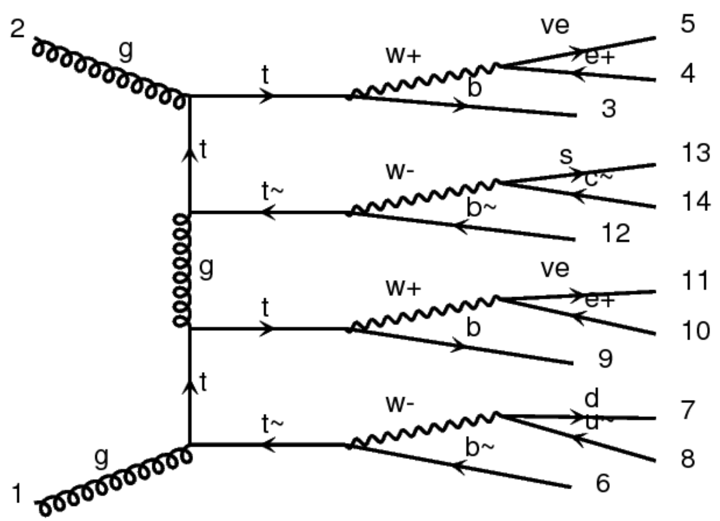
Four top-quarks at the LHC

Darius A. Faroughy

Jožef Stefan Institute

darius.faroughy@ijs.si



Brda 2017
Selected topics in high energy physics
October 11 - 13 2017, Goriška Brda, Slovenia

Outline

- Introduction
- Search strategy for Four-top production in the SM + Results
- Applications to (non-resonant) New Physics

Based on: **Four tops for LHC**

Alvarez, DF, Kamenik, Morales, Szynkman

[Nucl. Phys. B 915 19 (2017)]

Introduction

- The top-quark is a special particle in the SM (and beyond), e.g:
  - only "free" quark (decays weakly before it hadronizes)
  - only fermion living at the EW scale
  - only fermion coupling to the Higgs boson at order 1
- Least explored quark experimentally: plenty of room for New Physics to pop up
- **LHC** : top-quark factory (~10M top-pairs in Run-1)
- Top-quark physics entering precision era:
  - Top-pair and single-top production
  - starting to measure associated production ttV, ttH
- Next step: explore rare top-quark processes

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

- Is this SM process accessible at the LHC? **YES!**
- What are the implications for NP?

Some Motivations

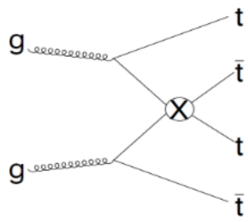
- Interesting Beyond the SM scenarios for four-top production: top compositness, KK gluons, etc...

  - Heavy resonance decaying to top-pairs.

- Additional handle for top-quark effective field theory.

  - Only process that can give constraints on four-top operator, e.g. $\mathcal{O}_{4t} = (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma_\mu t_R)$

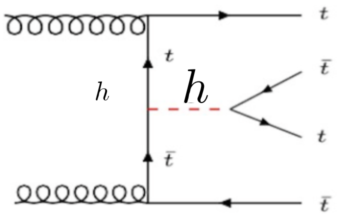
  - Can give constraints on $qqtt$ four-fermion operators **Cen Zhang [1708.05928]**



- Good place to search for effects of top-philic light mediators **Ian Low's talk from yesterday**

- Alternative probe for the top-quark Yukawa coupling at HL-LHC

  Cao et al. [1602.01934]



SM Four-tops at the LHC

- $pp \to t\bar{t}t\bar{t}$ production at the LHC:

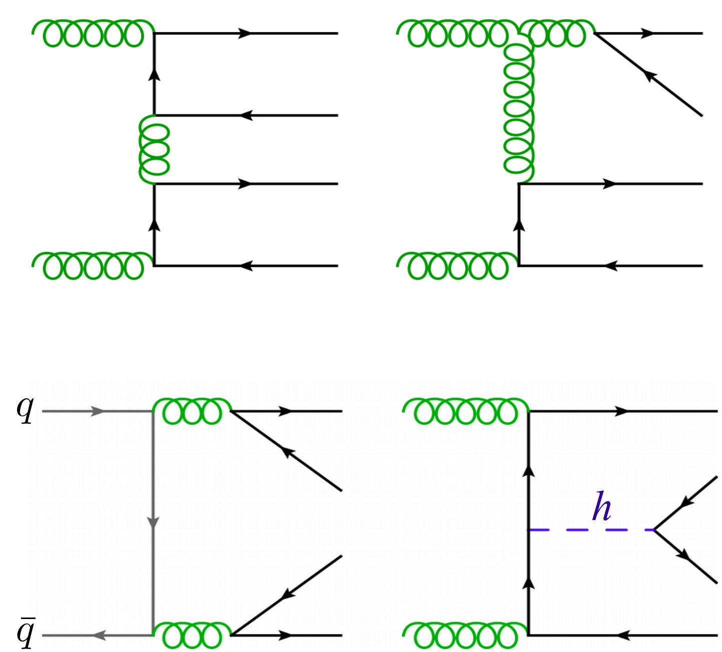
  - QCD production $\sim$90% $\mathcal{O}(\alpha_s^4)$

    driven by gluon fusion

  - Higgs-mediated $\sim$10% $\mathcal{O}(\alpha_s^2\, y_t^2)$

  - Large production treshold

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



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

$$\sigma(pp \to t\bar{t}t\bar{t})^{LO} \approx 9\,\mathrm{fb} \qquad \sigma(pp \to t\bar{t}t\bar{t})^{NLO} \approx 12\ \mathrm{fb}$$

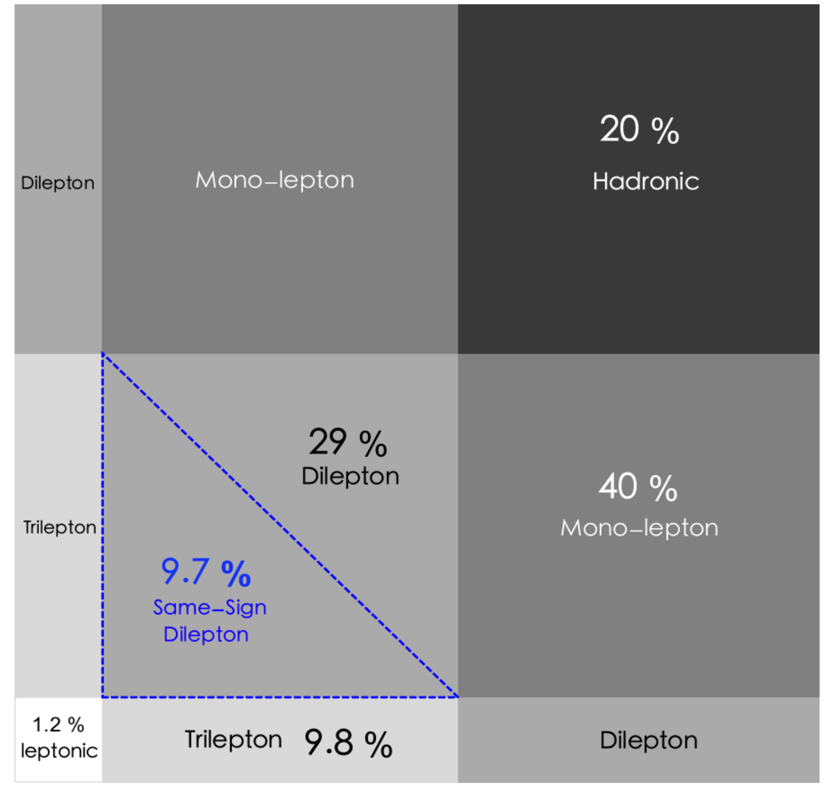
- Rare process: 5 orders of magnitude smaller than top-pair production

