New Physics, from Tops to Bottoms

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University of Zurich seminar, December 11, 2018

Overview

B-anomaly Introduction

Top-philic models for $R_{K^{(*)}}$

- SMEFT
- Simplified Dynamical Models

LHC implications

Outline one UV complete model

Describe Four-top search strategy for the LHC

- SM
- Light Z'

Based on:

Camargo-Molina, Celis , **DAF** Phys. Lett. B 784 (2018) 284-293

Alvarez, **DAF**, Kamenik, Morales, Szynkman Nucl. Phys. B 915 19 (2017)

Introduction: the B-anomalies

SM:

Gauge interactions are Lepton Flavor Universal (LFU)

SM sources of non-universality from Yukawa sector

Deviations from LFU implies BSM Physics!

$$\mathcal{L}_{SM} \supset -Y_{ij}\, \bar{\ell}^i_L \Phi e^j_R$$
$$m_e \neq m_\mu \neq m_\tau$$

LFU has been very well tested in 1st and 2nd generation during the last decades

3rd generation: Puzzling hints of **LFU violation** in B-decays:

$B \to D^{(*)} \tau \nu$ Charged currents (tree-level)

LFU ratio: $$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\, \tau \bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\, \ell \bar{\nu})}\Big|_{\ell = e, \mu}$$

$R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}}$

3.8σ excess!

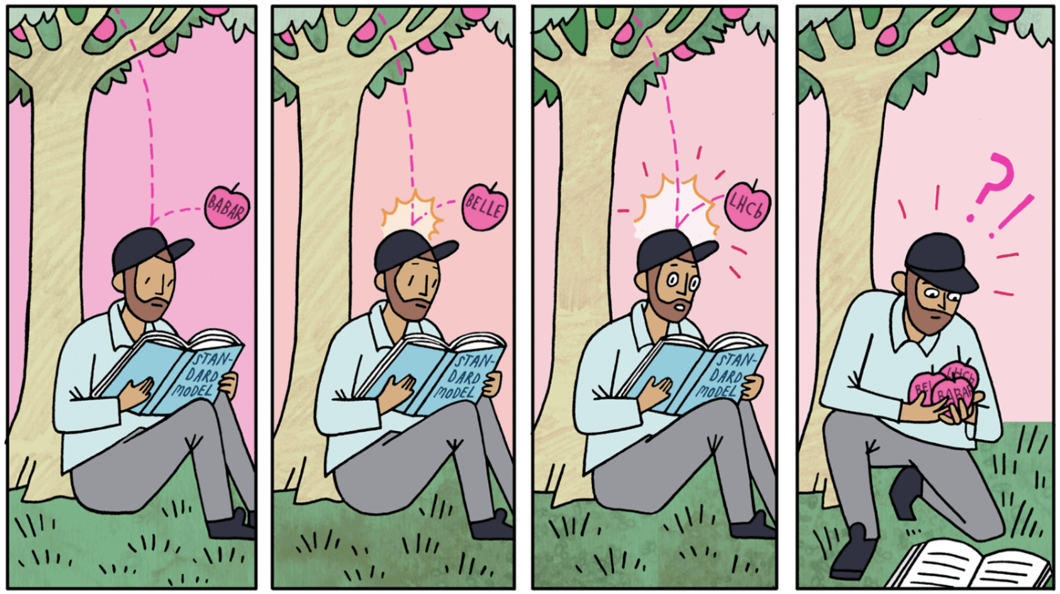
$B \to K^{(*)} \ell \bar{\ell}$ Neutral currents (loop FCNC)

LFU ratio: $$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\, \mu \bar{\mu})}{\mathrm{Br}(B \to D^{(*)}\, e \bar{e})}$$

$R^{\mathrm{exp}}_{K^{(*)}} < R^{\mathrm{SM}}_{K^{(*)}}$

2.5σ deficit!

If true... completely unexpected discovery (who ordered that? comparable the muon discovery)

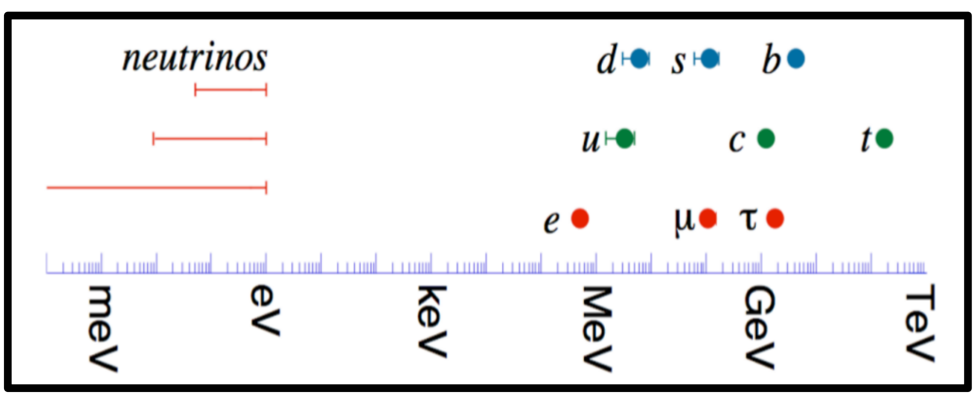


Artwork by Sandbox Studio, Chicago with Corinne Mucha

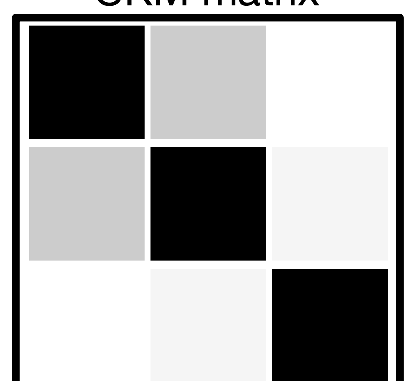
Presumably unrelated to some of the famous SM problems:

- Origin of neutrino masses
- Hierarchy problem
- Baryon asymmetry in Universe
- Strong CP problem
- Origin of DM, ...

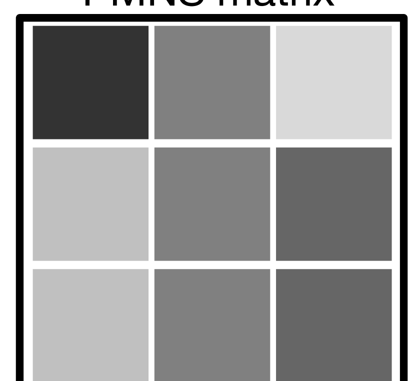
Connection with the SM Flavor Puzzle?



CKM matrix



PMNS matrix



see-saw? symmetry? symmetry? anarchy?

What kind of BSM physics can explain these large (~20%) deviations from the SM?

Bottom-up approach

Anomaly in data $\longrightarrow$ EFT $\longrightarrow$ SMEFT $\longrightarrow$ Simplified Models $\longrightarrow$ Ultra-Violet Theory

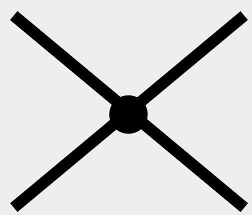
Guided by data with minimal theoretical bias

SM Effective Field Theory

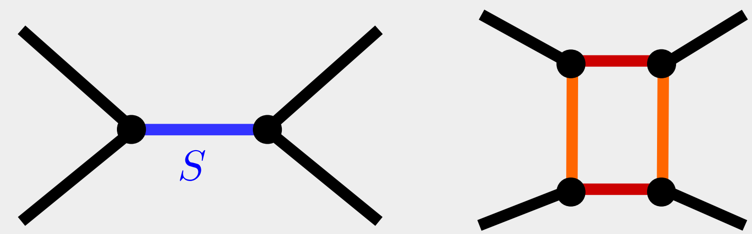
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{i,d} \frac{C^i}{\Lambda_{\rm NP}^{d-4}} \mathcal{O}_d^i$$

$E < \Lambda_{\rm NP}$
$d = 6, 7, \ldots$

e.g. $\mathcal{O} \sim \psi\psi\psi\psi$



Simplified Models



$\mathcal{L}_{\rm simple} \supset \psi\psi S + m_S^2 S^2$
$m_S \sim \Lambda_{\rm NP}$

B-anomalies scales of NP:

Di-Luzio, Nardecchia '17

$R_K^{(*)}$ **Tree-level NP** $\longrightarrow$ $\Lambda_{\rm NP} \lesssim 30$ TeV

$R_D^{(*)}$ **Tree-level NP**
$R_K^{(*)}$ **one-loop NP** $\longrightarrow$ $\Lambda_{\rm NP} \lesssim 3$ TeV

Large couplings

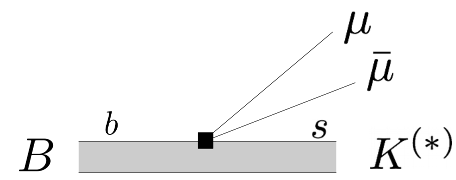
Strong physics case for LHC!!

Effective theory b→sll

- Semi-leptonic vectorial operators $B \to K^{(*)}\ell\bar{\ell}$

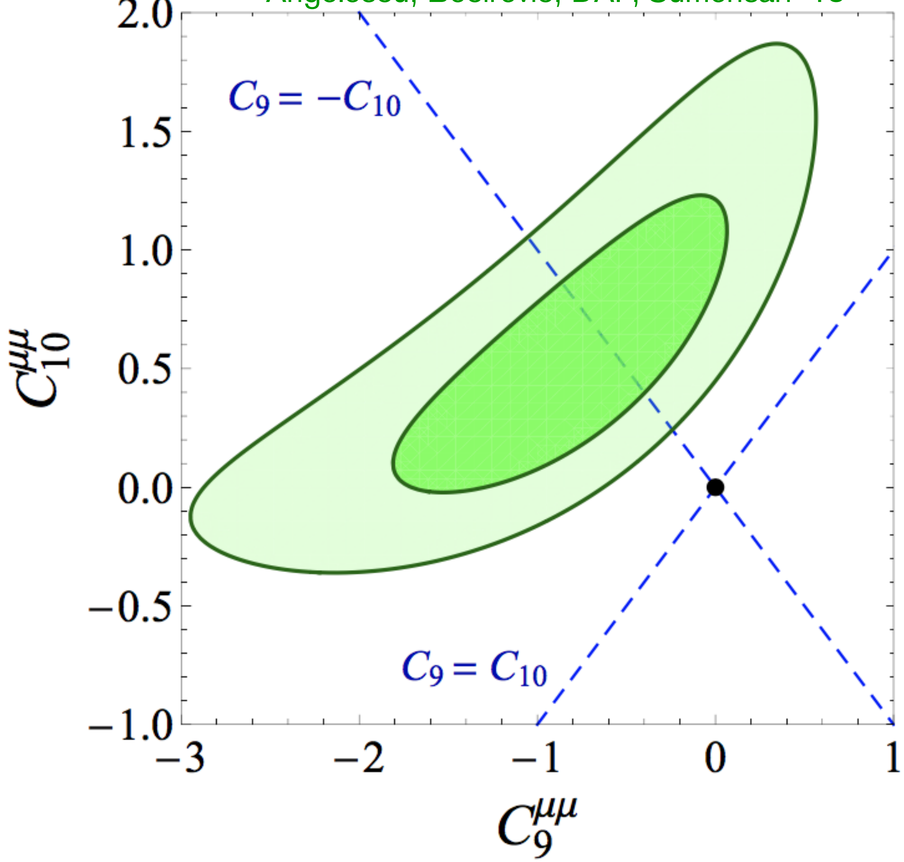
$$\mathcal{H}_{eff}^{NP} = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C'}_i \mathcal{O'}_i) + \mathrm{h.c.}$$

$$\mathcal{O}_9 = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}'_9 = (\bar{s}_R \gamma^\mu b_R)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O'}_{10} = (\bar{s}_R \gamma^\mu b_R)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



- Assuming NP in muons

Fit: $R_{K^{(*)}}$ & $\mathrm{Br}(B_s \to \mu\bar{\mu})$



Solutions:

$C_9 < 0$ vectorial muons

$C_9 = -C_{10} < 0$ V-A muons

B-anomaly from Tops

Can we explain the anomly in B-meson decays from New Physics in Tops?

Yes, but only at the 1-loop level!

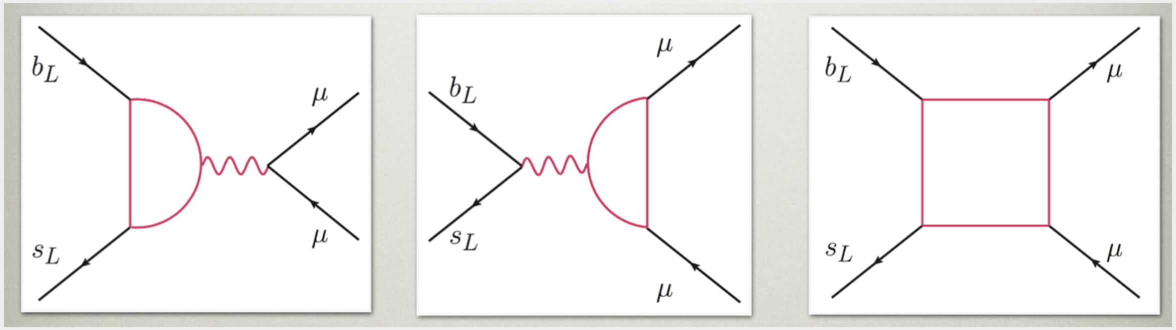
Motivation:

Low scale NP $\Lambda \sim \mathcal{O}(1)\,\mathrm{TeV}$ within LHC reach

NP can be more easily hidden in Tops

LHC is a Top-Factory

$R_{K^{(*)}}$ at 1-loop



Gripaios, Nardecchia, Renner [1509.05020]
Bauer, Neubert [1511.01900]
Bélanger, Delaunay [1603.03333]
Becirevic, Sumensari [1704.05835]
Kamenik, Soreq, Zupan [1704.06005]

B-anomaly from Tops

Camargo-Molina, Celis , **DAF**

Phys. Lett. B 784 (2018) 284-293

Main assumptions:

i) **Top-philic NP:** dominant couplings to right-handed tops in quark sector.

ii) NP couples only to muons in lepton sector.

iii) NP scale near the TeV (LHC accessible)

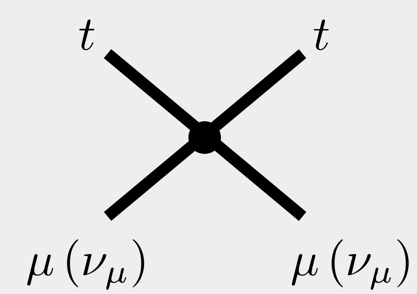
SMEFT:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i,d} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

$$\mathcal{O}_{eu} = (\bar{\mu}_R \gamma^\alpha \mu_R)(\bar{t}_R \gamma_\alpha t_R)$$

$$\mathcal{O}_{\ell u} = (\bar{\ell}_\mu \gamma^\alpha \ell_\mu)(\bar{t}_R \gamma_\alpha t_R)$$

$$\ell_\mu \equiv (\nu_\mu, \mu_L)^T$$

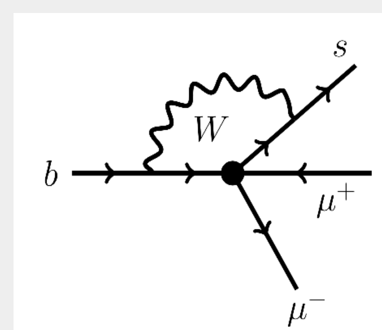


B-anomaly:

