Shedding Light on the Top Partner at the LHC

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with

J. Kim, K. Kong and I. Lewis

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(arXiv:1808.03649v1)

Top Partner

The Stability of Higgs mass.

Naturalness.

Interaction with SM top-quark.

- Supersymetry: New Scalar.
- Composite Higgs: New Fermion.

Assume Vector Like Quark.

Introduction

Simple Extension to SM with a VLQ: T

Conventionally: $T \to tZ, tH, bW$

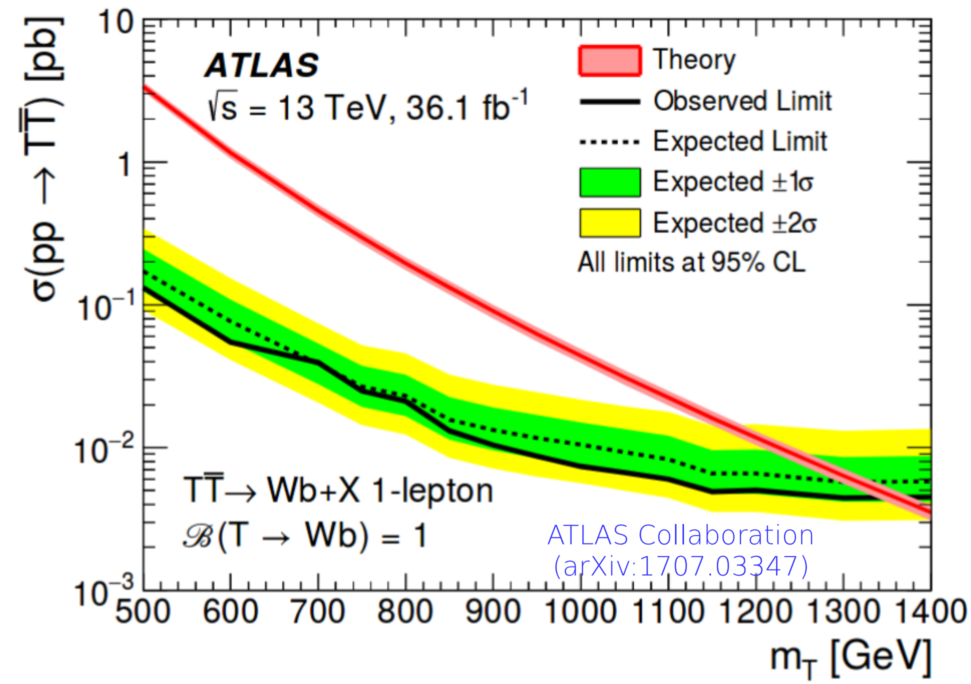
Exp. searches indicate no deviation from the SM.

What if T doesn't decay conventionally?

How about new decay modes?

Radiative decay Modes?

Can we probe this at the LHC?



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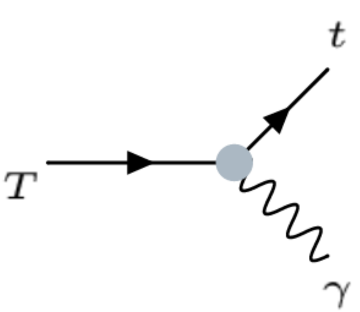

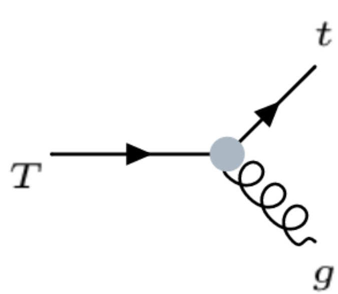

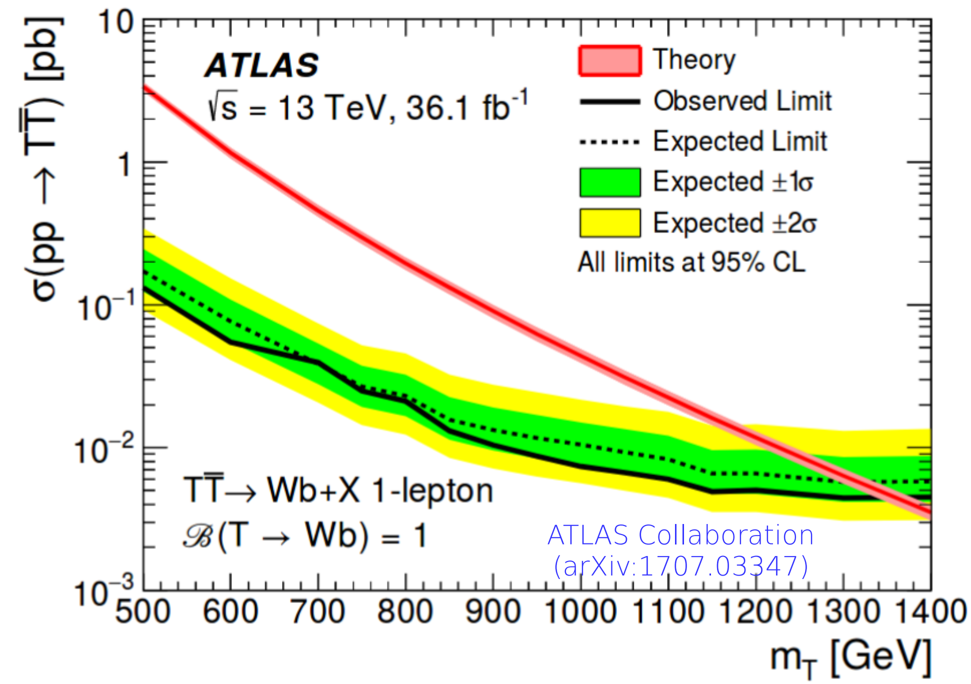

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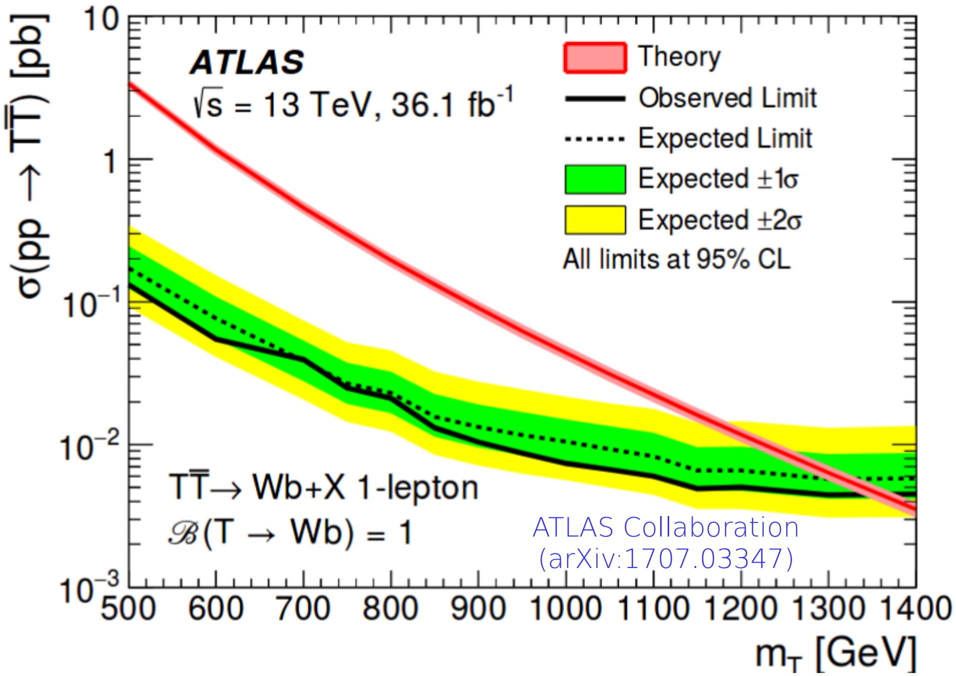
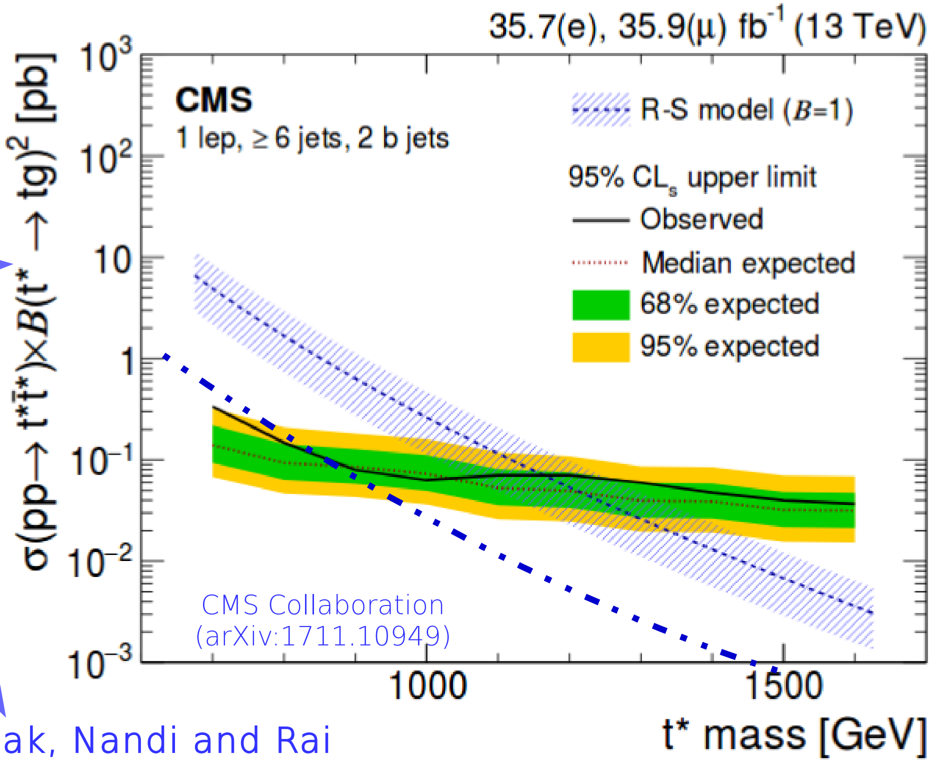
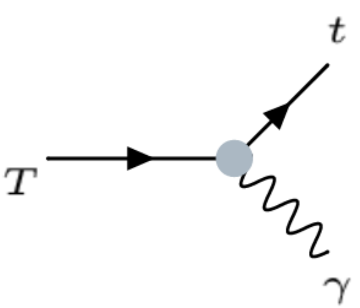
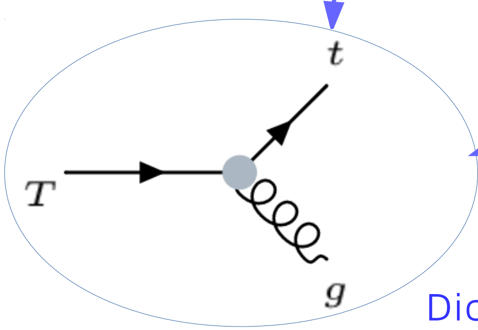


