \cdot j + \not{E}_T + X$$

- Rich & clean signals in the hadronic environment of the LHC

- Excellent test ground for NP (e.g., in pp → ttV, ttH, tV, tttt …):
    - Sensitive to many types of underlying NP

(lepton-flavor violation, lepton universality violation,
lepton-number violation - same sign leptons, CP violation …)

    - easy to construct observables with charged leptons

    - High-E/p_T (TeV energies …) leptons still relatively unexplored

- Allows flavor-blind searches of flavor-changing underlying NP

- Correlated multi-lepton channels due to common underlying NP !

multi-leptons signals – a window to NP

- Example: multi-leptons + top-quarks signals

- Source: SU(2) triplet 4-Fermi involving 3rd gen quarks and muons

$$\boxed{\mathcal{O}^{(3)}_{\ell q}(3322) = \left(\bar{q}_3 \gamma^\mu \tau^I q_3\right)\left(\bar{\ell}_2 \gamma_\mu \tau^I \ell_2\right)}$$

Dilepton + $jets/t$

$(010)_{\mu\mu} : pp \to \mu^+\mu^- + j_b$

$(110)_{\mu\mu} : pp \to \mu^+\mu^- + j + j_b$

$(020)_{\mu\mu} : pp \to \mu^+\mu^- + 2 \cdot j_b$

$(002)_{\mu\mu} : pp \to \mu^+\mu^- + t\bar{t}$

$\mathcal{O}^{(3)}_{lq}$

$(010)_{\not E_T} : pp \to j_b + \not E_T$

$(110)_{\not E_T} : pp \to j + j_b + \not E_T$

$(020)_{\not E_T} : pp \to 2 \cdot j_b + \not E_T$

$(002)_{\not E_T} : pp \to t\bar{t} + \not E_T$

$jets/t$ + MET

$(001)_{\mu} : pp \to \mu^\pm + t + \not E_T$

$(101)_{\mu} : pp \to \mu^\pm + j + t + \not E_T$

$(011)_{\mu} : pp \to \mu^\pm + j_b + t + \not E_T$

Single-lepton + $jets/t$ + MET

- Use correlations to gain sensitivity to NP
- i.e., amonng no-lepton, mono-lepton & di-lepton signals of single-top production

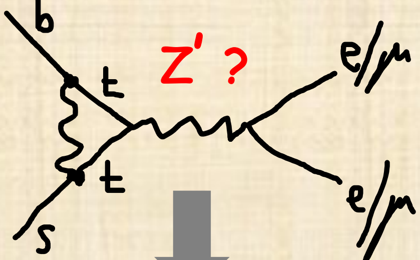
"High pT correlated tests of lepton universality in lepton(s) + jet(s) processes; An EFT analysis",
PLB(2020), 135908, arxiv: 2005.06457, Afik, SBS, Cohen, Soni, Wudka

Some hints for NP in multi-lepton – top-quark systems ?
with typical scale of NP around the TeV ...

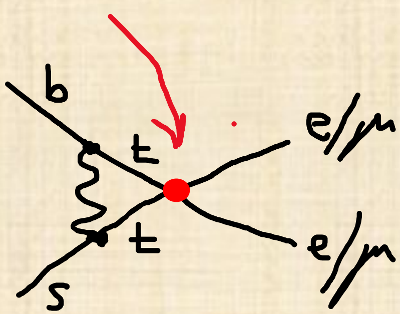
heavy states around the TeV-scale generate top-leptons 4-Fermi

B-anomalies

Kamenik,Soreq,Zupan PRD2018 (1704.06005);
Camargo-Molina,Celis,Faroughy PLB2018 (1805.04917);
Ciuchini,Coutinho,Fedele,Franco,Paul,Silvestrini,Valli, EPJC2019 (1903.09632)

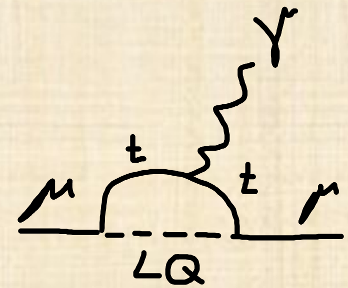


Required scale:
Λ~ O(1) TeV !

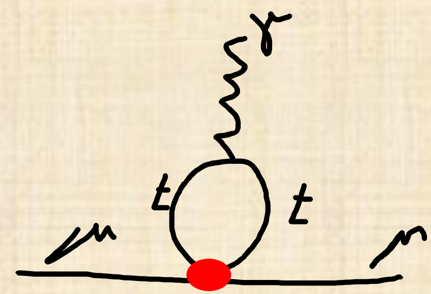


Underlying physics ...

muon g-2 anomaly



e.g., a tensor ttll 4-Fermi term
with Λ ~ few TeV



Our EFT parameterization for NP in top/bottom systems:

Vector Scalar Tensor

$$\mathcal{L}_{q_3 q_i \ell\ell} = \frac{1}{\Lambda_\ell^2} \sum_{i,j=L,R} \Big[V_{ij}^\ell \left(\bar{\ell}\gamma_\mu P_i \ell\right)\left(\bar{q}_3 \gamma^\mu P_j q_i\right) + S_{ij}^\ell \left(\bar{\ell} P_i \ell\right)\left(\bar{q}_3 P_j q_i\right) + T_{ij}^\ell \left(\bar{\ell}\sigma_{\mu\nu} P_i \ell\right)\left(\bar{q}_3 \sigma_{\mu\nu} P_j q_i\right) \Big]$$

can be generated through tree-level exchanges of heavy vectors & scalars (or their Fierz transforms).

Assume: $\Lambda(ll) \ll \Lambda(ll')$

Dictionary:

ℓ	:	LH e, μ lepton doublet
q	:	LH quark doublet
q_3	:	LH $t - b$ doublet
P_L/P_R	:	LH/RH projection doublet

Typical bounds on such 4-Fermi interactions with 1st & 2nd gen quarks are
Λ > O(10 TeV) – recent di-lepton searches give Λ > 20-30 TeV

Matching - SMEFT (e.g., top-quark 4-Fermi):

$4-\text{Fermi}:(\bar{L}L)(\bar{L}L)$	
$\mathcal{O}_{lq}^{(1)}(prst)$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$\mathcal{O}_{lq}^{(3)}(prst)$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

V_{LL}

$4-\text{Fermi}:(\bar{R}R)(\bar{R}R)$	
$\mathcal{O}_{eu}(prst)$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$

V_{RR}

$4-\text{Fermi}:(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{lu}(prst)$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qe}(prst)$	$(\bar{e}_p\gamma^\mu e_r)(\bar{q}_s\gamma_\mu q_t)$

V_{LR}

V_{RL}

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

$4-\text{Fermi}:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$\mathcal{O}_{lequ}^{(1)}(prst)$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$\mathcal{O}_{lequ}^{(3)}(prst)$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

S_{RR}

T_{RR}

e,u,d = RH singlets ...

$$\mathcal{L}_{q_3q_i\ell\ell}=\frac{1}{\Lambda_\ell^2}\sum_{i,j=L,R}\left[V_{ij}^\ell\left(\bar{\ell}\gamma_\mu P_i\ell\right)\left(\bar{q}_3\gamma^\mu P_j q_i\right)+S_{ij}^\ell\left(\bar{\ell}P_i\ell\right)\left(\bar{q}_3P_jq_i\right)+T_{ij}^\ell\left(\bar{\ell}\sigma_{\mu\nu}P_i\ell\right)\left(\bar{q}_3\sigma_{\mu\nu}P_jq_i\right)\right]$$

Current sensitivities (bounds ...)

what do we know about the dim.6 (2t)(2l) & (tu)(2l) opts

Flavor changing
(tu)(2l)

LEP: Λ(tuee) > 0.5 – 1.5 TeV
(depending on Lorentz structure)
SBS,Wudka PRD1999
PLB2002 (0210041) ; EPJC2011 (1102.4455)

LHC (pp → tt followed by t → μμ + jet):
Λ(tuμμ) ~ Λ(tuee) > ~ 0.4 – 1 TeV
(depending on Lorentz structure)

Chala,Santiago,Spannowsky JHEP2019 (1809.09624)
also studied in:
Davidson,Mangano,Perries,Sordini EPJC2015 (1507.07163)
Durieux,Maltoni,Zhang PRD2015 (1412.7166)
Aguilar-Saavedra NPB2011 (1008.3562)
Boughezal,Chen,Petriello,Wiegand PRD2019 (1907.00997)

Flavor diagonal
(2t)(2l)

LHC: Λ > ~ 0.5 TeV (scalar,vector: S,V =1)
Λ > ~ 1 TeV (tensor: T=1)

CMS: from pp → tt+leptons search
JHEP2021 (2012.04120)

ATLAS: our reinterpretation of pp → 3l & 4l measurements in 2107.00404

B-physics(bb → ee, μμ) + gauge invariance: bbll → ttll for opts with left handed quark isodoublets (V_{LL} and V_{RL})
Λ > ~ 2 TeV (V_{LL},V_{RL} =1)