  $\sim$ 30 times smaller than tth production

Four-top decay channels

- Four-top decay channels: $t\bar{t}t\bar{t} \rightarrow b\bar{b}b\bar{b}\ W^+W^-W^+W^-$

$t\bar{t}t\bar{t}$ 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



- LHC search in Mono-lepton channel

  Current upper limit: ~5 x SM cross-section

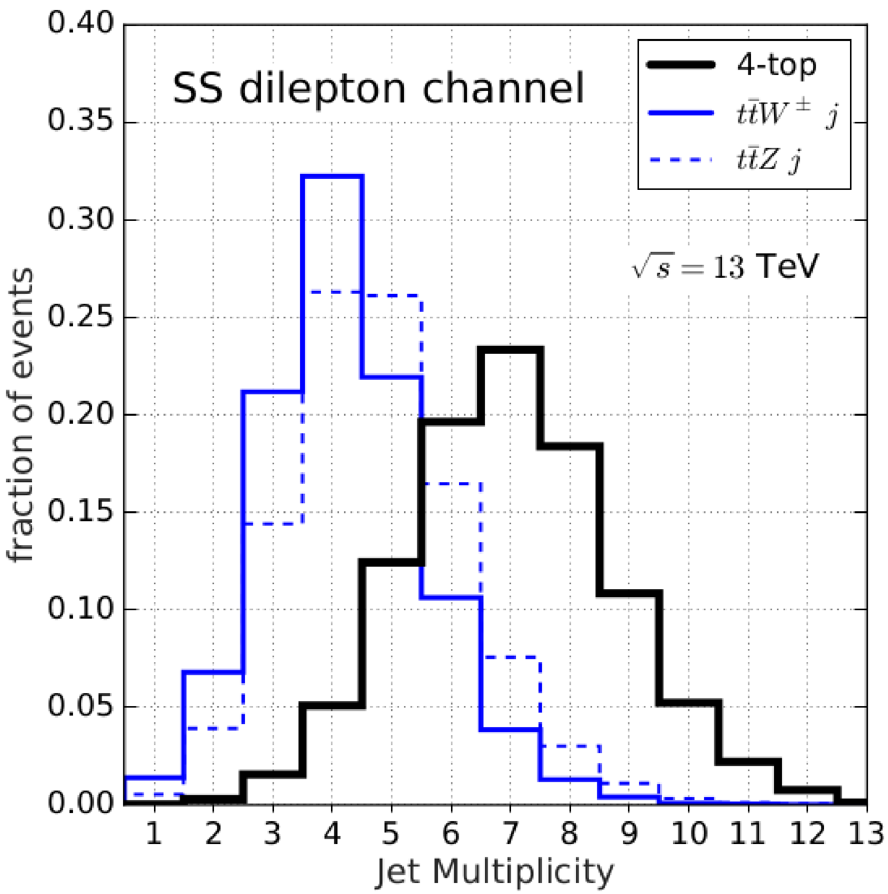
- Promising channel: Same-sign dileptons

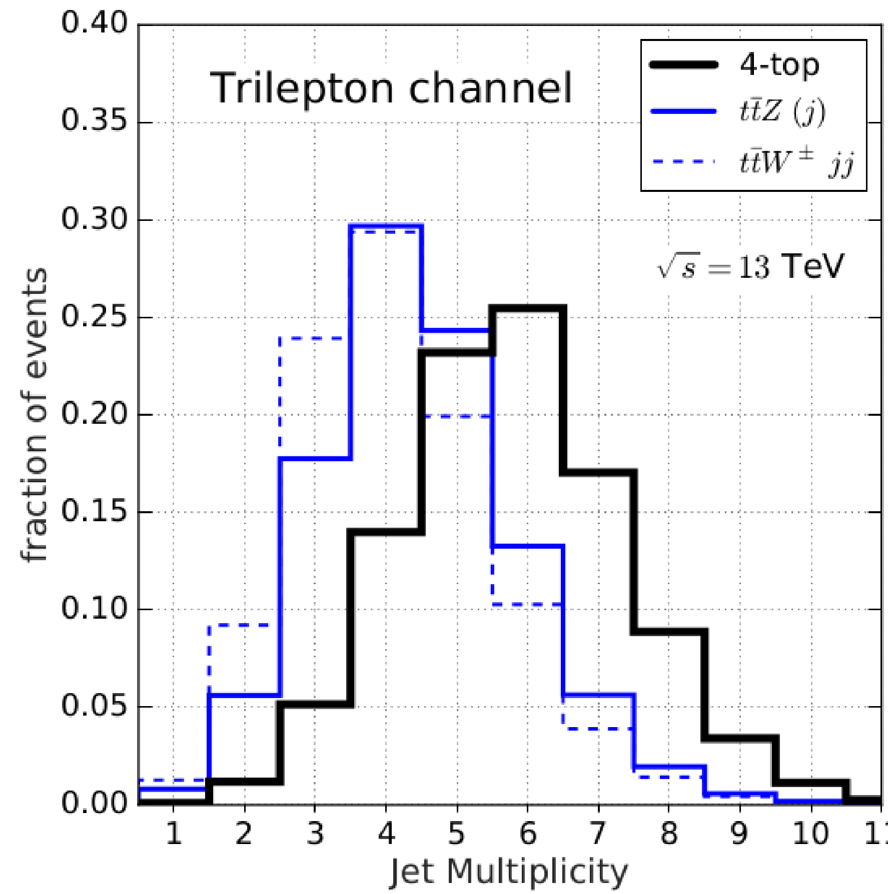
  Lillie, Shu, Tait [0712.3057]

- **Multi-lepton channels:** Same-Sign dileptons and trileptons
  - Combined BR ~ 20%
  - Lower particle multiplicity in final states
  - Lower backgrounds

Signal features

- Large light-jet multiplicity distributions in the multi-lepton channels:

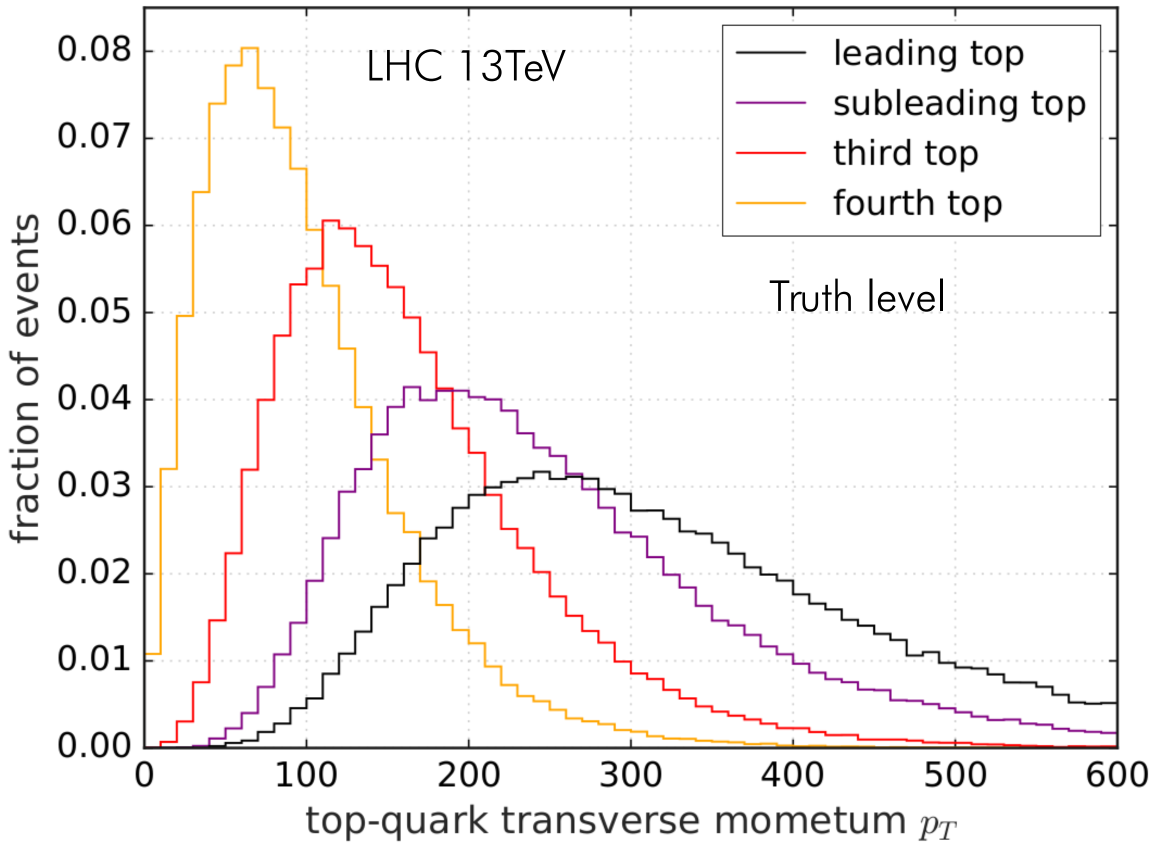




- Several b-tagged jets: Good background discriminator

Signal features

- Boosted tops in $pp \to t\bar{t}t\bar{t}$?

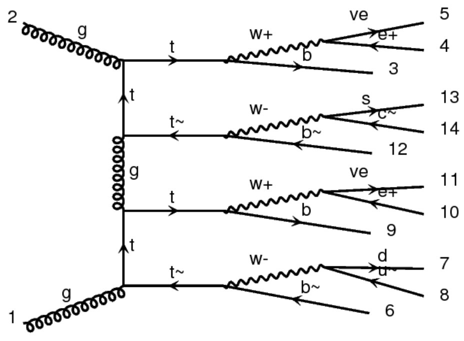


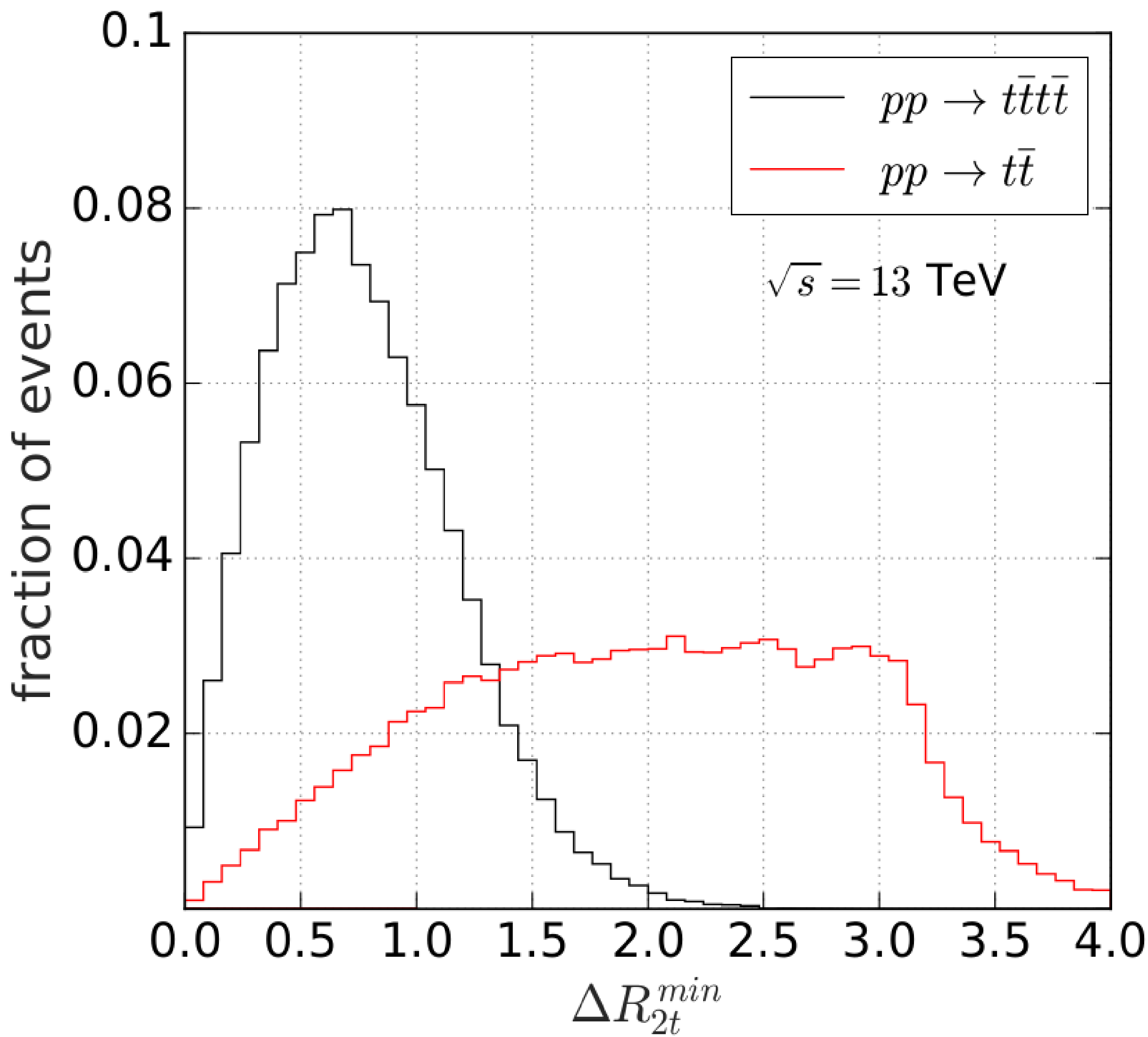
- **51%** (**28%**) events contain at least **one** (**two**) boosted tops with $p_T > 300$ GeV
- Tops fly predominantly along the central direction (small rapidities).

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

Signal features

- Crowded events with O(10) final states
- Expect accidental overlaps of top-decay products in detector



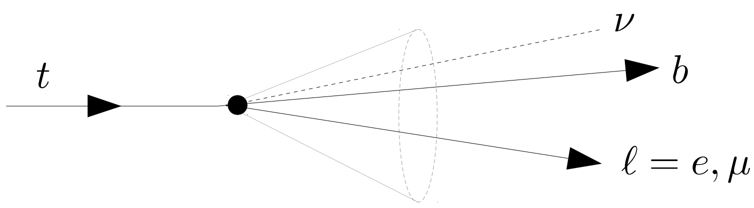


Leptonic isolation

- In four-top process:

  - accidental overlaps

  - boosted tops



Many signal leptons fail traditional isolation requirements
Hence, dramatic drop in signal efficiency

- "Traditional" leptonic isolation requirements:

$$I_{iso} \equiv \frac{p_T(\ell)}{\sum_{i \in R^{cone}} p_T(i)} \qquad I_{iso} < 1 - 10\% \qquad R^{cone} = 0.2 - 0.5$$

- Fix: **Mini-isolation** requirements

p_T-dependent cone:

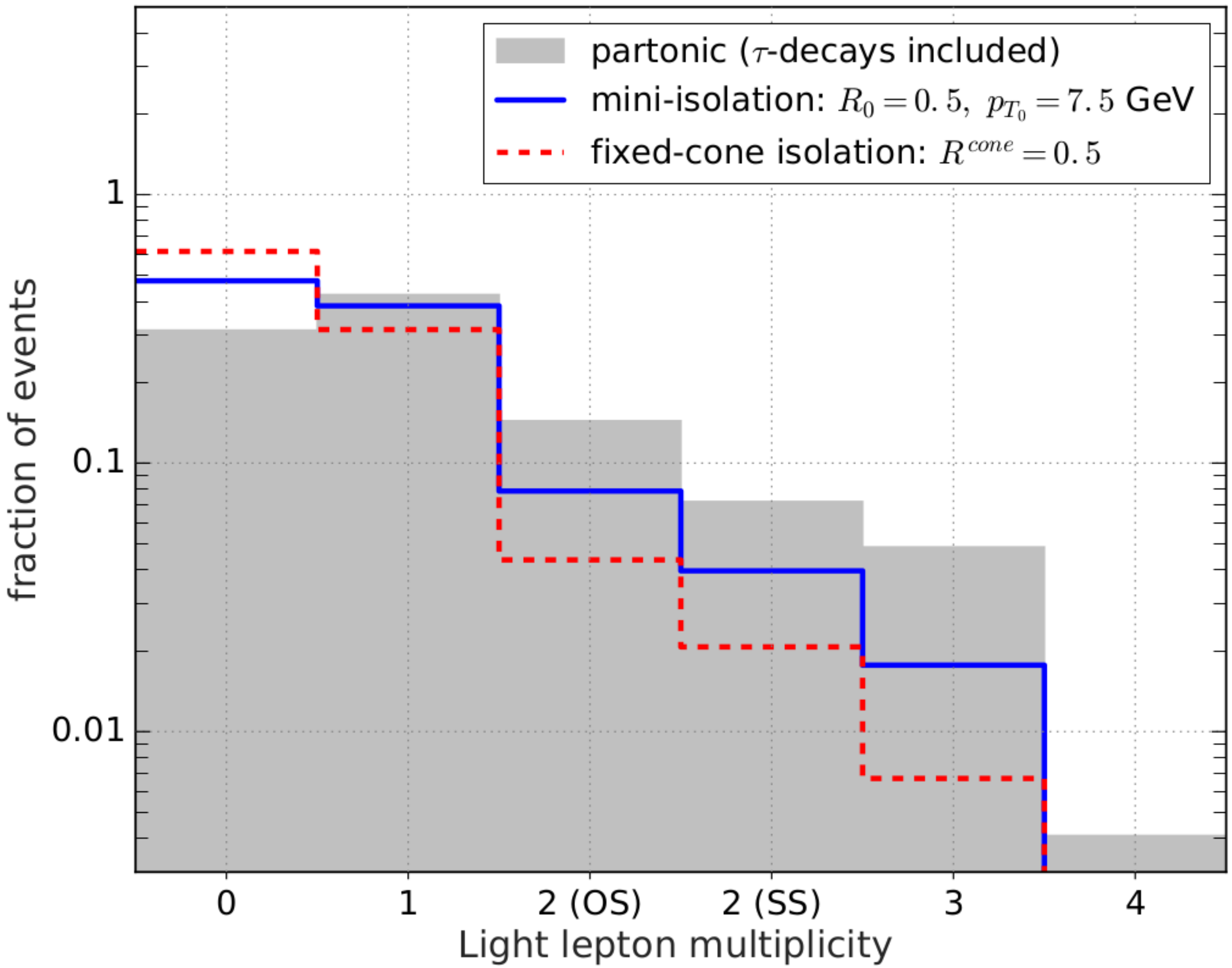
$$R^{cone}(p_T^\ell) = \frac{p_T^0}{p_T^\ell}$$

$$p_T^0 \sim 10 - 20\,\mathrm{GeV}$$

Rehermann, Tweedie [1007.2221]

Leptonic isolation

- $pp \to t\bar{t}t\bar{t} \to \ldots$ plus leptonic isolation requierements



- Mini-isolation is required for a four-top search in the multi-lepton channels

Four-top backgrounds

- Irreducible backgrounds for **Same-sign dilepton channel**

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

- Reducible backgrounds (mis-reconstructed objects in detector)

  - Fake leptons $j \to \ell^{\pm}$ $\quad t\bar{t} \to (b\nu\ell^{+})\ (jjb) \longrightarrow (b\nu\ell^{+})\ (\ell^{+}jb)$ $\quad \epsilon_{j\to\ell} \sim 10^{-4}$
  - Electron charge-flip $e^{\pm} \to e^{\mp}$ $\quad t\bar{t} \to (b\nu\ell^{+})\ (b\nu\ell^{-}) \longrightarrow (b\nu\ell^{+})\ (b\nu\ell^{+})$ $\quad \epsilon_{e^{\pm}\to e^{\mp}} \sim 10^{-3}$

- Similar for the **trilepton channel**… but no charge-flip reducible background!

LHC search strategy

- Simple non-invasive search strategy:

  - Optimized leptonic **mini-isolation**

  - Same-sign dilepton channel:

    - Exactly one SS dilepton (events with additional leptons are vetoed).
    - Jet multiplicity (of any flavor) satisfying $N_j \geq 6$.
    - b-jet multiplicity satisfying $N_b \geq 3$.

  - Trilpeton channel:

    - Exactly three charged leptons (events with additional leptons are vetoed).
    - Jet multiplicity (of any flavor) satisfying $N_j \geq 4$.
    - b-jet multiplicity satisfying $N_b \geq 3$.
    - A Z-mass window veto: $\mathbf{75\ GeV} < m_{\ell^+\ell^-} < \mathbf{110\ GeV}$

- Experimental collaborations can include additional cuts if necessary at higher lumi

LHC projections

- Results for each separate multi-lepton channel:

Same-sign dileptons

$\mathcal{L}$=300 fb^{-1}	SR6j	SR7j	SR8j
N_{exp}	139 (171)	85 (101)	43 (51)
$\mathbf{t\bar{t}t\bar{t}}$	**16.7**	**13.5**	**8.9**
$t\bar{t}W$	60.7	35.0	17.1
$t\bar{t}Z$	32.1	20.3	10.7
$t\bar{t}h$	5.5	3.1	1.3
Fakes	12.5 (17.3)	7.1 (9.8)	3.3 (4.6)
Q-flip	7.6 (34.4)	3.7 (16.6)	1.6 (7.4)
Other	4.4	2.4	1.0
S/B	**0.14 (0.11)**	**0.19 (0.15)**	**0.26 (0.21)**
$\mathbf{S/\sqrt{B}}$	**1.51 (1.34)**	**1.60 (1.44)**	**1.53 (1.37)**

Trileptons

$\mathcal{L}$=300 fb^{-1}	SR4j	SR5j	SR6j
N_{exp}	31 (32)	25 (26)	17 (17)
$\mathbf{t\bar{t}t\bar{t}}$	**8.6**	**7.8**	**6.0**
$t\bar{t}Z$	9.9	8.0	5.1
$t\bar{t}W$	6.7	4.9	2.9
$t\bar{t}h$	2.3	1.8	1.2
Fakes	2.5 (3.5)	1.7 (2.4)	0.9 (1.3)
Other	1.4	1.0	0.5
S/B	**0.38 (0.36)**	**0.45 (0.43)**	**0.57 (0.54)**
$\mathbf{S/\sqrt{B}}$	**1.80 (1.76)**	**1.87 (1.84)**	**1.84 (1.80)**

$$\epsilon_{j\to\ell} = 7.2\times 10^{-5} \quad (10^{-4})$$

$$\epsilon_{e^\pm\to e^\mp} = 2.2\times 10^{-3} \quad (10^{-3})$$

Faking probabilities estimated from fiting MC simualtions to data driven estimations

