

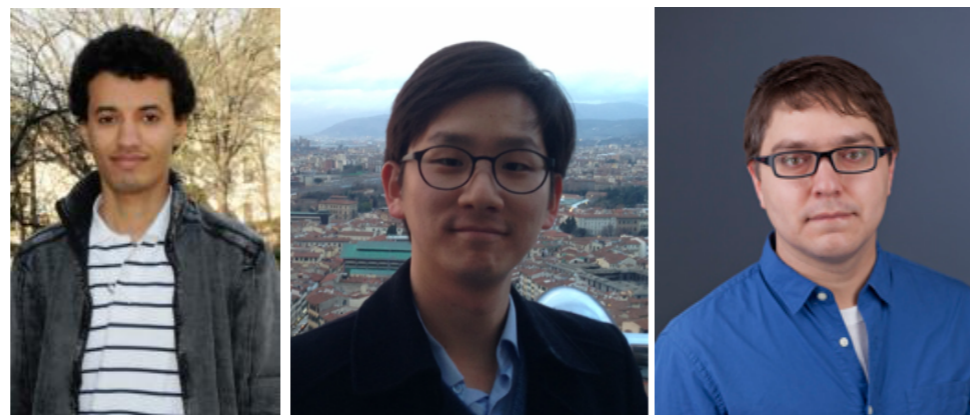
The unexplored landscape of top-partner decays

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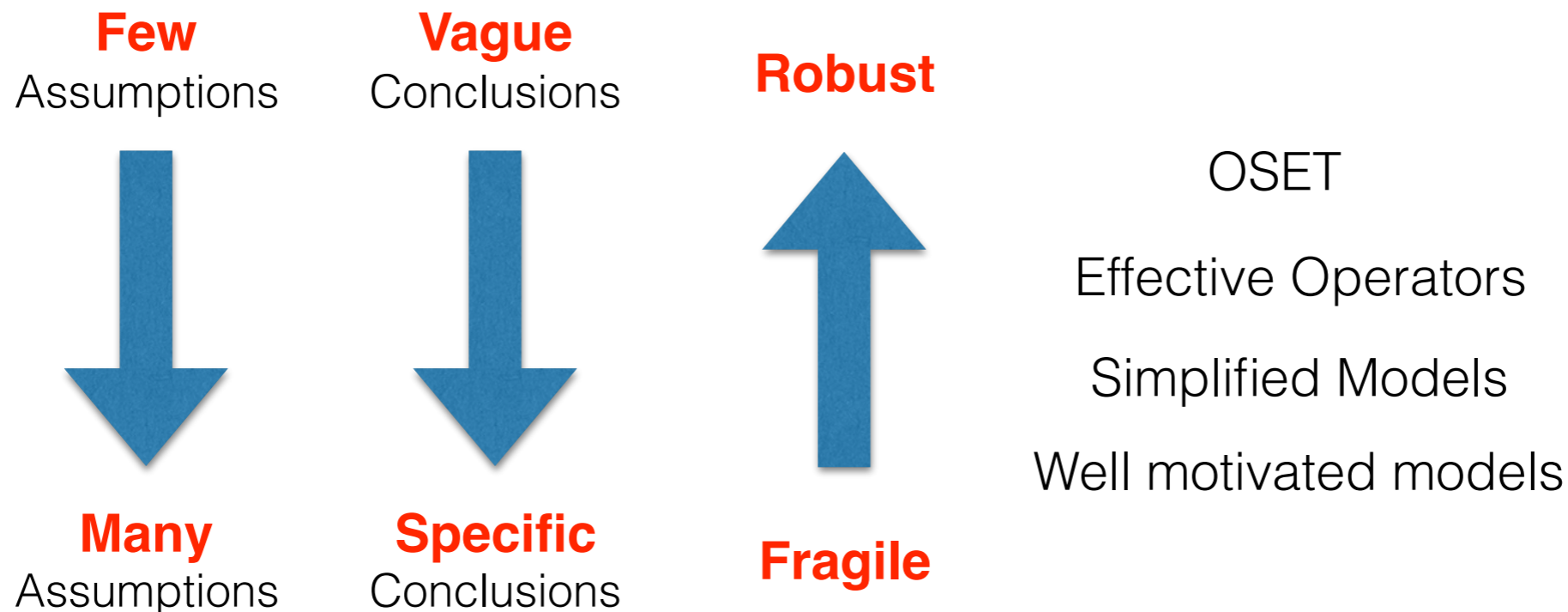
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based on work (1807.nextweek [hep-ph]) in collaboration with



How to Search for BSM

- There isn't a unique way. No right or wrong approach.
- Start with precision measurement of SM. Use Higgs / top quark.
- We have many “templates” for BSM physics.
- **Well motivated models**: Supersymmetry, extra dimensions, strong dynamics etc
- **OSET**: On-Shell Effective Theories (event topology with kinematics only)
- **Effective Operators**
- **Simplified Models**
- Alternatively, we propose a strategy for searching for theoretically-unanticipated new physics which avoids a large trials factor by focusing on **experimental strengths**. Searches for resonances decaying into pairs of visible particles are experimentally very powerful due to the localized mass peaks and have a rich history of discovery.
 - Yet, due to a focus on subsets of theoretically-motivated models, the landscape of such resonances is far from thoroughly explored.



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Unexplored Landscape of Two-Body Resonances

- Let us consider all possible combinations of two reconstructed objects (putting aside theoretical constraints.)

[illegible]

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	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\cancel{R}, H^{\pm\pm}$	$\cancel{R}, H^{\pm\pm}$	L^*	LQ, \cancel{R}	LQ, \cancel{R}	LQ, \cancel{R}	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\cancel{R}, H^{\pm\pm}$	L^*	LQ, \cancel{R}	LQ, \cancel{R}	LQ, \cancel{R}	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	LQ, \cancel{R}	LQ, \cancel{R}	LQ, \cancel{R}	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ				H, G_{KK}, \mathcal{Q}	Q^*	Q^*	Q^*	W_{KK}, \mathcal{Q}	H, \mathcal{Q}	Z_{KK}
j					Z', ρ, G_{KK}	W', \cancel{R}	T', \cancel{R}	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'
b						Z', H	W', \cancel{R}, H^\pm	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'
t							H, G', Z'	T'	T'	T'
W								H, G_{KK}, ρ	W', \mathcal{Q}	H^\pm, \mathcal{Q}, ρ
Z									H, G_{KK}, ρ	A, ρ
h										H, G_{KK}

TABLE II. Theory models motivating two-body final state resonance searches. Here Z' and W' denote additional gauge bosons, \cancel{R} denotes R-parity violating decays of sparticles in supersymmetry, $H^{\pm\pm}$ denotes doubly-charged Higgs bosons, H denotes additional neutral scalar or pseudoscalar Higgs bosons, L^* and Q^* denote excited fermions, X_{KK} denote various Kaluza-Klein excitations of gravitons or Standard Model fields, ρ denotes neutral or charged techni-rhos, LQ denotes leptoquarks, T' , B' , Q' denote vector-like top, bottom, and light-flavor quarks, and \mathcal{Q} denotes quirks. See also [38].

Unexplored Landscape of Two-Body Resonances

	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ	$(1, 2)^*$	$[1, 1]^*$	$(\bar{3}, 1^{(4)}/3) \diamond \heartsuit$	$[8, 1]^*$	$(\bar{3}, 4/3) \diamond \heartsuit$	$(\bar{3}, 1/3) \diamond \heartsuit$	$[1, 0]^*$	$[1, 1]^*$	$[1, 1]^*$
$\bar{\ell}$	$(1, 0)$	$[1, -1]^*$	$(\bar{3}, -2^{(5^*)}/3) \diamond \heartsuit$	$[8, -1]^*$	$(\bar{3}, -2/3) \diamond \heartsuit$	$(\bar{3}, -5/3)^*$	$[1, -2]^*$	$[1, -1]^*$	$[1, -1]^*$
γ	$[1, 1]^*$	$(1, 0)$	$[\bar{3}, 1^{(-2)}/3]$	$(8, 0)$	$[\bar{3}, 1/3]$	$[\bar{3}, -2/3]$	$(1, -1)$	$(1, 0)$	$(1, 0)$
q	$(\bar{3}, 1^{(4)}/3) \diamond \heartsuit$	$[\bar{3}, 1^{(-2)}/3]$	$(3, -1^{(2)}(-4)/3)$	$[\bar{3}, 1^{(-2)}/3]$	$(3, -1^{(2)}/3)$	$(3, -1^{(-4)}/3)$	$[\bar{3}, -2^{(-5^*)}/3]$	$[\bar{3}, 1^{(-2)}/3]$	$[\bar{3}, 1^{(-2)}/3]$
\bar{q}	$(3, 2^{(5^*)}/3) \diamond \heartsuit$	$[3, -1^{(2)}/3]$	$(1(8), 0(-1))$	$[3, -1^{(2)}/3]$	$(1(8), 0(-1))$	$(1(8), 0(-1))$	$[3, -1^{(-4^*)}/3]$	$[3, -1^{(2)}/3]$	$[3, -1^{(2)}/3]$
g	$[8, 1]^*$	$(8, 0)$	$[\bar{3}, 1^{(-2)}/3]$	$(1(8), 0)$	$[\bar{3}, 1/3]$	$[\bar{3}, -2/3]$	$(8, -1)$	$(8, 0)$	$(8, 0)$
b		$[\bar{3}, 1/3]$	$(3, -1^{(2)}/3)$	$[\bar{3}, 1/3]$	$(3, 2/3)$	$(3, -1/3)$	$[\bar{3}, -2/3]$	$[\bar{3}, 1/3]$	$[\bar{3}, 1/3]$
\bar{b}			$(1(8), 0(-1))$	$[3, -1/3]$	$(1(8), 0)$	$(1(8), -1)$	$[3, -4/3]^*$	$[3, -1/3]$	$[3, -1/3]$
t				$[\bar{3}, -2/3]$	$(3, -1/3)$	$(3, -4/3)$	$[\bar{3}, -5/3]^*$	$[\bar{3}, -2/3]$	$[\bar{3}, -2/3]$
\bar{t}					$(1(8), 1)$	$(1(8), 0)$	$[3, -1/3]$	$[3, 2/3]$	$[3, 2/3]$
W^+						$[3, -5/3]^*$	$(1, -2)^*$	$(1, -1)$	$(1, -1)$
W^-							$(1, 0)$	$(1, 1)$	$(1, 1)$
Z								$(1, 0)$	$(1, 0)$
h									$(1, 0)$

(): boson resonance


[]: fermionic resonance





*: no possible initial state at the LHC

$\diamond \Delta B = 1$
(if couples to q / g)
































































































































































































$\heartsuit \Delta L = 1$

Possible (QCD, EM) quantum numbers of each 2-body resonance

 indicates the existence of a resonant production via tree-level decay coupling, loop-induced processes involving the decay coupling, or the inclusion of additional couplings to quarks / gluons (allowed by quantum numbers).

, , , or  indicate the leading production mode in association with 1, 2, 3 and 4 SM particles using the same coupling for production and decay (in 4 flavor scheme).

 indicates the unavoidable existence of a pair production mode.