Greljo,Marzocca, EPJ2017 (1704.09015)

collider signatures of ttll & tull contact terms

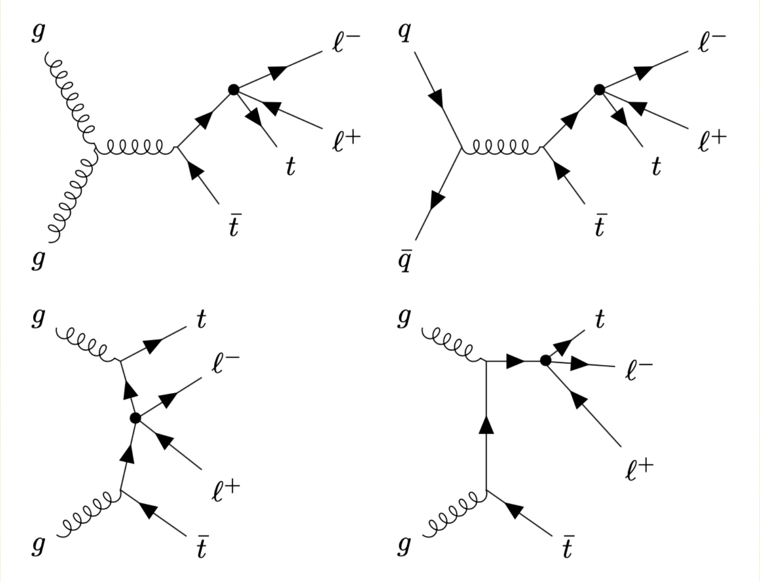
Vector Scalar Tensor

$$\mathcal{L}_{q_3 q_i \ell\ell} = \frac{1}{\Lambda_\ell^2} \sum_{i,j=L,R} \left[V_{ij}^\ell \left(\bar{\ell}\gamma_\mu P_i \ell\right) \left(\bar{q}_3 \gamma^\mu P_j q_i\right) + S_{ij}^\ell \left(\bar{\ell} P_i \ell\right) \left(\bar{q}_3 P_j q_i\right) + T_{ij}^\ell \left(\bar{\ell}\sigma_{\mu\nu} P_i \ell\right) \left(\bar{q}_3 \sigma_{\mu\nu} P_j q_i\right) \right]$$

ttll: flavor diagonal

NPB2022 (2111.13711), Afik, SBS, Pal, Soni, Wudka
PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

$$pp \to t\bar{t}\ell^+\ell^- \ ,$$
$$pp \to t(\bar{t})\ell^+\ell^- + j_b + j$$

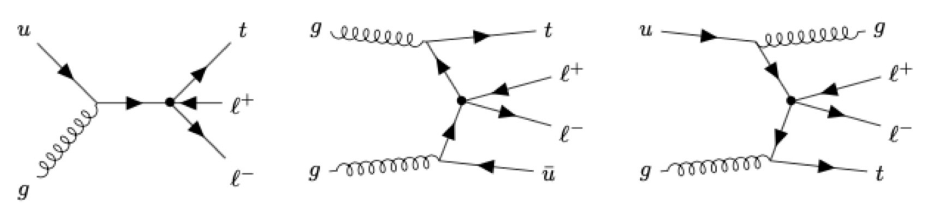


NP signals

tull: flavor changing

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

$$pp \to \ell^+\ell^- + t \ ,$$
$$pp \to \ell^+\ell^- + t + j$$



ttll: flavor diagonal

NPB2022 (2111.13711), Afik, SBS, Pal, Soni, Wudka
PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

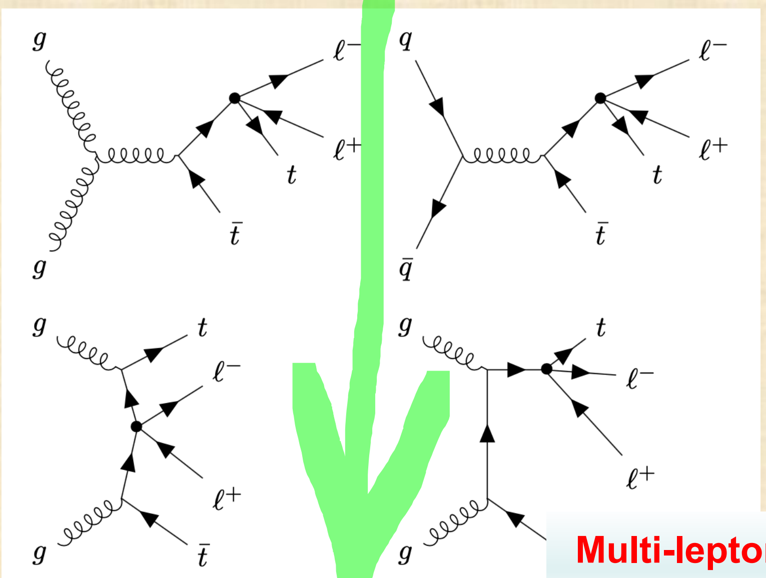
tull: flavor changing

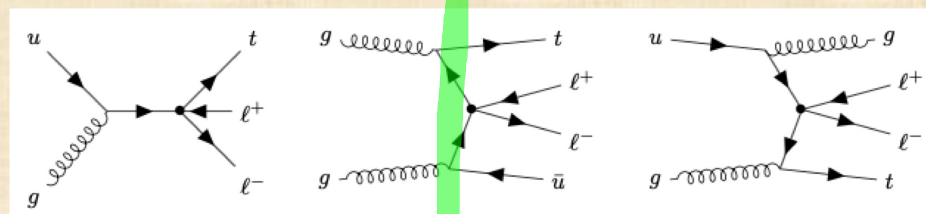
PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

NP signals

$$pp \to t\bar{t}\ell^+\ell^- \ ,$$
$$pp \to t(\bar{t})\ell^+\ell^- + j_b + j$$

$$pp \to \ell^+\ell^- + t \ ,$$
$$pp \to \ell^+\ell^- + t + j$$





Multi-leptons signals - channels

$$(tt\ell\ell)_{2\ell} \equiv pp \to \ell^+\ell^- + 2\cdot j_b + 4\cdot j \ ,$$
$$(tt\ell\ell)_{3\ell} \equiv pp \to \ell'^{\pm}\ell^+\ell^- + 2\cdot j_b + 2\cdot j + \not{E}_T \ ,$$
$$(tt\ell\ell)_{4\ell} \equiv pp \to \ell'^{\pm}\ell''^{\mp}\ell^+\ell^- + 2\cdot j_b + \not{E}_T \ ,$$
$$(t\ell\ell)_{2\ell} \equiv pp \to \ell^+\ell^- + 2\cdot j_b + 3\cdot j \ ,$$
$$(t\ell\ell)_{3\ell} \equiv pp \to \ell'^{\pm}\ell^+\ell^- + 2\cdot j_b + j + \not{E}_T \ ,$$

$$(t\ell\ell)_{2\ell} \equiv pp \to \ell^+\ell^- + j_b + 2/3\cdot j \ ,$$
$$(t\ell\ell)_{3\ell} \equiv pp \to \ell'^{\pm}\ell^+\ell^- + j_b + 0/1\cdot j + \not{E}_T$$

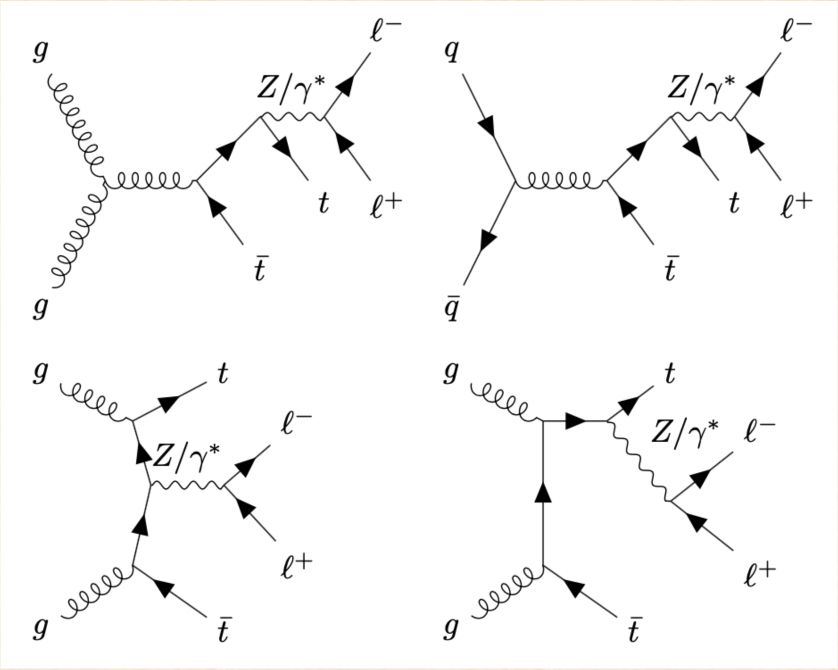
ttll: flavor diagonal

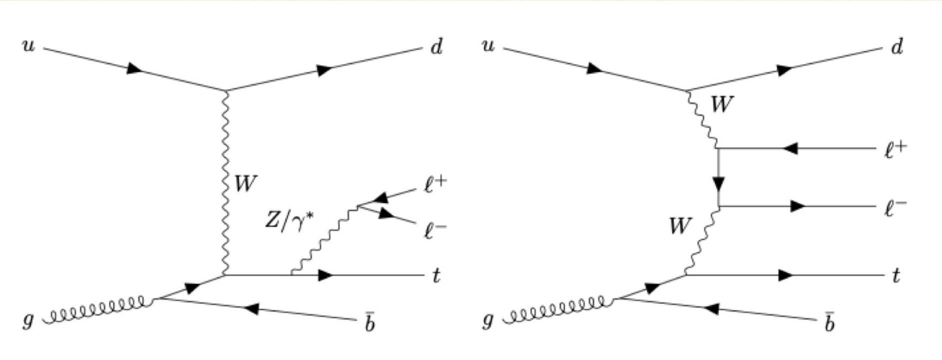
NPB2022 (2111.13711), Afik, SBS, Pal, Soni, Wudka
PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

tull: flavor changing

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

SM
(irreducible Backg)





ttll: flavor diagonal

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PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

tull: flavor changing

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

background

pp → tt, Z+jets, VV, ttV, tVV , followed by t and V decays …

Selections

Selection	2ℓ	3ℓ	4ℓ
Number of Leptons:	exactly 2	exactly 3	exactly 4
Jet multiplicity:	≥ 3	≥ 2	≥ 2
Number of b-jets:	≥ 1	≥ 1	≥ 1
$m_{\ell\ell}^{OSSF(nt)}$:		$> m_{\ell\ell}^{\texttt{min}}$	

$$(2\ell) : pp \to \ell^+\ell^- + n_{\geq 1}\cdot j_b + m_{\geq 3}\cdot j + X \ ,$$
$$(3\ell) : pp \to \ell'^{\pm}\ell^+\ell^- + n_{\geq 1}\cdot j_b + m_{\geq 2}\cdot j + X \ ,$$
$$(4\ell) : pp \to \ell'^{\pm}\ell''^{\mp}\ell^+\ell^- + n_{\geq 1}\cdot j_b + m_{\geq 2}\cdot j + X$$