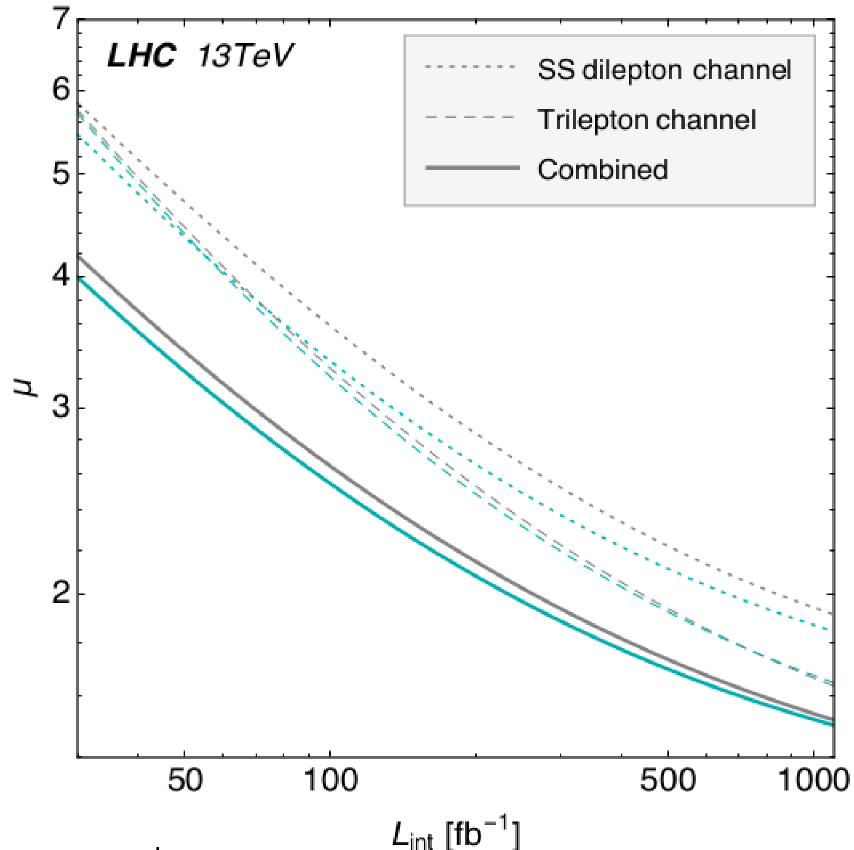
Same-sign Dilepton results are quite sensitive to reducible background yield estimations...

LHC projections

- Combined 95% CL upper limits for SM 4-top production in the multi-lepton channels:

$$\mu_{t\bar{t}t\bar{t}} \equiv \frac{\sigma(pp \to t\bar{t}t\bar{t})}{\sigma^{SM}(pp \to t\bar{t}t\bar{t})} \leq \mathbf{1.87}$$

$$(\,\mathcal{L}_{int} = 300\,\mathrm{fb}^{-1}\,)$$



Trileptons perform better than Same-sign dileptons

- Evidence/Discovery Luminosities for SM 4-top search:

Reducible Backgrds estimate	Evidence (3σ)	Discovery (5σ)
$\epsilon_{\rm fake} \simeq 7.2\times10^{-5}$, $\epsilon_{\rm Qflip} \simeq 2.2\times10^{-4}$	215 fb^{-1}	1060 fb^{-1}
$\epsilon_{\rm fake} \simeq \epsilon_{\rm Qflip} \simeq 0$	98 fb^{-1}	420 fb^{-1}

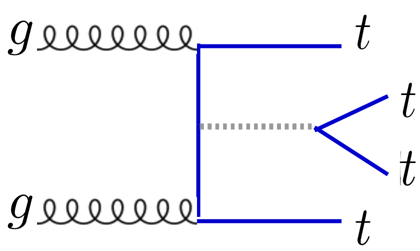
Alvarez, DF, Kamenik, Morales, Szynkman [Nucl. Phys. B 915 19 (2017)]

New Physics: Low-mass top-philic models

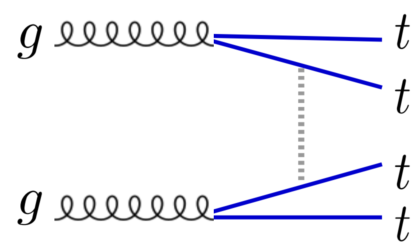
- New state coupled to top-quark below treshold $m_X < 2m_t$
  - SM-like kinematics
  - Just enhancement of 4-top cross-section

Colorful: light Axigluon, ...

Colorless: Z′, H′, ...



Non-resonant



- Relevant for NP resolutions for B-anomalies:
  - low-mass W′ resolution of $B \to D^{(*)}\tau\nu$ anomalies — see DF, Greljo, Kamenik [1704.06005]
  - low-mass Z′ model for $b \to s\mu\mu$ anomalies @1 loop — Kamenik, Soreq, Zupan [1704.06005]

- Relevant for top-philic Dark Matter models (scalar mediator) — Arina et al [1605.09242]

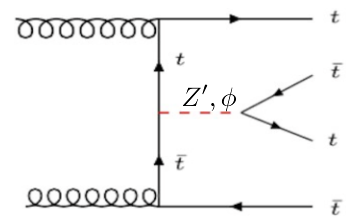
See also Jackson, Servant, Shaughnessy, Tait, Taoso [0912.0004]

- Two benchmark models:

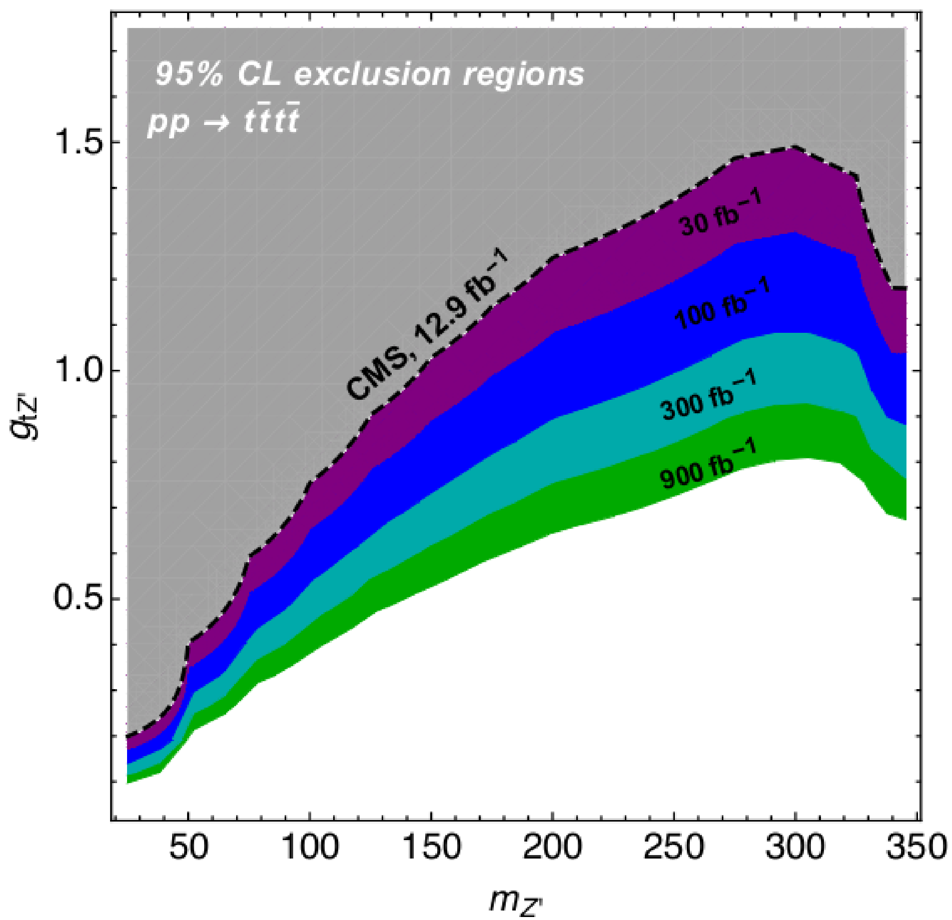
$$\mathcal{L} \supset -\, g_{tZ'}\, Z'_\mu\, (\bar{t}_R \gamma^\mu t_R)$$