ATLAS Collaboration (arXiv:1707.03347)



CMS Collaboration (arXiv:1711.10949)





Dicus, Karabacak, Nandi and Rai (arXiv:1208.5811)

Introduction

Loop Induced Single Top Partner Production and Decay at the LHC

Jeong Han Kim[a] Ian M. Lewis[a]

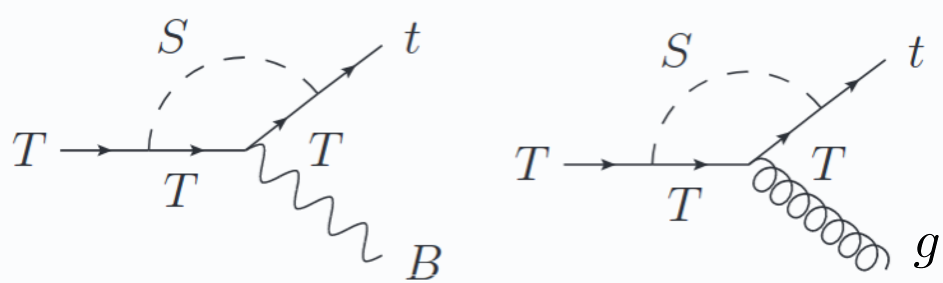
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas, 66045 USA

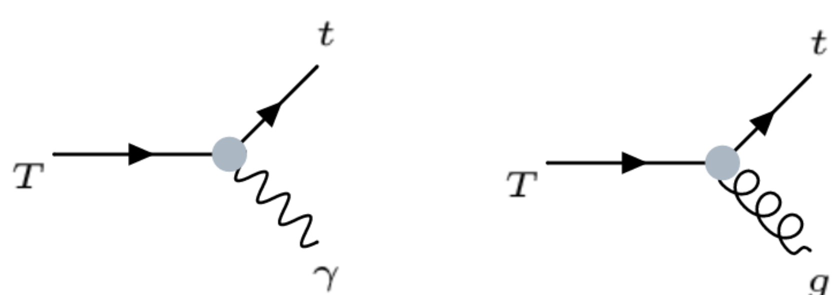
arXiv:1803.06351

Recent theoretical work → Complete ultraviolet model

Considers zero mixing angle between SM top and t-prime

Radiative decays are induced by loop processes





The Model

Simple Extension to SM:

SU(3) color triplet and SU(2) Singlet.

Production is fixed by QCD, $\mathcal{L}_{\text{Kinetic}}$.

Effective Lagrangian:

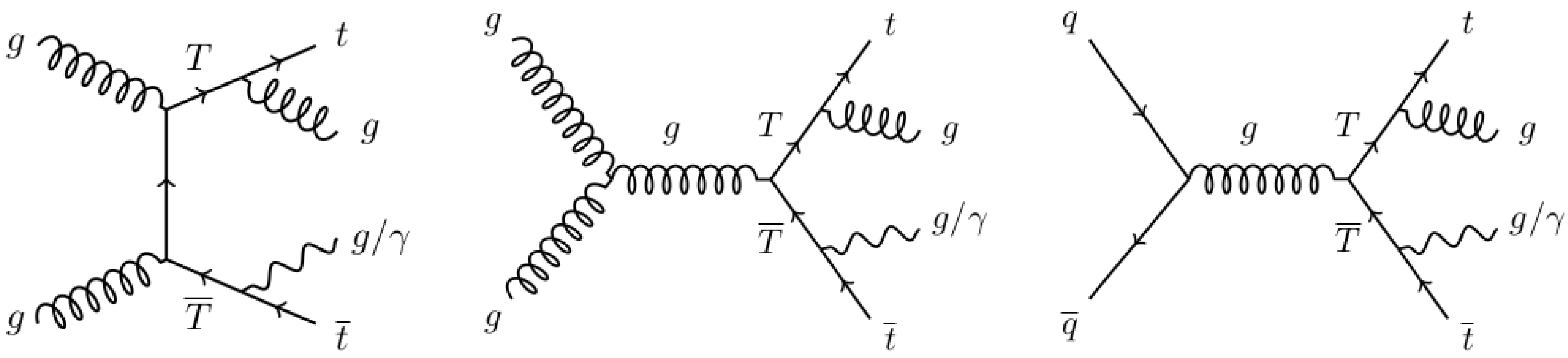
Free Parameters
$\{\mathcal{C}_1, \mathcal{C}_2, m_T\}$

$$\mathcal{L}_{\text{EFT}} = \bar{T}\,\sigma^{\mu\nu}\,\left(\mathcal{C}_1 T^a P_{L/R}\,t\,G^a_{\mu\nu} + \mathcal{C}_2 P_{L/R}\,t\,F_{\mu\nu}\right) + h.c.$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Kinetic}} + \mathcal{L}_{\text{EFT}}.$$

Final States

$pp \to t\bar{t}gg \,/\, t\bar{t}g\gamma$



Benchmark Point:

$$\mathcal{C}_1 = 1.0 \times 10^{-4}$$

$$\mathcal{C}_2 = 0.2 \times 10^{-4}$$

$$m_T = 1.0 \text{ TeV}$$

Branching Fractions:

$$BR(T \to tg) = 0.97$$

$$BR(T \to t\gamma) = 0.03$$

consider semileptonic decay

Semileptonic $t \to bjj$ & $t \to b\bar{l}\nu_l$

1. $t\bar{t}gg$ Final State

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm Kinetic} + \mathcal{L}_{\rm EFT}.$$

- Model implementation.
- Signal and Background generation.
- Anti-kT jet clustering.
- TOM for top tagging.
- Detector resolution effect is included (ATLAS parametrization).

2. $t\bar{t}g\gamma$ Final State

- All partons: $p_T > 30\,\mathrm{GeV}$ and $|\eta| < 5$
- Leptons: $p_T^l > 30\,\mathrm{GeV}$ and $|\eta^l| < 2.5$
- Photons: $p_T^\gamma > 300\,\mathrm{GeV}$ and $|\eta^\gamma| < 2.5$
- Additionally: $H_T > 700\,\mathrm{GeV}$

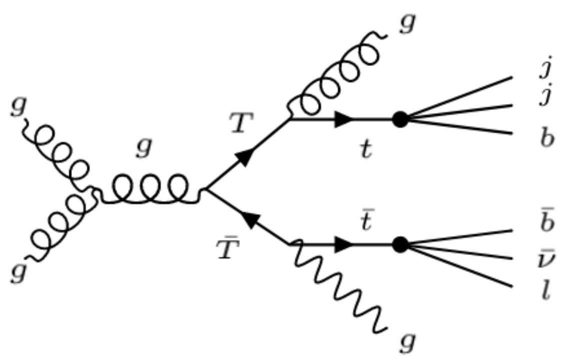
ATLAS Collaboration (arXiv:1407.5063)

Analysis

1. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,g$

Consider

$$m_T = 1\,\mathrm{TeV} \implies \sigma^{\mathrm{sig}} \cdot \mathrm{BR} \cdot \varepsilon_{\mathrm{gen}} = 4.4\,\mathrm{fb}$$



CMS: $pp \to t^* \bar{t}^*$

1. at 8 TeV (background) — CMS Collaboration arXiv:1311.5357

2. at 13 TeV (background) — CMS Collaboration arXiv:1711.10949

$t\bar{t}gg$ Final State

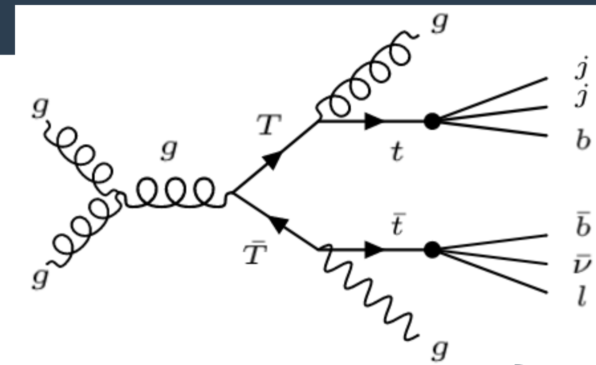
Abbreviations	Backgrounds	Matching	$\sigma \cdot \mathrm{BR} \cdot \varepsilon_{\mathrm{gen}}$
$t\bar{t}$	$t\bar{t}$ + jets	4-flavor	2.9×10^3 fb
Single t	tW + jets	5-flavor	4.1×10^3 fb
	t + jets	4-flavor	77 fb
W	W + jets	5-flavor	5.0×10^3 fb
VV	WW + jets	4-flavor	110 fb
	WZ + jets	4-flavor	44 fb