Selection	2ℓ	3ℓ
Number of Leptons:	exactly 2	exactly 3
Jet multiplicity:	inclusive	
Number of b-jets:	$= 1$	inclusive
$m_{\ell\ell}^{OSSF}$:	$> m_{\ell\ell}^{\texttt{min}}$	

$$(\ell'\ell\ell) : pp \to \ell'\ell^+\ell^- + X \ ,$$
$$(\ell\ell 1b) : pp \to \ell^+\ell^- + j_b + X$$

m_{ll} (di-lepton inv-mass): a key discriminating parameter !

ttll: flavor diagonal

NPB2022 (2111.13711), Afik, SBS, Pal, Soni, Wudka
PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

tull: flavor changing

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

Dominant background after selections

2l: pp → tt
3l: pp → WZ
4l: pp → ZZ

pp → tt, Z+jets

Selections

Selection	2ℓ	3ℓ	4ℓ
Number of Leptons:	exactly 2	exactly 3	exactly 4
Jet multiplicity:	≥ 3	≥ 2	≥ 2
Number of b-jets:	≥ 1	≥ 1	≥ 1
$m_{\ell\ell}^{OSSF(nt)}$:		$> m_{\ell\ell}^{\mathtt{min}}$	

Selection	2ℓ	3ℓ
Number of Leptons:	exactly 2	exactly 3
Jet multiplicity:	inclusive	
Number of b-jets:	$= 1$	inclusive
$m_{\ell\ell}^{OSSF}$:	$> m_{\ell\ell}^{\mathtt{min}}$	

$$(2\ell) : pp \to \ell^+\ell^- + n_{\geq 1} \cdot j_b + m_{\geq 3} \cdot j + X \ ,$$
$$(3\ell) : pp \to \ell'^{\pm}\ell^+\ell^- + n_{\geq 1} \cdot j_b + m_{\geq 2} \cdot j + X \ ,$$
$$(4\ell) : pp \to \ell'^{\pm}\ell''^{\mp}\ell^+\ell^- + n_{\geq 1} \cdot j_b + m_{\geq 2} \cdot j + X$$

$$(\ell'\ell\ell) : pp \to \ell'\ell^+\ell^- + X \ ,$$
$$(\ell\ell 1b) : pp \to \ell^+\ell^- + j_b + X$$

m_{ll} (di-lepton inv-mass): a key discriminating parameter !

ttll: flavor diagonal

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tull: flavor changing

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Dominant background after selections

2l: pp → tt
3l: pp → WZ
4l: pp → ZZ

pp → tt, Z+jets

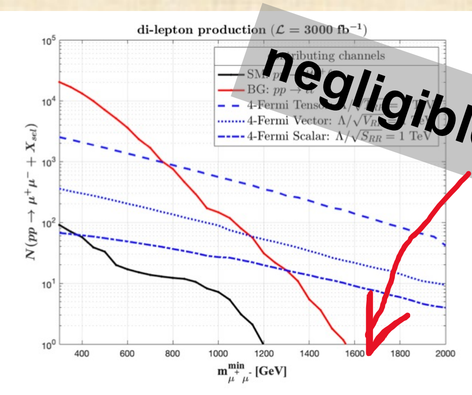
Number of background $pp \to \mu\mu + j_b + X$ events/140 fb^{-1}

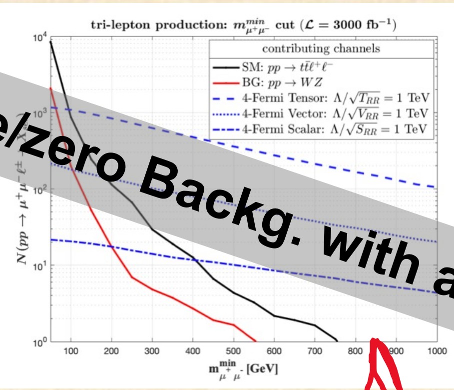
sub-process	$m^{\min}_{\mu^+\mu^-} = 500$ GeV	$m^{\min}_{\mu^+\mu^-} = 1000$ GeV	$m^{\min}_{\mu^+\mu^-} = 1500$ GeV	$m^{\min}_{\mu^+\mu^-} = 2000$ GeV
VV	13.0	1.2	0.2	0.1
$t\bar{t}$	336.4	6.9	0.3	0.0
$Z+$jets	128.2	10.9	1.9	0.4
Wt	67.1	1.3	0.1	0.0
Total $\mu\mu j_b$ Background events	477.7	19.1	2.4	0.5

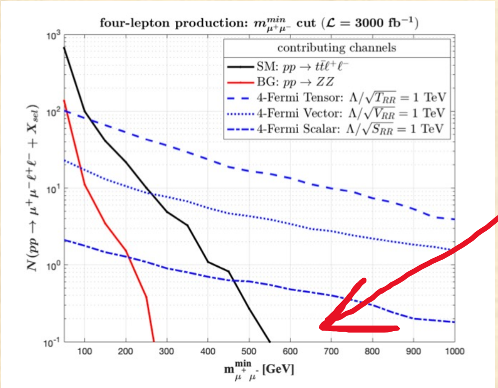
Number of background $pp \to e\mu\mu + X$ events/140 fb^{-1}

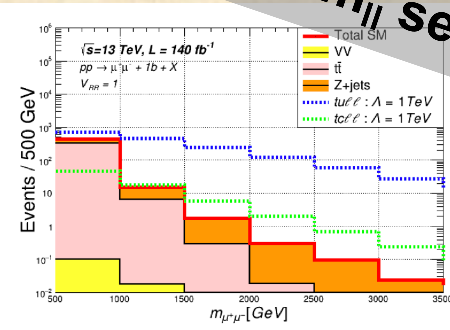
sub-process	$m^{\min}_{\mu^+\mu^-} = 500$ GeV	$m^{\min}_{\mu^+\mu^-} = 1000$ GeV	$m^{\min}_{\mu^+\mu^-} = 1500$ GeV	$m^{\min}_{\mu^+\mu^-} = 2000$ GeV
VV	7.1	1.0	0.2	0.1
$t\bar{t}$	78.2	1.6	0.1	0.0
$Z+$jets	16.5	1.3	0.2	0.0
Wt	9.5	0.2	0.0	0.0
Total $e\mu\mu$ Background events	111.8	4.1	0.5	0.1

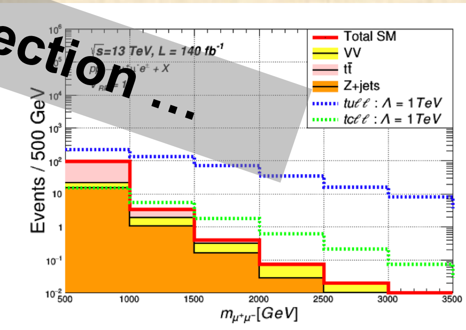
negligible/zero Backg. with a high enough m_{ll} selection …











Expected sensitivities

Simulations of events samples

- Simulation: MadGraph5_aMC@NLO
- NP models: UFO models generated with FeynRules
- PDF set: NNPDF30LO (ttll) & MSTW2008lo68cl (tull) - 5 flavor scheme
- Selections & cuts: MadAnalysis5
- Parton shower: Pythia 8
- Detector simulation: Delphes 3

Expected sensitivity to

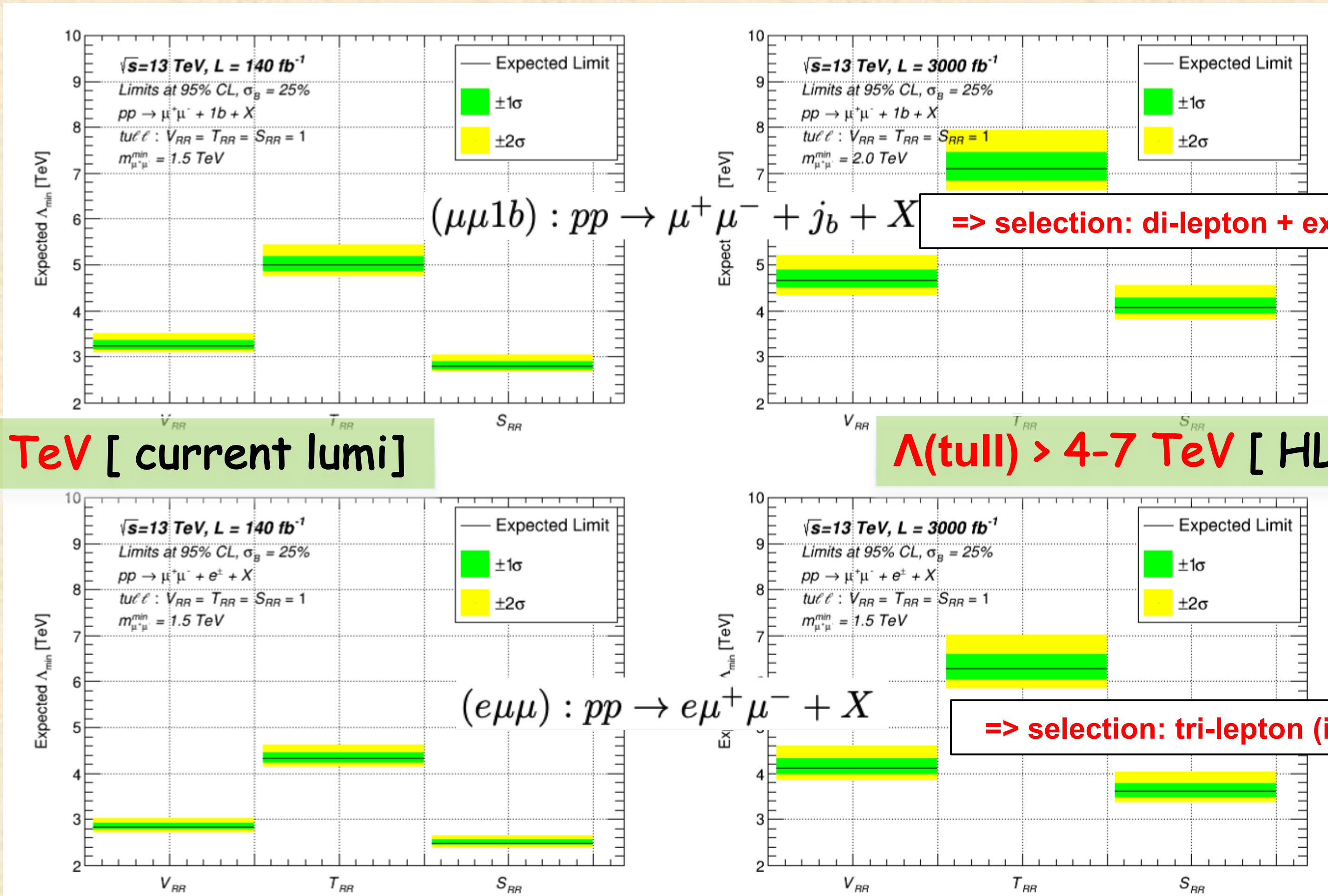
FC $tu\ell\ell$ 4-Fermi terms

@ LHC

Generic tuμμ NP (also applicable to tuee …)