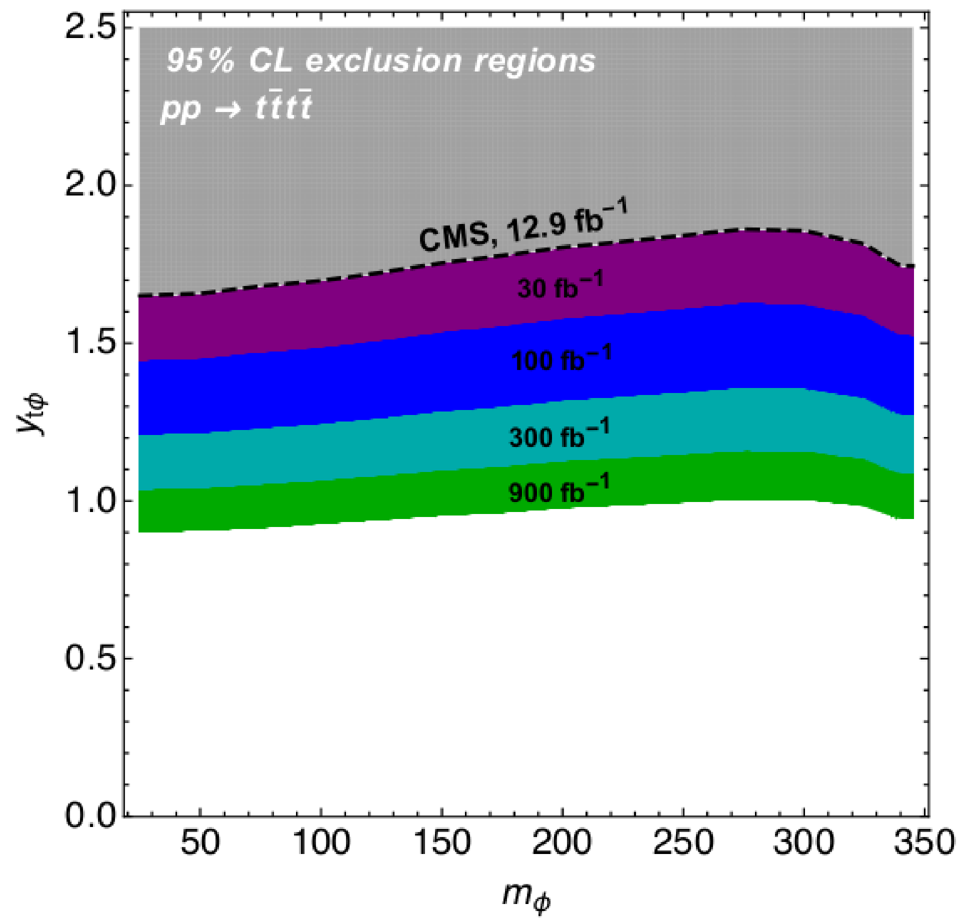
$$\mathcal{L} \supset -\, y_{t\phi}\, \phi\, (\bar{t}_L t_R) \;+\; \text{h.c.}$$

$$m_{Z',\phi} < 2m_t$$



- Limits from multi-lepton four-top search:





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

Conclusions

- The LHC can (and should) start exploring rare processes in top-quark physics such as four-top production. The four-top process is not a monster.

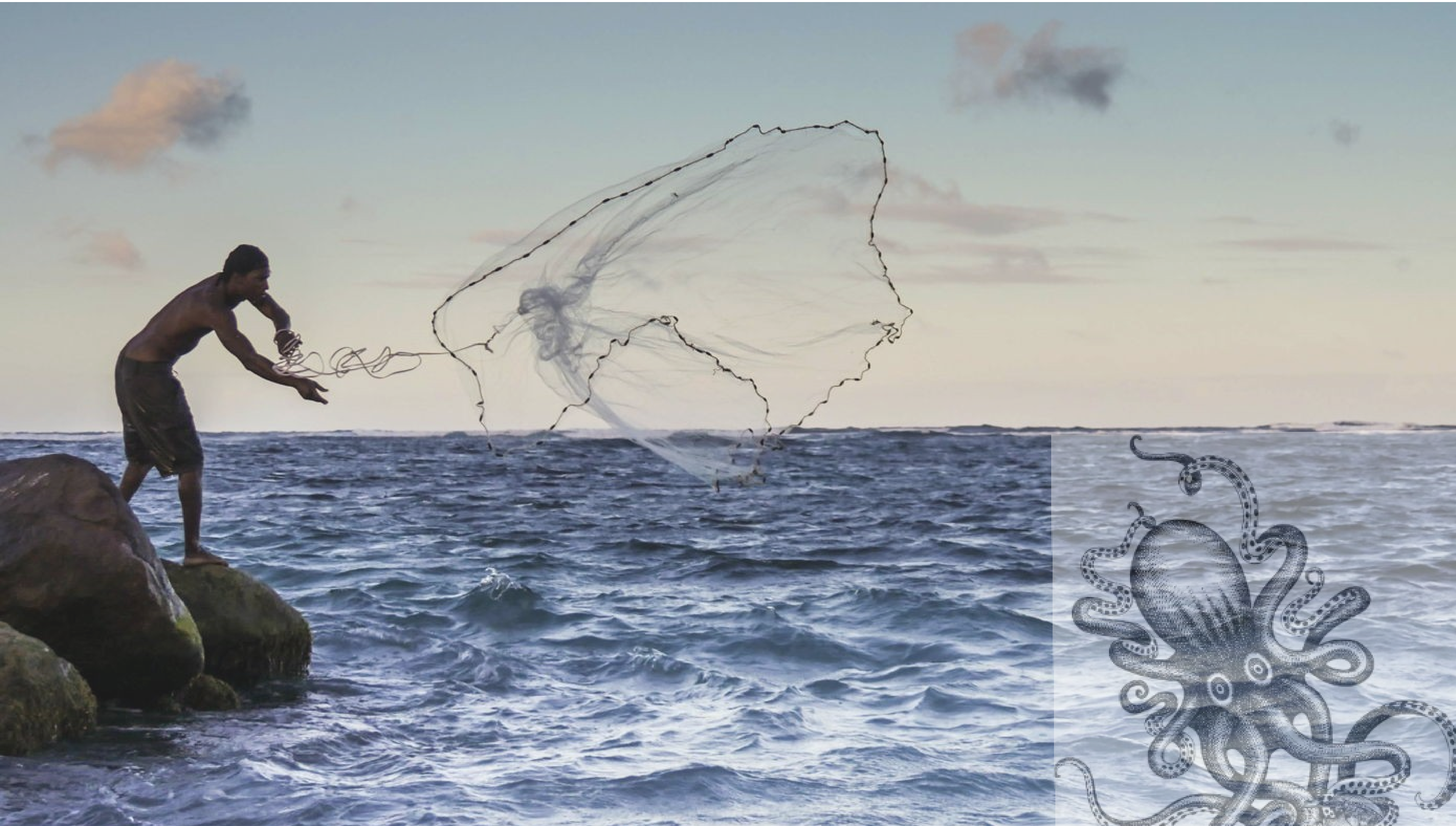
- Interesting BSM apear in four-top production:
  - resonant production
  - low-mass mediators or EFT (non-resonant)

- We presented for the first time a realistic SM four-top search strategy in the multi-lepton channel:
  - included irreducible backgrounds (fakes + Q-flips) for the first time.
  - trileptons performs better than same-sign dileptons)

- We expect the four-top produciton in the SM to be accessible at the LHC in the multi-lepton channel: possibly 3 sigma evidence at 300 fb^{-1} and a discovery at HL-LHC.