	ℓ			γ			q			g			b			t			W^+			Z			h		
ℓ																											
$\bar{\ell}$																											
γ																											
q																											
\bar{q}																											
g																											
b																											
\bar{b}																											
t																											
\bar{t}																											
W^+																											
W^-																											
Z																											
h																											

Survey of $n=2$ Final State at the LHC

[illegible]

Survey of $n=2$ Final State at the LHC

[illegible]

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp[4], \pm\pm[5]$	$\pm\pm[5, 6]$	$\pm\mp[6, 7]$	[7]	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset
μ		$\pm\mp[4], \pm\pm[5]$	[7]	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset
τ			[8]	\emptyset	\emptyset	\emptyset	[9]	\emptyset	\emptyset	\emptyset
γ				[10]	[11–13]	\emptyset	\emptyset	[14]	[14]	\emptyset
j					[15]	[16]	[17]	[18]	[18]	\emptyset
b						[16]	[19]	\emptyset	\emptyset	\emptyset
t							[20]	[21]	\emptyset	\emptyset
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

- Existing two-body exclusive final state resonance searches at 7 and 8 TeV LHC, with striking features that most diagonal entries have existing searches, whereas most off-diagonal entries do not. (Numbers represent ATLAS/CMS references.)
- \emptyset symbol indicates no existing searches at the LHC (7 and 8 TeV).
- No Tevatron analyses included. No 13 TeV analyses included.

Top partner

- Color triplet fermion with charge $2/3$: spin $1/2$ or spin $3/2$
- Consider mixing between SM top (t) and Top partner (T)
- T inherits interaction of SM top quark

	Wb	tZ	tH
Wb			
tZ			
tH			

Top partner

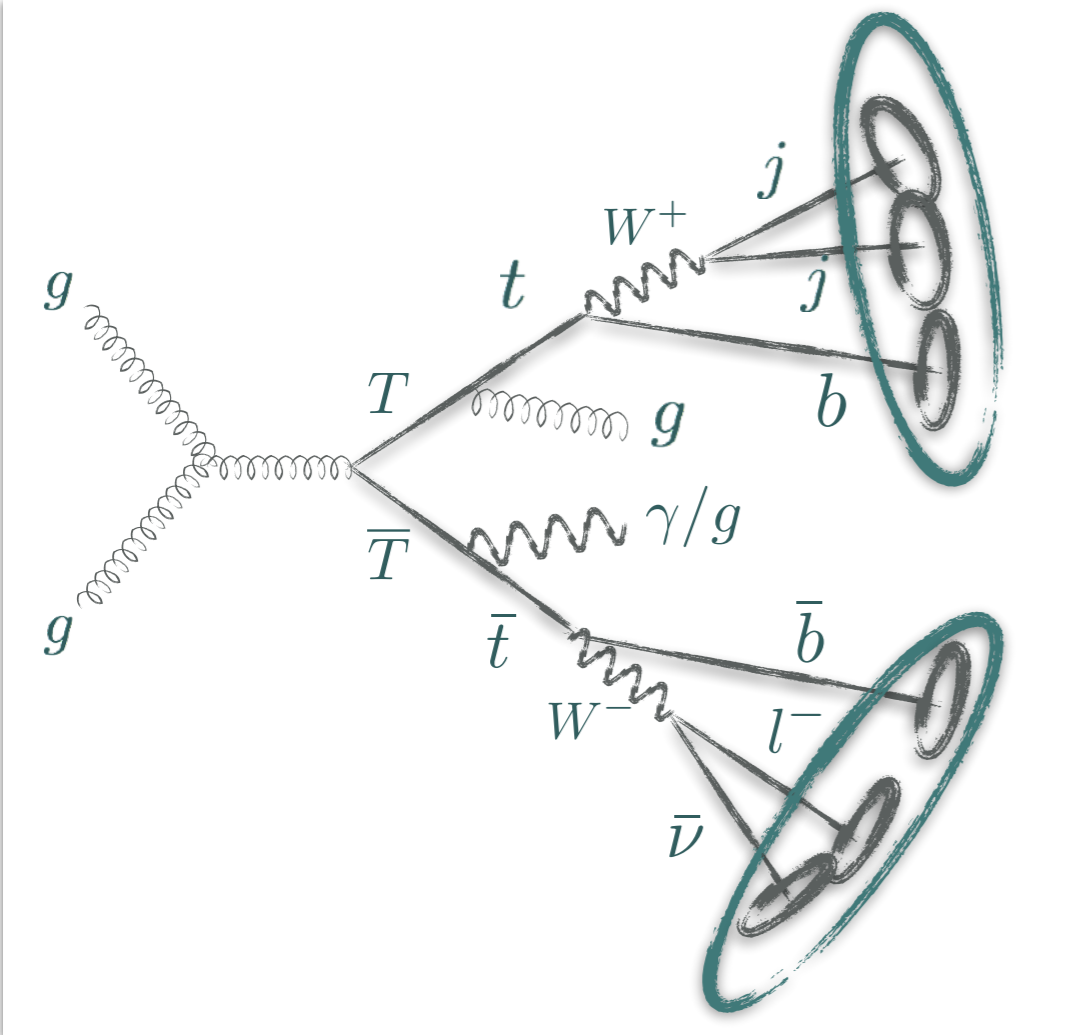
- Color triplet fermion with charge 2/3: spin 1/2 or spin 3/2
- Consider mixing between SM top (t) and Top partner (T)
- T inherits interaction of SM top quark

	Wb	tZ	tH	tg	$t\gamma$
Wb					
tZ					
tH					
tg					
$t\gamma$					

Top partner

- Color triplet fermion with charge 2/3: spin 1/2 or spin 3/2
- Consider mixing between SM top (t) and Top partner (T)
- T inherits interaction of SM top quark

	Wb	tZ	tH	tg	$t\gamma$	$t(S \rightarrow gg)$
Wb						
tZ						
tH						
tg						
$t\gamma$						
$t(S \rightarrow gg)$						



Top partner

Charge 2/3: spin 1/2 or spin 3/2

SM top (t) and Top partner (T)

SM top quark

	Wb	tZ	tH	tg	$t\gamma$	$t(S \rightarrow gg)$
Wb						
tZ						
tH						
tg				✓	✓	
$t\gamma$						
$t(S \rightarrow gg)$						

Top partner Interaction with gluon / photon

- Pair production of color triplet fermions at the LHC is given by SM QCD.
- Spin 1/2

$$\mathcal{L}_{EFT} = \frac{c_3 g_3}{\Lambda} \bar{T}_L \sigma^{\mu\nu} T^A t_R G_{\mu\nu}^A + \frac{c_2 g_2}{\Lambda} \bar{T}_L \sigma^{\mu\nu} \frac{\sigma^a}{2} t_R W_{\mu\nu}^a + \frac{c_1 g_1}{\Lambda} \bar{T}_L \sigma^{\mu\nu} Y_{t_R} t_R B_{\mu\nu} + \text{h.c.}$$

$$\mathcal{L}_{EFT} = c_g \bar{T}_L \sigma^{\mu\nu} T^A t_R G_{\mu\nu}^A + c_\gamma \bar{T}_L \sigma^{\mu\nu} t_R F_{\mu\nu} + c_Z \bar{T}_L \sigma^{\mu\nu} t_R Z_{\mu\nu} + \text{h.c.}$$

Kuhn, Zerwas, 1984

De Rujula, Maiani, Petronzio, 1984

Baur, Hinchliffe, Zeppenfeld, 1987

- Spin 3/2

Baur, Spira, Zerwas, 1990

$$\mathcal{L} \ni g_3 \bar{\psi}_\alpha \left(\frac{3z^2 + 2z + 1}{2} \gamma^\alpha \gamma^\mu \gamma^\beta + z g^{\alpha\mu} \gamma^\beta + z \gamma^\alpha g^{\mu\beta} + g^{\beta\alpha} \gamma^\mu \right) T^A \psi_\beta G_\mu^A, \quad \text{Rarita, Schwinger 1946}$$

Moussallam, Son 1989

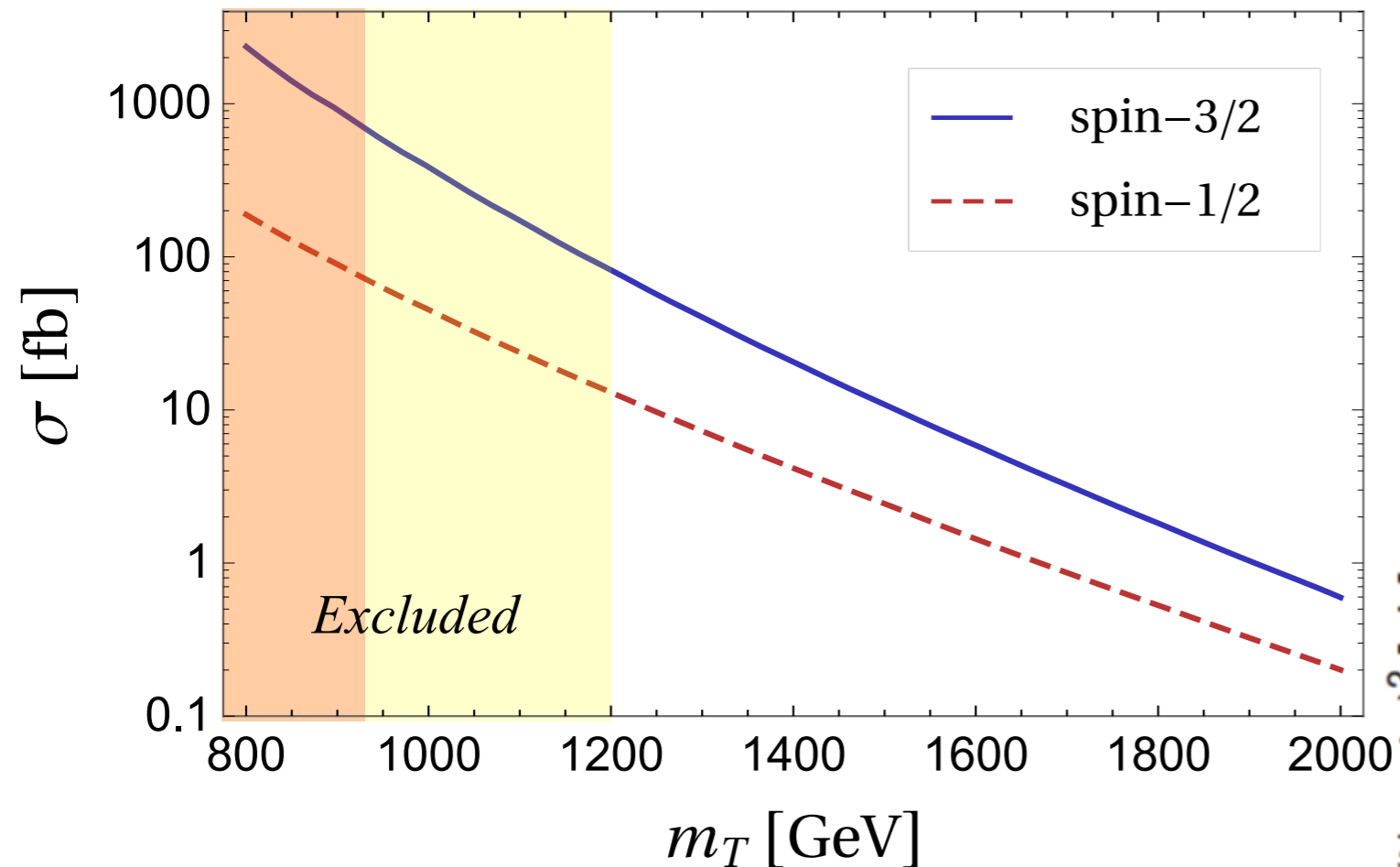
Hassanain, March-Russell, Rosa, 2009

$$\mathcal{L}_{EFT} = i \frac{g_i c_i}{\Lambda} \bar{\psi}_\mu (g^{\mu\alpha} + z \gamma^\mu \gamma^\alpha) \gamma^\beta T_i^a P_{L/R} t F_{i,\alpha\beta}^a + \text{h.c.},$$