"cut & count" : 95% CL bounds on NP from

tuμμ 4-Fermi



$(\mu\mu 1b) : pp \to \mu^+\mu^- + j_b + X$

=> selection: di-lepton + exactly 1 b-jet

$(e\mu\mu) : pp \to e\mu^+\mu^- + X$

=> selection: tri-lepton (inclusive)

Λ(tull) > 3-5 TeV [current lumi]

Λ(tull) > 4-7 TeV [HL-LHC]

Λ(tcll) > 1-2 TeV [current lumi]

Λ(tcll) > 1.5-2.5 TeV [HL-LHC]

Expected sensitivity to

diagonal $tt\ell\ell$ 4-Fermi terms

@ LHC

Generic tt$\mu\mu$ NP (also applicable to ttee ...) - "cut & count"

"cut & count" : 95% CL bounds on NP from tt$\mu\mu$ 4-Fermi

Jet Selections: $N_j \geq 3, N_b \geq 1$

	Final State	$pp \to \mu^+\mu^- + X$	
	Coupling	$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]
$\mathcal{L} = 140\ \mathrm{fb}^{-1}$	$S_{RR} = 1$ $T_{RR} = 1$ $V_{RR} = 1(-1)$	1400	0.8 1.6 1.0 (1.0)
$\mathcal{L} = 300\ \mathrm{fb}^{-1}$	$S_{RR} = 1$ $T_{RR} = 1$ $V_{RR} = 1(-1)$	1400	0.9 1.8 1.1(1.1)
$\mathcal{L} = 3000\ \mathrm{fb}^{-1}$	$S_{RR} = 1$ $T_{RR} = 1$ $V_{RR} = 1(-1)$	1600	1.4 2.8 1.8(1.7)

Di-lepton signal

Jet Selections: $N_j \geq 2, N_b \geq 1$

$pp \to \mu^+\mu^-\ell^\pm + X$	
$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]
500	0.7 1.8 1.1 (1.1)
500	0.8 2.0 1.3(1.2)
800	1.3 2.9 2.0(1.9)

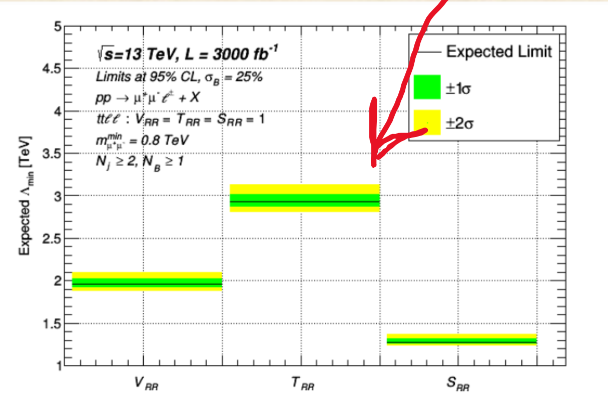
tri-lepton signal

$pp \to \mu^+\mu^-\ell^\pm\ell'^\mp + X$	
$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]
300	0.4 1.0 0.7 (0.7)
300	0.5 1.1 0.8(0.7)
500	0.8 1.8 1.3(1.2)

four-lepton signal

$\Lambda(V_{RR},T_{RR})$ ~ 2-3 TeV [HL-LHC & $m_{\min}(\mu\mu)$ > 800 GeV]

Sensitivity via tri-lepton signal:
(di-lepton comparable ...)



Lepton Flavor Non-Universality (NP = tt$\mu\mu$ only …)

the case $\Lambda_\mu << \Lambda_e$

sensitivity via MC sim of synthetic data

Construct generic LFU tests & search for asymmetric rates of muons vs electrons in multi-leptons signals

Ratio observables

particularly useful/reliable: potentially minimize theor. & sys(exp) uncertainties (NLO QCD, loop-EFT, PDF ...)

di-lepton
$$R^{2l}_{\mu/e} = \frac{\sigma(pp \to \mu^+\mu^- + X)}{\sigma(pp \to e^+e^- + X)} ,$$

$\boldsymbol{X \in our\ selections}$

tri-lepton
$$R^{3l}_{\mu/e} = \frac{\sum_{\ell=e,\mu}\sigma(pp \to \ell^\pm\mu^+\mu^- + X)}{\sum_{\ell=e,\mu}\sigma(pp \to \ell^\pm e^+e^- + X)} ,$$

four-leptons
$$R^{4l}_{\mu/e} = \frac{\sum_{\ell,\ell'=e,\mu}\sigma(pp \to \ell^\pm\ell'^\mp\mu^+\mu^- + X)}{\sum_{\ell=e,\mu}\sigma(pp \to \ell^\pm\ell'^\mp e^+e^- + X)}$$

SM: $R^{nl}_{\mu/e}$=1 (up to negligible Higgs-leptons Yukawa ...)

Construct generic LFU tests & search for asymmetric rates of muons vs electrons in multi-leptons signals

Ratio observables

particularly useful/reliable: potentially minimize theor. & sys(exp) uncertainties (NLO QCD, loop-EFT, PDF …)

di-lepton
$$R^{2l}_{\mu/e} = \frac{\sigma(pp \to \mu^+\mu^- + X)}{\sigma(pp \to e^+e^- + X)} \, ,$$

X ∈ our selections

tri-lepton
$$R^{3l}_{\mu/e} = \frac{\sum_{\ell=e,\mu} \sigma(pp \to \ell^\pm \mu^+\mu^- + X)}{\sum_{\ell=e,\mu} \sigma(pp \to \ell^\pm e^+e^- + X)} \, ,$$

four-leptons
$$R^{4l}_{\mu/e} = \frac{\sum_{\ell,\ell'=e,\mu} \sigma(pp \to \ell^\pm \ell'^\mp \mu^+\mu^- + X)}{\sum_{\ell=e,\mu} \sigma(pp \to \ell^\pm \ell'^\mp e^+e^- + X)}$$

NP(tt$\mu\mu$): $R^{nl}_{\mu/e} \sim 1 + \delta(\Lambda)$

$$\delta(\Lambda) \propto \frac{c^{\rm INT} \cdot \sigma^{\rm INT}_{n\ell} + c^{\rm NP} \cdot \sigma^{\rm NP}_{n\ell}}{\sigma^{\rm SM}_{n\ell}}$$

	$c^{\rm INT}$	$c^{\rm NP}$
scalar	0	$S^2_{RR}/\Lambda^4_{\rm TeV}$,
tensor	0	$T^2_{RR}/\Lambda^4_{\rm TeV}$,
vector	$V_{ij}/\Lambda^2_{\rm TeV}$	$V^2_{ij}/\Lambda^4_{\rm TeV}$.

LFNU $tt\mu\mu$ NP – MC sim of synthetic data

$$\chi^2 = \sum_{n=2,3,4} \frac{\left[R^{nl}(\Lambda) - R^{nl}(\mathrm{exp})\right]^2}{(\delta R^{nl})^2}$$

- Generate O(10^4) values/realizations of $R^{nl}(exp)$
- For each realization determine Λ_{min} that minimizes the χ^2 - like test
-
- Obtain the the distribution P(Λ_{min})

95% CL bounds on LFNU ttll NP:

		95% bounds on Λ [TeV]	
$\mathcal{L}$ [fb^{-1}]	NP $\Downarrow$	$\boldsymbol{\delta R^{n\ell} = 25\%}$	$\boldsymbol{\delta R^{n\ell} = 15\%}$
140	$S_{RR} = 1$	0.9	1
	$T_{RR} = 1$	2.1	2.3
	$V_{RR} = 1(-1)$	1.3(1.2)	1.6(1.3)
300	$S_{RR} = 1$	0.9	1.1
	$T_{RR} = 1$	2.2	2.4
	$V_{RR} = 1(-1)$	1.4(1.2)	1.6(1.4)
3000	$S_{RR} = 1$	1.7	1.9
	$T_{RR} = 1$	3.7	4.2
	$V_{RR} = 1(-1)$	2.5(2.2)	2.9(2.4)

Λ > 1-2 TeV [current lumi]

Λ > 2-4 TeV [HL-LHC]

SUMMARY

CONCLUSION

- Multi-leptons signals provide an excellent & rich testing ground of NP - in particular LFUV NP

  @LHC13 & beyond

  - good reasons to suspect TeV-scale NP/LFNU in 3rd gen fermion systems
  - $(q_3 q)(\ell\ell)$ – useful window into NP …
  - Flavor-blind signals to detect FC underlying NP

SUMMARY

CONCLUSION

- Current LHC data can significantly improve existing bounds on bsll, bbll, tull & ttll contact terms ($\in$ heavy V', LQ's ...)

or discover tails of NP effects via multi-lepton signals searches

- Sensitivity to top - leptons (S,V,T ...) interactions (LFU or LFUV)

		@current LHC13	@HL-LHC
flavor-changing:	up to	$\Lambda \sim 5$ TeV	$\Lambda \sim 7$ TeV
flavor-diagonal:	up to	$\Lambda \sim 2$ TeV	$\Lambda \sim 3$ TeV

Backups

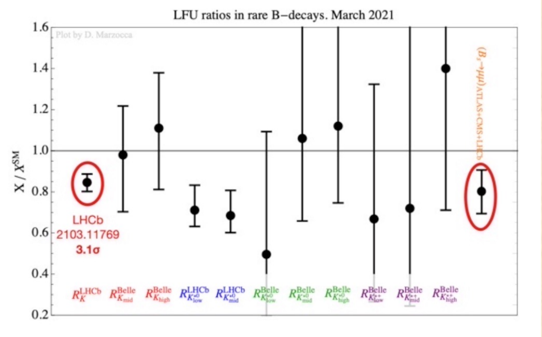
B-anomalies:

B-anomalies: ($R_{D^{(*)}}$, $R_{K^{(*)}}$): may be connected - SU(2) …

b → sμμ/see:

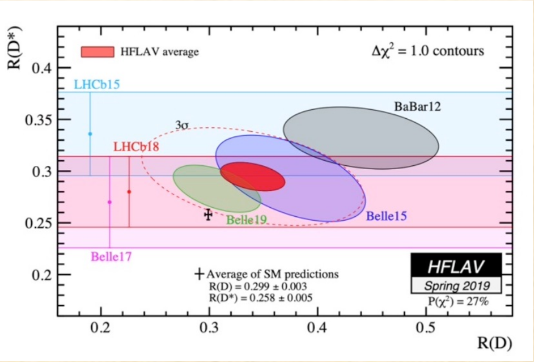
$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)}\mu^+\mu^-)}{Br(B \to K^{(*)}e^+e^-)} < 1 \ (\sim 4\sigma \ global\ significace)$$

(+ dB/dq^2 + P_5' + deviations in: $B_s \to \mu\mu$, $B^0 \to K^0\mu\mu$, $B^+ \to K^+\mu\mu$, $B_s \to \phi\mu\mu$, $B^0 \to K^{*0}\mu\mu$, $B^+ \to K^{*+}\mu\mu$)



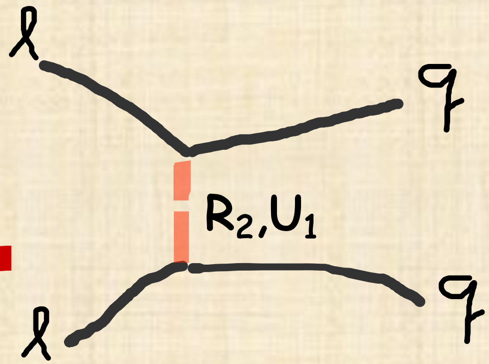
b → cτν/cμν/ceν :

$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\mu\nu/e\nu)} > R_{D^{(*)}}(SM) \ (\sim 3\sigma \ tension)$$



Matching – underlying BSM scenarios (e.g., top-quark 4-Fermi):

Yukawa & vector-like couplings to quark-lepton pair:



$$\mathcal{L}_Y^{R_2} = z\bar{e}R_2^{i\star}q^i - y\bar{u}R_2^i\epsilon_{ij}\ell^j + \text{h.c.}$$
$$\mathcal{L}_Y^{U_1} \supset x\bar{q}\gamma_\mu U_1^\mu \ell + \text{h.c.} \; ,$$

Tree-level exchanges of the heavy R_2, U_1 LQ's (after Fierz):

V_{LL}

$$U_1 : \alpha_{\ell q}^{(1)} = \alpha_{\ell q}^{(3)} = -\frac{xx^\star}{2M_{U_1}^2} \; ,$$

$$R_2 : \alpha_{qe} = -\frac{zz^\star}{2M_{R_2}^2} \; , \; \alpha_{\ell u} = \frac{yy^\star}{2M_{R_2}^2} \; , \; \alpha_{\ell equ}^{(1)} = 4\alpha_{\ell equ}^{(3)} = -\frac{yz}{2M_{R_2}^2}$$

V_{RL} V_{LR} S_{RR} T_{RR}

Matching to SMEFT: Correletions …

Correlations among up-down sectors can be exploited to get an enhanced sensitivity

Example: gauge invariance relating top-bottom 4-Fermi:

$$\mathcal{O}_{lq}^{(1)}(pr31) = (\bar{\ell}_p \gamma_\mu P_L \ell_r) \cdot \left[(\bar{t}\gamma^\mu P_L u) + (\bar{b}\gamma^\mu P_L d) \right] \ ,$$
$$\mathcal{O}_{lq}^{(3)}(pr31) \supset (\bar{\ell}_p \gamma_\mu \tau^3 P_L \ell_r) \cdot \left[(\bar{t}\gamma^\mu P_L u) - (\bar{b}\gamma^\mu P_L d) \right] \ ,$$
$$\mathcal{O}_{qe}(pr31) = (\bar{\ell}_p \gamma^\mu P_R \ell_r) \cdot \left[(\bar{t}\gamma_\mu P_L u) + (\bar{b}\gamma_\mu P_L d) \right] \ .$$

$$V_{LL}(tu\ell\ell) = \alpha_{\ell q}^{(1)} - \alpha_{\ell q}^{(3)} \ \leftrightarrow \ V_{LL}(bd\ell\ell) = -\alpha_{\ell q}^{(1)} - \alpha_{\ell q}^{(3)}$$
$$V_{RL}(tu\ell\ell) = V_{RL}(bd\ell\ell) = \alpha_{qe}$$

=> V_{LL} & V_{RL} top and bottom couplings are related (t -> u/c VS b -> d/s):

But caution: notice sign difference (V_{LL}) – important when considering the underlying heavy physics …

Matching – underlying BSM scenarios (e.g., top-quark 4-Fermi):

Resulting 4-Fermi (our parameterization):

- R_2-type scalar LQ: generates V_{RL}, V_{LR} (vector), S_{RR} (scalar), T_{RR} (tensor) 4-Fermi

- U_1-type vector LQ: no 4-Fermi interactions in up-sector (ttll,tull,tcll) ! ($V_{LL} = \alpha_{\ell q}^{(1)} - \alpha_{\ell q}^{(3)}$)

  but generates bbll,bsll,bdll vector 4-Fermi for which $\boxed{V_{LL} = \alpha_{\ell q}^{(1)} + \alpha_{\ell q}^{(3)}}$

V_{LL}

$$U_1 : \alpha_{\ell q}^{(1)} = \alpha_{\ell q}^{(3)} = -\frac{xx^\star}{2M_{U_1}^2} \ ,$$

$$R_2 : \alpha_{qe} = -\frac{zz^\star}{2M_{R_2}^2} \ , \ \alpha_{\ell u} = \frac{yy^\star}{2M_{R_2}^2} \ , \ \alpha_{\ell equ}^{(1)} = 4\alpha_{\ell equ}^{(3)} = -\frac{yz}{2M_{R_2}^2}$$

V_{RL} V_{LR} S_{RR} T_{RR}

ttll: flavor diagonal

NPB2022 (2111.13711), Afik, SBS, Pal, Soni, Wudka
PLB2020 (2005.06457), Afik, SBS, Cohen, Soni, Wudka

tull: flavor changing

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

The (cumulative) cross-section

$$\sigma(m_{\ell\ell}^{\rm min}) = \sigma^{\rm SM}(m_{\ell\ell}^{\rm min}) + \cancel{\frac{f}{\Lambda^2}\cdot\sigma^{\rm SM\times NP}(m_{\ell\ell}^{\rm min})} + \frac{f^2}{\Lambda^4}\cdot\sigma^{\rm NP}(m_{\ell\ell}^{\rm min})$$

m_{ll}^{min} - important discriminating parameter !

$$\sigma(m_{\ell\ell}^{\rm min}) \equiv \sigma(m_{\ell\ell} \geq m_{\ell\ell}^{\rm min}) = \int_{m_{\ell\ell}\geq m_{\ell\ell}^{\rm min}} dm_{\ell\ell}\frac{d\sigma}{dm_{\ell\ell}}$$

interference term subleading
(using selections that optimize S/B & "kill" the SM contribution ...)

No interference with SM
(NP = QCD & SM=EW ...)

selections:

- m_{ll}^{min} (OSSF none-top)
- No. of leptons
- No. of jets

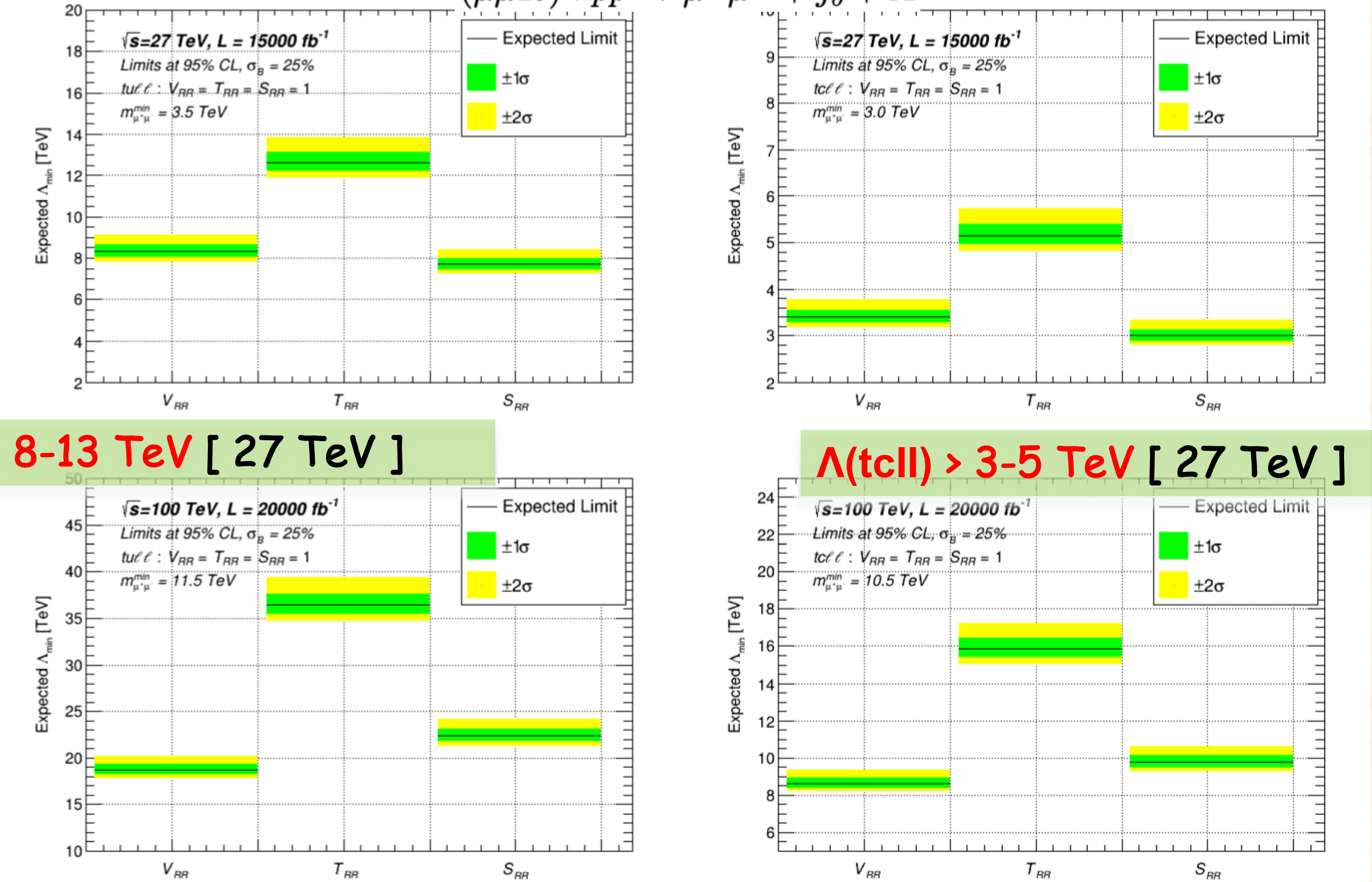
Leading NP term is $\propto \frac{f^2}{\Lambda^4}$