Generates LFU violation at the 1-loop level

Predicts V-A stucture for quark current

Only source of flavor violation is the CKM



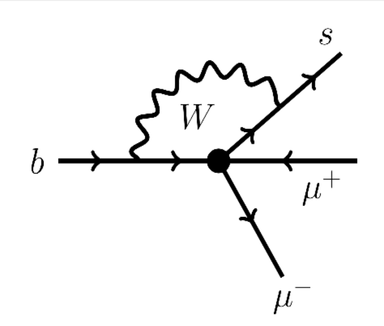
Low-energy phenomenology

$b \to s\mu\bar{\mu}$ from $\mathcal{O}_{\ell u}$ $\mathcal{O}_{eu}$

$$\mathcal{H}^{NP}_{eff} = -\frac{\alpha G_F}{\sqrt{2}\pi} V^*_{ts} V_{tb} \left[\mathcal{C}_9 (\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \mu) + \mathcal{C}_{10} (\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \gamma_5 \mu) \right] + \text{h.c.}$$

$$\mathcal{C}_9 \simeq \frac{\alpha}{8\pi} \left(\frac{m_t^2}{\Lambda^2}\right) \log\left(\frac{\Lambda}{M_W}\right) \left[\mathcal{C}_{eu} + \mathcal{C}_{\ell u}\right] + \ldots$$

$$\mathcal{C}_{10} \simeq \frac{\alpha}{8\pi} \left(\frac{m_t^2}{\Lambda^2}\right) \log\left(\frac{\Lambda}{M_W}\right) \left[\mathcal{C}_{eu} - \mathcal{C}_{\ell u}\right] + \ldots$$



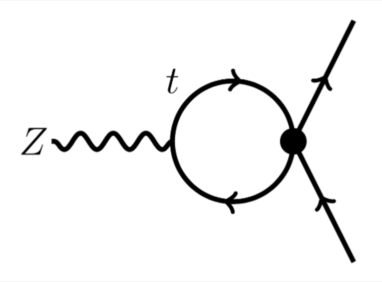
$Z \to \mu\bar{\mu}$

$$\mathcal{L} = \frac{g}{c_W} \bar{\mu}\gamma_\alpha (\delta g_L P_L + \delta g_R P_R) \mu Z^\alpha$$

Modified Z coupling to muons

$$\delta g_L \simeq \frac{3}{4\pi^2} \left(\frac{m_t^2}{\Lambda^2}\right) \log\left(\frac{\Lambda}{m_t}\right) \mathcal{C}_{\ell u} + \ldots$$

$$\delta g_R \simeq \frac{3}{4\pi^2} \left(\frac{m_t^2}{\Lambda^2}\right) \log\left(\frac{\Lambda}{m_t}\right) \mathcal{C}_{eu} + \ldots$$



Relevant constraints from LEP:
LFU tests & forward-background asymmetry

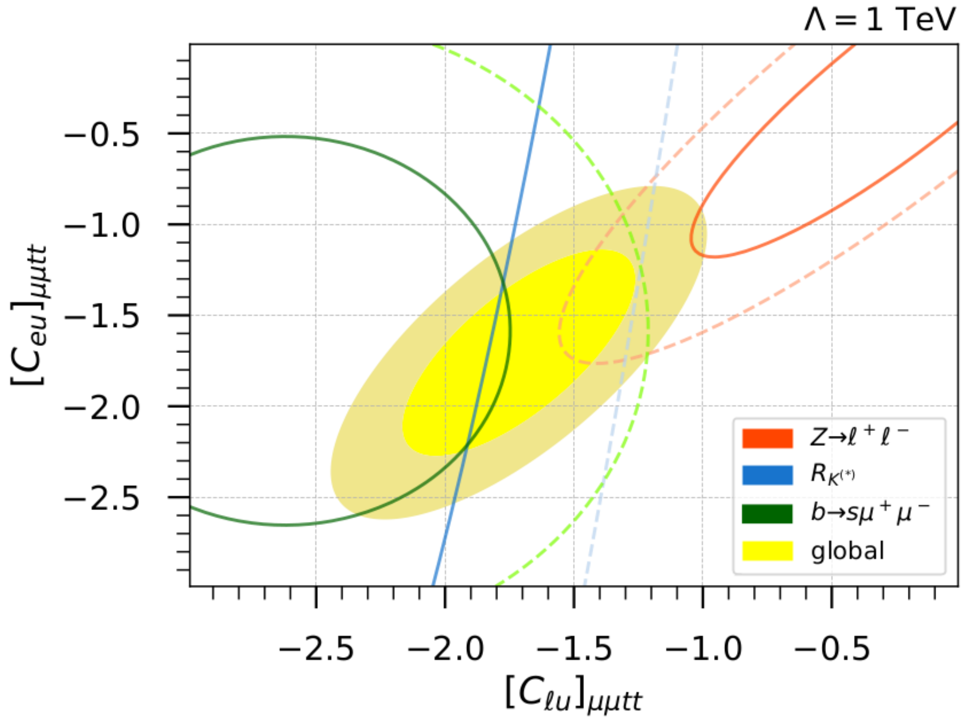
$$R_{e\mu} \equiv \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

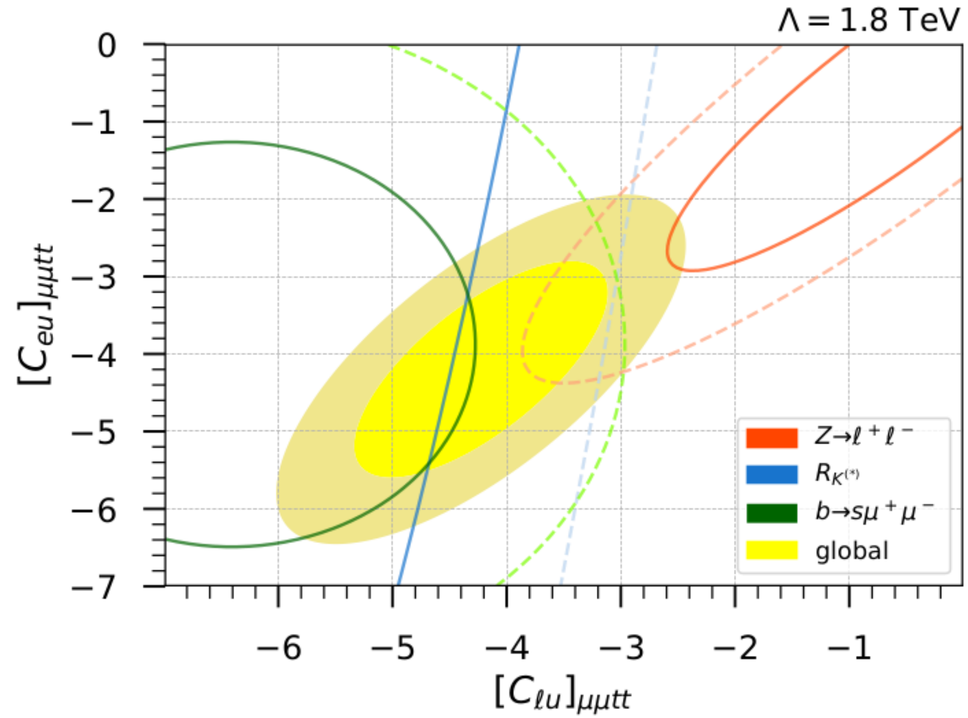
Less relevant constraints from $b \to s\nu\nu$

Global fit results:

Camargo-Molina, Celis, DAF 1805.04917

$$\mathcal{O}_{eu} = (\bar{\mu}_R \gamma^\alpha \mu_R)(\bar{t}_R \gamma_\alpha t_R)$$
$$\mathcal{O}_{\ell u} = (\bar{\ell}_\mu \gamma^\alpha \ell_\mu)(\bar{t}_R \gamma_\alpha t_R)$$





χ^2	$b \to s\mu^+\mu^-$	$R_{K^{(*)}}$	$Z \to \ell^+\ell^-$
SM	25.8	22.5	0.5
$\Lambda = 1$ TeV	2.5	5	7.9
$\Lambda = 1.5$ TeV	2.5	5	7.8
$\Lambda = 1.8$ TeV	2.4	5	7.8

Prefered region: $\mathcal{C}_{\ell u} \sim \mathcal{C}_{eu} < 0$

Some tension with LEP

Large Wilson Coeffs.

$$(\mathcal{C}_9, \mathcal{C}_{10}) = (-1.11, 0.273)$$

Anomaly solved mainly through $\mathcal{C}_9$

Vectorial coupling to muons!

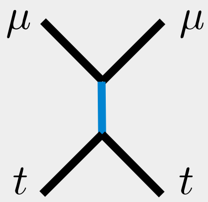
Simplified models

EFT description may break down at the LHC...

NP Mediators needed for more reliable studies.

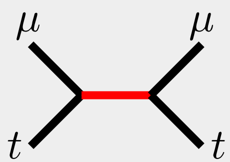
Two types of mediators:

Color neutral



$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$

Colorful



Leptoquarks (LQ)

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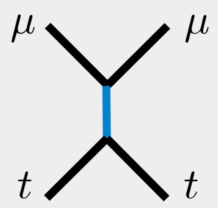

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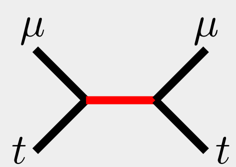
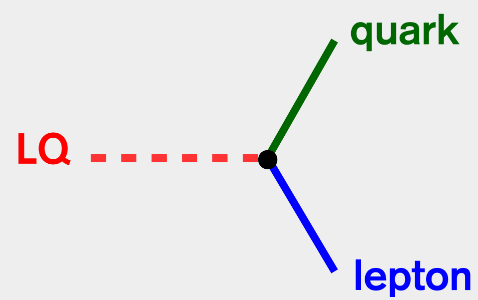


Leptoquarks (LQ)

What is a Leptoquark?

Hypothetical Scalar or Vector boson

Color tiplet with hypercharge:



$$Q_{em} = \{\pm\frac{1}{3},\ \pm\frac{2}{3}, \pm\frac{4}{3}, \pm\frac{5}{3}\}$$

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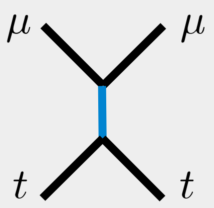
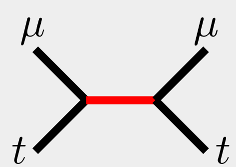


$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$

Colorful



Leptoquarks (LQ)

Leptoquark Bestiary:

$(SU(3), SU(2), U(1))$	Spin	Symbol
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$

Simplified models

EFT description may break down at the LHC...

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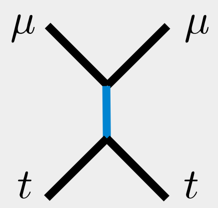
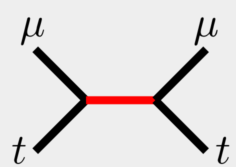
Two types of mediators:

Color neutral



$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$

Colorful



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$(\mathbf{\bar{3}}, \mathbf{2}, 5/6)$	1	V_2
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$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$

	Z'	S_1	R_2	$\tilde{U}_1$	$\tilde{V}_2$
$[\mathcal{O}_{\ell u}]_{\mu\mu tt}$	✓	✗	✓	✗	✓
$[\mathcal{O}_{eu}]_{\mu\mu tt}$	✓	✓	✗	✓	✗
$\mathcal{C}_{\ell u}, \mathcal{C}_{eu} < 0$	✓	✗	✓	✓	✗

Camargo-Molina, Celis, DAF 1805.04917

Which Top-philic Mediators?

Only one single mediator solution: Z'

Two LQ solution: 1 vector + 1 scalar

$$\tilde{U}_1^{\mu} \sim (\mathbf{3}, \mathbf{1}, 5/3) \quad R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$$

$$R_2 = (R_2^{(5/3)}, R_2^{(2/3)})^T$$

Simplified Z' model:

$$\mathcal{L}_{Z'} = \frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} - \frac{1}{2} M_{Z'} Z'_\alpha Z'^\alpha + Z'_\alpha \left[\epsilon_R^{tt} (\bar{t}_R \gamma^\alpha t_R) + \epsilon_R^{\mu\mu} (\bar{\mu}_R \gamma^\alpha \mu_R) + \epsilon_L^{\mu\mu} (\bar{\ell}_\mu \gamma^\alpha \ell_\mu) \right]$$

1 mass + 3 couplings

$\ell_\mu \equiv (\nu_\mu, \mu_L)^T$

Matching conditions: $\mathcal{C}_{\ell u} = -\epsilon_R^{tt} \epsilon_L^{\mu\mu}$, $\mathcal{C}_{eu} = -\epsilon_R^{tt} \epsilon_R^{\mu\mu}$

Fit prefers vectorial muonic couplings: $\epsilon_V^{\mu\mu} \equiv \epsilon_R^{\mu\mu} = \epsilon_L^{\mu\mu}$

UV completion: Top-philic U(1)' models Kamenik, Soreq, Zupan [1704.06005] Fox, Low, Zhang [1801.03505]

Simplified LQ model: $\widetilde{U}_1^\mu \sim (\mathbf{3}, \mathbf{1}, 5/3)$ $R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$ $R_2 = (R_2^{(5/3)}, R_2^{(2/3)})^T$

$$\mathcal{L}_{\rm LQ} = (D_\alpha R_2)^\dagger (D^\alpha R_2) - \frac{1}{2} \widetilde{U}^\dagger_{\alpha\beta} \widetilde{U}^{\alpha\beta} - i g_s \widetilde{U}^\dagger_\alpha G^{\alpha\beta} \widetilde{U}_\beta + \kappa_S \, \bar{t}_R (R_2^T i \tau_2 \ell_\mu) + \kappa_V \, (\bar{t}_R \gamma^\alpha \mu_R) \widetilde{U}_\alpha + \text{h.c.}$$

2 masses + 2 couplings

Matching conditions: $\mathcal{C}_{\ell u} = -|\kappa_S|^2/2$, $\mathcal{C}_{eu} = -|\kappa_V|^2$

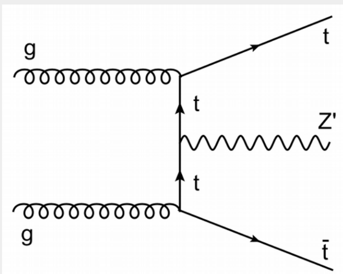
vector LQ: only RH couplings

UV completion: none yet... Camargo-Molina, Celis, DAF [in prepration]

Z' Phenomenology

Direct searches at Colliders:

$pp \to t\bar{t}Z'$



$pp \to t\bar{t}t\bar{t}$

$pp \to t\bar{t}\mu\bar{\mu}$

$pp \to t\bar{t}\nu\bar{\nu}$

4-tops at LHC

CMS $35.9\,\mathrm{fb}^{-1}$ Eur. Phys. J. C78 (2018) no.2, 140

$\sigma^{\mathrm{NP}}(t\bar{t}t\bar{t}) < 32\,\mathrm{fb}$ at 95%, CL

$tt\mu\bar{\mu}$ production

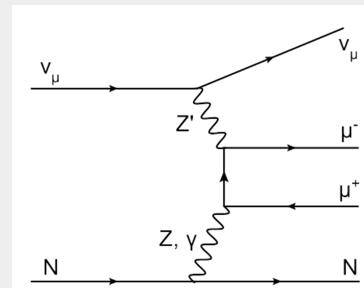
We recast Z' di-muon inclusive searches

ATLAS $36.1\,\mathrm{fb}^{-1}$ $pp \to \mu^+\mu^- + X$

JHEP 10 (2017) 182

Low-energy:

neutrino tridents $\nu_\mu\gamma^* \to \nu_\mu\mu^+\mu^-$



Altmannshofer, Gori, Pospelov, Yavin [1406.2332]

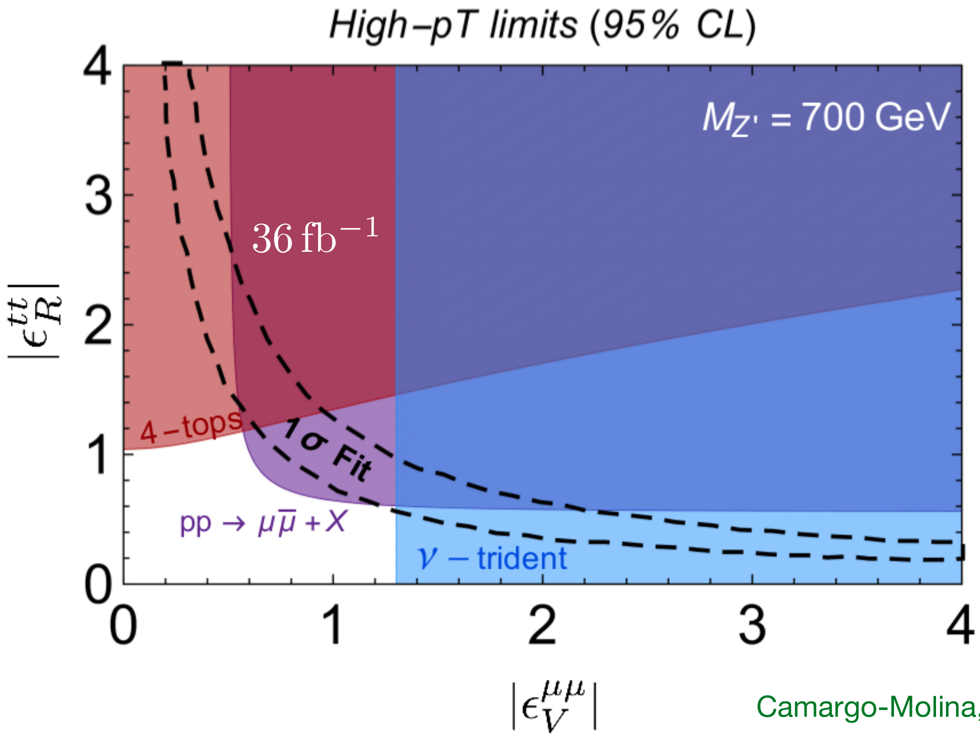
$$\frac{\sigma^{\mathrm{NP}}_{\nu_\mu\mu\bar{\mu}}}{\sigma^{\mathrm{SM}}_{\nu_\mu\mu\bar{\mu}}} = \frac{1 + \left(1 + 4s^2_{\theta_W} + \frac{2v^2\,(\epsilon_V^{\mu\mu})^2}{M^2_{Z'}}\right)^2}{1 + (1 + 4s^2_{\theta_W})^2}.$$

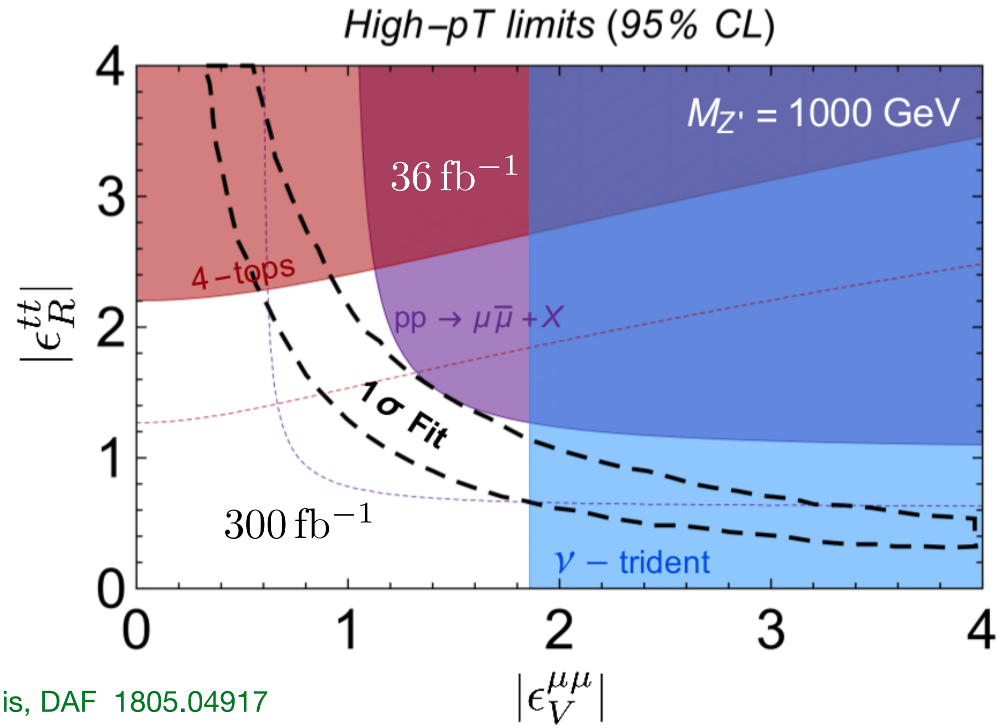
Probed at fixed target neutrino dump experiments

CCFR collaboration measurement

$$\sigma^{\mathrm{NP}}_{\nu_\mu\mu\bar{\mu}}/\sigma^{\mathrm{SM}}_{\nu_\mu\mu\bar{\mu}} = 0.82 \pm 0.28$$

Phys. Rev. Lett 66 (1991) 3117





Camargo-Molina, Celis, DAF 1805.04917

Nice high-pT / low-energy complementarity!

- For 4-top projections at 300/fb: $\sigma^{\rm NP}(t\bar{t}t\bar{t}) < 23\,\mathrm{fb}$ at $95\%\,\mathrm{CL}$

  Alvarez, DAF, Kamenik, Morales, Szynkman [Nucl. Phys. B 915 19 (2017)]

- LHC can probe parameter space relevant for the B-anomaly

- Need Dedicated searches for

  $$pp \to t\bar{t}Z' \to t\bar{t}t\bar{t}$$
  $$pp \to t\bar{t}Z' \to t\bar{t}\mu\bar{\mu}$$

  (low and high mass Z’)

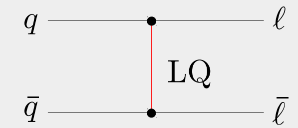
Leptoquark Pheno: $R_2\,,\ \widetilde{U}_\mu$

- Main LQ production mechanisms at hadron colliders:

Pair production
$gg(q\bar{q}) \to \mathrm{LQ}^\dagger\mathrm{LQ}$

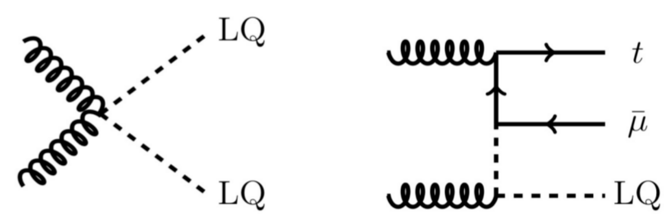
Single production
$qg \to \mathrm{LQ}\,\ell$

Drell-Yan
$q\bar{q} \to \ell\bar{\ell}$



- Implication of no tops inside proton:

  i) Pair production is completely QCD driven.
  ii) No t-channel Drell-Yan production.
  iii) No $2 \to 2$ single LQ production.

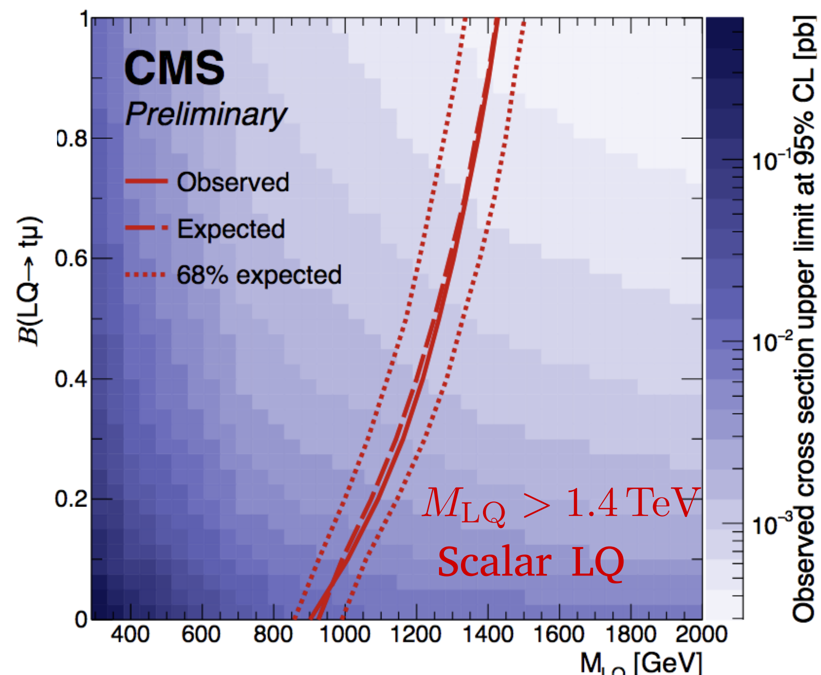


- Branching ratios in this model:

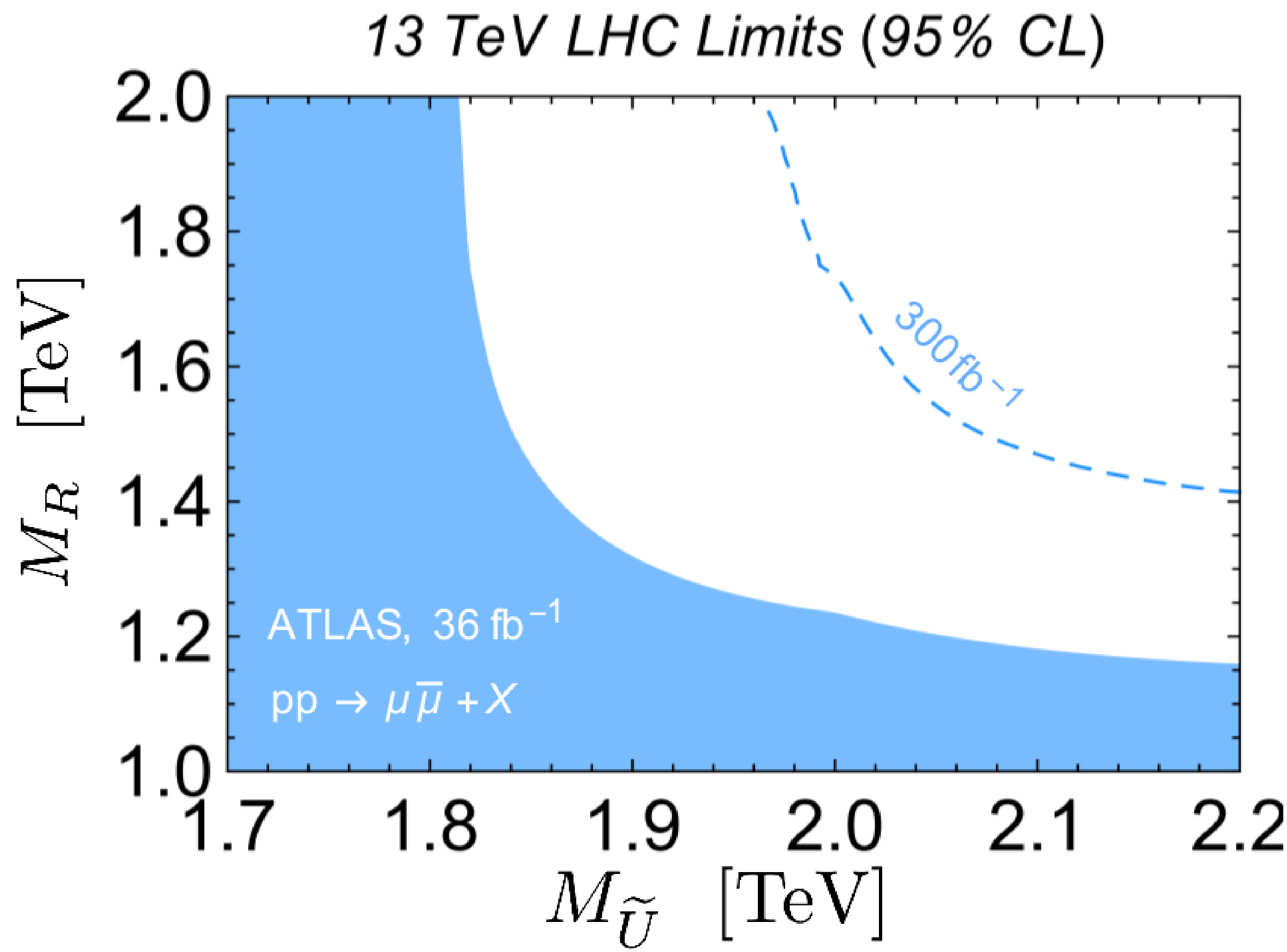
$\beta(\widetilde{U}_\mu \to t\mu) = 1$ $\quad\beta(R_2^{(5/3)} \to t\mu) = 1$ $\quad\beta(R_2^{(2/3)} \to t\nu_\mu) = 1$

LHC only provides limits on LQ masses

- very recent search by CMS:
`CMS-B2G-16-027, CERN-EP-2018-233`

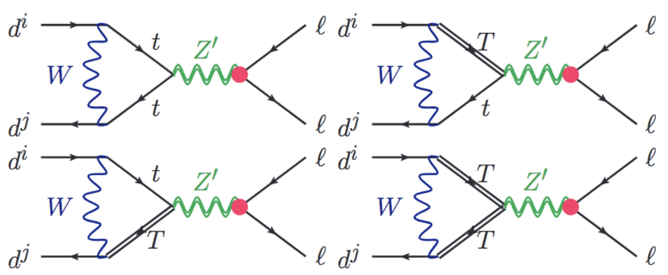


Limits for top-philic LQ model: $pp \to R_2^\dagger R_2,\ \widetilde{U}_\mu^\dagger \widetilde{U}_\mu \to t\bar{t}\mu^+\mu^-$



Currently probing relevant portions of parameter space for the anomaly

Toward UV complete theories



Abelian models:

Minimal U(1)' model Kamenik, Soreq, Zupan [1704.06005]

$$\mathcal{G}_{\rm SM} \times {\rm U}(1)_{Y'}$$

In a nutshell:

All SM matter singlets under U(1)'

Hidden Sector: New **vector-like top** T charged under U(1)'.

After SSB, top and muon couple to Z' via fermion mixing.

Non-abelian models?