Dicus, Karabacak, Nandi, Rai, 2012

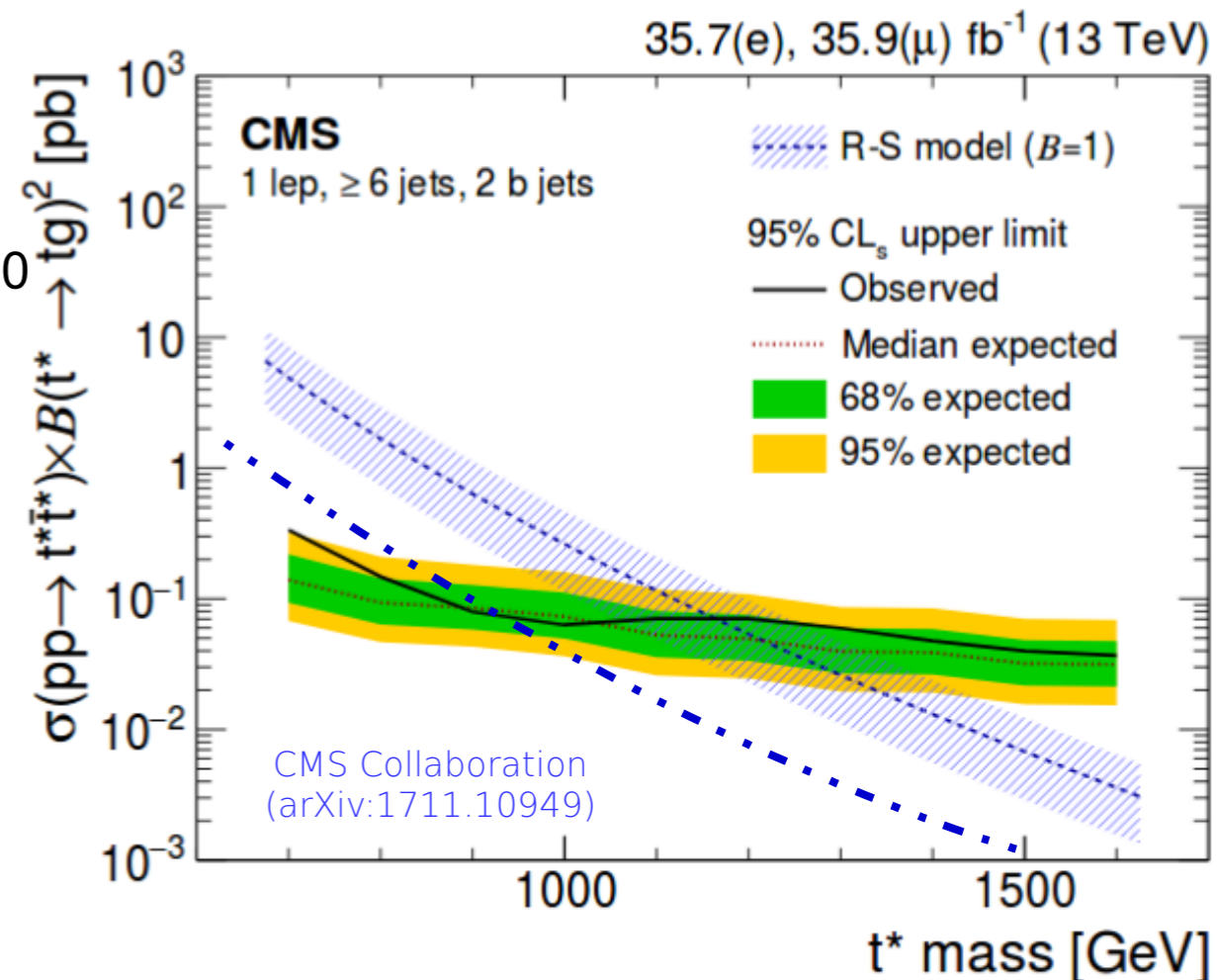
Stirling, Vryonidou, 2012

Production



- Pair production of color triplet fermions at the LHC is given by SM QCD.
- See talk by I. Lewis for single production.

- Current limit
 - $m_T > 1.2$ TeV for spin 3/2
 - $m_T > 930$ GeV for spin 1/2



Decays

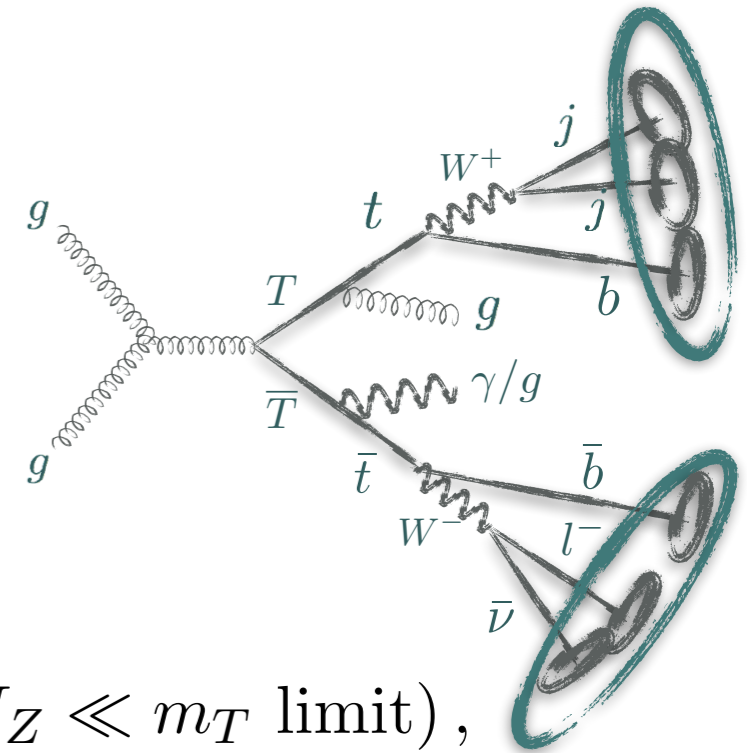
$$\Gamma = \frac{\mathcal{C}}{64\pi} \frac{m_T^3}{\Lambda^2} \left(1 - \frac{m_t^2}{m_T^2}\right)^3,$$

for spin $\frac{1}{2}$,

$$\Gamma = \frac{\mathcal{C}}{192\pi} \frac{m_T^3}{\Lambda^2} \left(1 - \frac{m_t^2}{m_T^2}\right)^3 \left(3 + \frac{m_t^2}{m_T^2}\right),$$

for spin $\frac{3}{2}$,

$$\mathcal{C} = \begin{cases} (g_1 Y_{t_R} \cos \theta_W)^2 = (eQ_t)^2 & \text{for } \gamma t \\ (g_1 Y_{t_R} \sin \theta_W)^2 = (eQ_t \tan \theta_W)^2, & \text{for } Z t \text{ (in the } M_Z \ll m_T \text{ limit),} \\ g_3^2 C_2(R) = \frac{4}{3} g_3^2 & \text{for } g t \end{cases}$$



$$\begin{aligned} \Gamma(T \rightarrow \gamma t) : \Gamma(T \rightarrow Z t) : \Gamma(T \rightarrow g t) &= (eQ_t)^2 : (eQ_t \tan \theta_W)^2 : g_3^2 C_2(R) \\ &= 0.021 : 0.00601 : 0.9725. \end{aligned}$$

- Benchmark point
 - $m_T = 1 \text{ TeV}$
 - $\text{BR}(T \rightarrow t \text{ photon}) = 3\%$ and $\text{BR}(T \rightarrow t \text{ gluon}) = 97\%$
- Assume narrow width / no tree level decays
- Two parameters
 - m_T
 - $\text{BR}(T \rightarrow t \text{ photon})$

$t\bar{t}gg$ Channel

- Basic cuts (consider semi-leptonic decay of $t\bar{t}$ at the 14 TeV LHC)
 - at least 1 slim jet with $p_T^j > 30 \text{ GeV}$ and $|\eta^j| < 2.5$
 - at least 1 lepton with $p_T^\ell > 30 \text{ GeV}$ and $|\eta^\ell| < 2.5$
 $p_T^\ell / p_T^\Sigma > 0.7$ within $\Delta R = 0.3$ isolation cone
 - at least 1 hard fat jet with $p_T^j > 350 \text{ GeV}$ and $|\eta^j| < 2.5$
 - at least 1 hadronic top and 1 leptonic top (template overlap method)
 - additionally, require $H_T > 700 \text{ GeV}$ and $\cancel{E}_T > 50 \text{ GeV}$
- Used FenRules, MadGraph5_aMC@NLO, PYTHIA6, Fastjet.
- Used Template Overlap Method for boosted hadronic / leptonic top tagging.

$t\bar{t}gg$ Channel

Abbreviations	Backgrounds	Matching	$\sigma \cdot \text{BR}(\text{fb})$
$t\bar{t}$	$t\bar{t} + \text{jets}$	4-flavor	$2.91 \times 10^3 \text{ fb}$
Single t	$tW + \text{jets}$	5-flavor	$4.15 \times 10^3 \text{ fb}$
	$tq + \text{jets}$	4-flavor	77.2 fb
W	$W + \text{jets}$	5-flavor	$4.96 \times 10^3 \text{ fb}$
VV	$WW + \text{jets}$	4-flavor	111 fb
	$WZ + \text{jets}$	4-flavor	43.5 fb

CMS, 1311.5357 (8 TeV)

CMS, 1711.10949 (13 TeV)

$$H_T^{\text{reco}} = p_{T,t_{\text{had}}}^{\text{reco}} + p_{T,t_{\text{lep}}}^{\text{reco}} + p_{T,g_1}^{\text{reco}} + p_{T,g_2}^{\text{reco}}$$

- **b-tagging** would help reduce the systematic uncertainty.