"safe" with respect to next $\frac{1}{\Lambda^4}$ terms from SMXNP(dim8) ...

Generic tuμμ NP (also applicable to tuee ...)

"cut & count" : @27 & 100 TeV proton collider

$(\mu\mu 1b) : pp \to \mu^+\mu^- + j_b + X$



Λ(tull) > 8-13 TeV [27 TeV]

Λ(tcll) > 3-5 TeV [27 TeV]

Λ(tull) > 20-35 TeV [100 TeV]

Λ(tcll) > 9-16 TeV [100 TeV]

Generic $tu\mu\mu$ NP (also applicable to tuee …)

"cut & count" : 95% CL bounds on $tu\mu\mu$ NP

$(\mu\mu 1b) : pp \to \mu^+\mu^- + j_b + X$

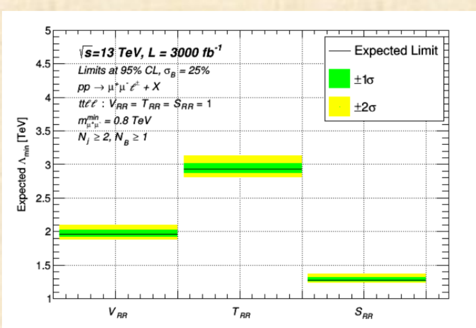
	Operator	$tu\mu\mu$ 4-Fermi case		$tc\mu\mu$ 4-Fermi case	
	Coupling	$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]	$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]
$\mathcal{L} = 140$ fb^{-1}	$S_{RR} = 1$	1500	$2.8^{+0.1}_{-0.1}$	1000	$1.0^{+0.1}_{-0.1}$ [EFT?]
	$T_{RR} = 1$		$5.0^{+0.1}_{-0.2}$		$1.8^{+0.1}_{-0.1}$
	$V_{RR} = 1$		$3.2^{+0.1}_{-0.1}$		$1.1^{+0.1}_{-0.1}$
$\mathcal{L} = 3000$ fb^{-1}	$S_{RR} = 1$	2000	$4.1^{+0.1}_{-0.2}$	1500	$1.3^{+0.1}_{-0.1}$ [EFT?]
	$T_{RR} = 1$		$7.1^{+0.3}_{-0.3}$		$2.4^{+0.1}_{-0.1}$
	$V_{RR} = 1$		$4.7^{+0.2}_{-0.2}$		$1.5^{+0.1}_{-0.1}$ [EFT?]

$(e\mu\mu) : pp \to e\mu^+\mu^- + X$

	Operator	$tu\mu\mu$ 4-Fermi case		$tc\mu\mu$ 4-Fermi case	
	Coupling	$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]	$m^{\min}_{\mu^+\mu^-}$ [GeV]	$\Lambda_{\min}(95\%\ CL)$ [TeV]
$\mathcal{L} = 140$ fb^{-1}	$S_{RR} = 1$	1500	$2.3^{+0.0}_{-0.1}$	1000	$0.9^{+0.0}_{-0.0}$ [EFT?]
	$T_{RR} = 1$		$4.1^{+0.1}_{-0.1}$		$1.7^{+0.1}_{-0.1}$
	$V_{RR} = 1$		$2.7^{+0.0}_{-0.1}$		$1.1^{+0.0}_{-0.0}$
$\mathcal{L} = 3000$ fb^{-1}	$S_{RR} = 1$	1500	$3.5^{+0.1}_{-0.1}$	1000	$1.1^{+0.1}_{-0.1}$
	$T_{RR} = 1$		$6.3^{+0.2}_{-0.3}$		$2.1^{+0.1}_{-0.1}$
	$V_{RR} = 1$		$4.1^{+0.1}_{-0.2}$		$1.3^{+0.1}_{-0.1}$

"cut & count"

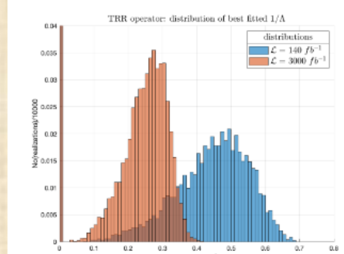
- Given a signal yield & background uncertainty, calculate the expected number of standard deviations (the Z-value) from the background-only hypothesis (using BinomialExpZ by RooFit)
- Then find an optimized selection $m_{ll}^{min}(\mu\mu)$ by maximizing the expected Z-value for each signal hypothesis.
- Calculate the p-value (using BinomialExpZ by RooFit) of the background-only and background+signal hypotheses for each point and then perform a CLs test to determine the 95% Confidence Level (CL) exclusion values for Λ.



Monte Carlo simulation of synthetic data

- Generate (synthetic) realizations of a set of experimental measurements y_{exp} around $y_{exp}(x_{SM})$, assuming some underlying overall uncertainty
  - obtain the expected distribution of the data P(x) assuming no NP …
- "Inject" NP into the data (into y_{exp}) and choose a "metric" to test the no NP hypothesis for each realization.
  - find $x_{best\text{-}fit}$ (that minimizes the test-metric) for each realization
  - obtain the distribution $P(x_{best\text{-}fit})$
  - $x_{best\text{-}fit}$ depends on NP parameters (Λ) …

$P(x_{best\text{-}fit})$ allows us to obtain the predicted sensitivities & bounds …



High-P_T correlated tests of lepton-universality

in pp $\rightarrow$ leptons+jets

@ LHC & beyond

NP: $(q_3q)(\ell\ell)$ 4-Fermi terms

NP: SU(2) – triplet & singlet 4-Fermi (vector) opts

$$\mathcal{O}_{lq}^{(3)}(prst) = \left(\bar{l}_p \gamma_\mu \tau^I l_r\right)\left(\bar{q}_s \gamma^\mu \tau^I q_t\right)$$
$$\mathcal{O}_{qe}(prst) = \left(\bar{e}_q \gamma_\mu e_r\right)\left(\bar{q}_s \gamma^\mu q_t\right) \ ,$$

Recall: $V_{LL} \propto \alpha_{lq}^{(3)}$ & $V_{RL} \propto \alpha_{qe}$

These 2 opts may be responsible for NP effects in:

$$(mnp)_{\ell\ell} : pp \to \ell_i^+ \ell_i^- + m \cdot j + n \cdot j_b + p \cdot t$$
$$(mnp)_{\ell} : pp \to \ell_i^\pm + m \cdot j + n \cdot j_b + p \cdot t + \not{E}_T$$

NP: SU(2) – triplet & singlet 4-Fermi (vector) opts

$$\mathcal{O}_{lq}^{(3)}(prst) = \left(\bar{l}_p \gamma_\mu \tau^I l_r\right)\left(\bar{q}_s \gamma^\mu \tau^I q_t\right)$$
$$\mathcal{O}_{qe}(prst) = \left(\bar{e}_q \gamma_\mu e_r\right)\left(\bar{q}_s \gamma^\mu q_t\right) \;,$$

Recall: $V_{LL} \propto \alpha_{lq}^{(3)}$ & $V_{RL} \propto \alpha_{qe}$

e.g.,

Dilepton $+\ jets/t$

$(010)_{\mu\mu} : pp \to \mu^+\mu^- + j_b$
$(110)_{\mu\mu} : pp \to \mu^+\mu^- + j + j_b$
$(020)_{\mu\mu} : pp \to \mu^+\mu^- + 2\cdot j_b$
$(002)_{\mu\mu} : pp \to \mu^+\mu^- + t\bar{t}$

$\mathcal{O}_{lq}^{(3)}$

$(010)_{\not{E}_T} : pp \to j_b + \not{E}_T$
$(110)_{\not{E}_T} : pp \to j + j_b + \not{E}_T$
$(020)_{\not{E}_T} : pp \to 2\cdot j_b + \not{E}_T$
$(002)_{\not{E}_T} : pp \to t\bar{t} + \not{E}_T$

$jets/t +$ MET

$(001)_\mu : pp \to \mu^\pm + t + \not{E}_T$
$(101)_\mu : pp \to \mu^\pm + j + t + \not{E}_T$
$(011)_\mu : pp \to \mu^\pm + j_b + t + \not{E}_T$

Single-lepton $+\ jets/t +$ MET

The LFNU χ^2 – *like* test-metric:

$$\chi^2 = \sum_X \frac{\left[T_{\ell\ell}^X(\Lambda) - T_{\ell\ell}^{X,\text{exp}}\right]^2}{\left(\delta T^X\right)^2} + \sum_Y \frac{\left[T_\ell^Y(\Lambda) - T_\ell^{Y,\text{exp}}\right]^2}{\left(\delta T^Y\right)^2}$$

$X, Y \in (m, n, p)$ denote the $\ell\ell$ and single ℓ channels

T 's are ratio observables sensitive to LFNU ...