Top-philic SU(4) model Camargo-Molina, Celis, DAF [in preparation]

$$\mathcal{G}_{\rm SM} \times {\rm SU}(4)$$

4321 Gauge group

$\widetilde{U}_\mu \sim (\mathbf{3}, \mathbf{1}, 5/3)$ as a gauge boson of SU(4)!

Di Luzio, Greljo, Nardecchia '17
Diaz, Schmaltz, Zhong '17
Bordone, Cornella, Fuentes-Martin, Isidori '17

Would-be SM fields

fields	SU(4)	$SU(3)_{c'}$	$SU(2)_L$	$U(1)_{Y'}$
Q_L^i	1	$\mathbf{3}$	$\mathbf{2}$	1/6
L_L^i	1	1	$\mathbf{2}$	−1/2
u_R^i	1	$\mathbf{3}$	1	2/3
d_R^i	1	$\mathbf{3}$	1	−1/3
e_R^i	1	1	1	−1
$\Psi_{L,R}$	$\mathbf{4}$	1	1	1/4
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	1	5/12
Ω_2	$\bar{\mathbf{4}}$	1	$\mathbf{2}$	−3/4
Ω_1	$\bar{\mathbf{4}}$	1	1	−5/4
H	1	1	$\mathbf{2}$	1/2

$$SU(4) \times SU(3)_{c'} \times SU(2)_L \times U(1)_{Y'}$$

$$g_4 \qquad g_3 \qquad g_2 \qquad g_1$$

- Many similarities with '4321' model

  Di Luzio, Greljo, Nardecchia ‘17

1 Heavy vector fermion

3 Heavy scalars

- Heavy gauge bosons:

$\widetilde{U}_\mu \sim (\mathbf{3}, \mathbf{1}, 5/3)$ Vector LQ $\rightarrow$ $R_K^{(*)}$

$G'_\mu \sim (\mathbf{8}, \mathbf{1}, 0)$ Coloron

$Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

$$m_{Z'} \lesssim m_{\widetilde{U}} \lesssim m_{G'}$$

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H	1	1	$\mathbf{2}$	1/2

- 2 scalars induce SSB (like ‘Pati-Salam 4321’):

$$SU(4) \times SU(3)_{c'} \times U(1)_{Y'} \to SU(3)_c \times U(1)_Y$$

$$\langle \Omega_3 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_3 & 0 & 0 \\ 0 & v_3 & 0 \\ 0 & 0 & v_3 \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle \Omega_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix},$$

$$\Omega_3 \sim (\mathbf{8}, \mathbf{1}, 0) \oplus \underline{(\mathbf{3}, \mathbf{1}, 5/3)} \oplus (\mathbf{1}, \mathbf{1}, 0)$$

$$\Omega_1 \sim \underline{(\bar{\mathbf{3}}, \mathbf{1}, -5/3)} \oplus (\mathbf{1}, \mathbf{1}, 0)$$

Would-be-Goldstone swollowed by $\widetilde{U}_\mu \sim (\mathbf{3}, \mathbf{1}, 5/3)$

fields	SU(4)	$SU(3)_{c'}$	$SU(2)_L$	$U(1)_{Y'}$
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$\Psi_{L,R}=(T,E)^T_{L,R}$

T: top partner
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$$\mathcal{L}\supset\frac{g_4}{\sqrt{2}}\widetilde{U}_\mu(\bar{T}_L\gamma^\mu E_L+\bar{T}_R\gamma^\mu E_R)$$

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- Mass matrix and fermion mixing:

$$(\bar{t}_L,\bar{T}_L)\begin{pmatrix}\frac{y_t v}{\sqrt{2}} & 0\\ \frac{\lambda_t v_3}{\sqrt{2}} & M_\Psi\end{pmatrix}\begin{pmatrix}t_R\\T_R\end{pmatrix}$$

- $M_\Psi\sim v_3,\,v_1>>v$ Large vector-like fermion mass
- θ_R Large RH mixing angles.
- $\theta_L\sim v/M_\Psi$ Suppressed LH mixing!

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- $M_\Psi \sim v_3, \, v_1 >> v$ Large vector-like fermion mass
- θ_R Large RH mixing angles.
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Four-top production at the LHC

Nucl. Phys. B 915 19 (2017)

Alvarez, **DAF**, Kamenik, Morales, Szynkman

SM Four-top production

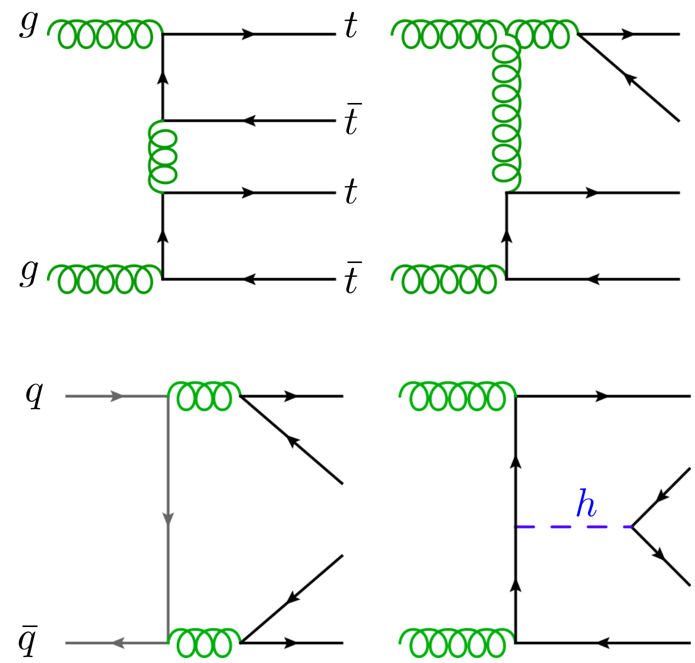
- $pp \to t\bar{t}t\bar{t}$ production at the LHC:
  - QCD driven ~90% $\mathcal{O}(\alpha_s^4)$
  - Higgs & EW mediated ~10% $\mathcal{O}(\alpha_s^2\, y_t^2)$ $\mathcal{O}(\alpha_s^2\, \alpha^2)$
- Largest production treshold at the LHC

$$E > 4m_t \sim 700\,\mathrm{GeV}$$

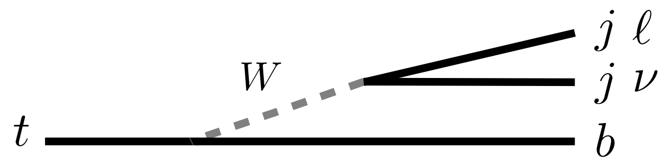
- The 13 TeV production cross-sections at the LHC:

$$\sigma(pp \to t\bar{t}t\bar{t})_{13\,\mathrm{TeV}} \approx 9\,\mathrm{fb}$$

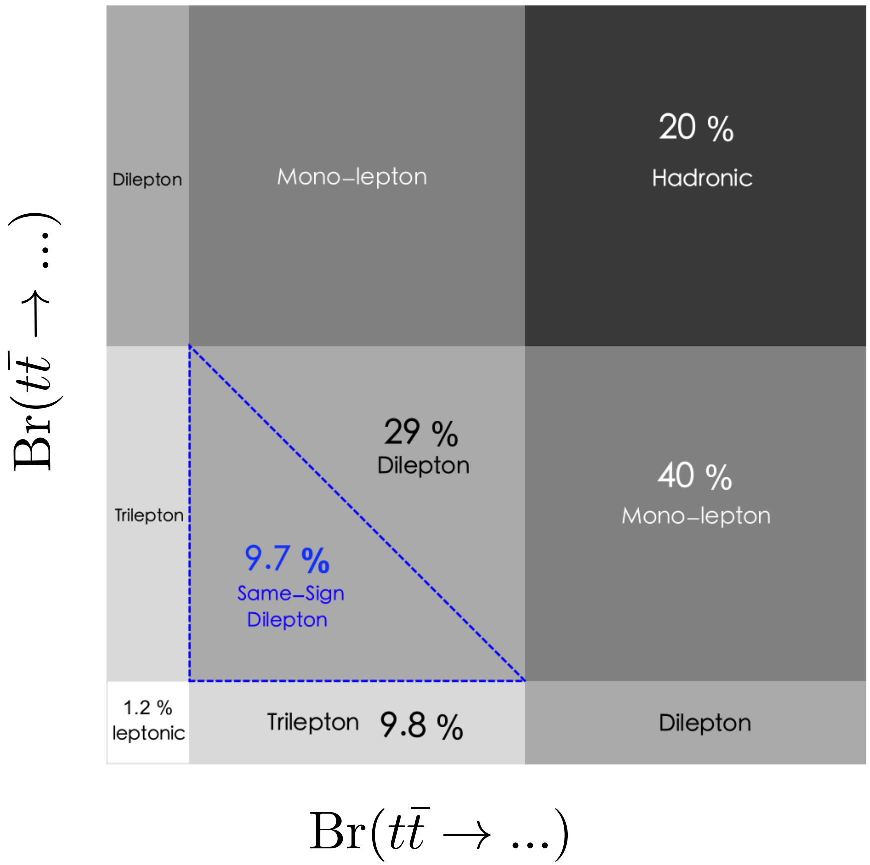
5 orders of magnitude smaller than $t\bar{t}$
30 times smaller than $t\bar{t}h$



Decay modes



$$t\bar{t}t\bar{t} \to b\bar{b}b\bar{b}\, W^+W^-W^+W^-$$



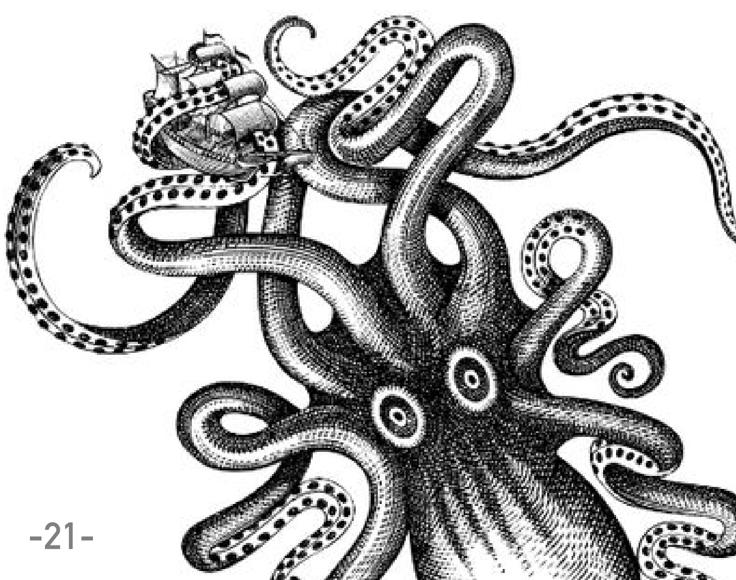
$t\bar{t}t\bar{t}$ channels	leptons	$N_{b-\text{jets}}$	N_{jets}
hadronic	0	4	8
mono-lepton	$\ell^{\pm}$	4	6
OS dilepton	$\ell^{+}\ell^{-}$	4	4
SS dilepton	$\ell^{\pm}\ell^{\pm}$	4	4
trilepton	$\ell^{\pm}\ell^{\pm}\ell^{\mp}$	4	2
leptonic	$\ell^{+}\ell^{-}\ell^{+}\ell^{-}$	4	0

Very large jet multiplicity: 6 -12 jets!