1. Basic Cuts: { $\not{E}_T > 50\,\mathrm{GeV}$, at least 1 slim jet, at least 1 fat jet and exactly 1 isolated lepton.}

2. Boosted top tagging: {select one fat jet with the best overlap score}

Analysis

1. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,g$



$t\bar{t}gg$ Final State

3. Slim jet flavors: {match slim jets to C and B hadrons}

4. Isolated slim jets: {at leas 3 jets are isolated from the fat jet}

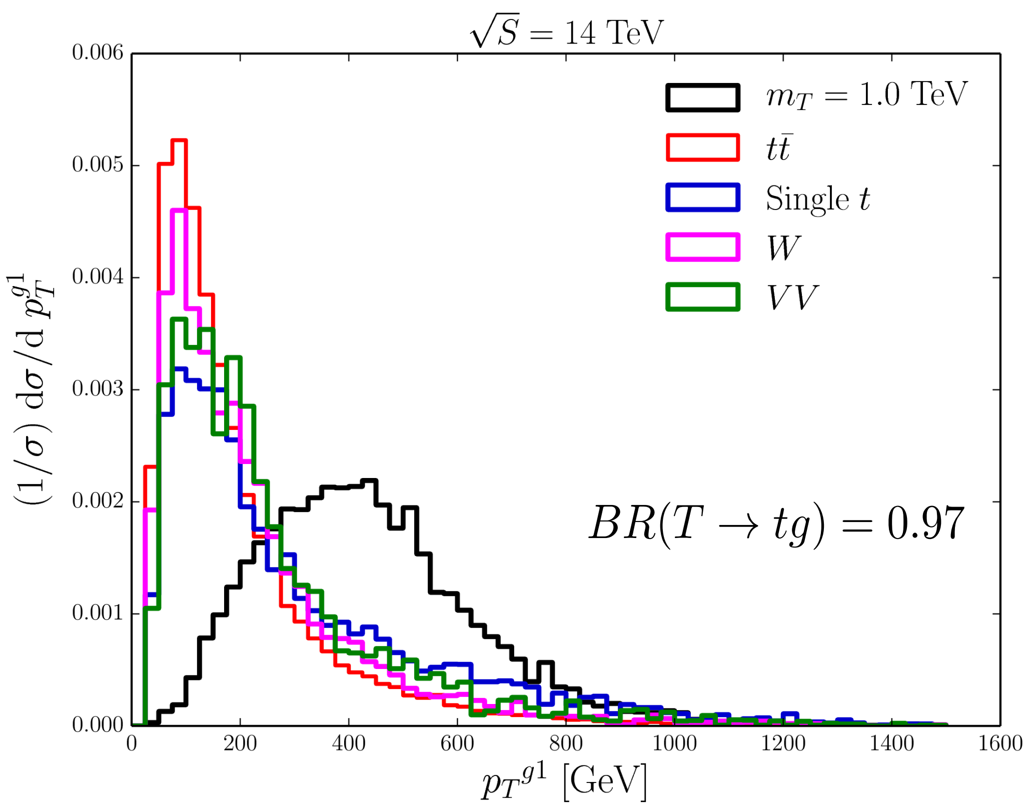
5. b-quark from t-leptonic: { $m_{lj} < m_{lb}^{\max}$ } → $\{\mathrm{jet}\}^{\mathrm{b}}$

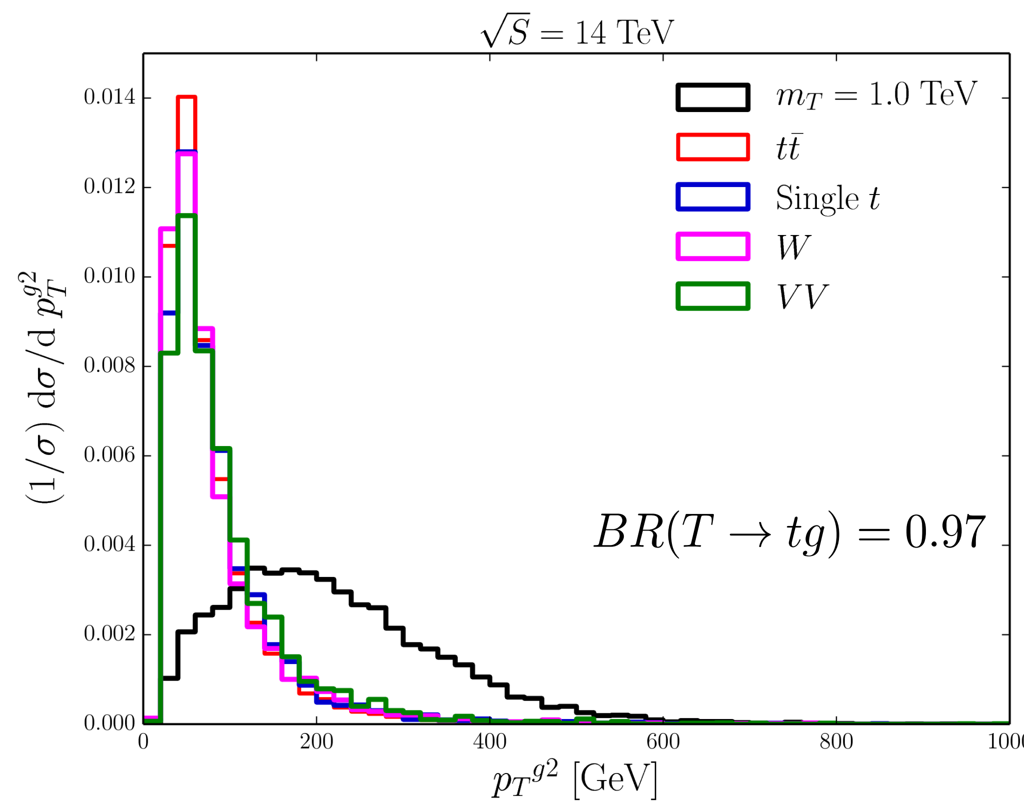
6. Boosted top tagging: { $\not{E}_T + l + \{\mathrm{jet}\}^{\mathrm{b}}$, find the combination with the best overlap results}

7. Realization of g jets: { two highest jets in p_T }

Analysis

1. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,g$





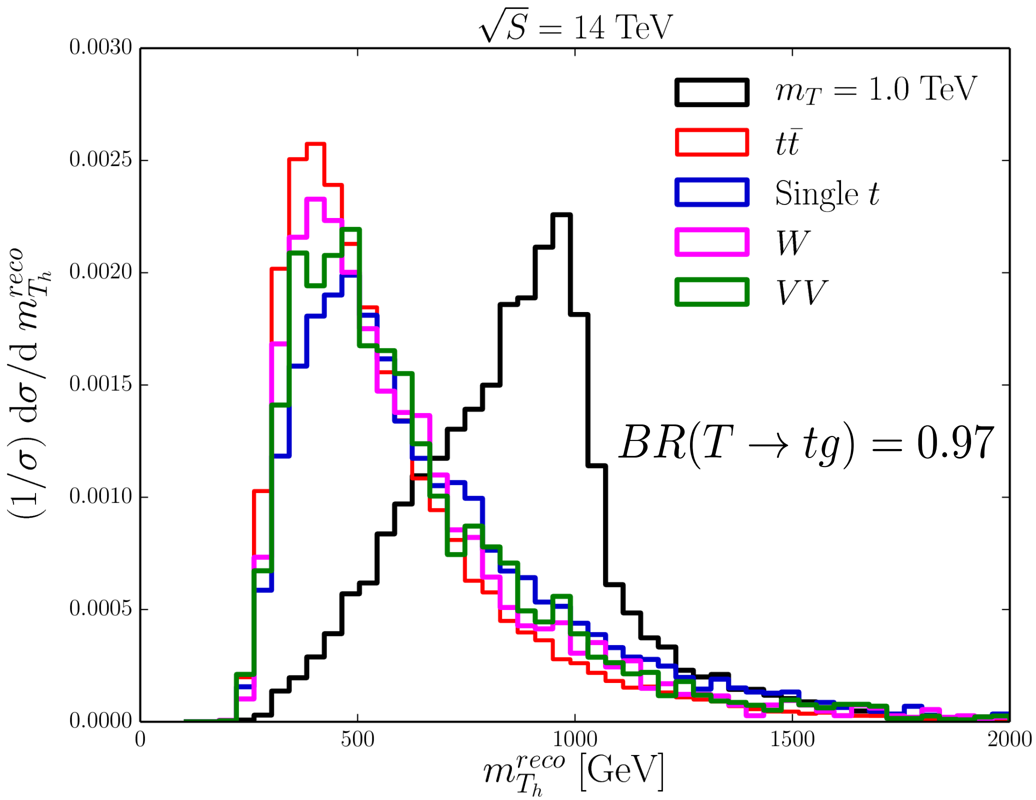
p_T^{g1} : The first hardest gluon jet.

p_T^{g2} : The second hardest gluon jet.

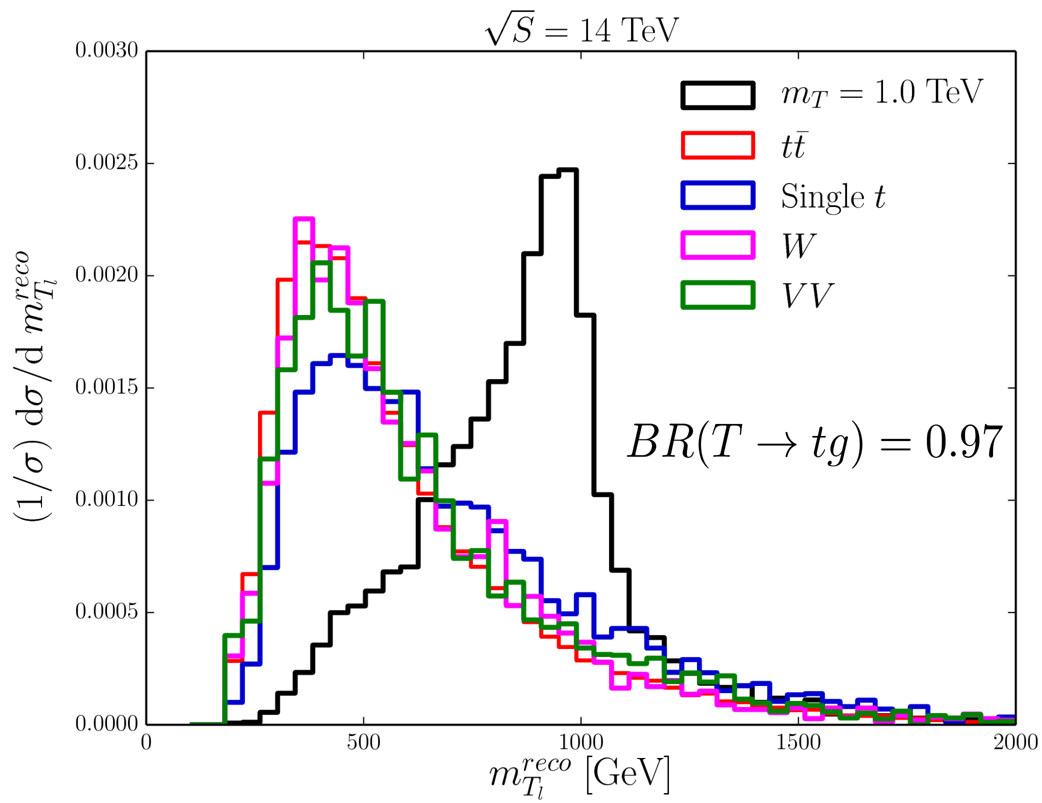
Analysis

1. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,g$

mass difference : Δm



$m_{T_h}^{reco}$ hadronic top partner.



$m_{T_l}^{reco}$ leptonic top partner.