$t\bar{t}gg$ channel	Signal [fb]	$t\bar{t}$ [fb]	Single t [fb]	W [fb]	VV [fb]	σ_{dis}	σ_{excl}
Basic cuts	2.8	1.1×10^3	2.6×10^3	2.1×10^3	68	2.0	2.0
$N_{t_{\text{had}}} = 1$	1.4	650	790	390	14	1.8	1.8
$N_{t_{\text{lep}}} = 1$	0.60	140	51	28	1.6	2.2	2.2
$p_{T,\{g_1,g_2\}}^{\text{reco}} > \{250, 150\} \text{ GeV}$	0.35	9.17	4.63	2.48	0.19	4.78	4.76
$H_T^{\text{reco}} > 1600 \text{ GeV}$	0.29	4.86	3.42	1.58	0.12	5.05	5.03
$750 < m_{T_{1,2}}^{\text{reco}} < 1100 \text{ GeV}$	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 $t_{\text{had}} \& t_{\text{lep}}$	0.061	0.30	0.084	5.1×10^{-4}	1.0×10^{-5}	5.28	5.15

- $m_T = 1 \text{ TeV}$, $\text{BR}(T \rightarrow t \text{ photon}) = 3\%$, $\text{BR}(T \rightarrow t \text{ gluon}) = 97\%$

$t\bar{t}g\gamma$ Channel

Abbreviations	Backgrounds	Matching	$\sigma \cdot \text{BR}(\text{fb})$
$t\bar{t}\gamma$	$t\bar{t} + \gamma + \text{jet}$	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

- Photon isolation

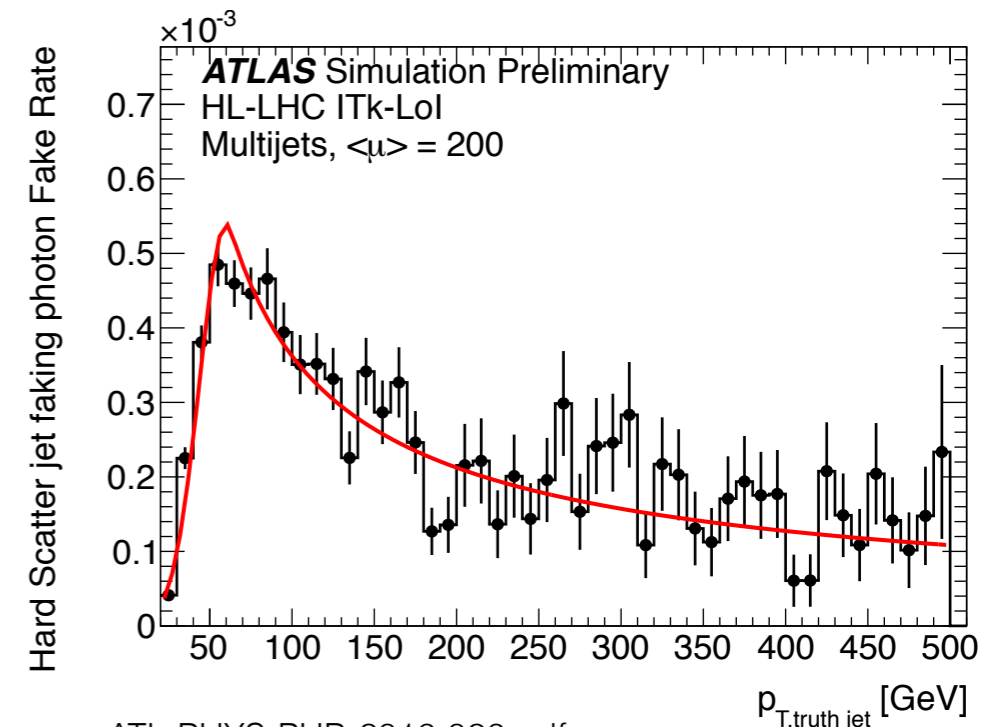
$$p_T^\Sigma / p_T^\gamma < 0.1 \text{ within } \Delta R = 0.4$$

$$p_T^\gamma > 300 \text{ GeV} \quad \text{and} \quad |\eta^\gamma| < 2.5$$

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

Goncalves, Han, Kling, Plein, Takeuchi 2018

Alhazmi, Kim, Kong, Lewis 2018



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$t\bar{t}g\gamma$ Channel

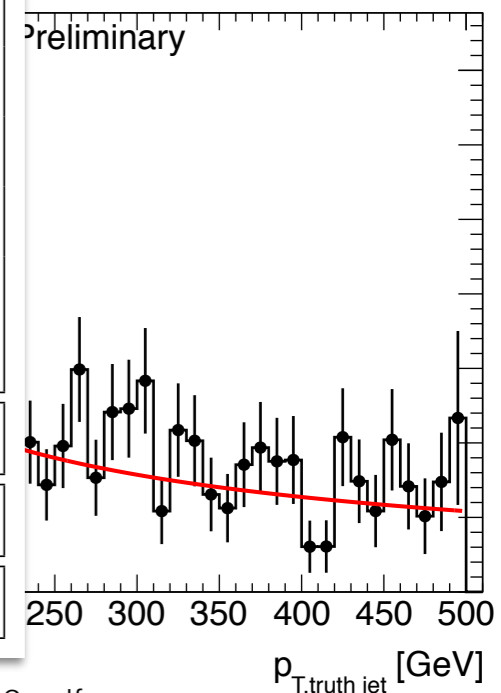
Abbreviations	Backgrounds	Matching	$\sigma \cdot \text{BR}(\text{fb})$
$t\bar{t}\gamma$	$t\bar{t} + \gamma + \text{jet}$	4-flavor	1.0 fb
$t\gamma$	$tW + \gamma + \text{jets}$	5-flavor	1.9 fb
	$t + \gamma + \text{jets}$	4-flavor	0.085 fb
$W\gamma$	$W + \gamma + \text{jets}$	5-flavor	5.4 fb
$VV\gamma$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

- Photon isolation

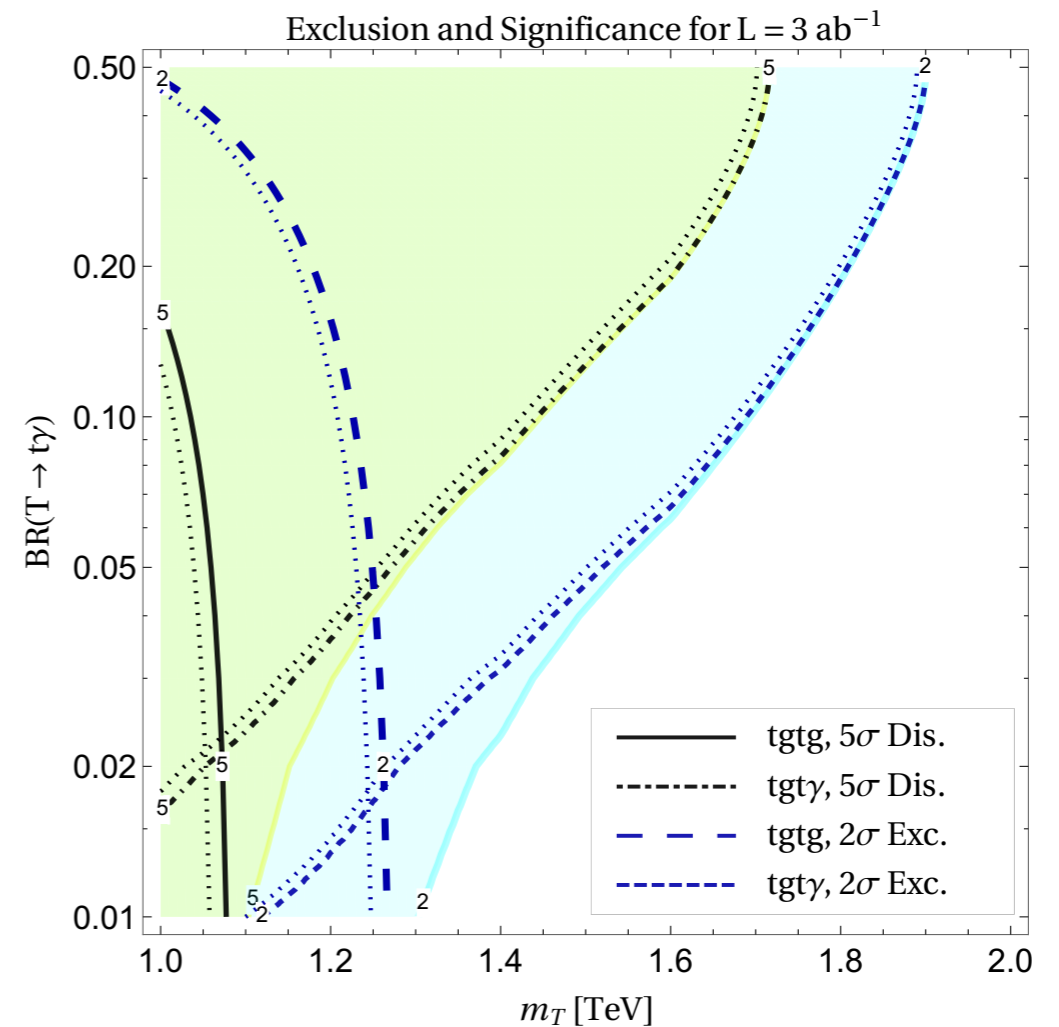
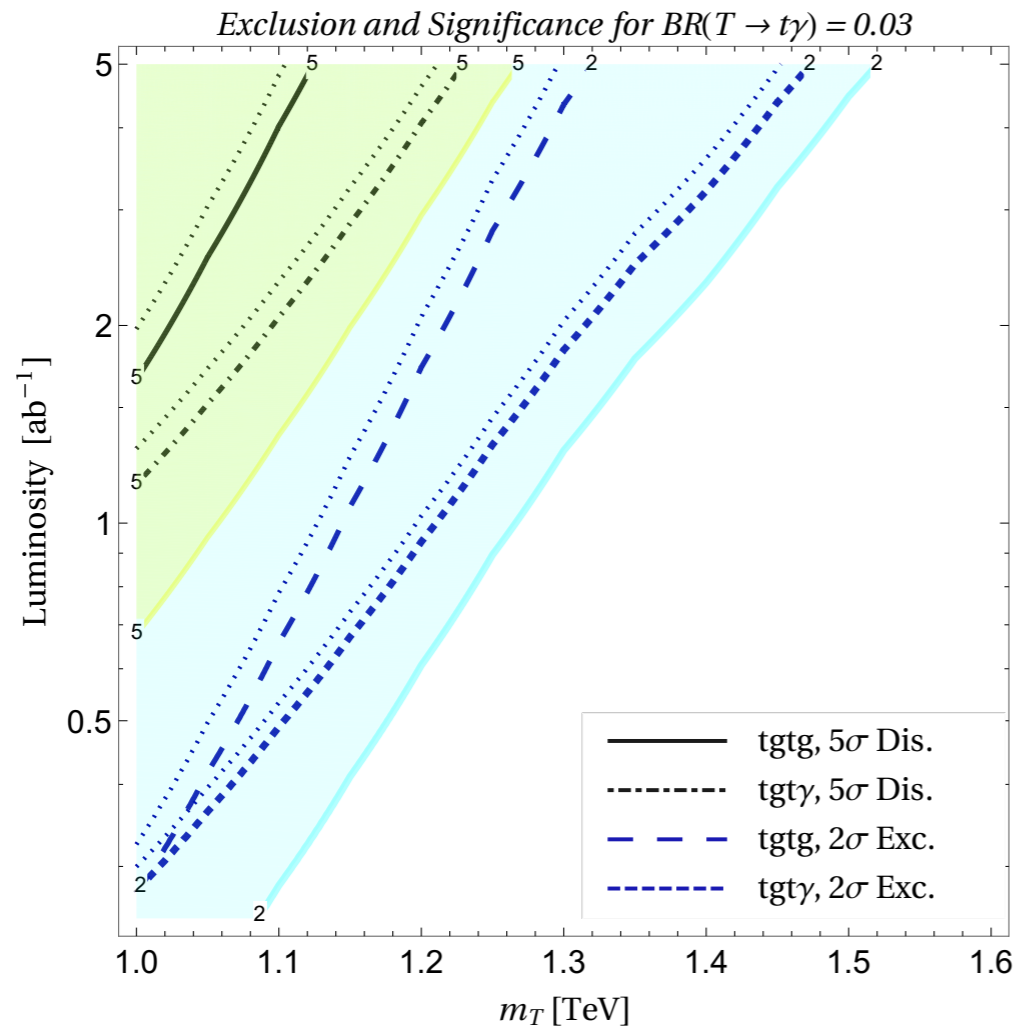
$$p_T^\Sigma / p_T^\gamma < 0.1 \text{ within } \Delta R = 0.4$$