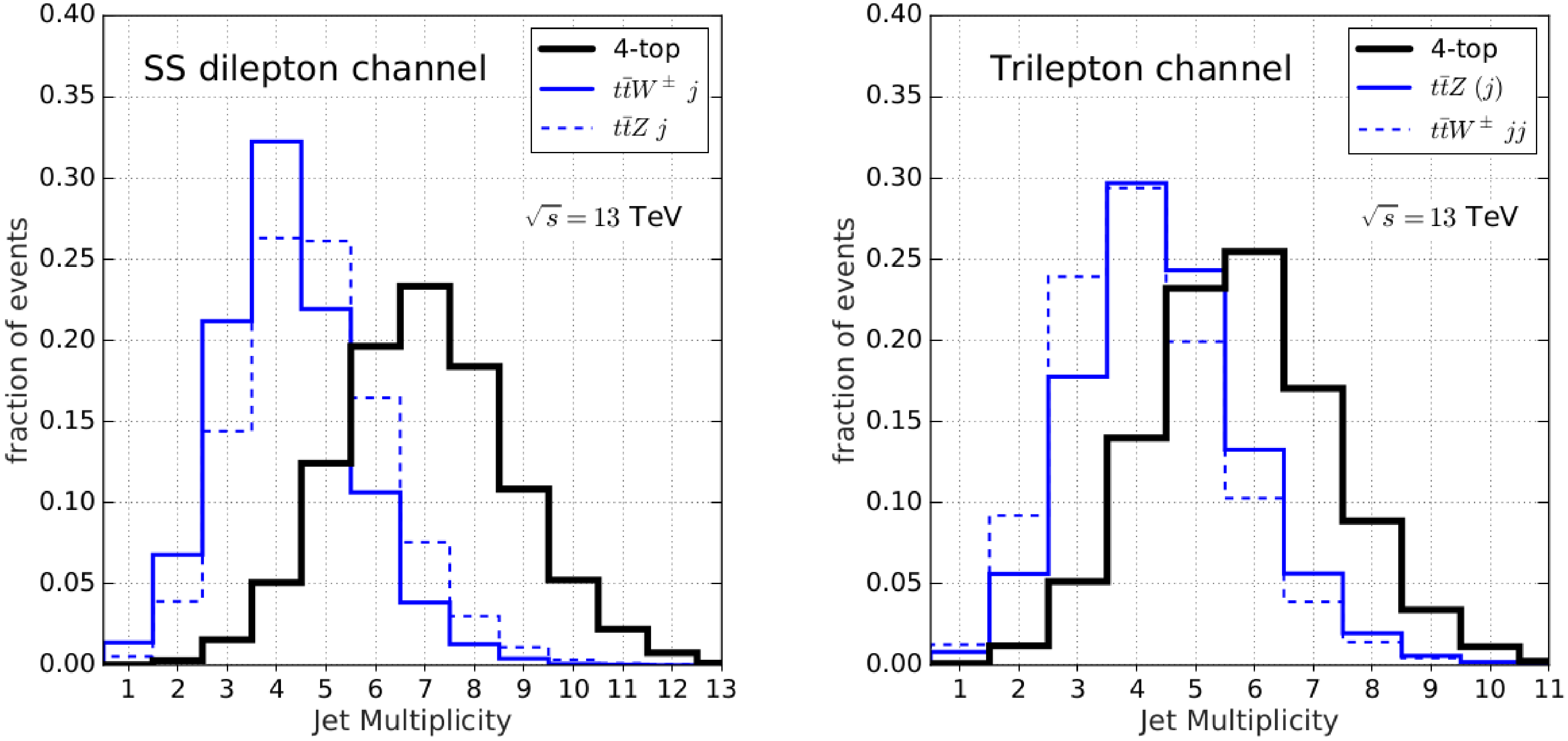
Same-Sign dilepton

Trilepton

BR ~ 20%
Cleanner channels
Lower backgrounds

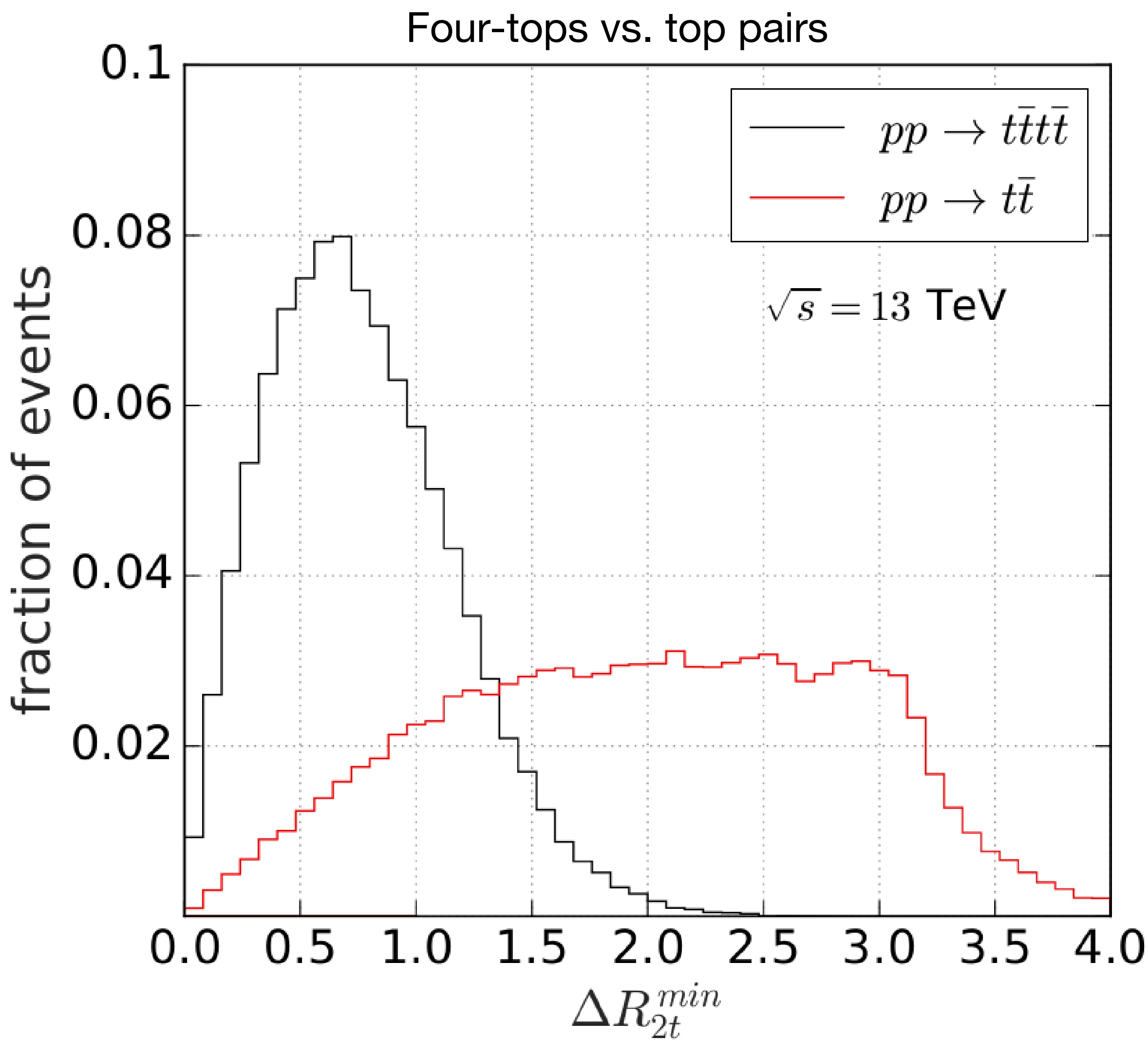


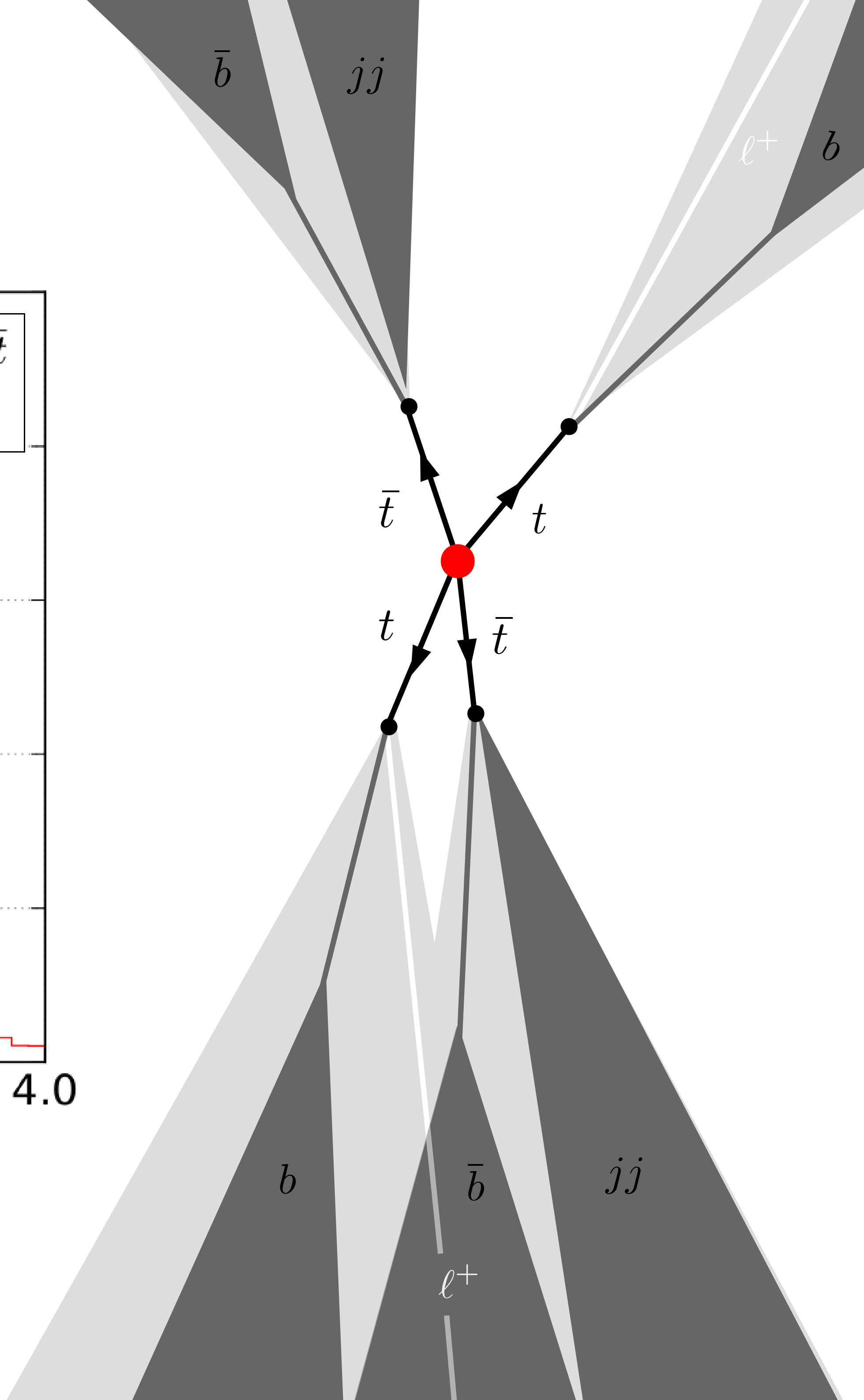
Jet multiplicites



Very good background discriminator

Overlaps





Expect accidental overlaps of top-decay products in detector

Leptonic isolation

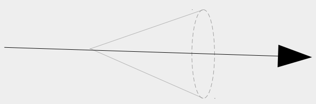
Many leptons fail isolation requirements for lepton ID

- Traditional (fixed cone) Leptonic isolation requirements:

$$I_{iso} \equiv \frac{p_T(\ell)}{\sum_{i \in R^{cone}} p_T(i)}$$

$$R^{cone} = 0.2 - 0.5$$

$$I_{iso} < 1 - 10\%$$


$\ell = e, \mu$

- **Mini-isolation**

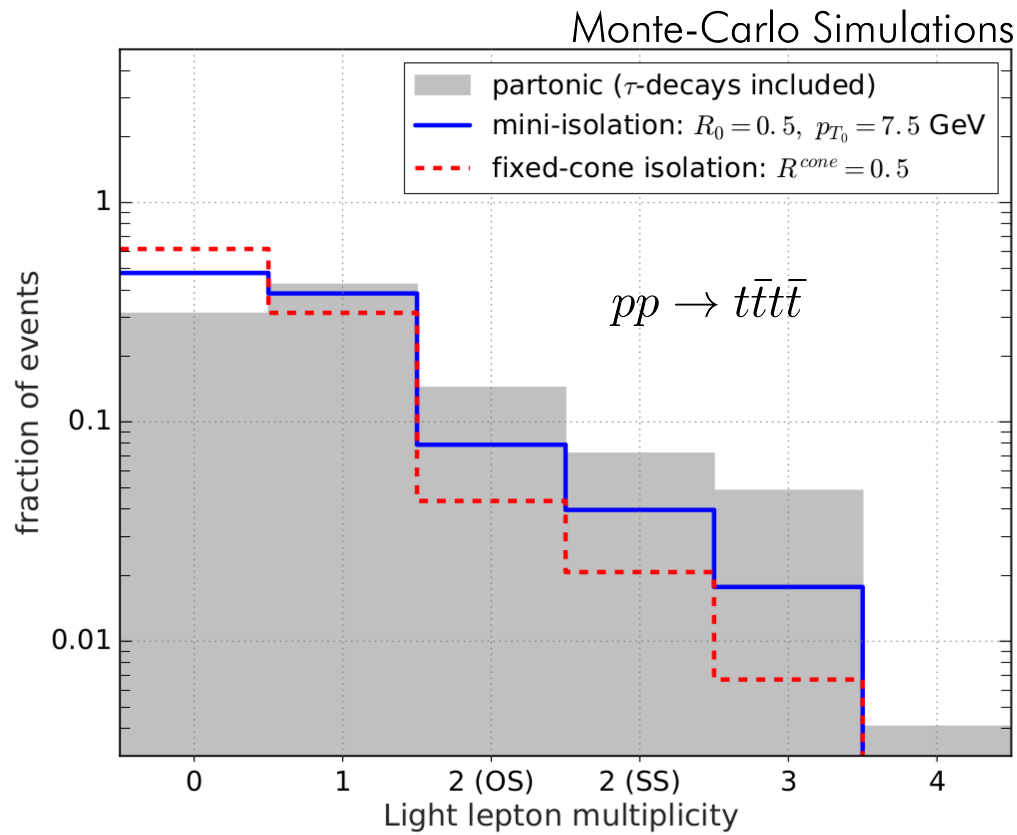
Rehermann, Tweedie [1007.2221]

Use p_T-dependent cone:

$$R^{cone}(p_T^{\ell}) = \min\left(R_0, \frac{p_T^0}{p_T^{\ell}}\right)$$

$$p_T^0 \sim 7.5 - 20\,\text{GeV}$$

$$R_0 = 0.2 - 0.5$$



Backgrounds

Irreducible Backgrounds:

Category	Backgrounds	FS	σ [fb]	decay mode	$\sigma \times BR$ [fb]
$t\bar{t}W$	$t\bar{t}\ W^{\pm}$	5	350.4	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	16.84
	$t\bar{t}\ W^{\pm}\ j$	5	167.8	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	8.06
	$t\bar{t}\ W^{\pm}\ jj$	5	96.8	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	4.65
	$t\bar{t}\ W^{\pm}\ jj$	5		$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\mp}$	1.58
	$t\bar{t}\ W^{\pm}\ bjj$	5	2.3	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	0.11
	$t\bar{t}\ W^{\pm}\ b\bar{b}\ jj$	4	2.1	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	0.10
$t\bar{t}Z$	$t\bar{t}\ Z$	5	583.3	$W_{\ell^\pm}\ W_{\mathrm{had}}\ Z_{\ell}$	22.33
	$t\bar{t}\ Z\ j$	5	404.7	$W_{\ell^\pm}\ W_{\mathrm{had}}\ Z_{\ell}$	15.50
	$t\bar{t}\ Z\ jj$	5	194.9	$W_{\ell^\pm}\ W_{\mathrm{had}}\ Z_{\ell}$	7.46
	$t\bar{t}\ Z\ jj$	5		$W_{\ell^\pm}\ W_{\ell^\pm}\ Z_{\ell}$	3.18
$t\bar{t}h$	$t\bar{t}\ h$	4	397.6	$W_{\ell^\pm}\ W_{\mathrm{had}}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	4.70
	$t\bar{t}\ h$	4		$W_{\ell^\pm}\ W_{\mathrm{had}}\ Z_{\ell}\ Z_{\mathrm{had}}$	0.37
	$t\bar{t}\ h$	5	401.3	$W_{\ell^\pm}\ W_{\mathrm{had}}\ \tau_{\ell^\pm}\ \tau_{\mathrm{had}}$	2.18
Others	$tZ\ bjj$	5	176.7	$W_{\ell^\pm}\ Z_{\ell}$	4.52
	$t\bar{t}\ W^{+}W^{-}$	4	8.0	$W_{\ell^\pm}\ W_{\mathrm{had}}\ W_{\ell^\pm}\ W_{\mathrm{had}}$	0.57
	$t\bar{t}\ W^{+}W^{-}$	4		$W_{\ell^\pm}\ W_{\mathrm{had}}\ W_{\ell^+}\ W_{\ell^-}$	0.39
	$W^{\pm}W^{\pm}\ b\bar{b}jj$	4	1.25	$W_{\ell^\pm}\ W_{\ell^\pm}$	1.94
	$ZZ\ b\bar{b}j$	4	30.2	$Z_{\ell}\ Z_{\ell}$	0.31
Signal	$t\bar{t}t\bar{t}$	4	**9.2**	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\mathrm{had}}\ W_{\mathrm{had}}$	**0.66**

MC simulations (MadGraph, AlpGen)

Same-Sign
Dilepton channel

$$\ell^{\pm}\ell^{\pm}$$

Similar for Trileptons...