Analysis

1. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,g$

Cut-flow table of tgtg final state

Log likelihood ratio

$$H_T^{reco} = p_T^{t_h} + p_T^{t_l} + p_T^{g1} + p_T^{g2}$$

cross section in fb

	Signal	tt	t	W	VV	Significance	Exclusion
Basic Cuts	3.0	1100	2600	2100	68	2.14	2.14
t-tagging	0.59	142.8	63.19	32.19	1.83	2.12	2.12
$p_T^{\{g_1,g_2\}} > \{250, 150\}$ GeV	0.35	9.17	4.63	2.48	0.19	4.78	4.76
$H_T^{reco} > 1600$ GeV	0.29	4.86	3.42	1.58	0.12	5.05	5.03
$750 < M_T < 1100$ GeV	0.16	0.84	0.62	0.23	0.017	6.73	6.63
b-tag on t_{had}	0.10	0.51	0.29	5.6×10^{-3}	1.0×10^{-3}	5.90	5.78
b-tag on t_{lep}	0.10	0.49	0.21	0.016	1.7×10^{-4}	6.40	6.26
b-tag on t_{had} & t_{lep}	0.061	0.30	0.084	5.1×10^{-4}	1.0×10^{-5}	5.28	5.15

$BR(T \to tg) = 0.97$

Luminosity $= 3\ \mathrm{ab}^{-1}$

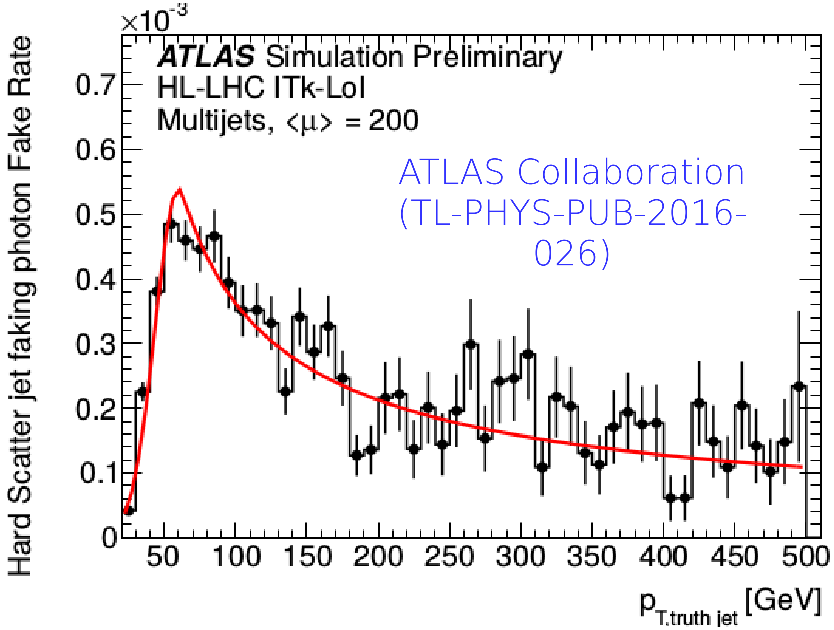
Analysis

2. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,\gamma$

Consider

$$m_T = 1\,\text{TeV} \Longrightarrow \sigma^{\text{sig}} \cdot \text{BR} \cdot \varepsilon_{\text{gen}} = 0.22\,\text{fb}$$

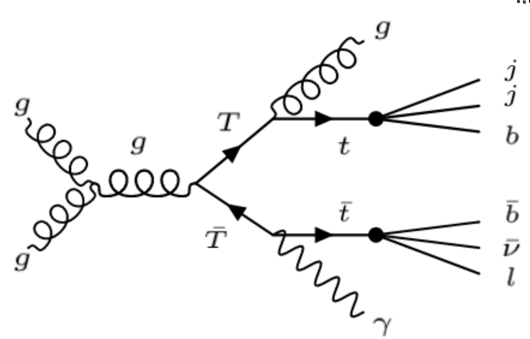
Abbreviations	Backgrounds	Matching	$\sigma \cdot \text{BR} \cdot \varepsilon_{\text{gen}}$
$t\bar{t}\gamma$	$t\bar{t} + \gamma + \text{jets}$	4-flavor	1.0 fb
$t\gamma$	$tW + \gamma + \text{jets}$	5-flavor	1.9 fb
	$t + \gamma + \text{jets}$	4-flavor	0.085 fb
$W\gamma$	$W + \gamma + \text{jets}$	5-flavor	5.4 fb
$VV\gamma$	$WW + \gamma + \text{jets}$	4-flavor	0.17 fb
	$WZ + \gamma + \text{jets}$	4-flavor	0.057 fb



ATLAS Collaboration (TL-PHYS-PUB-2016-026)

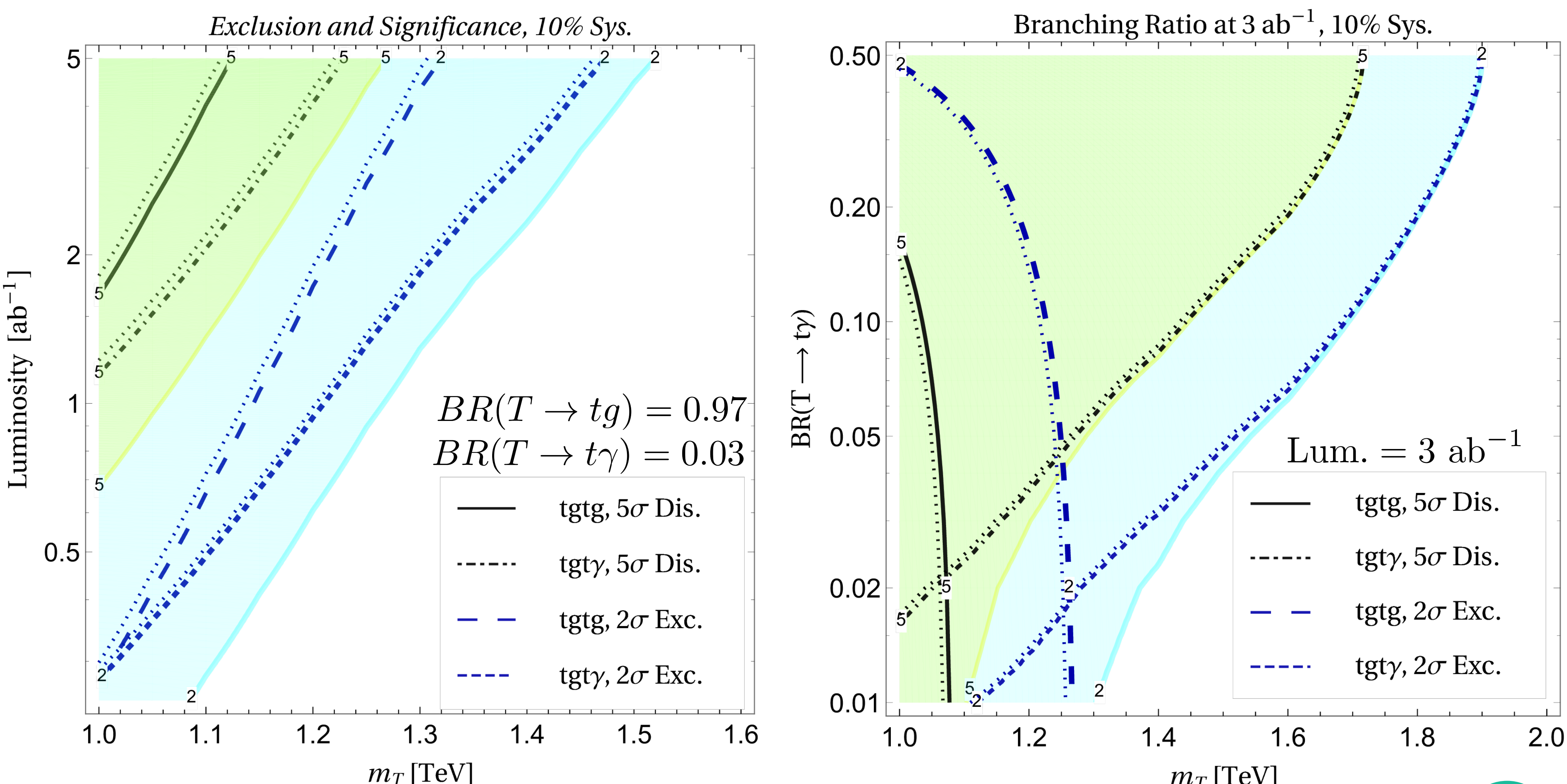
Photon Fake Rate

$$\epsilon_{j\to\gamma} = \begin{cases} 5.3 \times 10^{-4} \exp\left(-6.5\left(\frac{p_{T,j}}{60.4\text{GeV}} - 1\right)^2\right) & \text{for} \quad p_{T,j} < 65\,\text{GeV}, \\ 0.88 \times 10^{-4}\left[\exp\left(-\frac{p_{T,j}}{943\text{GeV}}\right) + \frac{248\text{GeV}}{p_{T,j}}\right] & \text{otherwise}, \end{cases}$$



Goncalves, Han, Kling, Plehn, Takeuchi, (arXiv:1802.04319)

Results


Exclusion and Significance, 10% Sys.
Luminosity [ab^{-1}]
m_T [TeV]
$BR(T \to tg) = 0.97$
$BR(T \to t\gamma) = 0.03$
tgtg, 5σ Dis.
tgtγ, 5σ Dis.
tgtg, 2σ Exc.
tgtγ, 2σ Exc.
Branching Ratio at 3 ab^{-1}, 10% Sys.
BR(T ⟶ tγ)
m_T [TeV]
Lum. = 3 ab^{-1}
tgtg, 5σ Dis.
tgtγ, 5σ Dis.
tgtg, 2σ Exc.
tgtγ, 2σ Exc.

Conclusion

$pp \to T\bar{T} \to t\,g\,\bar{t}\,g$ and $pp \to T\bar{T} \to t\,g\,\bar{t}\,\gamma$

- Radiative decay modes serve as a complementary search to the conventional decay modes.
- Radiative decay modes become extremely important when Exp limits are stronger on the conventional decay modes.
- Despite its small BR, photon final state provides better significance and allow exploration of larger part of the parameter space.
- Combining the two final states helps increase the sensitivity.