$$p_T^\gamma > 300 \text{ GeV} \quad \text{and} \quad |\eta^\gamma| < 2.5$$

$t\bar{t}g\gamma$ channel	Signal [fb]	$t\bar{t}\gamma$ [fb]	$t\gamma$ [fb]	$W\gamma$ [fb]	$VV\gamma$ [fb]	σ_{dis}	σ_{excl}
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
$\{p_T^\gamma, p_{T,g}^{reco}\} > \{300, 140\} \text{ GeV}$	0.021	0.023	0.0114	0.0118	8.8×10^{-4}	5.1	4.7
$H_T > 1600 \text{ GeV}$	0.02	0.016	9.5×10^{-3}	9.7×10^{-3}	7.4×10^{-4}	5.2	4.8
$900 < m_{T_\gamma}^{reco} < 1100 \text{ GeV}$	0.015	3.1×10^{-3}	1.5×10^{-3}	1.3×10^{-3}	1.1×10^{-4}	8.1	6.6
$700 < m_{T_g}^{reco} < 1100 \text{ GeV}$							
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

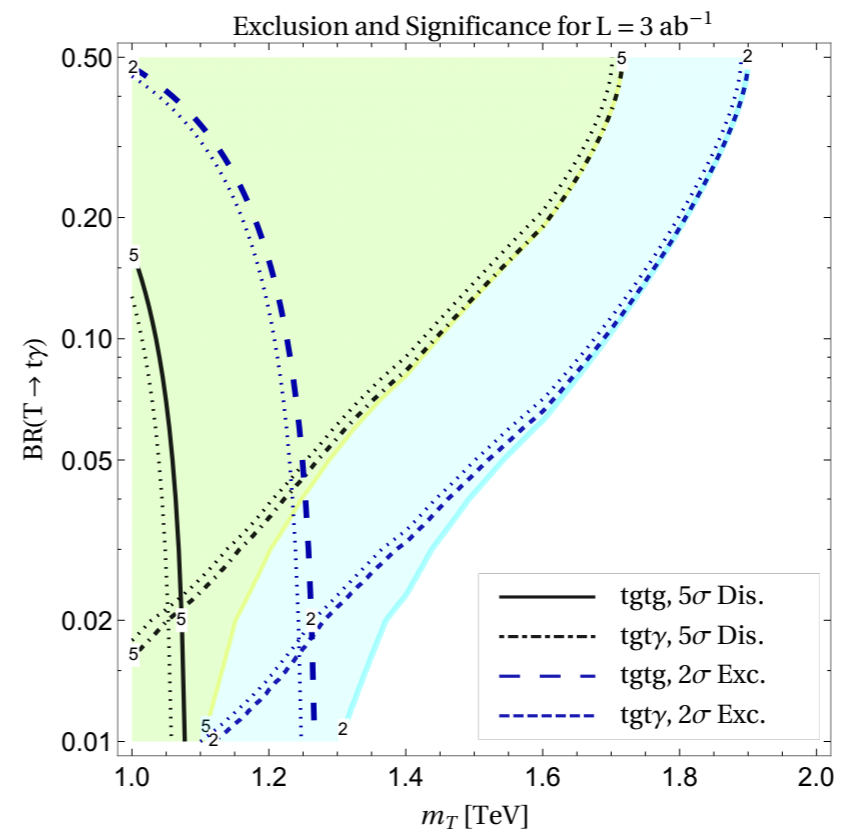
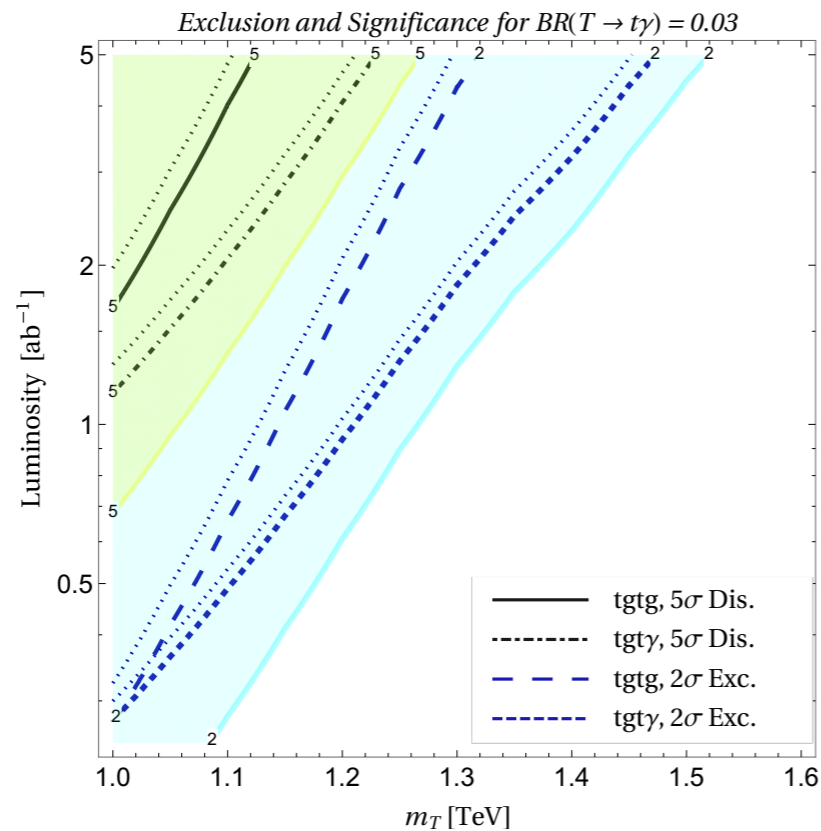


Combined results

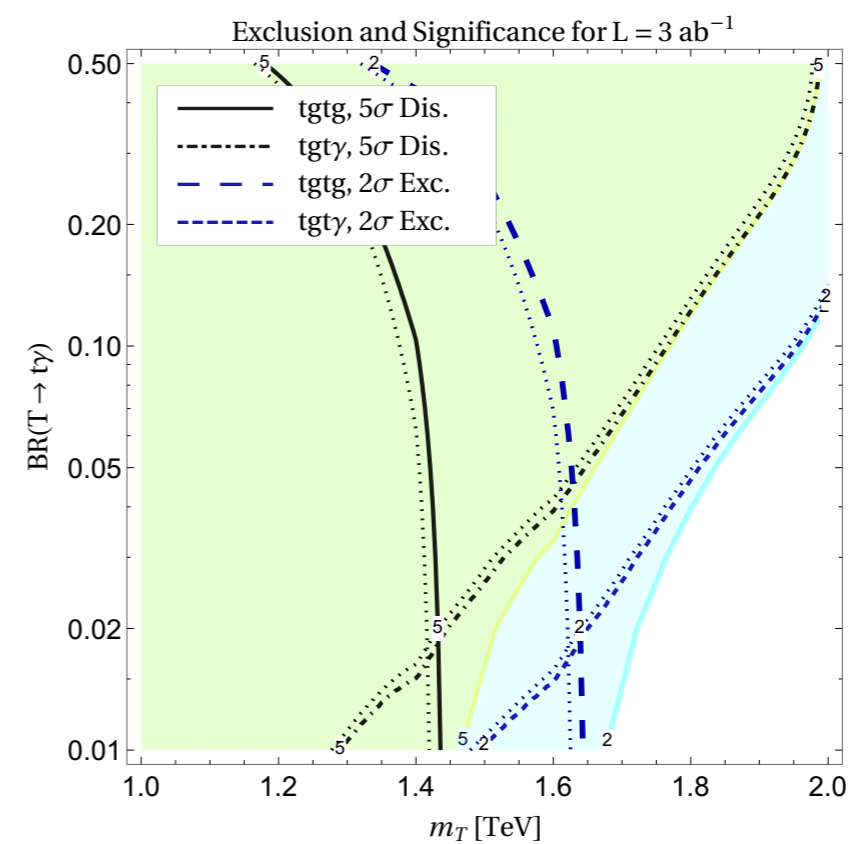
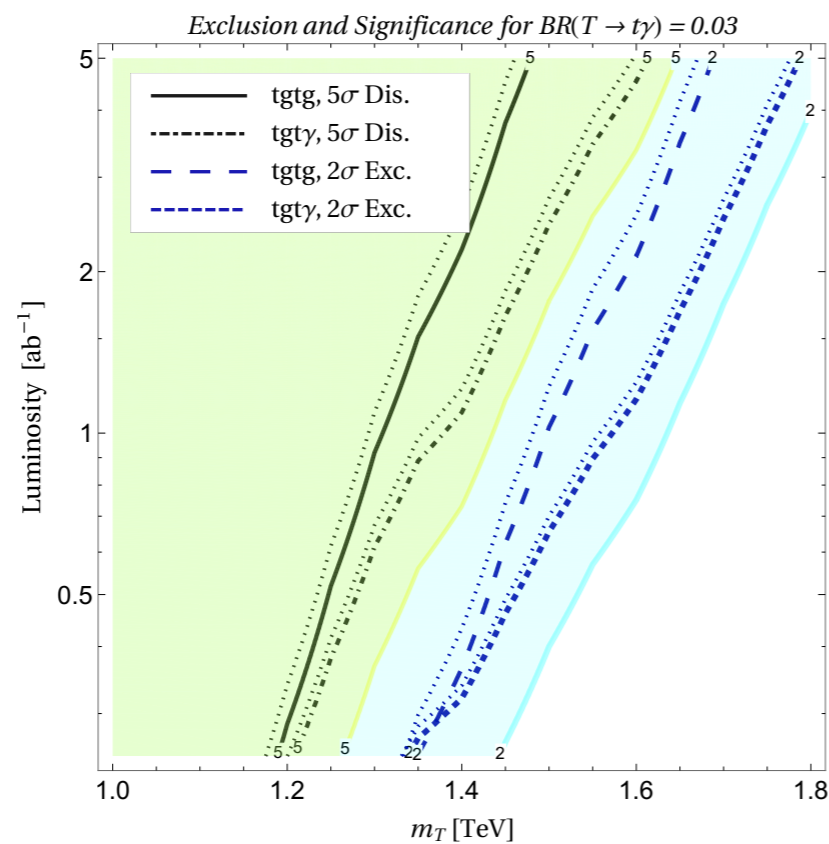


The required-integrated luminosity (in ab^{-1}) for 5 σ discovery and 2 σ exclusion (left), and the minimum branching fraction of $T \rightarrow t\gamma$ for a fixed luminosity of 3 ab^{-1} (right) as a function of the top-partner mass (m_T in TeV) for spin- $\frac{1}{2}$ top partner. In both plots, the 5 σ discovery result for $t\bar{t}gg$ ($t\bar{t}g\gamma$) is shown in black-solid (black-dot-dashed) curve, while the 2 σ exclusion is shown in blue-long-dashed (blue-short-dashed) curve, respectively. The green- and cyan-shade areas represent the combined 5 σ discovery and 2 σ exclusion, considering both $t\bar{t}gg$ and $t\bar{t}g\gamma$ channels. Dotted curves represent the corresponding results including 20% systematic uncertainty in the estimation of the background.