Fakes & Charge flips

Two types of Instrumentation backgrounds: (object mis-reconstruction)

Fake leptons $j \to \ell^{\pm}$

Source: non-prompt lepton from heavy meson decays

$$t\bar{t} \to (b\nu\ell^+)\ (jjb) \longrightarrow (b\nu\ell^+)\ (\ell^+ jb)$$

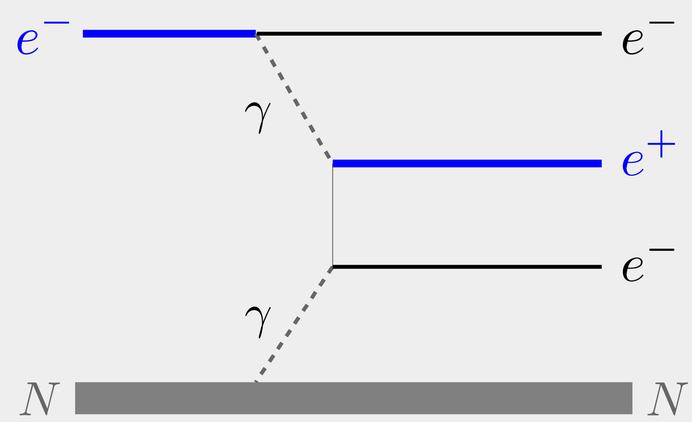
$\text{probability}: \ \epsilon_{j\to\ell} \sim \mathcal{O}(10^{-4})$

Charge flipped electrons $e^- e^+ \to e^{\pm} e^{\pm}$

Source: Trident electrons in tracker (negligible for muons)

$$t\bar{t} \to (b\nu\ell^+)\ (b\nu\ell^-) \longrightarrow (b\nu\ell^+)\ (b\nu\ell^+)$$

$\text{probability}: \ \epsilon_{e^{\pm}\to e^{\mp}} \sim \mathcal{O}(10^{-3})$



Fitting MC simulations to data driven estimation by ATLAS

$$\epsilon_{j\to\ell} = 7.2 \times 10^{-5} \qquad \epsilon_{e^{\pm}\to e^{\mp}} = 2.2 \times 10^{-4}$$

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LHC search strategy

- Our multi-lepton search strategy:

Same-sign dilepton channel:

- Exactly one Same-Sign diletpon (extra lepton veto) $\ell^{\pm}\ell^{\mp}$
- Jet mulitplicity cut $N_j \geq 7$
- b-jet multiplicity cut $N_b \geq 3$

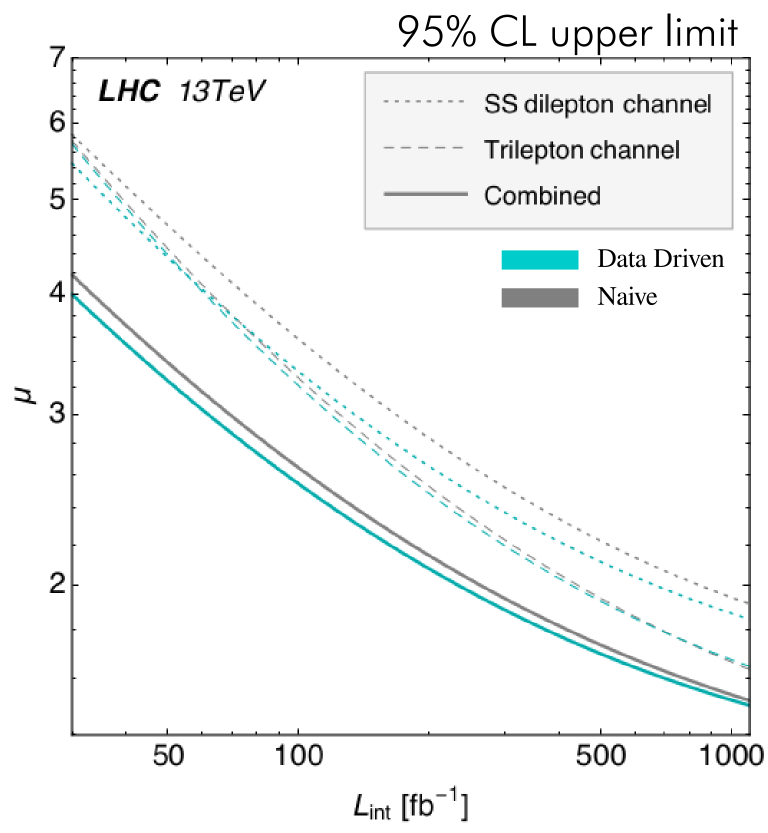
Trilpeton channel:

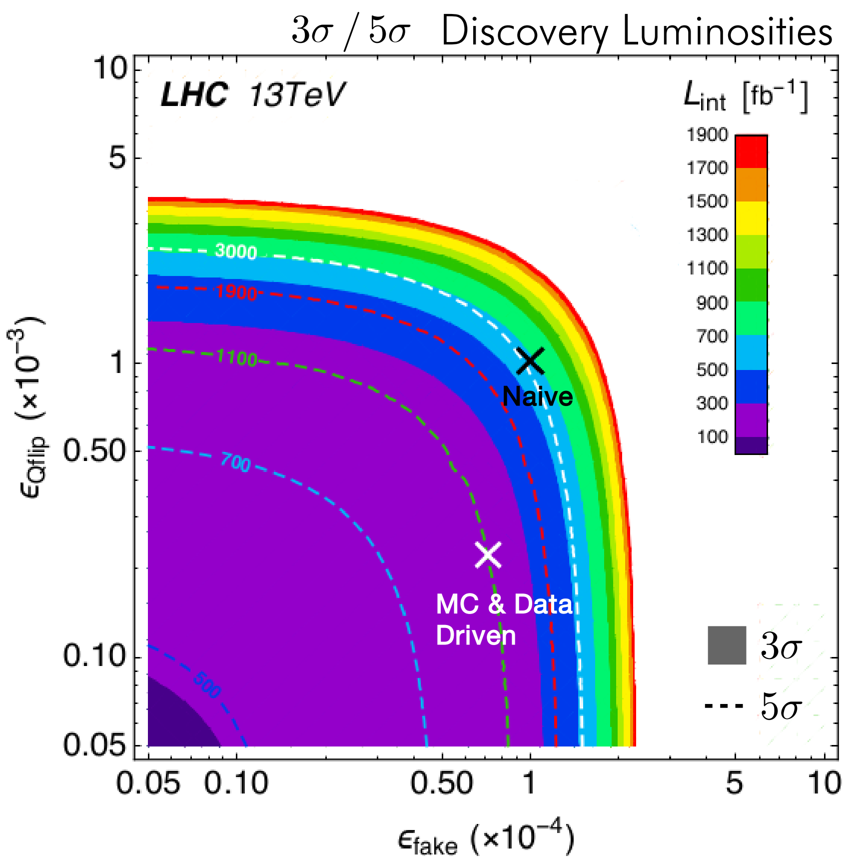
- Exactly one trilepton (extra lepton veto) $\ell^{\pm}\ell^{\pm}\ell^{\mp}$
- Jet mulitplicity cut $N_j \geq 5$
- b-jet multiplicity cut $N_b \geq 3$
- Z-mass window cut $75\,\mathrm{GeV} < m_{\ell\ell} < 110\,\mathrm{GeV}$

Very basic, extra cuts can be implemented if needed

LHC Results

95% CL upper limit: $\mu_{t\bar{t}t\bar{t}} \equiv \dfrac{\sigma(pp \to t\bar{t}t\bar{t})}{\sigma^{\rm SM}(pp \to t\bar{t}t\bar{t})} < 1.87 \qquad (\mathcal{L}_{int} = 300\,{\rm fb}^{-1})$





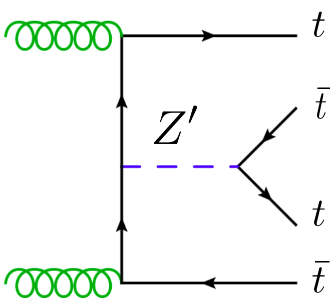
Trileptons perform better than Same-sign dilepton!

The HL-LHC should discover SM four-top production

New Physics in Four-Tops

Top-philic resolution of $b \to s\mu\mu$ anomaly

Z'
- U(1)' model (can be light)
- SU(4) model (heavy)



Heavy Z'

High-mass resonance $pp \to t\bar{t}Z' \to t\bar{t}t\bar{t}$ $m_{Z'} > 2m_t$

Multi-lepton search strategy not optimized

Boosted tops

Light Z'

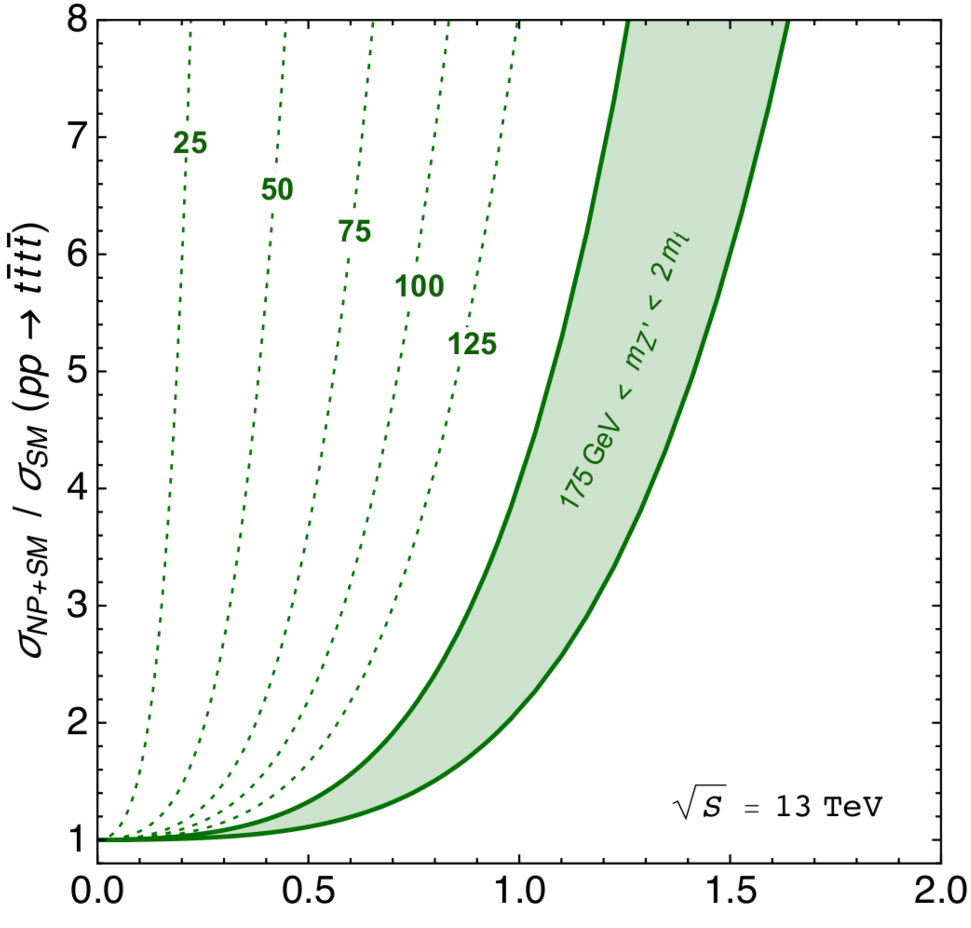
Non-resonant prodcuction $m_{Z'} < 2m_t$

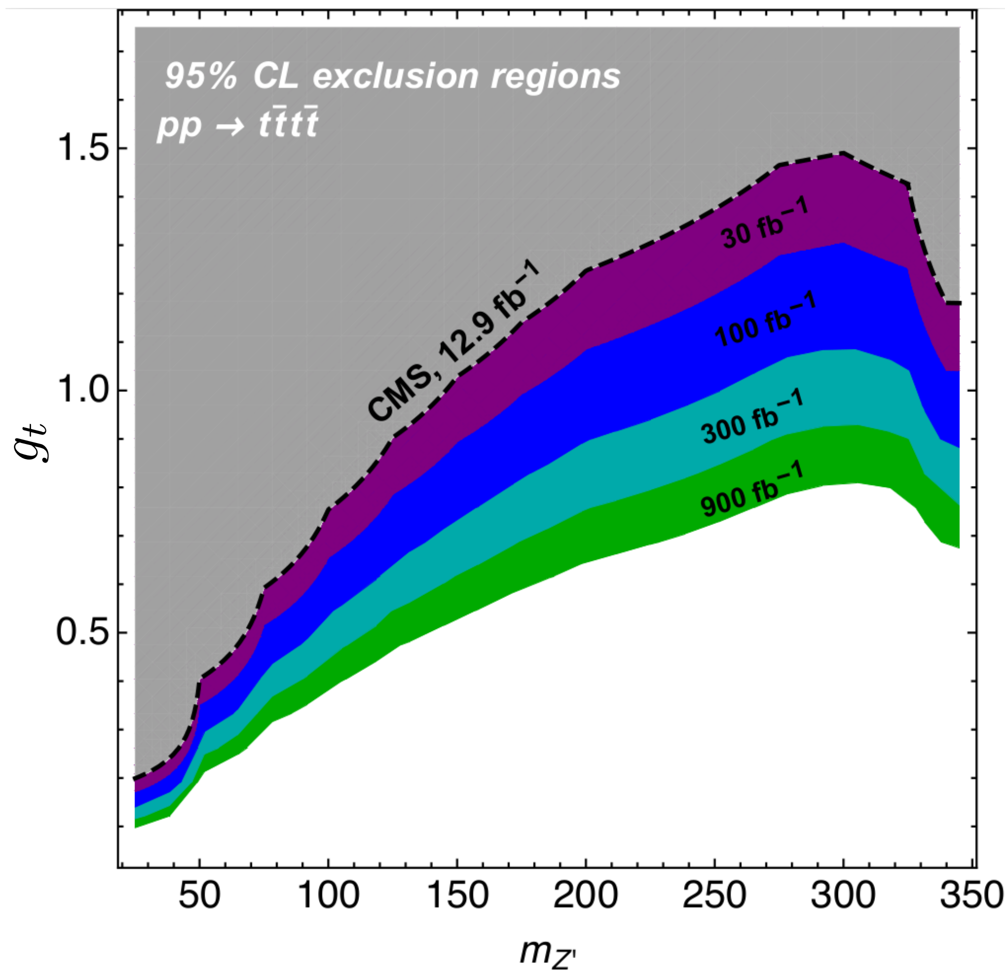
SM-like kinematic distributions, enhanced x-section

We can use the Multi-lepton search strategy

Top-philic Z' forces

Light Z' $\qquad \mathcal{L} \supset -g_t\, Z'_\mu\, (\bar{t}_R \gamma^\mu t_R)$





Conclusions

We explored the possibility of explaining the LHCb anomalies in $B \to K^{(*)}\ell\bar{\ell}$ with **Top-philic New Physics.**

We identified the SMEFT operators relevant for the B-anomalies at 1-loop, as well as all possible mediators accomodating low energy data

Two possibilities:

- 1 colorless mediator: Z'
- 2 Leptoquarks: $R_2 \; + \; \widetilde{U}_\mu$

We outlined one possible UV completion for the leptoquark model

We confronted LHC searches with each model

The LHC is currently probing significant portions of parameter space

We also proposed a SM 4-top search strategy in the multi-lepton channels

And provided bounds on a light top-philic Z’

Conclusions

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Thank you!

- Backup-

Leptoquark model 'catalog'

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vectors	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

V-A structure

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

Only state that can solve both B-anomalies!

Butazzo et al [1706.07808]

- UV completion necessary: e.g. Pati-Salam boson '4321' models

$$G_{4321} = SU(4) \times SU(3)_{c'} \times SU(2)_L \times U(1)_{Y'} \rightarrow G_{SM}$$

Di Luzio et al [1708.08450]
Bordone, Cornella, Fuentes-Martin, Isidori '18

- No single scalar LQ solves both B-anomalies.