Questions

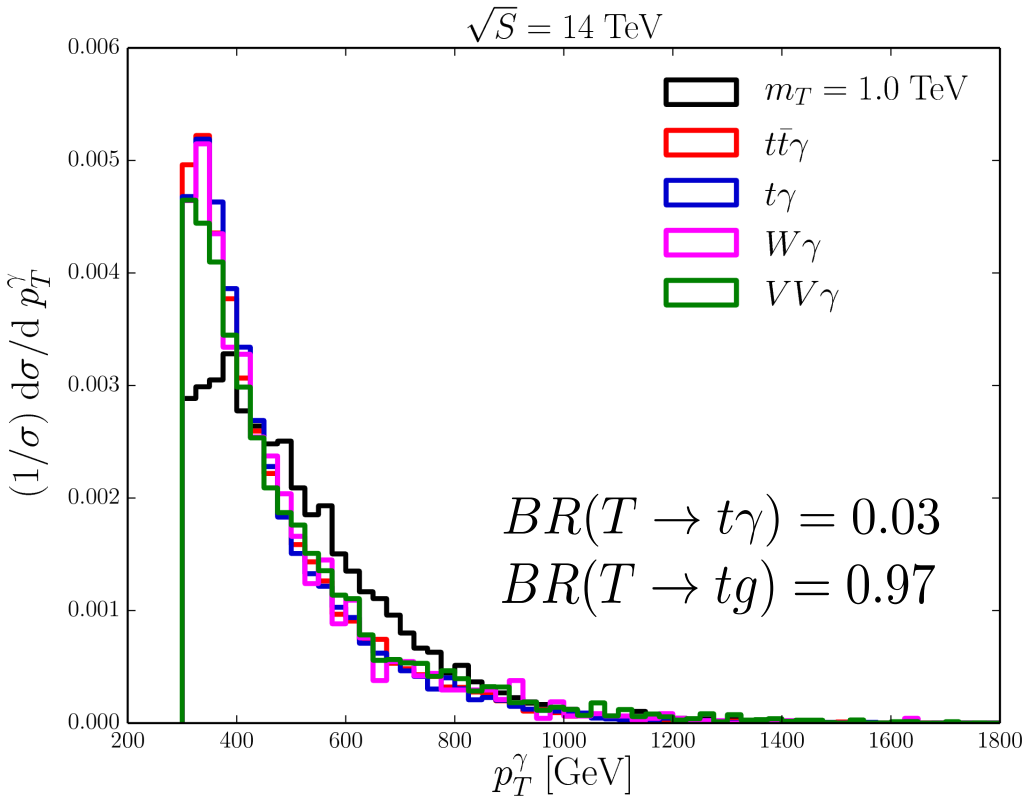
Thank You

BACKUP

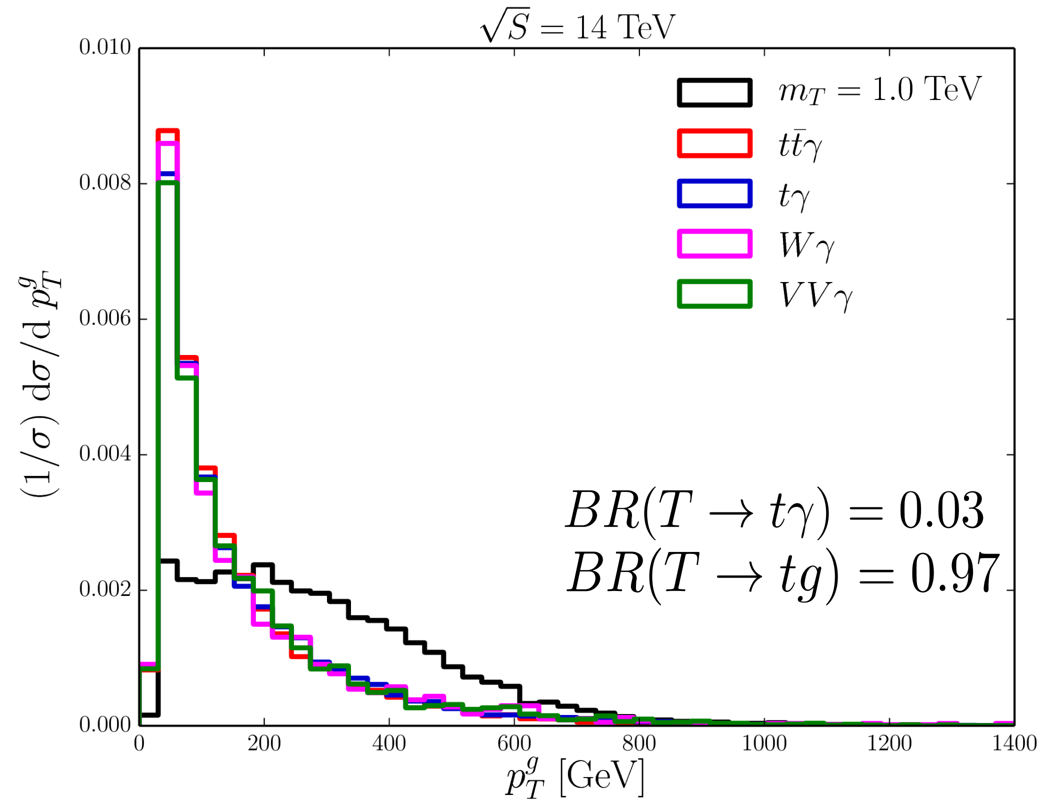
Analysis

2. Semileptonic $\quad pp \to T\bar{T} \to t\,g\,\bar{t}\,\gamma$

$$M^2 = |m(\gamma + t)^2 - m_T^2| + |m(g_i + t)^2 - m_T^2|$$



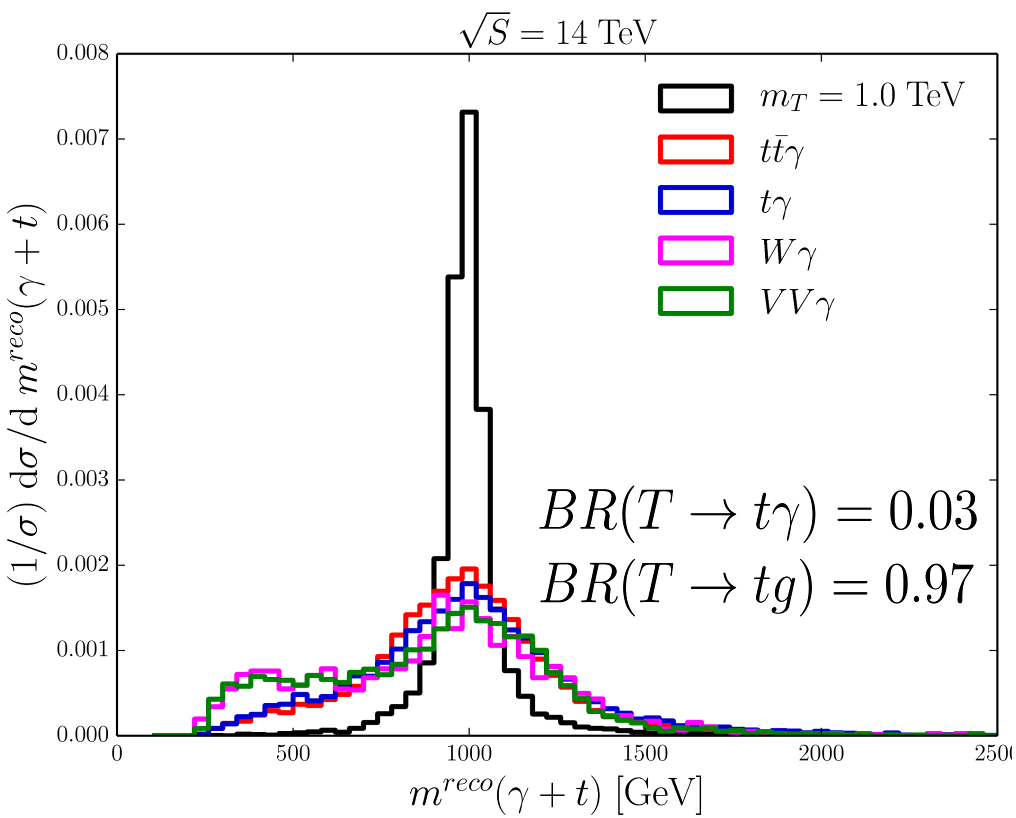
p_T^γ : transverse momentum of photon.



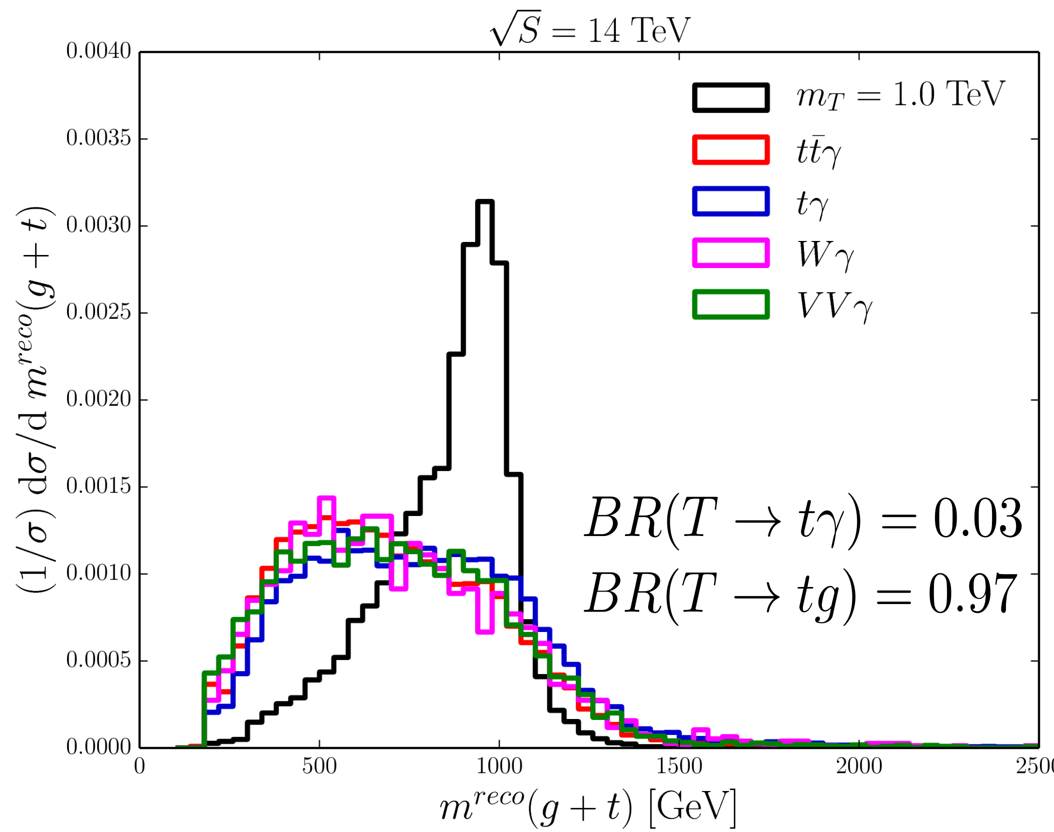
p_T^g : transverse momentum of gluon.