Combined results



spin 1/2



spin 3/2

Summary

- Discussed diverse Top partner decays, depending on the mixing angle.
- Two interesting decays: $t\bar{t}gg$ and $t\bar{t}g\gamma$
 - Radiative decay modes are complementary to the conventional decay modes and become important when existing experimental limits get stronger (heavy Top partner or small mixing angle).
 - Boosted top tagging improves signal sensitivity.
 - Better signal sensitivity with only 2-3% BR into top + photon final state.

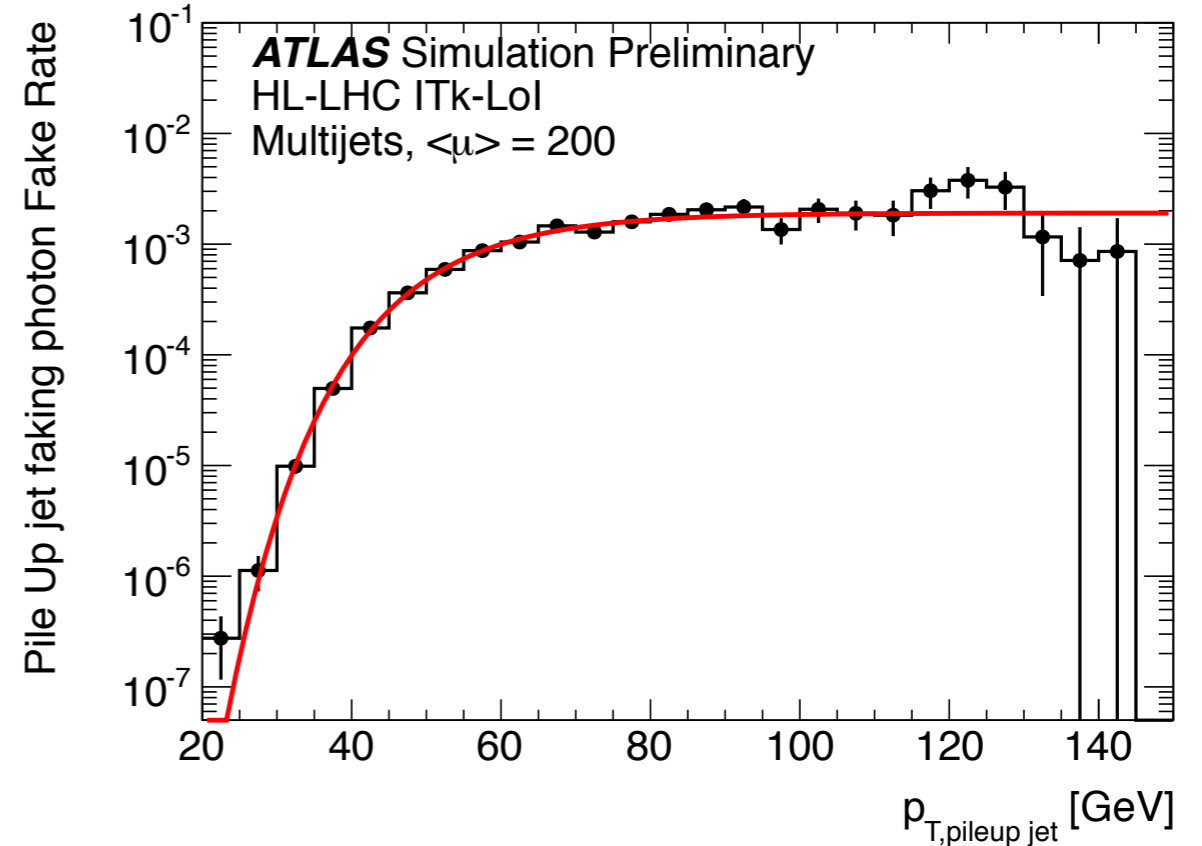
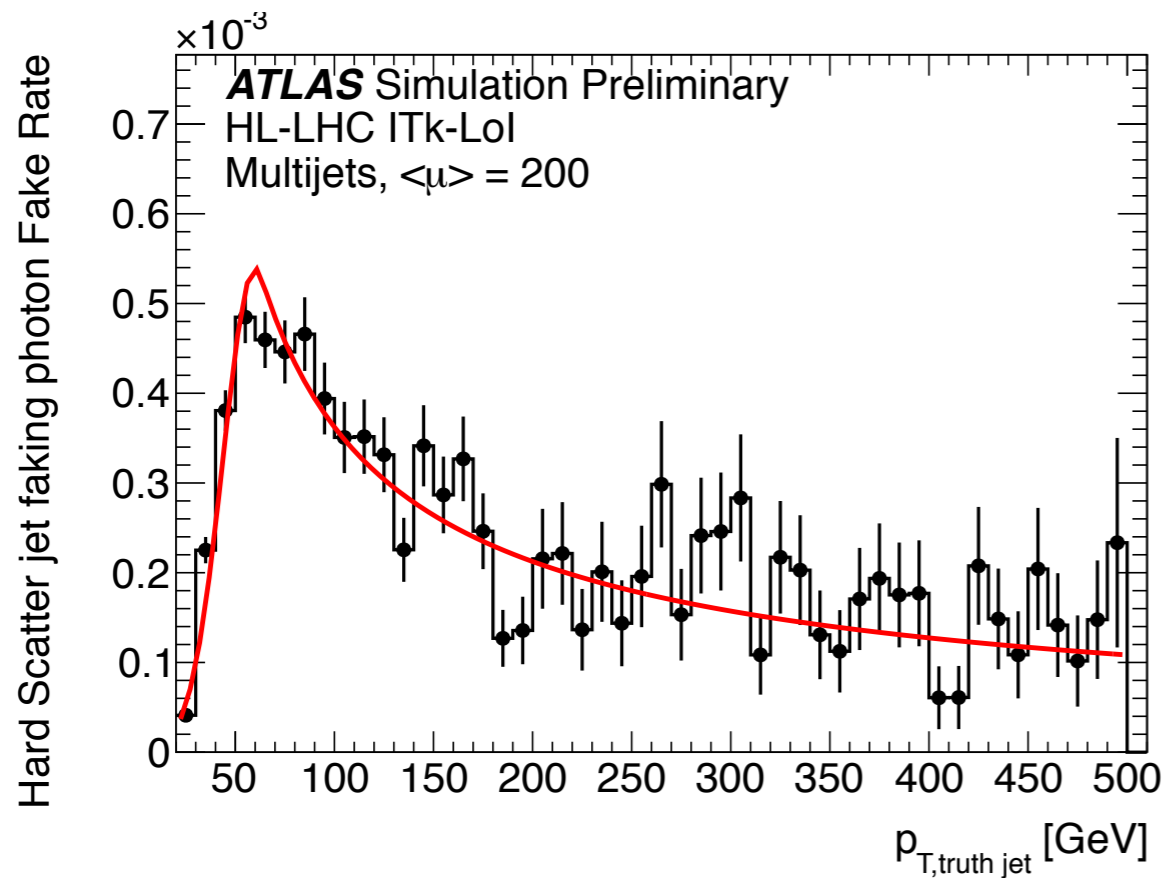
	Wb	tZ	tH	tg	$t\gamma$	$t(S \rightarrow gg)$
Wb						
tZ						
tH						
tg						
$t\gamma$						
$t(S \rightarrow gg)$						

$$\epsilon_{\gamma \rightarrow \gamma} = 0.863 - 1.07 \cdot e^{-p_{T,\gamma}/34.8 \text{ GeV}}$$

Goncalves, Han, Kling, Plein, Takeuchi 2018

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

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$$\sigma_{dis} \equiv \sqrt{-2 \ln \left(\frac{L(B|Sig+B)}{L(Sig+B|Sig+B)} \right)} \quad \text{with} \quad L(x|n) = \frac{x^n}{n!} e^{-x}$$

$$\sigma_{exc} \equiv \sqrt{-2 \ln \left(\frac{L(Sig+B|B)}{L(B|B)} \right)}.$$

- Nthad=1: eff(signal)=50%, eff(tt)=59%, eff(t)=30%, eff(W)=19%, eff(VV)=21%
- Ntlep=1: eff(signal)=43%, eff(tt)=22%, eff(t)=6.5%, eff(W)=7.2%, eff(VV)=11%