  Two (or more) scalar LQ needed:

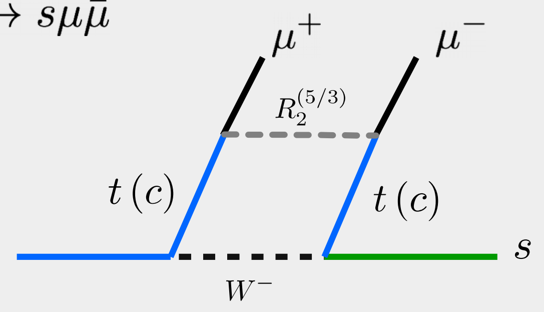
  - R_2 & S_3 (Scalar + Tensor & V-A) e.g. GUT inspired model Becirevic et al [1808.08179]
  - S_1 & S_3 (V-A) e.g. Strongly coupled model Marzocca [1803.10972]

Neutral currents (loop- level): Becirevic, Sumensari '17

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{s\mu} & 0 \\ 0 & y_L^{b\mu} & 0 \end{pmatrix} \qquad y_R = 0$$

No direct coupling to down quarks

$b \to s\mu\bar{\mu}$



$$C_9 = -C_{10} = \frac{1}{32\pi\alpha}\left[\frac{m_t^2\,|y_L^{t\mu}|^2}{m_W^2}\mathcal{F}\left(\frac{m_t^2}{m_W^2}\right) + \frac{V_{cs}}{V_{ts}}\frac{m_t m_c\, y_L^{c\mu}(y_L^{t\mu})^*}{m_W^2}\mathcal{F}(m_t^2, m_c^2) \;+\; \ldots\right]$$

relative supression

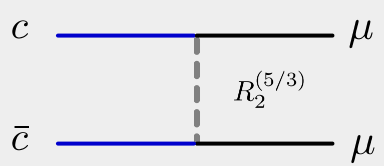
$$m_c V_{ts}^{-1}/m_t \sim 1/6$$

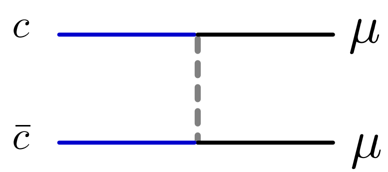
$$R_{K^{(*)}} < R_{K^{(*)}}^{\rm SM}$$

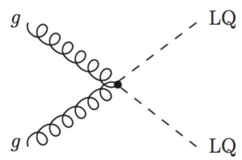
Model needs very large charm Yukawa couplings...

Modification of Z couplings $Z \to \mu^+\mu^-$ strong limits from LEP

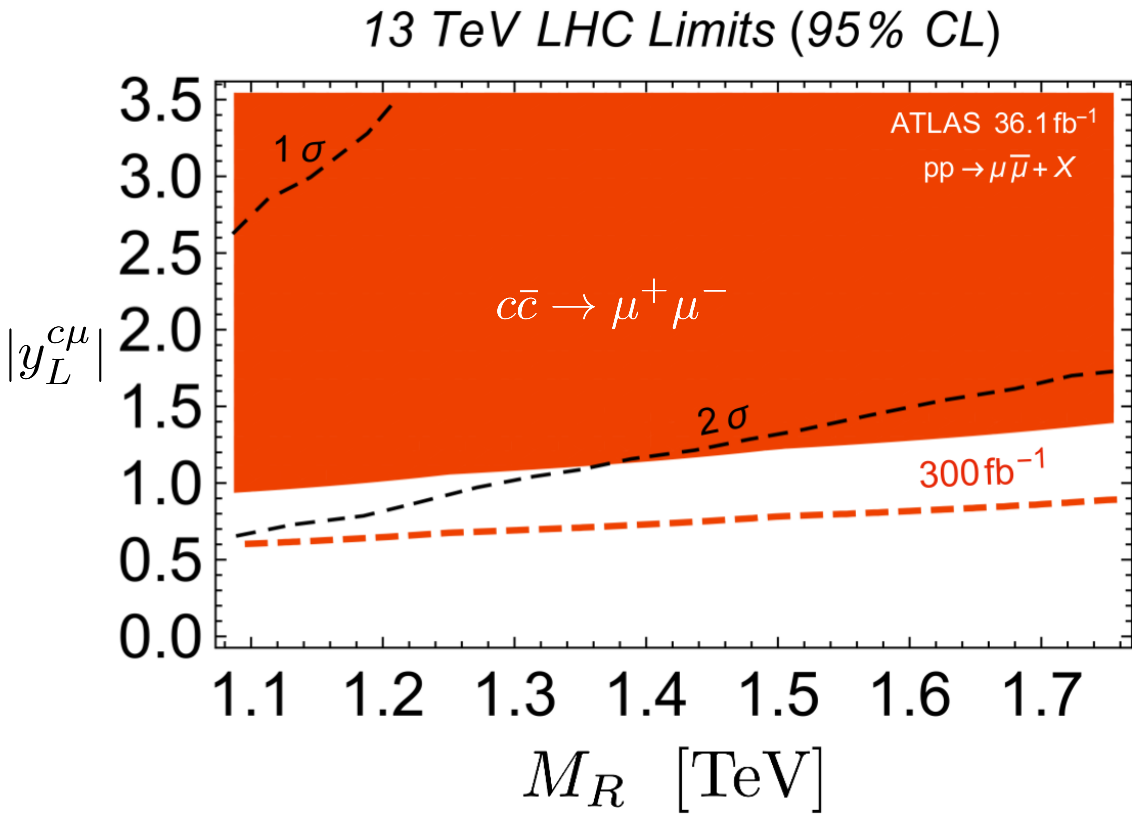
LHC processes: $pp \to R_2^* R_2 \to tt\mu\mu, cc\mu\mu$ $\qquad c\bar{c} \to \mu^+\mu^-$







$M_R > 1150$ GeV



LHC direct searches excludes this model for $R_{K^{(*)}}$

Motivates loop models with top-quarks coupling only (Top-philic models)

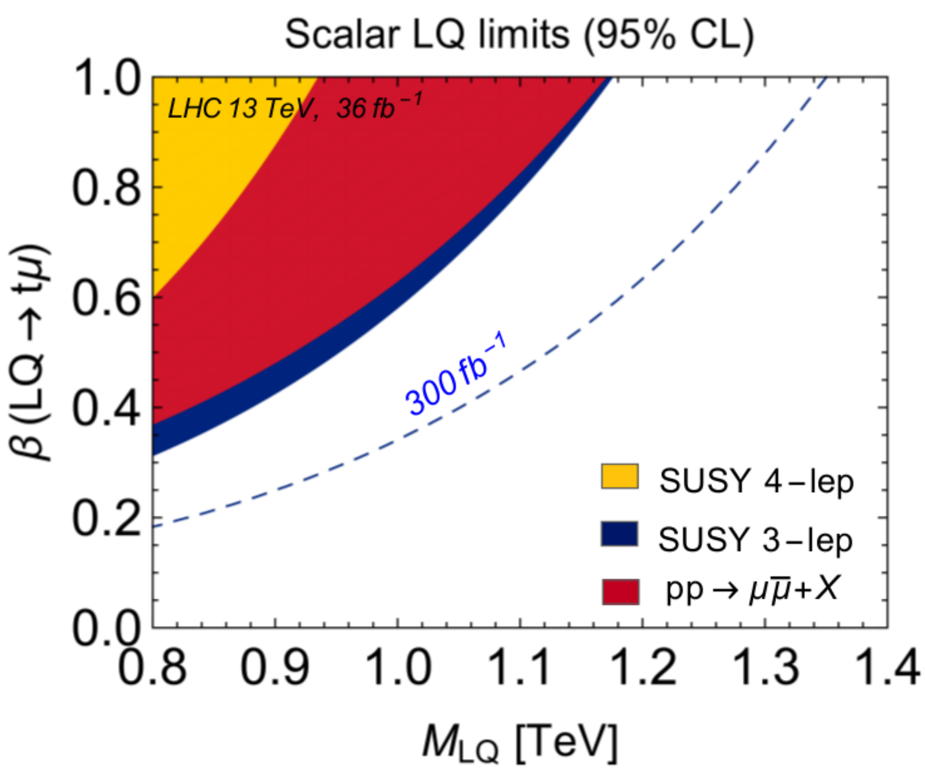
- Data from 3 LHC searches:

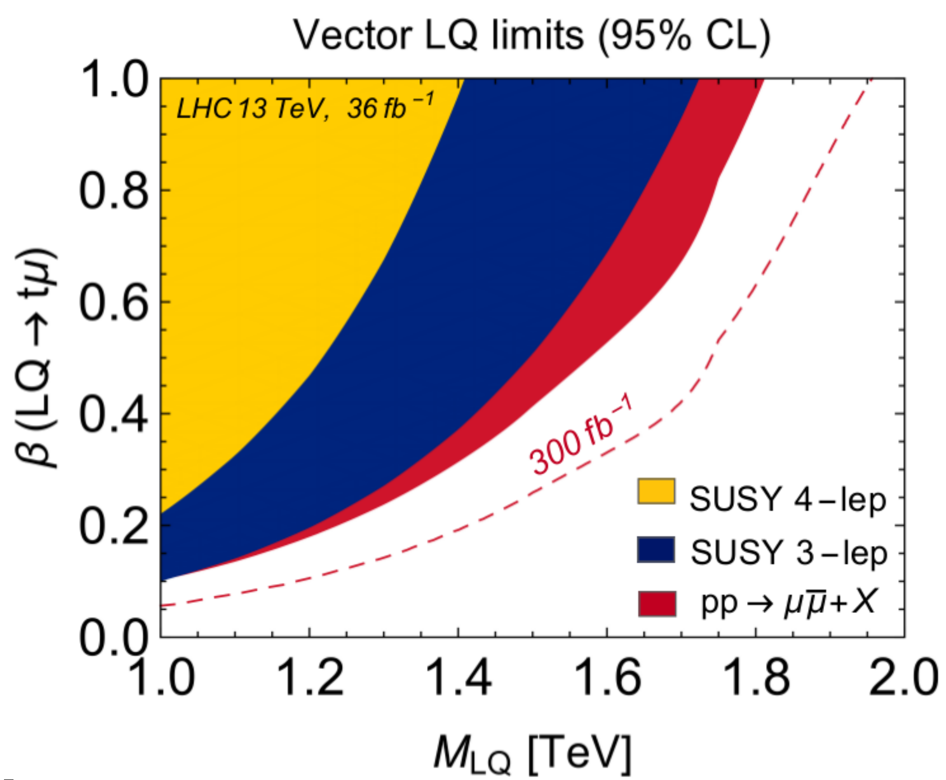
  - ATLAS $36.1\,\mathrm{fb}^{-1}$ 4-lepton SUSY search
    CERN-EP-2017-300 [1804.03602]
  - ATLAS same sign dilepton + 3-lepton SUSY search
    JHEP 9 (2017) 084
  - ATLAS di-lepton tail search $pp \to \mu^+\mu^- + X$ JHEP 10 (2017) 182

    High-mass cut: $m_{\mu\mu} > 1200\,\mathrm{GeV}$

SUSY Signal Regions:
cuts in sumed pT,
missing energy, b-jet
multiplicity etc...

- Model-independent limits: $pp \to \mathrm{LQ}^\dagger\mathrm{LQ} \to t\bar{t}\mu\bar{\mu}$ Camargo-Molina, DF, Celis 1805.04917



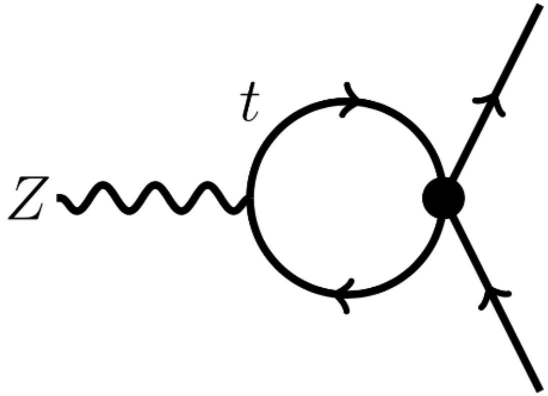


Weak effective theory

- $Z \to \mu\bar{\mu}$

$\mathcal{O}_{\ell u}, \mathcal{O}_{eu}$ modifies the Z coupling to muons at one-loop level

$$\mathcal{O}_{\phi\ell}^{(1)} = \varphi^\dagger i D_\mu \varphi (\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{\phi\mu}^{(1)} = \varphi^\dagger i D_\alpha \varphi (\bar{\mu}\gamma^\alpha \mu)$$



- $\mathcal{L} = \frac{g}{c_W}\bar{\mu}\gamma_\alpha(\delta g_L P_L + \delta g_R P_R)\mu Z^\alpha$

$$\delta g_R = -\frac{3y_t^2}{8\pi^2}\frac{v^2}{\Lambda^2}\left[\log\left(\frac{m_t}{\Lambda}\right) - \frac{4s_{\theta_W}^2}{9}(F+1) + \frac{F}{2}\right]\mathcal{C}_{eu}$$

$$\delta g_L = -\frac{3y_t^2}{8\pi^2}\frac{v^2}{\Lambda^2}\left[\log\left(\frac{m_t}{\Lambda}\right) - \frac{4s_{\theta_W}^2}{9}(F+1) + \frac{F}{2}\right]\mathcal{C}_{\ell u}$$

$F \equiv F\left(\frac{4m_t^2}{M_Z^2}\right)$ Loop function

- The leading log from RG evolution dominates over finite pieces

Disclaimer: Additional model dependent corrections could arise from UV completion.

e.g. tree-level Z-Z′ mixing can compete with the one loop contribution.

Low Energy Pheno

We perform a fit to relevant low energy observables:

- **LEP-I** : Observables highly sensitive to $\delta g_{L,R}$

$$R_{e\mu} \equiv \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

e/μ Universality holds at per mille level

$$\mathcal{A}_\mu \equiv \frac{\Gamma(Z \to \mu_L^+\mu_L^-) - \Gamma(Z \to \mu_R^+\mu_R^-)}{\Gamma(Z \to \mu^+\mu^-} = 0.1456 \pm 0.0091$$

Muon Asymetry Parameter holds at %

- **LHCb anoamlies**: $B \to K^{(*)}\ell\bar{\ell}$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036\,, \quad q^2 \in [1,6]\ \mathrm{GeV}^2\,,$$

$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024\,, \quad q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2\,,$$

$$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047\,, \quad q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2\,. \quad (2)$$

$b \to s\mu^+\mu^-$ angular observables

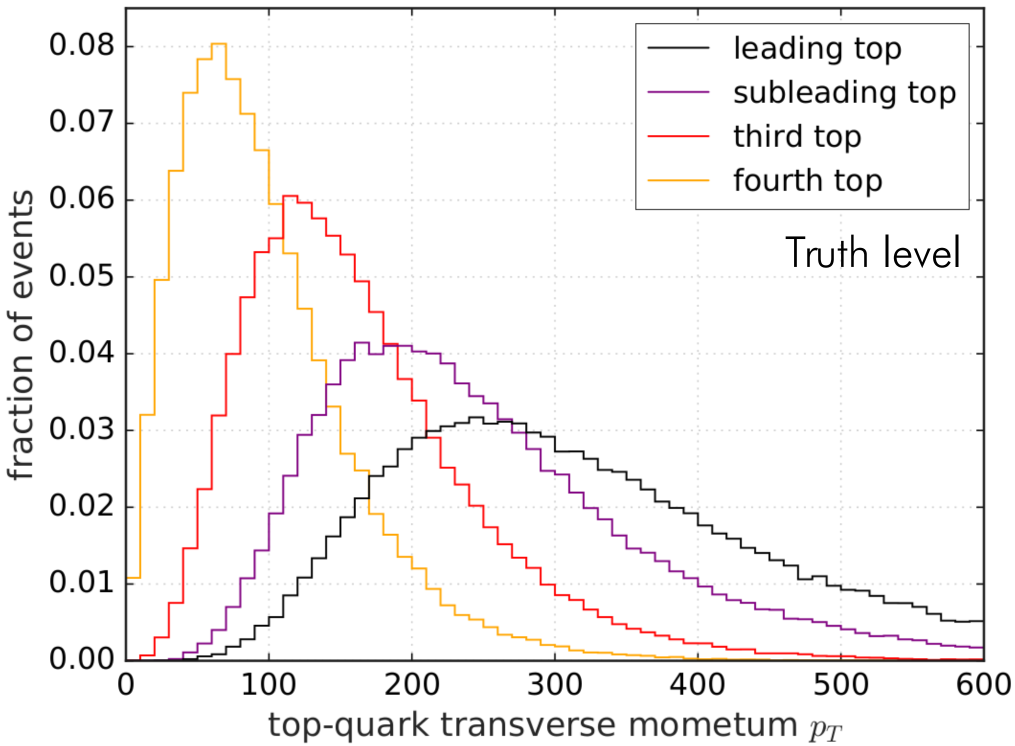
- Observables not cosidered: ...Not relevant yet...