Analysis

2. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,\gamma$



invariant mass of $\gamma + \mathrm{t}$



invariant mass of $\mathrm{g} + \mathrm{t}$

Analysis

2. Semileptonic $pp \to T\bar{T} \to t\,g\,\bar{t}\,\gamma$

Cut-flow table of $t\,g\,\bar{t}\,\gamma$ final state

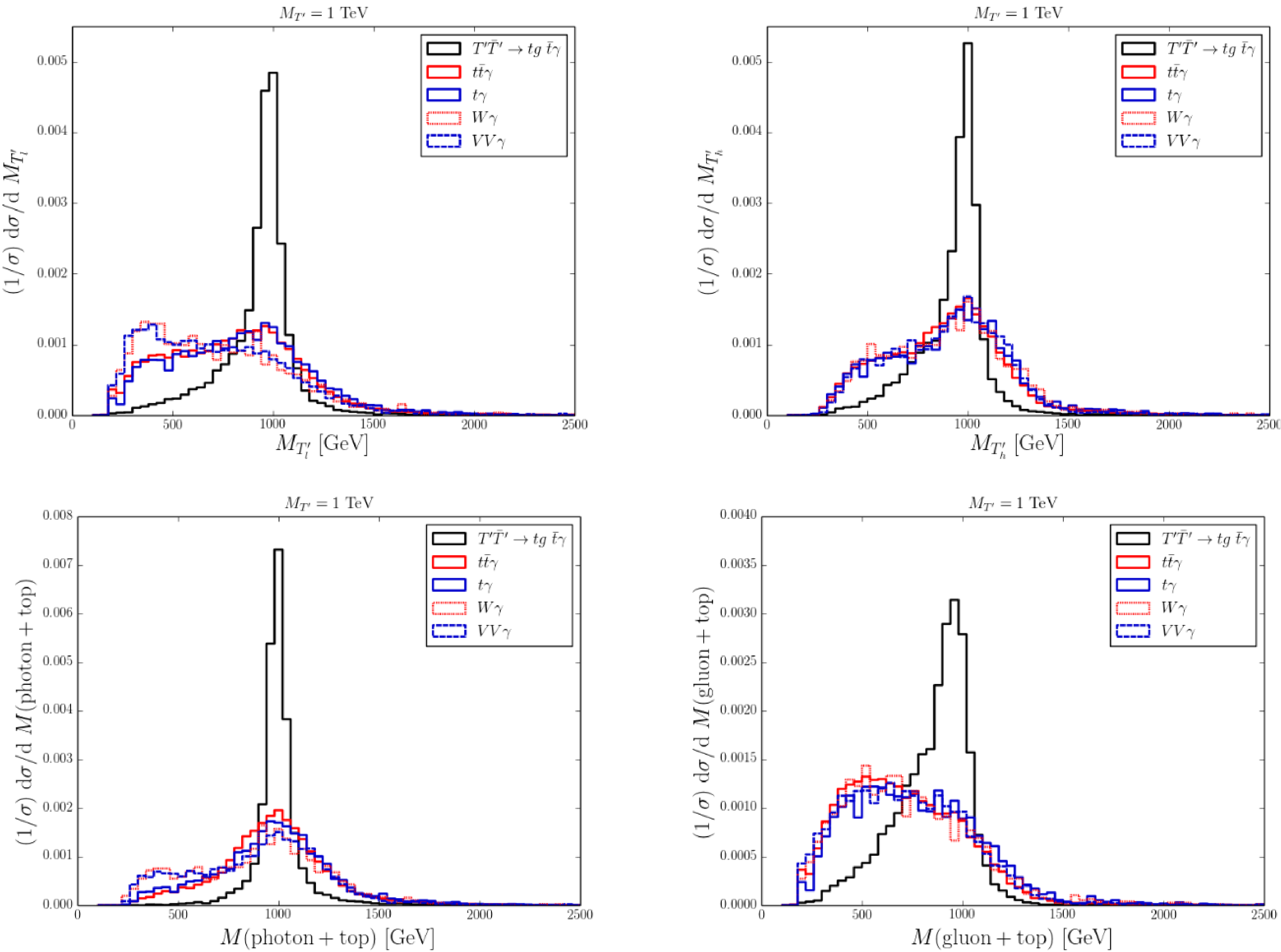
Log likelihood ratio

$H_T^{reco} = p_T^{t_h} + p_T^{t_l} + p_T^{g} + p_T^{\gamma}$

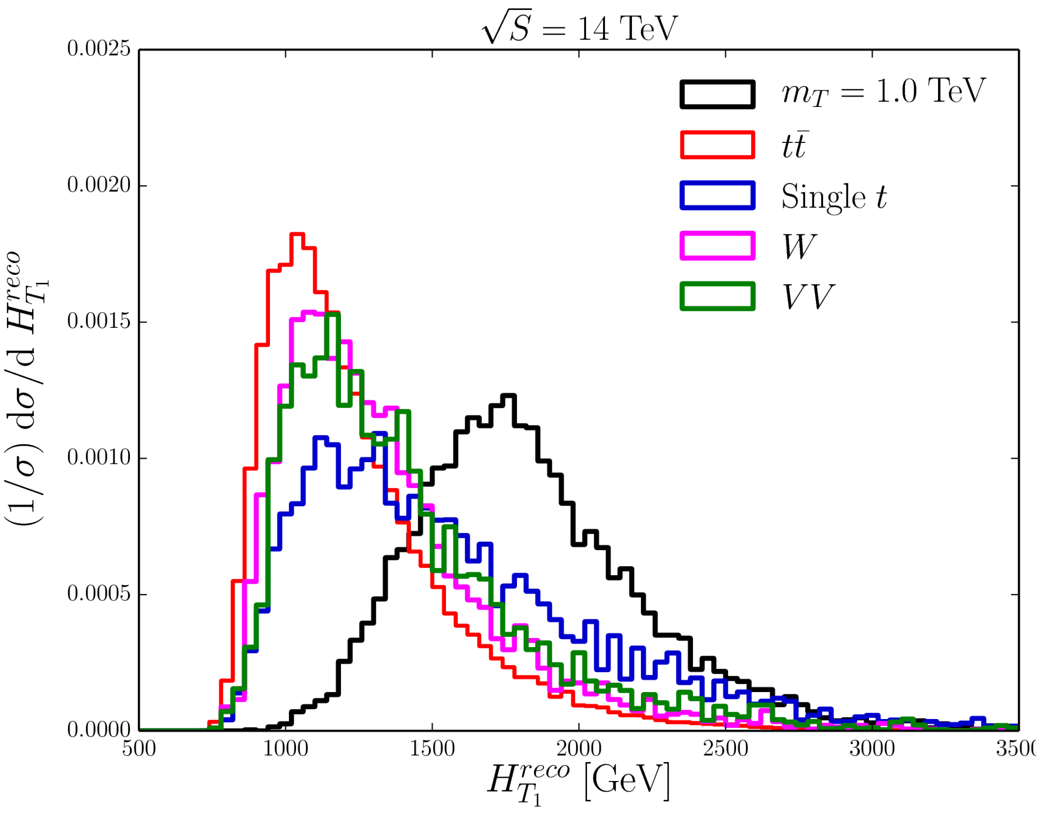
cross section in fb

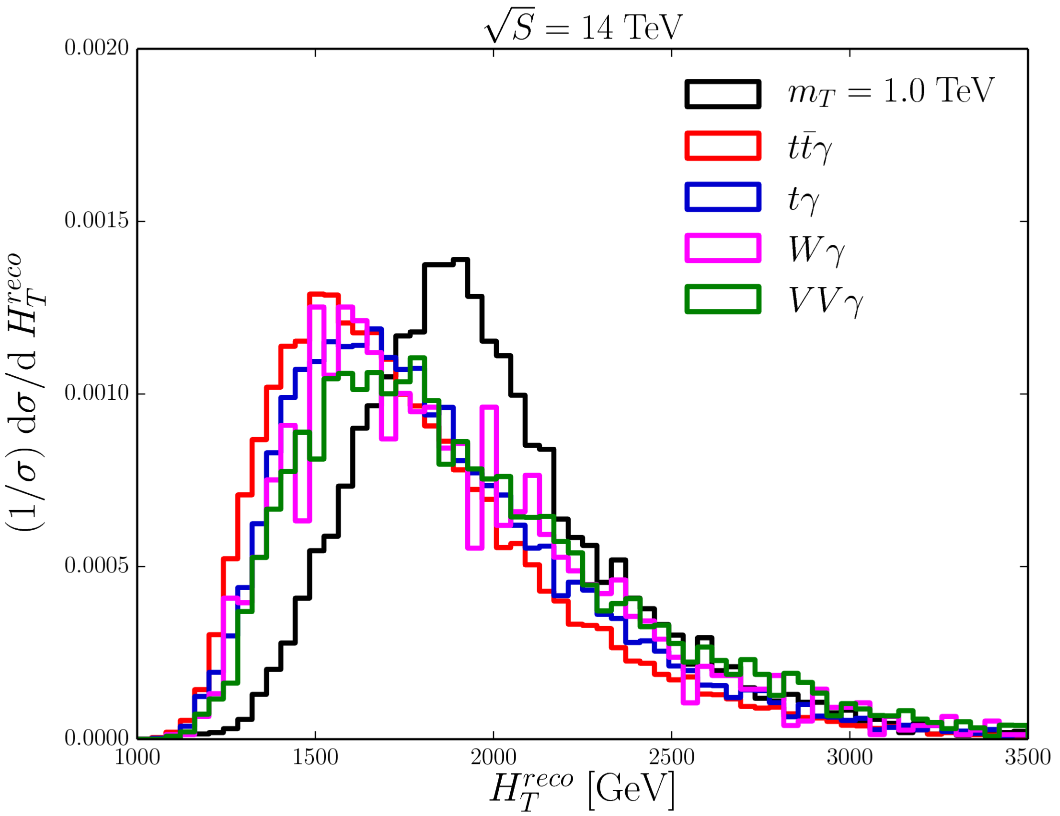
	Signal	$tt\gamma$	$t\gamma$	$W\gamma$	$VV\gamma$	Significance	Exclusion
Basic Cuts	0.12	0.32	1.3	2.4	0.10	3.22	3.21
t-tagging	0.029	0.062	0.037	0.034	2.5×10^{-3}	4.23	4.09
$p_T^{\{\gamma,g\}} > \{300, 140\}$ GeV	0.021	0.023	0.011	0.012	8.8×10^{-4}	5.05	4.74
$H_T^{reco} > 1600$ GeV	0.02	0.016	9.5×10^{-3}	9.7×10^{-3}	7.4×10^{-4}	5.20	4.84
$900 < m_T^{\gamma} < 1100$ GeV $700 < m_T^{g} < 1100$ GeV	0.015	3.1×10^{-3}	1.5×10^{-3}	1.3×10^{-3}	1.1×10^{-4}	8.08	6.59
b-tag on t_{had}	9.6×10^{-3}	2.0×10^{-3}	7.4×10^{-4}	1.4×10^{-4}	6.1×10^{-6}	7.22	5.68
b-tag on t_{lep}	9.4×10^{-3}	1.8×10^{-3}	4.8×10^{-4}	2.7×10^{-5}	2.9×10^{-6}	7.61	5.84
b-tag on t_{had} & t_{lep}	6.2×10^{-3}	1.2×10^{-3}	1.4×10^{-4}	2.1×10^{-6}	1.9×10^{-7}	6.41	4.83