$$T_{\ell\ell}^{mnp} = \frac{\sigma_{\ell\ell}^{mnp}}{\sigma_{ee}^{mnp}} \quad , \quad T_\ell^{mnp} = \frac{\sigma_\ell^{mnp}}{\sigma_e^{mnp}}$$

$$\boldsymbol{\sigma_{ll,l}^{mnp}} \in \begin{array}{l} (mnp)_{\ell\ell} : pp \to \ell_i^+ \ell_i^- + m \cdot j + n \cdot j_b + p \cdot t \\ (mnp)_\ell : pp \to \ell_i^\pm + m \cdot j + n \cdot j_b + p \cdot t + \not{E}_T \end{array}$$

normally distributed around the average T(SM)=1

$$T_{\ell\ell}^{X,\text{exp}} = \mathcal{N}\left(1, \left(\delta T^X\right)^2\right), \; T_\ell^{Y,\text{exp}} = \mathcal{N}\left(1, \left(\delta T^Y\right)^2\right)$$

overall uncertainties

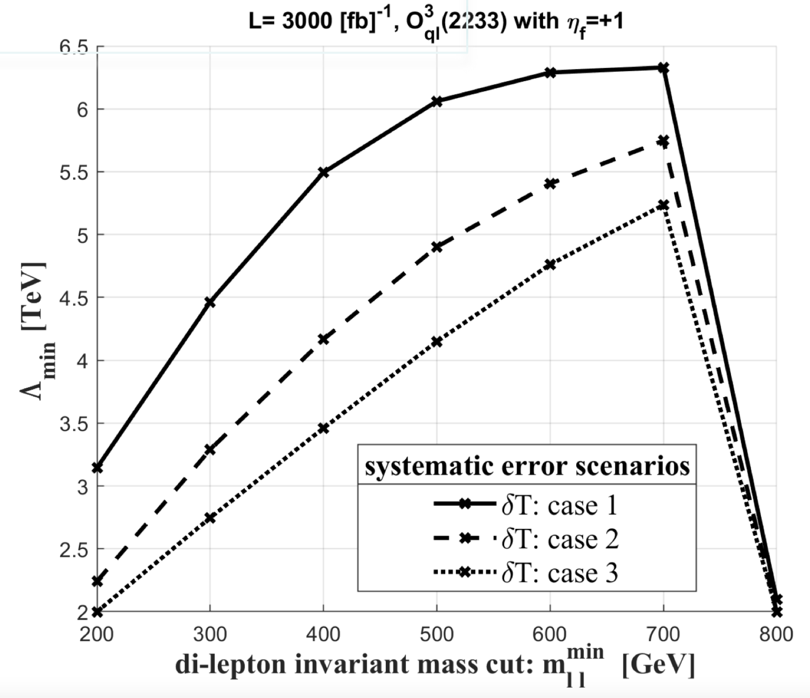
$$\delta T^{X,Y} = \sqrt{\left(\delta T_{\text{stat}}^{X,Y}\right)^2 + \left(\delta T_{\text{sys}}^{X,Y}\right)^2}$$

Results – sensitivities :

Demonstrate on QCD-generated processes (therefore dominant):

$$
\begin{aligned}
(010)_{\mu\mu} &: pp \to \mu^+\mu^- + j_b \\
(110)_{\mu\mu} &: pp \to \mu^+\mu^- + j + j_b \\
(020)_{\mu\mu} &: pp \to \mu^+\mu^- + 2\cdot j_b \\
(002)_{\mu\mu} &: pp \to \mu^+\mu^- + t\bar{t}\ ,
\end{aligned}
$$

Sensitivity depends on lower cut on dilepton invariant mass …



Results – sensitivities :

Demonstrate on QCD-generated processes (therefore dominant):

$$(010)_{\mu\mu} : pp \to \mu^+\mu^- + j_b$$
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$$(020)_{\mu\mu} : pp \to \mu^+\mu^- + 2 \cdot j_b$$
$$(002)_{\mu\mu} : pp \to \mu^+\mu^- + t\bar{t} \ ,$$

Sensitivity depends on lower cut on dilepton invariant mass …

	95% CL bounds: $\Lambda_{\mathcal{O}_{lq}^{(3)}(2233)}$ $(\Lambda_{\mathcal{O}_{qe}(2233)})$ [TeV]					
	$\mathcal{L} = 140$ $[\mathrm{fb}]^{-1}$ $m_{\mu\mu}^{\mathtt{min}} = 300$ GeV		$\mathcal{L} = 300$ $[\mathrm{fb}]^{-1}$ $m_{\mu\mu}^{\mathtt{min}} = 400$ GeV		$\mathcal{L} = 3000$ $[\mathrm{fb}]^{-1}$ $m_{\mu\mu}^{\mathtt{min}} = 700$ GeV	
	$\eta_f = +1$	$\eta_f = -1$	$\eta_f = +1$	$\eta_f = -1$	$\eta_f = +1$	$\eta_f = -1$
$\delta T \sim 10\%$ (case 1)	3.4(2.6)	3.2(4.2)	4.1(3.1)	3.9(4.9)	6.3(4.4)	6.0(6.4)
$\delta T \sim 15\%$ (case 2)	3.0(2.5)	2.7(3.8)	3.7(3.0)	3.3(4.5)	5.8(4.2)	5.5(5.9)
$\delta T \sim 20\%$ (case 3)	2.6(2.4)	2.3(3.4)	3.3(2.9)	2.9(4.2)	5.1(4.1)	4.7(5.5)

$\Lambda \sim 3$ TeV [current lumi & $m_{min}(\mu\mu) > 300$ GeV]
$\Lambda \sim 5\text{-}6$ TeV [HL-LHC & $m_{min}(\mu\mu) > 700$ GeV]

EFT-validity

Two "measures" to consider:

$$\sigma^{NP}(g,\Lambda,m_{\ell\ell}) = \frac{g^2}{\Lambda^2}\cdot\sigma^{SM\times NP}(m_{\ell\ell}) + \frac{g^4}{\Lambda^4}\cdot\sigma^{NP\times NP}(m_{\ell\ell})$$

$$\mathcal{R}_\Lambda \equiv \frac{\hat{s}}{\Lambda^2}$$

Addresses the validity of the specific calculation within the EFT framework – depends on the details of the underlying heavy physics and the process at hand

$$\mathcal{R}_{\Lambda/g} \equiv \frac{\hat{s}}{\Lambda^2/g^2}$$

The EFT expansion param – the expansion of the effective Lagrangian at leading order in g/Λ

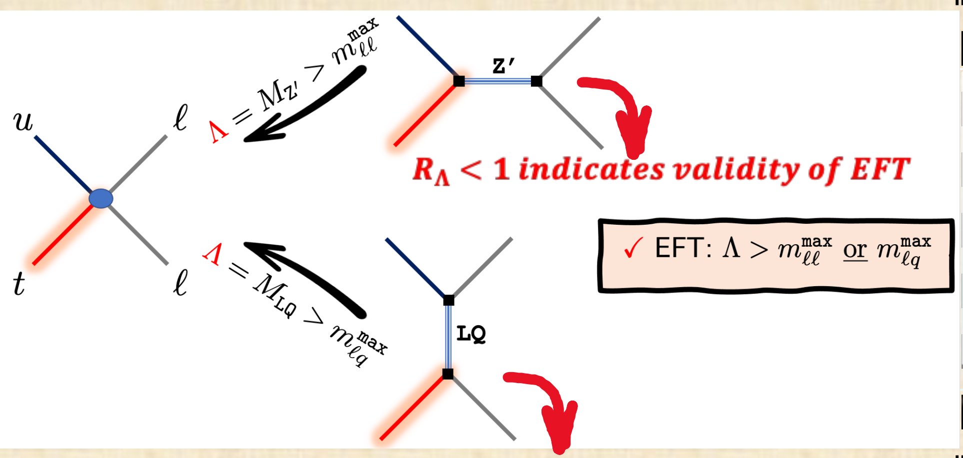
EFT-validity

Two "measures" to consider:

$$\sigma^{NP}(g,\Lambda,m_{\ell\ell}) = \frac{g^2}{\Lambda^2}\cdot\sigma^{SM\times NP}(m_{\ell\ell}) + \frac{g^4}{\Lambda^4}\cdot\sigma^{NP\times NP}(m_{\ell\ell})$$

$$\mathcal{R}_\Lambda \equiv \frac{\hat{s}}{\Lambda^2}$$

Addresses the validity of the specific calculation within the EFT framework – depends on the details of the underlying heavy physics and the process at hand



EFT may hold also when $R_\Lambda > 1$

$$\mathcal{R}_{\Lambda/g} \equiv \frac{\hat{s}}{\Lambda^2/g^2}$$

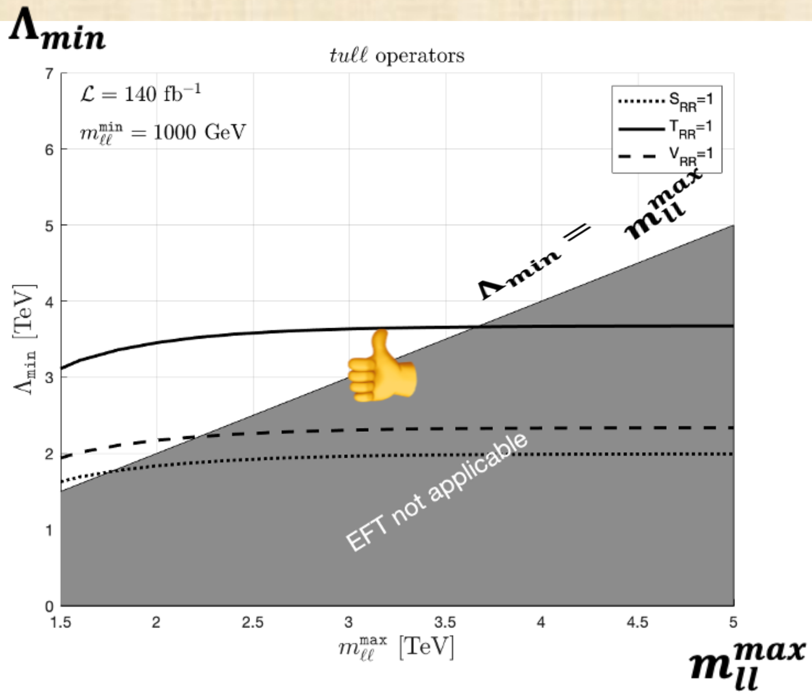
The EFT expansion param – the expansion of the effective Lagrangian at leading order in g/Λ