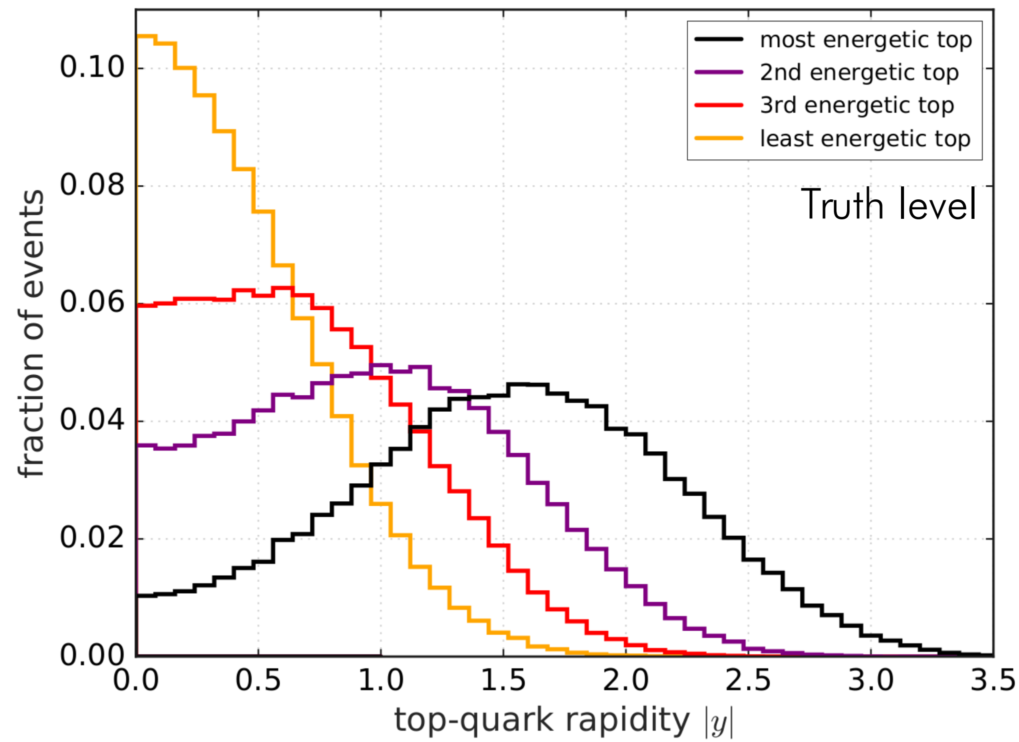
$B \to K^{(*)}\nu\bar{\nu}$ J.F. Kamenik, Y. Soreq, J. Zupan [1704.06005]

$K \to \pi^{(*)}\nu\bar{\nu}$ S. Fajfer, N. Kosnik, L. Vale Silva [1802.00786]

4-top kinematics

Basic kinematics:





51% (**28%**) events contain at least **one** (**two**) boosted tops with $p_T > 300$ GeV

Tops fly predominantly along the central direction (small rapidities).

SM Searches with subtructure techniques not worthed at LHC...

Irreducible Backgrounds:

Category	Backgrounds	FS	σ [fb]	decay mode	$\sigma \times BR$ [fb]
$t\bar{t}W$	$t\bar{t}\ W^{\pm}\ jj$	5	96.8	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\pm}$	1.58
	$t\bar{t}\ W^{\pm}\ bjj$	5	2.3	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\pm}$	0.04
	$t\bar{t}\ W^{\pm}\ b\bar{b}\ jj$	4	2.1	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\pm}$	0.03
$t\bar{t}Z$	$t\bar{t}\ Z$	5	583.3	$W_{\ell^\pm}\ W_{\text{had}}\ Z_\ell$	22.33
	$t\bar{t}\ Z\ j$	5	404.7	$W_{\ell^\pm}\ W_{\text{had}}\ Z_\ell$	15.50
	$t\bar{t}\ Z\ jj$	5	194.9	$W_{\ell^\pm}\ W_{\text{had}}\ Z_\ell$	7.46
	$t\bar{t}\ Z\ jj$	5		$W_{\ell^\pm}\ W_{\ell^\pm}\ Z_\ell$	3.18
$t\bar{t}h$	$t\bar{t}\ h$	4	397.6	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\mp}\ W_{\text{had}}$	1.60
	$t\bar{t}\ h$	4		$W_{\ell^\pm}\ W_{\ell^\mp}\ Z_\ell\ Z_{\text{had}}$	0.06
	$t\bar{t}\ h$	5	401.3	$W_{\ell^\pm}\ W_{\ell^\mp}\ \tau_{\ell^\pm}\ \tau_{\text{had}}$	0.74
Others	$t\ Z\ bjj$	5	176.7	$W_{\ell^\pm}\ Z_\ell$	4.52
	$W^{\pm}Z\ b\bar{b}\ jj$	4	70.3	$W_{\ell^\pm}\ Z_\ell$	1.80
	$t\bar{t}\ W^+W^-$	4	8.0	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\mp}\ W_{\text{had}}$	0.39
	$ZZ\ b\bar{b}j$	4	30.2	$Z_\ell\ Z_\ell$	0.31
Signal	$t\bar{t}t\bar{t}$	4	**9.2**	$W_{\ell^\pm}\ W_{\ell^\pm}\ W_{\ell^\mp}\ W_{\text{had}}$	**0.45**

Trilepton channel

$$\ell^{\pm}\ell^{\pm}\ell^{\mp}$$

How to estimate probabilities more accurately?

Curtin, Galloway, Wacker [1306.5695]

1) Perform MC simulations of all SM process that could contribute to **fakes** or **Q-flip**

Sam-sign dileptons

Category	Backgrounds	FS	σ [pb]	decay mode	$\sigma \times BR \times \epsilon$ [fb]
Fake	$t\bar{t}\,j$	5	301.6	$W_{\ell^\pm} W_{\rm had}$	11.43
	$t\bar{t}\,jj$	5	124.9	$W_{\ell^\pm} W_{\rm had}$	4.74
	$t\bar{t}\,bjj$	5	5.3	$W_{\ell^\pm} W_{\rm had}$	0.20
	$t\bar{t}\,b\bar{b}\,jj$	4	3.0	$W_{\ell^\pm} W_{\rm had}$	0.11
	$t\bar{t}\,b\bar{b}\,3j$	4	2.3	$W_{\ell^\pm} W_{\rm had}$	0.09
Q-flip	$t\bar{t}\,jj$	5	124.9	$W_{\ell^\pm} W_{\ell^\mp}$	8.03
	$t\bar{t}\,bjj$	5	5.3	$W_{\ell^\pm} W_{\ell^\mp}$	0.34
	$t\bar{t}\,b\bar{b}\,jj$	4	3.0	$W_{\ell^\pm} W_{\ell^\mp}$	0.19
	$t\bar{t}\,b\bar{b}\,3j$	4	2.3	$W_{\ell^\pm} W_{\ell^\mp}$	0.15
	$Z\,b\bar{b}\,2j$	4	26.3	Z_ℓ	2.66

$$\ell^\pm j \to \ell^\pm \ell^\pm$$

$$e^\pm e^\mp \to e^\pm e^\pm$$

Trileptons

Category	Backgrounds	FS	σ [pb]	decay mode	$\sigma \times BR \times \epsilon$ [fb]
Fake	$t\bar{t}\,jj$	5	124.9	$W_{\ell^\pm} W_{\ell^\mp}$	0.80
	$t\bar{t}\,bjj$	5	5.3	$W_{\ell^\pm} W_{\ell^\mp}$	0.03
	$t\bar{t}\,b\bar{b}\,jj$	4	3.0	$W_{\ell^\pm} W_{\ell^\mp}$	0.02
	$t\bar{t}\,b\bar{b}\,3j$	4	2.3	$W_{\ell^\pm} W_{\ell^\mp}$	0.01
	$Z\,b\bar{b}\,2j$	4	26.3	Z_ℓ	0.27

$$\ell^\mp \ell^\pm j \to \ell^\pm \ell^\pm \ell^\mp$$

Use existing LHC search with a data driven estimation:

SUSY multi-lepton searches!
ATLAS-CONF-2016-037

2) Fit MC simulate to the data-driven estimations in different Signal Regions

Assuming flat fake letpon and Q-flip probabilities....

Fit data from different Signal Regions:

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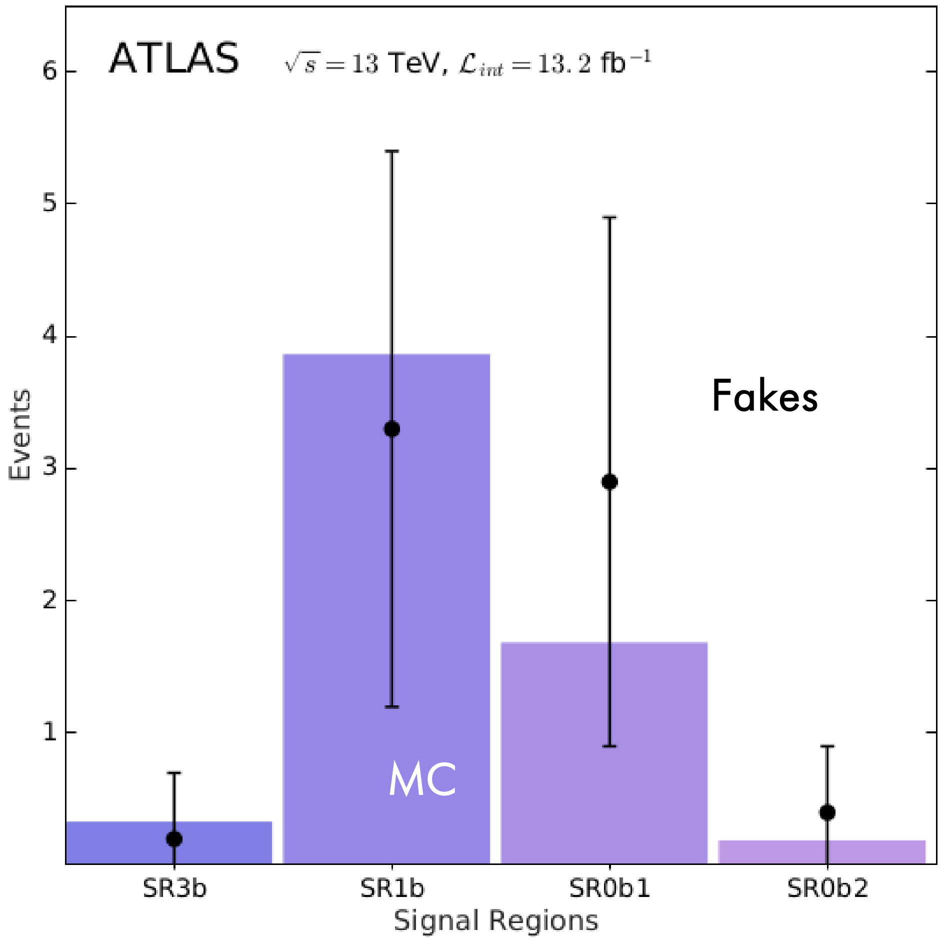

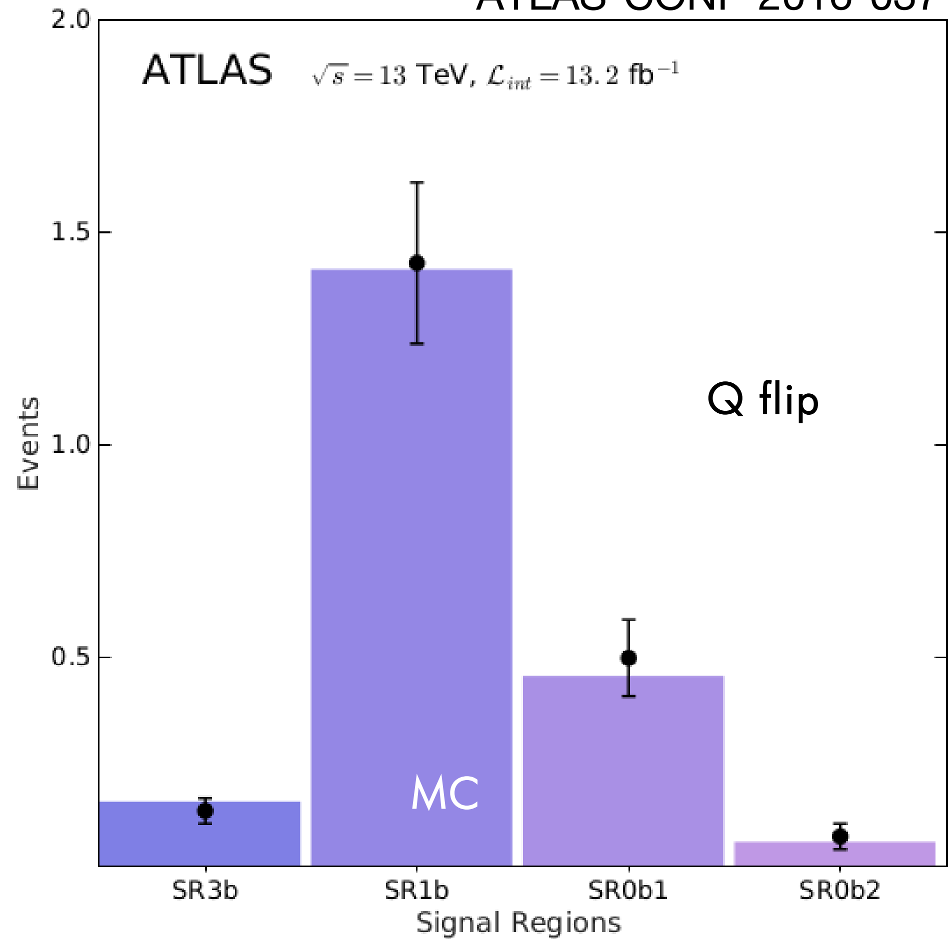

Best fit probabilities:

$$\epsilon_{\text{fake}} = 7.2 \times 10^{-5}$$

$$\epsilon_{Q\text{flip}} = 2.2 \times 10^{-4}$$