$BR(T \to t\gamma) = 0.03$ $BR(T \to tg) = 0.97$ Luminosity $= 3\ \text{ab}^{-1}$



$M_{T'} = 1$ TeV
$(1/\sigma)\ d\sigma/d\ M_{T'_l}$
$M_{T'_l}$ [GeV]
$M_{T'} = 1$ TeV
$(1/\sigma)\ d\sigma/d\ M_{T'_h}$
$M_{T'_h}$ [GeV]
$M_{T'} = 1$ TeV
$(1/\sigma)\ d\sigma/d\ M(\text{photon} + \text{top})$
$M(\text{photon} + \text{top})$ [GeV]
$M_{T'} = 1$ TeV
$(1/\sigma)\ d\sigma/d\ M(\text{gluon} + \text{top})$
$M(\text{gluon} + \text{top})$ [GeV]
$T'\bar{T}' \to tg\ \bar{t}\gamma$
$t\bar{t}\gamma$
$t\gamma$
$W\gamma$
$VV\gamma$


$\sqrt{S} = 14$ TeV
$m_T = 1.0$ TeV
$t\bar{t}$
Single t
W
VV
$(1/\sigma)\ d\sigma/d\ H_{T_1}^{reco}$
$H_{T_1}^{reco}$ [GeV]
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
500
1000
1500
2000
2500
3000

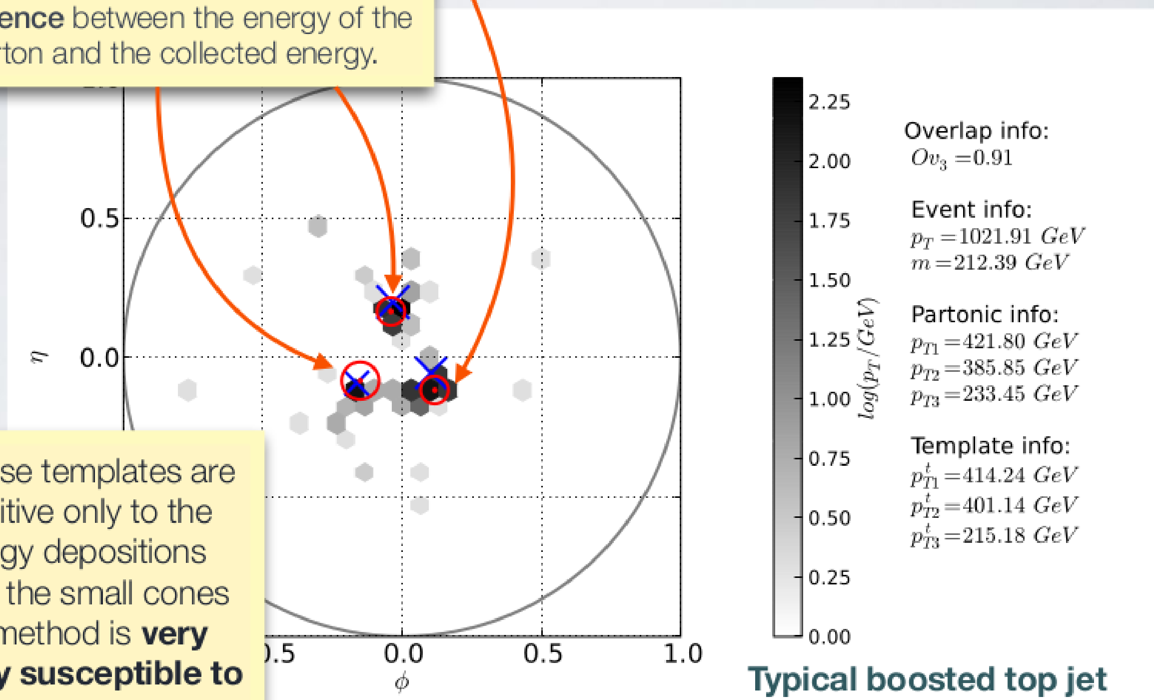

$\sqrt{S} = 14$ TeV
$m_T = 1.0$ TeV
$t\bar{t}\gamma$
$t\gamma$
$W\gamma$
$VV\gamma$
$(1/\sigma)\ d\sigma/d\ H_{T}^{reco}$
H_{T}^{reco} [GeV]
0.0000
0.0005
0.0010
0.0015
0.0020
1000
1500
2000
2500
3000
3500

TOM

Tagging of **Boosted Objects**

Blue - positions of truth level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.

Templates are matched to jet energy distribution **by collecting radiation within some small cone around each parton and minimizing the difference** between the energy of the parton and the collected energy.



Typical boosted top jet

Because templates are sensitive only to the energy depositions within the small cones the method is **very weakly susceptible to pileup.**

arXiv:1409.0409

M. Backovic

Sys.

13 TeV.

Source of uncertainty	Implementation on simulated signal sample
Integrated luminosity	Normalization shift by $\pm 2.5\%$
Statistical uncertainty	Normalization shift by ± 1 s.d.
Jet correction	Correction factor varied by ± 1 s.d.
Jet resolution	Jet resolution shift by ± 1 s.d.
b tagging SF	SF varied by ± 1 s.d.
Lepton efficiency SF	SF varied by ± 1 s.d.
Pileup	pp inelastic cross section shifted by $\pm 4.6\%$ [41]
Modeling	Smoothing parameter ρ varied over range $[1.17, 1.66]$
PDF uncertainty	Generator parameter varied by ± 1 s.d.
Scale uncertainty	Generator parameter varied by ± 1 s.d.

CMS
arXiv:1711.10949

8 TeV.

Source	μ+jets	e+jets
Luminosity	2.6%	2.6%
JES	2.3–3.9%	2.2–4.1%
JER	<1%	<1%
Trigger efficiency	1.0%	1.0%
Lepton efficiency	0.9–1.3%	< 1%
b-tagging	0.6–1.5%	0.8–1.4%
Pileup	<1%	<1%
PDF	0.3–1.9%	1.3–1.9%
MC statistics	1.9%	2.0%

CMS
arXiv:1311.5357

Matching: (A. George (UCSB))

Basic Idea

Two ways to deal with ISR (initial state radiation):

- **Matrix Element**: calculate the matrix element directly with extra jets, using something like **Madgraph**. This is **less accurate when the particles are soft or collinear**.
- **Parton Shower**: generate only the simplest event, then make extra partons, using something like **Pythia**. This is **more accurate when the particles are soft or collinear**.

To get the best of both worlds, we generate the events in **Madgraph** and decay in **Pythia**.

- But this will double count! Madgraph and Pythia both assign the correct number of jets; using both will give too many jets on average!
- **Matching is the attempt to avoid this double counting.**

We now turn to the boosted leptonic top, t_{lep}, reconstruction [46] within the TOM framework. The TOM also has an ability to identify the leptonically-decaying boosted top, recycling the identical set of three-pronged templates used in the hadronic top analysis. An overlap Ov_3^{lep}, where *lep* denotes the leptonic top, requires three inputs, four-momenta of a jet and a lepton and missing transverse momentum ($\vec{\not{P}}_T$) [6]. The absence of information on the longitudinal component of $\vec{\not{P}}_T$ makes the difference between Ov_3^{had} and Ov_3^{lep} where the azimuthal distance $\Delta\phi$ between the template and $\vec{\not{P}}_T$ is used in the matching procedure when calculating a likelihood score Ov_3^{lep}. Therefore in general it does not allow for a precise reconstruction of the truth top axis. However, adding Ov_3^{lep} to our analysis will prove to be useful: i) We can select a correct lepton-jet pair which gives the highest Ov_3^{lep} score among all possible assignments. After this selection, In 85% of the signal events, a b-hadron is found inside the selected jet. Therefore, it can help to resolve the combinatorial problem which is crucial for precise reconstructions of the top partner masses. ii) It can reject the background events efficiently and boost a signal sensitivity.