$t\bar{t}gg$ Channel

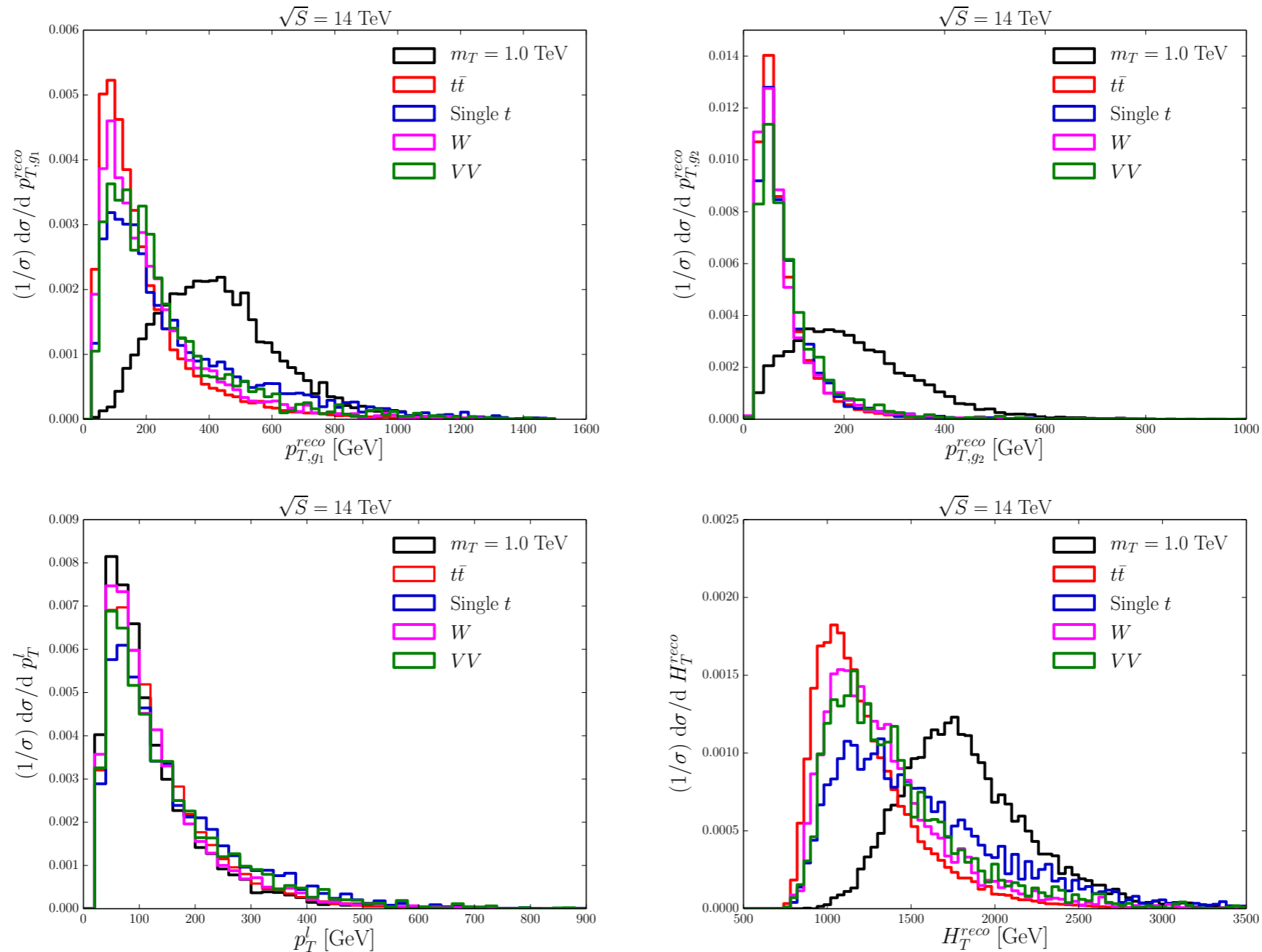


Figure 4. The p_T distributions of the first (top, left) and second (top, right) hardest reconstructed gluons, and the isolated lepton (bottom, left), in the $t\bar{t}gg$ channel for $m_T = 1.0$ TeV. The scalar sum of the transverse momenta of reconstructed hadronic and leptonic tops, and two gluons is shown in the bottom-right panel.

$t\bar{t}gg$ Channel

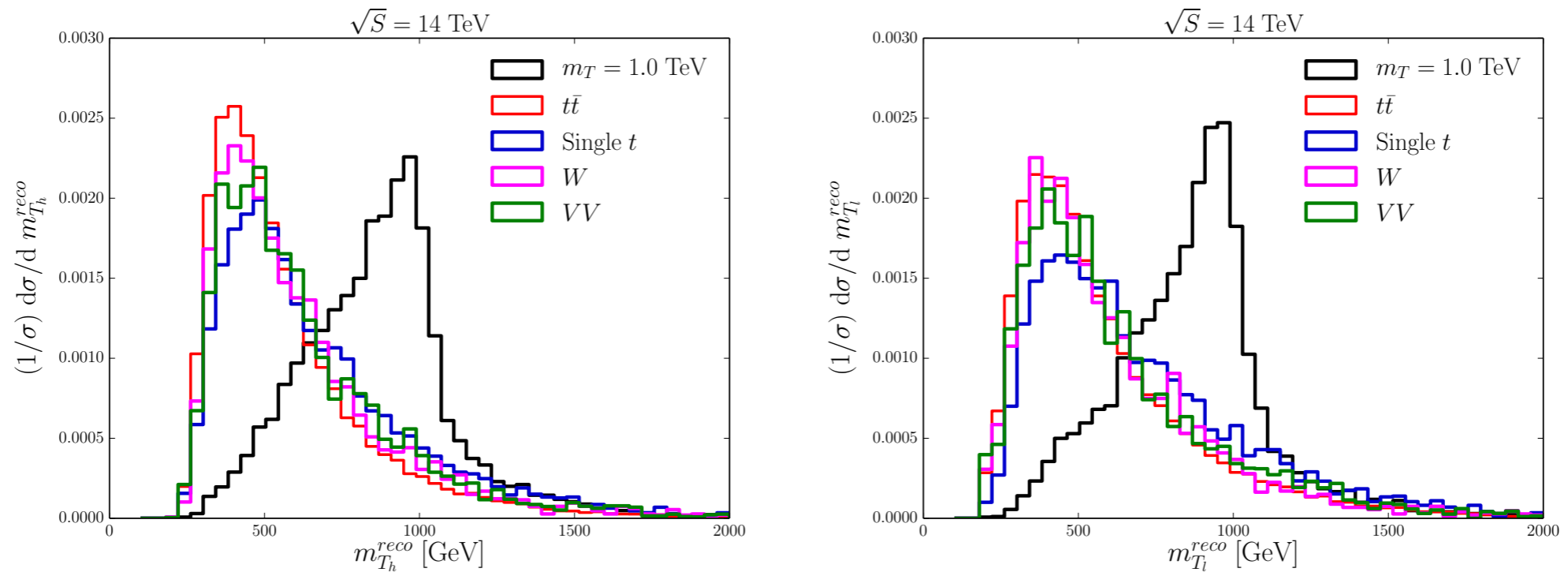


Figure 5. The distributions of reconstructed top partner invariant masses $m_{T_h}^{reco}$ and $m_{T_\ell}^{reco}$ in the $t\bar{t}gg$ channel for $m_T = 1.0$ TeV, after resolving the combinatorial problem based on the mass asymmetry in Eq.(4.19).

$t\bar{t}g\gamma$ Channel

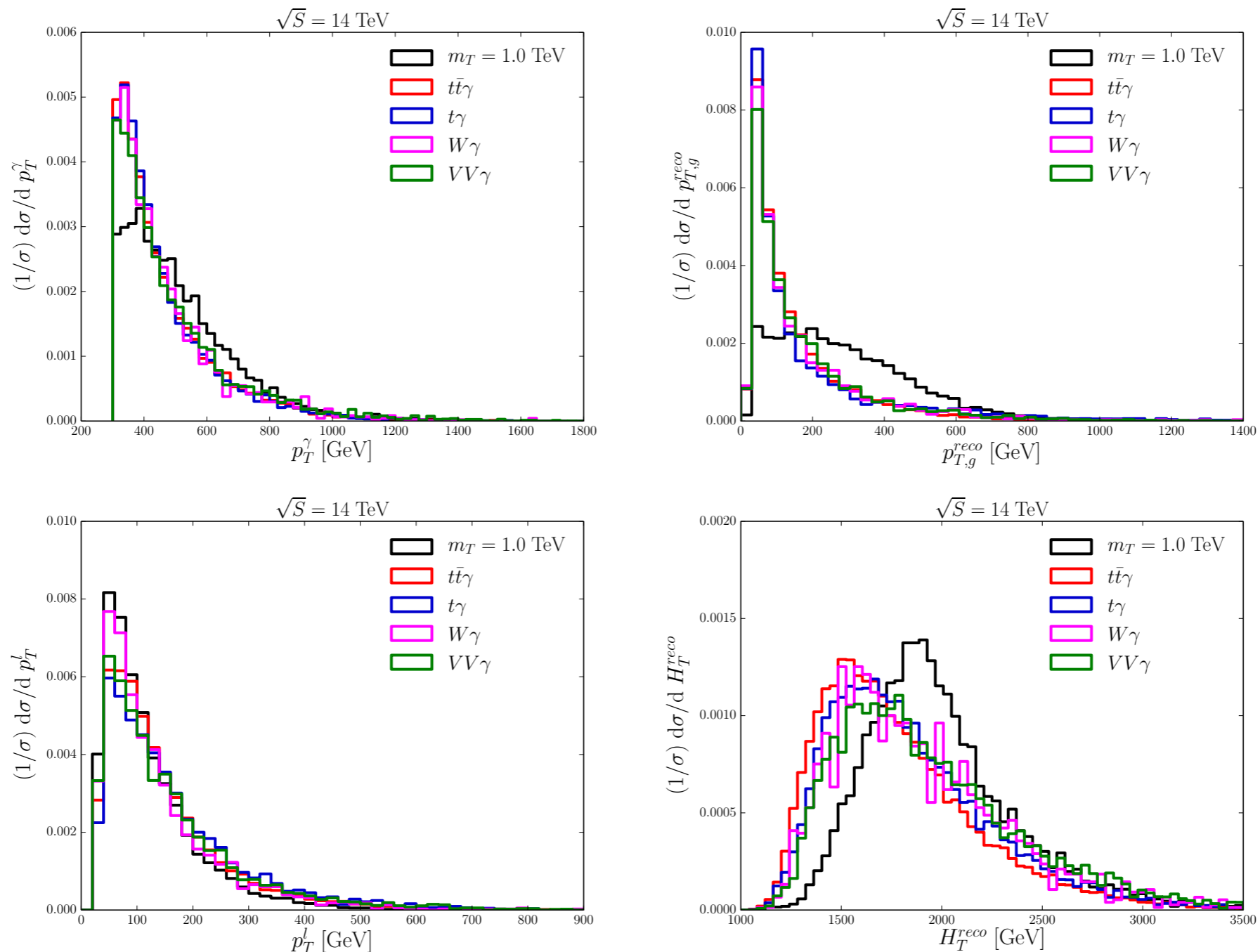


Figure 8. The p_T distributions of the isolated photon (top, left), the hardest reconstructed gluon (top, right), and the isolated lepton (bottom, left), in the $t\bar{t}g\gamma$ channel for $m_T = 1.0$ TeV. The scalar sum of the transverse momenta of reconstructed hadronic and leptonic tops, the isolated photon, and the hardest gluon is shown in the bottom-right panel.