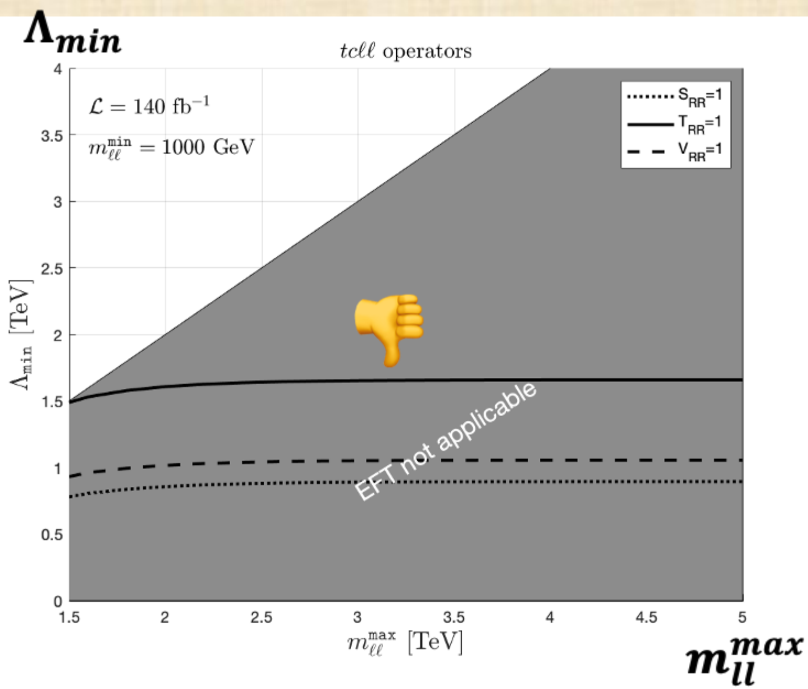
SMxNP interference term $\propto O(R_{\Lambda/g})$
NPxNP term $\propto O(R_{\Lambda/g}^2)$

*$R_{\Lambda/g} < 1$ naively indicate the **regime of validity** of the EFT prescription & the potential effects from higher dim opts can be assessed from $R_{\Lambda/g}$*

EFT-validity

Consider bounds (Λ_{min}) obtained on the scale Λ of an s-channel underlying NP pp $\rightarrow NP \rightarrow l^+l^-$; $\hat{s} = m_{ll}$





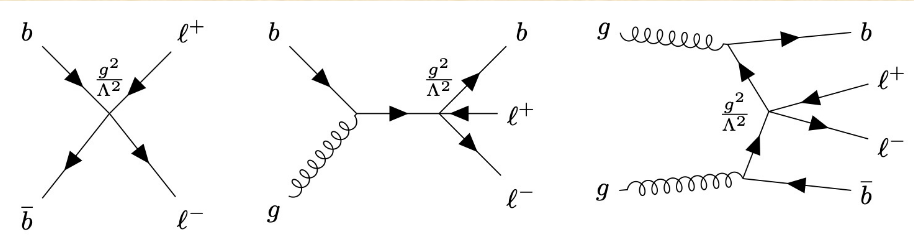
b-physics

collider signatures of bbll & bsll vector contact terms

$$\mathcal{L}_{eff} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij} (\bar{b}_i \gamma_\mu b_i)(\bar{\ell}_j \gamma^\mu \ell_j)$$

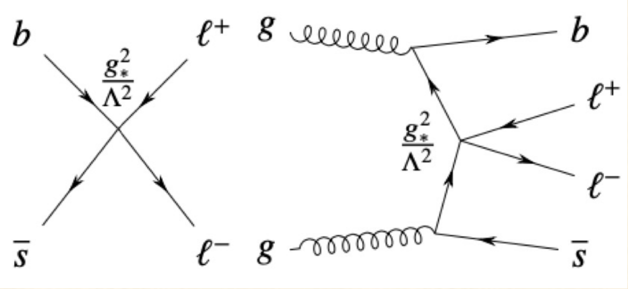
bbll: flavor diagonal

PLB807 (2020), 135541 (1912.00425), Afik, SBS, Cohen, Rozen



bsll: flavor changing

JHEP08 (2018), 056 (1805.11402), Afik, Cohen, Gozani, Kajomovits, Rozen

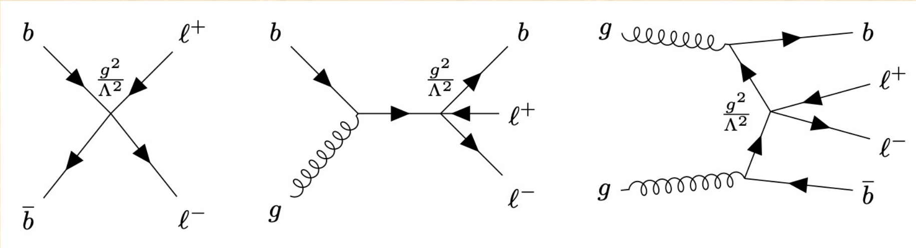


background: tt, Z+jets, VV, ttV

$$\sigma(m_{\ell\ell}) = \sigma^{SM}(m_{\ell\ell}) + \frac{g^2}{\Lambda^2}\cdot\sigma^{SM\times NP}(m_{\ell\ell}) + \frac{g^4}{\Lambda^4}\cdot\sigma^{NP\times NP}(m_{\ell\ell})$$

bbll: flavor diagonal

PLB807 (2020), 135541 (1912.00425), Afik, SBS, Cohen, Rozen



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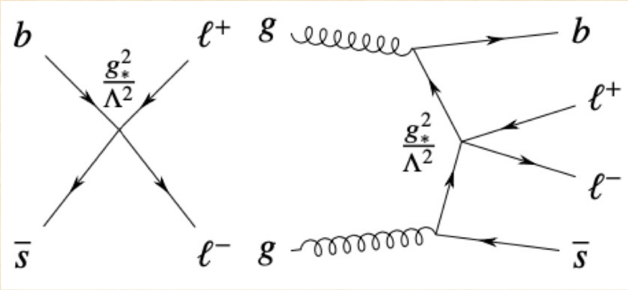

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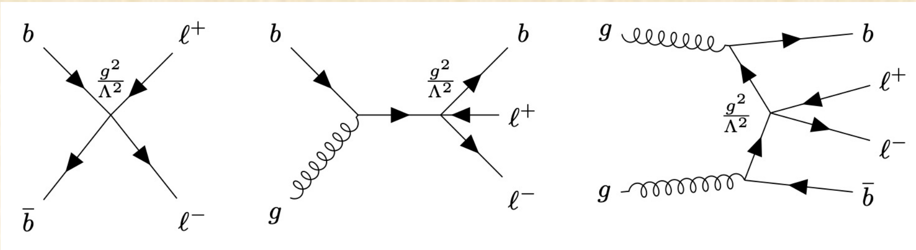
selections: ***exactly one b-jet*** **(pp → ee/μμ + j_b) & *m_{ll} lower cut , m_{ll} > O(TeV)***

***m_{ll}* - important discriminating variable**

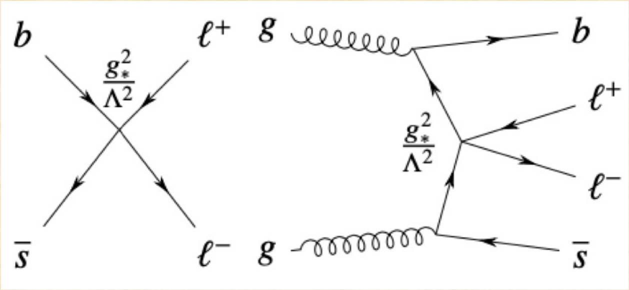
bbll: flavor diagonal

PLB807 (2020), 135541 (1912.00425), Afik, SBS, Cohen, Rozen



bsll: flavor changing

JHEP08 (2018), 056 (1805.11402), Afik, Cohen, Gozani, Kajomovits, Rozen



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selections: *exactly one b-jet* (pp → ee/μμ + j_b) *& m_{ll} lower cut , m_{ll} > O(1 TeV)*

expected sensitivity:
Λ ~ 8 TeV (L=140 fb^{-1}) ; 10 TeV (L=3000 fb^{-1})

expected sensitivity:
Λ ~ 4 TeV (L=140 fb^{-1}) ; 8 TeV (L=3000 fb^{-1})

Significantly better than inclusive searches (pp → ee/μμ + X)

searches: ...

searches: ATLAS (PRL 2021),
Λ ~ 2(ee) & 2.5(μμ) TeV @ L=140 fb^{-1}

LFNU $tt\mu\mu$ NP – MC sim of synthetic data

LFNU χ^2 - like test /metric

$$\chi^2 = \sum_{n=2,3,4} \frac{\left[R^{nl}(\Lambda) - R^{nl}(\text{exp})\right]^2}{\left(\delta R^{nl}\right)^2}$$

$R^{nl}(\Lambda) = expected\ from\ NP\ in\ the\ data$

$R^{nl}(exp) = expected\ exp.\ measurements\ of\ R$

$\delta R^{nl} = 15\%\ or\ 25\%;\ overall\ exp + theor\ uncertainty\ (sys + stat)$

For the purpose of extracting a bound, assume:

no NP in the data, $R^{nl}(exp)$ normally distributed & at least 5 events ("adjust" $m_{min}(\ell\ell)$ ...)

LFNU $tt\mu\mu$ NP – MC sim of synthetic data

$$\chi^2 = \sum_{n=2,3,4} \frac{\left[R^{nl}(\Lambda) - R^{nl}(\text{exp})\right]^2}{(\delta R^{nl})^2}$$

- Generate O(10^4) values/realizations of $R^{nl}(exp)$
- For each realization determine Λ_{min} that minimizes the χ^2 - like test
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- Obtain the the distribution P(Λ_{min})

distribution of best-fitted Λ (Λ_{min}) of the tensor (T_{RR}) opt which minimizes the χ^2 - like test