- BSM:
  - extracted bounds for low-mass top-philic mediators (scalar and Z′) relevant for DM models and B-anoamlies.
  - Four-top production is also relevant for setting competetive constrains on top-quark four-fermion operators.

THANK YOU!

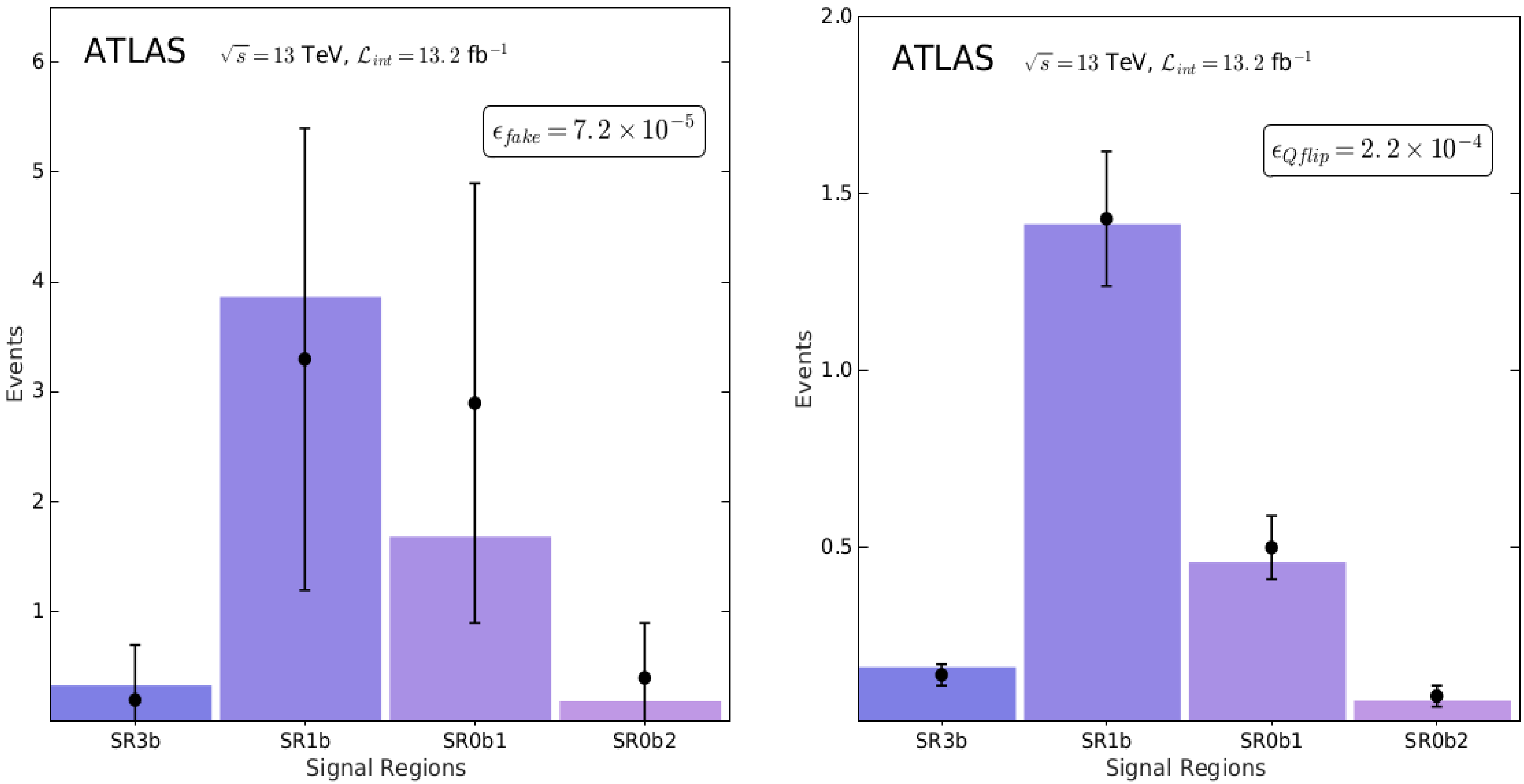


Fakes & Q-flips

- How to estimate probabilities more accurately? **Curtin, Galloway, Wacker [1306.5695]**

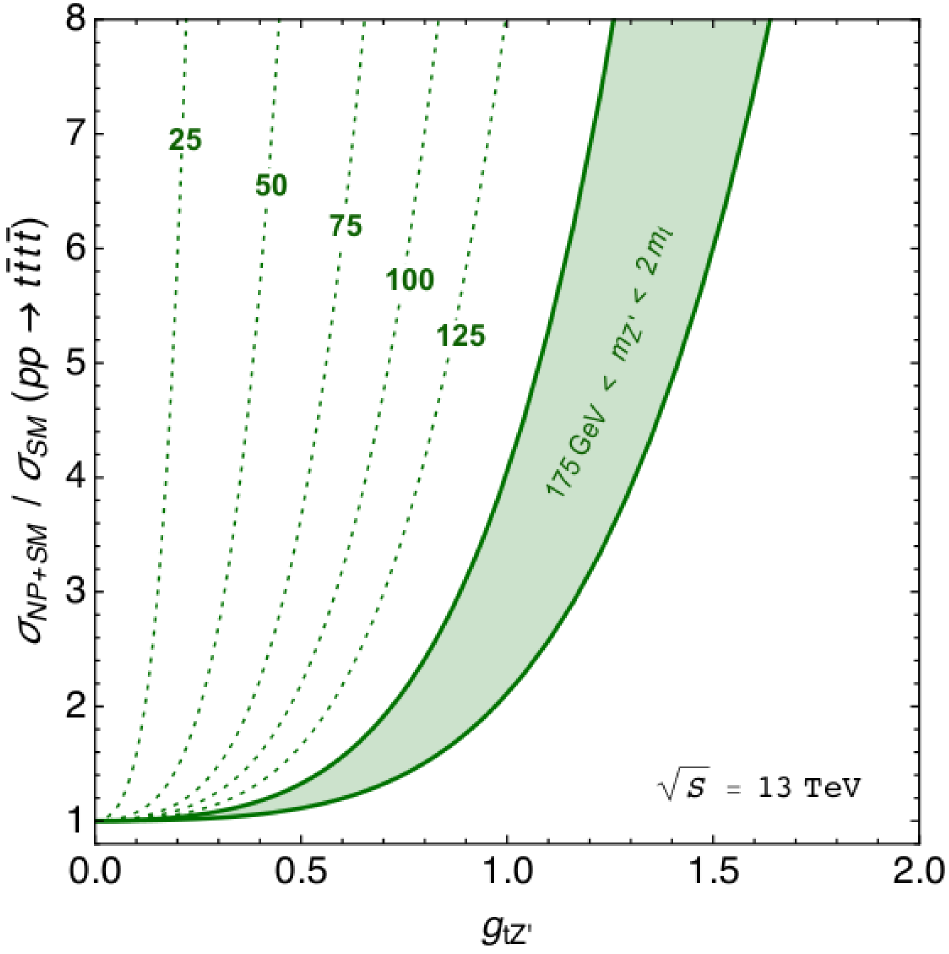
  - Perform MC simulations of all SM process that will contribute to fake lepton or Q-flip mis-id:

  - Fit fake/Qflip probabilities to background estimations by ATLAS or CMS

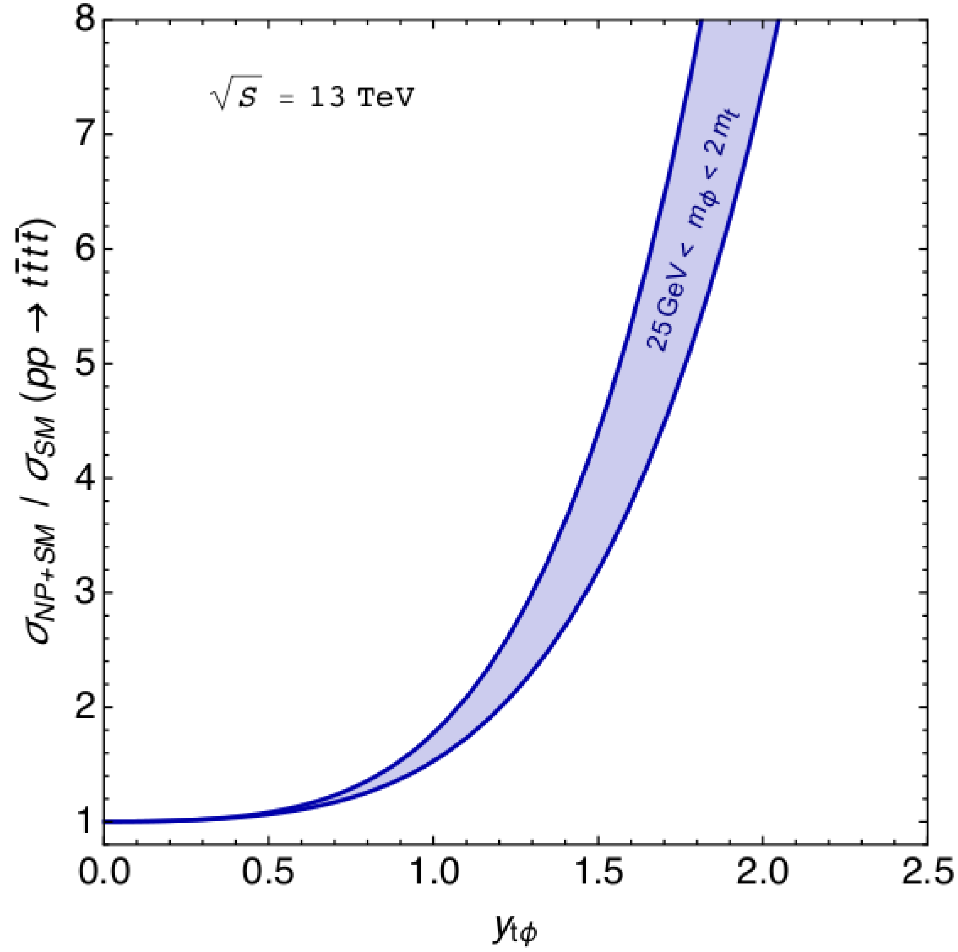


Signal Regions from ATLAS-CONF-2016-037

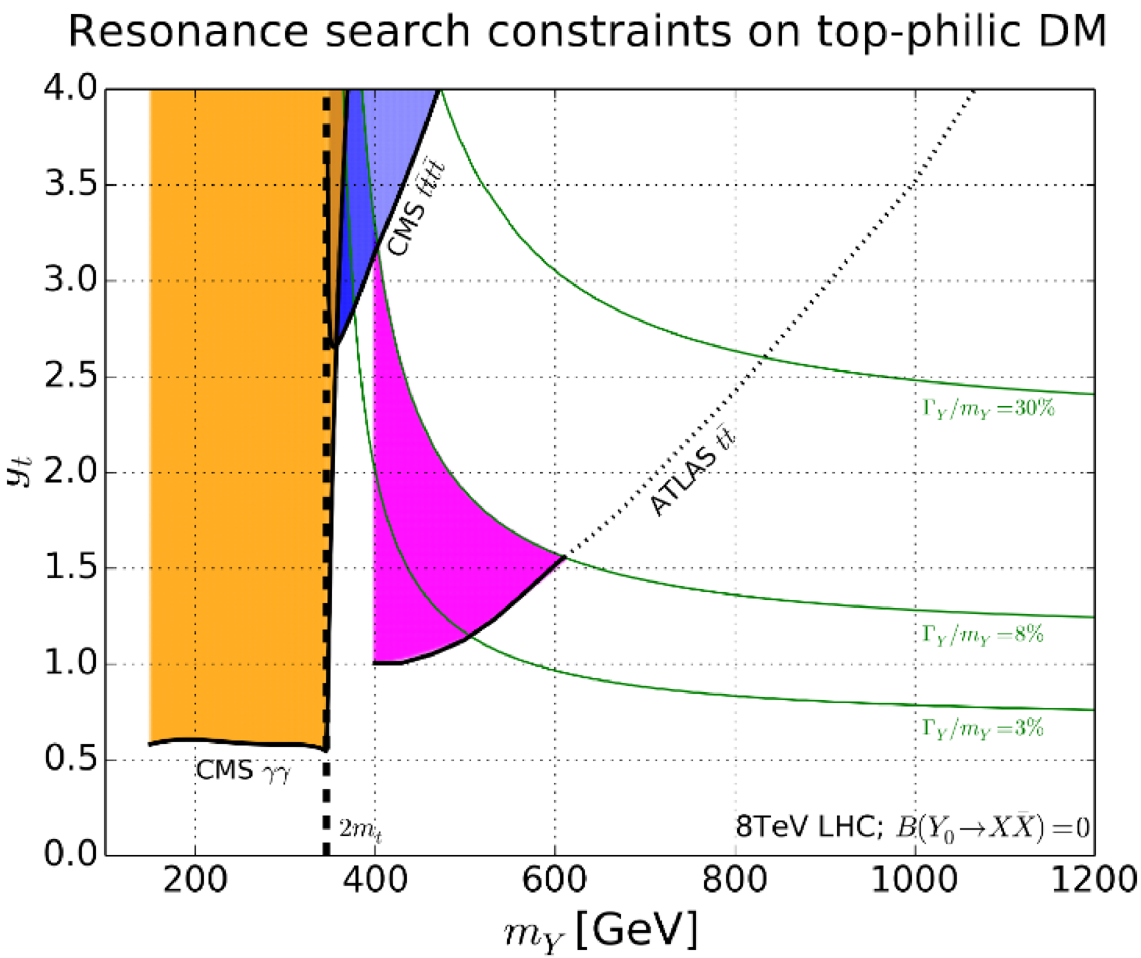
$$\mathcal{L} \supset -\, g_{tZ'}\, Z'_\mu\, (\bar{t}_R \gamma^\mu t_R)$$



$$\mathcal{L} \supset -\, y_{t\phi}\, \phi\, (\bar{t} \gamma^\mu t)$$



$\kappa_t \leq 2.2$ for $\mathcal{L} = 100\ \mathrm{fb}^{-1}$ and $\kappa_t \leq 1.2$ for $\mathcal{L} = 500\ \mathrm{fb}^{-1}$.



Top compositness:

$$\frac{g_S}{\Lambda^2}\left\{g_1\left[\left(H\overline{Q}_3\right)\sigma^{\mu\nu}\lambda^a P_R t\right]G^a_{\mu\nu} + g_2\left[\bar{t}\gamma^\mu\lambda^a D^\nu P_R t\right]G^a_{\mu\nu}\right\}$$