Smearing

$$\Gamma_{\mathrm{EFT}}(T \to tg) \approx \frac{\alpha_s\, C_F\, \lambda_1^2 \lambda_2^2}{576\, \pi^4} \frac{m_T^5}{m_S^4} \left(1 + \frac{3}{4} \log \frac{m_T^2}{m_S^2}\right)^2$$

$$\Gamma_{\mathrm{EFT}}(T \to t\gamma) \approx \frac{\alpha\, \lambda_1^2 \lambda_2^2}{1296\, \pi^4} \frac{m_T^5}{m_S^4} \left(1 + \frac{3}{4} \log \frac{m_T^2}{m_S^2}\right)^2$$

$$\Gamma_{\mathrm{EFT}}(T \to tZ) \approx \frac{\alpha\, \lambda_1^2 \lambda_2^2\, s_W^2}{1296\, \pi^4\, c_W^2} \frac{m_T^5}{m_S^4} \left(1 + \frac{3}{4} \log \frac{m_T^2}{m_S^2}\right)^2 .$$

$$\text{Significance} = \sqrt{-2\ \ln \frac{\mathrm{L(B|S+B)}}{\mathrm{L(S+B|S+B)}}}$$

$$\text{Exclusion} = \sqrt{-2\ \ln \frac{\mathrm{L(S+B|B)}}{\mathrm{L(B|B)}}}$$

$$L(x|n) = \frac{x^n}{n!}\, e^{-x}$$

$t\bar{t}gg$ channel	Signal [fb]	$t\bar{t}$ [fb]	Single t [fb]	W [fb]	VV [fb]	σ_{dis}	σ_{exc}
Basic cuts	2.8	1.1×10^3	2.6×10^3	2.1×10^3	68	2.0	2.0
$N_{t_{had}} = 1$	1.4	650	790	390	14	1.8	1.8
$N_{t_{lep}} = 1$	0.60	140	51	28	1.6	2.2	2.2
$p^{reco}_{T,\{g_1,g_2\}} > \{250, 150\}$ GeV	0.35	9.17	4.63	2.48	0.19	4.78	4.76
$H^{reco}_T > 1600$ GeV	0.29	4.86	3.42	1.58	0.12	5.05	5.03
$750 < m^{reco}_{T_{1,2}} < 1100$ GeV	0.16	0.84	0.62	0.23	0.017	6.73	6.63
b-tag on t_{had}	0.10	0.51	0.29	5.6×10^{-3}	1.0×10^{-3}	5.90	5.78
b-tag on t_{lep}	0.10	0.49	0.21	0.016	1.7×10^{-4}	6.40	6.26
b-tag on t_{had} & t_{lep}	0.061	0.30	0.084	5.1×10^{-4}	1.0×10^{-5}	5.28	5.15

$t\bar{t}g\gamma$ channel	Signal [fb]	$tt\gamma$ [fb]	$t\gamma$ [fb]	$W\gamma$ [fb]	$VV\gamma$ [fb]	σ_{dis}	σ_{exc}
Basic cuts	0.13	0.32	1.1	2.4	0.10	3.6	3.6
$N_{t_{had}} = 1$	0.076	0.22	0.39	0.47	0.022	3.9	3.8
$N_{t_{lep}} = 1$	0.033	0.061	0.030	0.029	2.1×10^{-3}	4.9	4.7
$\{p^{\gamma}_T, p^{reco}_{T,g}\} > \{300, 140\}$ GeV	0.021	0.023	0.0114	0.0118	8.8×10^{-4}	5.1	4.7
$H_T > 1600$ GeV	0.02	0.016	9.5×10^{-3}	9.7×10^{-3}	7.4×10^{-4}	5.2	4.8
$900 < m^{reco}_{T_\gamma} < 1100$ GeV $700 < m^{reco}_{T_g} < 1100$ GeV	0.015	3.1×10^{-3}	1.5×10^{-3}	1.3×10^{-3}	1.1×10^{-4}	8.1	6.6
b-tag on t_{had}	9.6×10^{-3}	2.0×10^{-3}	7.4×10^{-4}	1.4×10^{-4}	6.1×10^{-6}	7.2	5.7
b-tag on t_{lep}	9.4×10^{-3}	1.8×10^{-3}	4.8×10^{-4}	2.7×10^{-5}	2.9×10^{-6}	7.6	5.8
b-tag on t_{had} & t_{lep}	6.2×10^{-3}	1.2×10^{-3}	1.4×10^{-4}	2.1×10^{-6}	1.9×10^{-7}	6.4	4.8

Why VLQ?

Vector-like quarks in many models of New Physics

- Warped or universal **extra-dimensions**
  KK excitations of bulk fields
- **Composite Higgs** models
  VLQ appear as excited resonances of the bounded states which form SM particles
- **Little Higgs** models
  partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- **Gauged flavour group** with low scale gauge flavour bosons
  required to cancel anomalies in the gauged flavour symmetry
- Non-minimal **SUSY extensions**
  VLQs increase corrections to Higgs mass without affecting EWPT

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[7] In our semi-realistic approach for the b-jet identification, $r = 0.4$ jets are classified into three categories where our heavy-flavor tagging algorithm iterates over all jets that are matched to b-hadrons or c-hadrons. If a b-hadron (c-hadron) is found inside, it is classified as a b-jet (c-jet). The remaining unmatched jets are called light-jets. Each jet candidate is further multiplied by a tag-rate [158], where we apply a flat b-tag rate of $\epsilon_{b\to b} = 0.7$ and a mis-tag rate that a c-jet (light-jet) is misidentified as a b-jet of $\epsilon_{c\to b} = 0.2$ ($\epsilon_{j\to b} = 0.01$). For a $r = 1.0$ fat jet to be b-tagged, on the other hand, we require that a b-tagged $r = 0.4$ jet is found inside a fat jet. To take into account the case where more than one b-jet might land inside a fat jet, we reweight a b-tagging efficiency depending on a b-tagging scheme described in Ref. [20].

C Parameterization of Detector Resolution Effects

We include detector effects based on the ATLAS detector performances [148]. The jet energy resolution is parametrized by noise (N), stochastic (S), and constant (C) terms

$$\frac{\sigma}{E} = \sqrt{\left(\frac{N}{E}\right)^2 + \left(\frac{S}{\sqrt{E}}\right)^2 + C^2}\,, \tag{C.1}$$

where in our analysis we use $N = 5.3$, $S = 0.74$ and $C = 0.05$ for jets; and $N = 0.3$, $S = 0.1$, and $C = 0.01$ for electrons.

Outlines:

Top Partner:

- Introduction.
- Radiative Decay Modes.
- Analysis.
- Results.
- Conclusion.

The muon energy resolution is derived by the Inner Detector (ID) and Muon Spectrometer (MS) resolution functions

$$\sigma = \frac{\sigma_{\mathrm{ID}}\ \sigma_{\mathrm{MS}}}{\sqrt{\sigma_{\mathrm{ID}}^2 + \sigma_{\mathrm{MS}}^2}}\ , \tag{C.2}$$

where

$$\sigma_{\mathrm{ID}} = E\ \sqrt{a_1^2 + (a_2\ E)^2} \tag{C.3}$$

$$\sigma_{\mathrm{MS}} = E\ \sqrt{\left(\frac{b_0}{E}\right)^2 + b_1^2 + (b_2\ E)^2}\ . \tag{C.4}$$

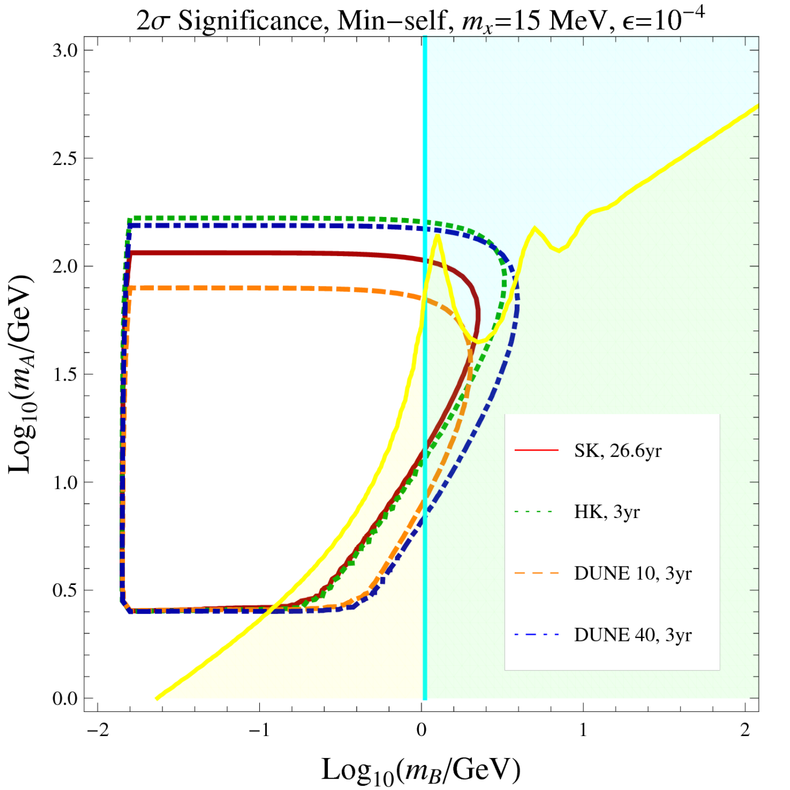
We use $a_1 = 0.023035$, $a_2 = 0.000347$, $b_0 = 0.12$, $b_1 = 0.03278$ and $b_2 = 0.00014$ in our study.

Boosted Dark Matter

Multi-Component DM → BDM

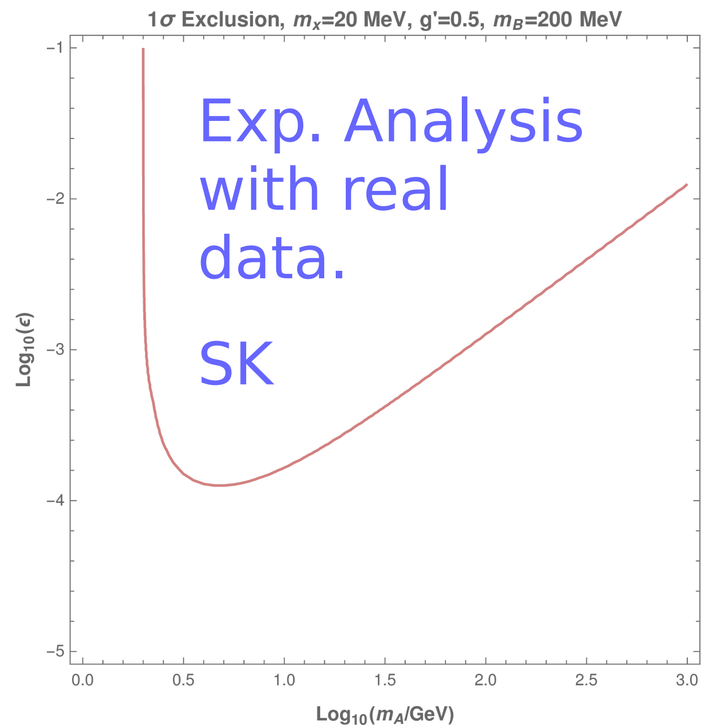
Cosmological Motivation

Self Interaction



[Boosted Dark Matter at the Deep Underground Neutrino Experiment]()

JHEP 1704 (2017) 158, (arXiv:1611.09866)



The Super-Kamiokandde Collaboration (arXiv:1711.05278v1)