$t\bar{t}g\gamma$ Channel

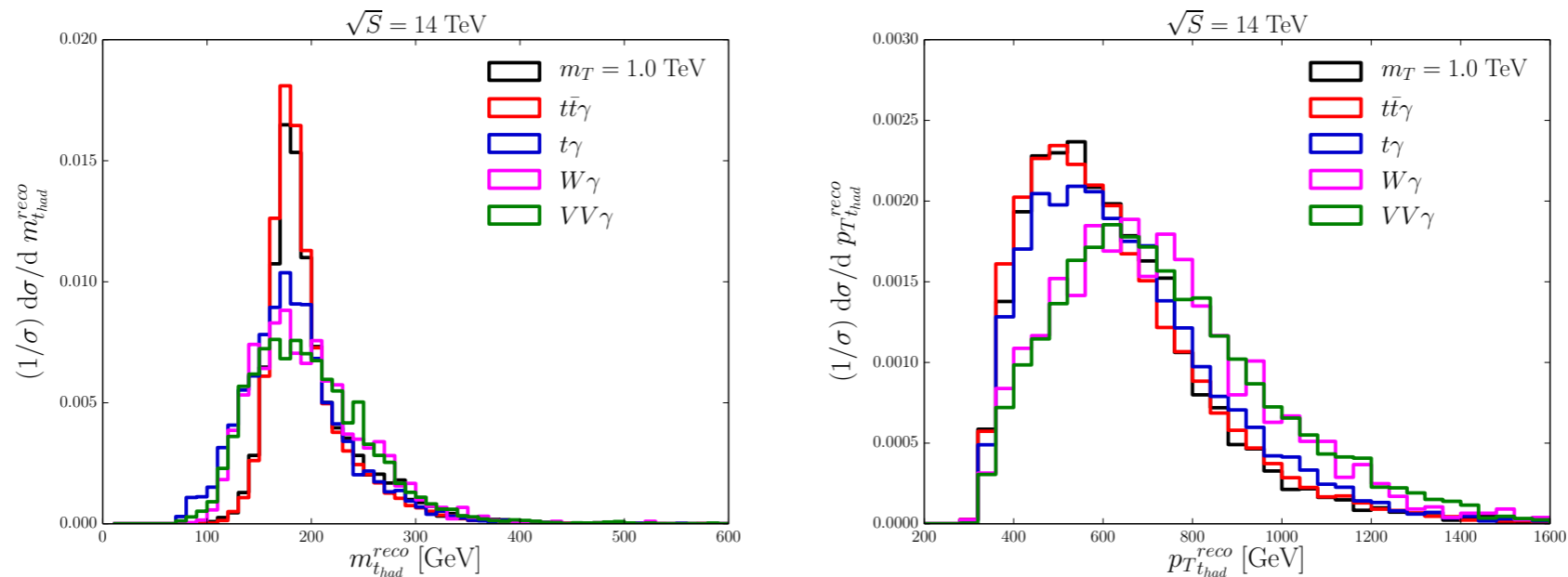


Figure 6. The reconstructed invariant mass distribution of the top-tagged fat jet (left) and the corresponding p_T distribution (right) in the $t\bar{t}g\gamma$ channel for $m_T = 1.0$ TeV.

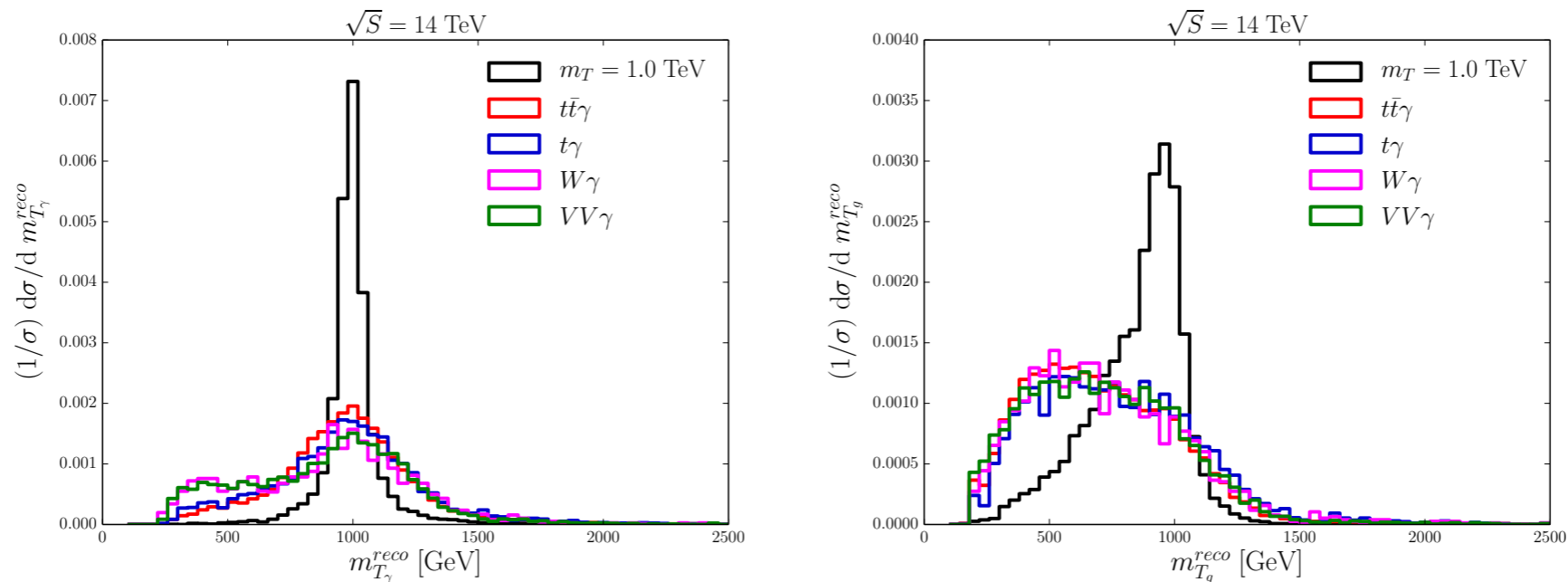


Figure 7. The distributions of reconstructed top partner invariant masses $m_{T_1}^{reco}$ and $m_{T_2}^{reco}$ in the $t\bar{t}g\gamma$ channel for $m_T = 1.0$ TeV, after resolving the combinatorial problem based on the mass asymmetry in Eq.(4.19).

m_T (TeV)	Cuts	σ^{Signal} (fb)	σ^{BG} (fb)	σ_{dis}	σ_{excl}
1.0	BC & t -tagging	0.5999	239.97	2.1202	2.1193
	$p_T^{\{g_1, g_2\}} > \{250, 150\}$ GeV & $H_T > 1600$ GeV & $M_{t^{\text{had}}} > 145$ GeV	0.2932	9.9995	5.0545	5.0302
	$750 < M_{T'} < 1100$ GeV	0.1638	1.7214	6.7346	6.6333
1.2	BC & t -tagging	0.1912	239.97	0.6759	0.6758
	$p_T^{\{g_1, g_2\}} > \{250, 150\}$ GeV & $H_T > 1700$ GeV & $M_{t^{\text{had}}} > 145$ GeV	0.1207	8.3195	2.2860	2.2806
	$950 < M_{T'} < 1300$ GeV	0.0546	0.960	3.022	2.9945
1.4	BC & t -tagging	0.0644	239.97	0.2277	0.2277
	$p_T^{\{g_1, g_2\}} > \{250, 150\}$ GeV & $H_T > 1850$ GeV & $M_{t^{\text{had}}} > 145$ GeV	0.0457	6.2833	0.9980	0.9968
	$1050 < M_{T'} < 1500$ GeV	0.0214	0.9523	1.1969	1.1925
1.6	BC & t -tagging	0.0227	239.97	0.0804	0.0804
	$p_T^{\{g_1, g_2\}} > \{400, 200\}$ GeV & $H_T > 2100$ GeV & $M_{t^{\text{had}}} > 145$ GeV	0.0144	2.3249	0.5168	0.5162
	$1100 < M_{T'} < 1800$ GeV	9.26e-3	0.7409	0.5883	0.5871
1.8	BC & t -tagging	8.093e-3	239.97	0.0286	0.0286
	$p_T^{\{g_1, g_2\}} > \{500, 200\}$ GeV & $H_T > 2350$ GeV & $M_{t^{\text{had}}} > 145$ GeV	5.12e-3	1.3104	0.2449	0.2448
	$1150 < M_{T'} < 2100$ GeV	3.59e-3	0.5326	0.2683	0.2680
2.0	BC & t -tagging	2.94e-3	239.97	0.010e	0.0104
	$p_T^{\{g_1, g_2\}} > \{500, 200\}$ GeV & $H_T > 2500$ GeV & $M_{t^{\text{had}}} > 145$ GeV	1.95e-3	0.9403	0.1104	0.1103
	$1150 < M_{T'} < 2500$ GeV	1.53e-3	0.4521	0.1252	0.1251

Table 6. Cumulative cut-flow in the $t\bar{t}gg$ channel for both signal (spin- $\frac{1}{2}$ top partner) and backgrounds. The significance and the exclusion are calculated for a luminosity of 3000 fb^{-1} . The case with spin- $\frac{3}{2}$ top partner is similar.

$t\bar{t}gg$

m_T (TeV)	Cuts	σ^{Signal} (fb)	σ^{BG} (fb)	σ_{dis}	σ_{excl}
1.0	BC & t -tagging	0.0295	0.1364	4.2294	4.0937
	$p_T^{\{\gamma,g\}} > \{300, 140\}$ GeV & $H_T > 1600$ GeV & $M_{t\text{had}} > 145$ GeV	0.0196	0.0365	7.5814	6.8712
	$900 < M_{T'}^\gamma < 1100$ GeV $700 < M_{T'}^g < 1100$ GeV	0.0147	6.02e-3	8.0807	6.5927
1.2	BC & t -tagging	0.0115	0.1364	1.6779	1.6555
	$p_T^{\{\gamma,g\}} > \{300, 150\}$ GeV & $H_T > 2000$ GeV & $M_{t\text{had}} > 145$ GeV	6.67e-3	0.0189	4.1985	3.8795
	$1100 < M_{T'}^\gamma < 1300$ GeV $850 < M_{T'}^g < 1300$ GeV	4.72e-3	2.34e-3	4.2913	3.5768
1.4	BC & t -tagging	4.204e-3	0.1364	0.6204	0.6173
	$p_T^{\{\gamma,g\}} > \{300, 150\}$ GeV & $H_T > 2200$ GeV & $M_{t\text{had}} > 145$ GeV	2.70e-3	0.0134	1.2376	1.2004
	$1250 < M_{T'}^\gamma < 1500$ GeV $1000 < M_{T'}^g < 1550$ GeV	1.9185e-3	1.7438e-3	2.1896	1.9358
1.6	BC & t -tagging	1.515e-3	0.1364	0.2243	0.2239
	$p_T^{\{\gamma,g\}} > \{300, 200\}$ GeV & $H_T > 2300$ GeV & $M_{t\text{had}} > 145$ GeV	1.0428e-3	0.0103	0.5534	0.5446
	$1400 < M_{T'}^\gamma < 1700$ GeV $1000 < M_{T'}^g < 1700$ GeV	7.7161e-4	1.646e-3	0.9730	0.9127
1.8	BC & t -tagging	5.65e-4	0.1364	0.0837	0.0837
	$p_T^{\{\gamma,g\}} > \{300, 200\}$ GeV & $H_T > 2600$ GeV & $M_{t\text{had}} > 145$ GeV	3.83e-4	5.47e-3	0.4113	0.4046
	$1700 < M_{T'}^\gamma < 1900$ GeV $1100 < M_{T'}^g < 2000$ GeV	2.36e-4	4.15e-4	0.5865	0.5441
2.0	BC & t -tagging	2.07e-4	0.1364	0.0308	0.0308
	$p_T^{\{\gamma,g\}} > \{300, 150\}$ GeV & $H_T > 2700$ GeV & $M_{t\text{had}} > 145$ GeV	1.54e-4	4.81e-3	0.1210	0.1203
	$1800 < M_{T'}^\gamma < 2100$ GeV & $1300 < M_{T'}^g < 2100$ GeV	9.51e-5	2.90e-4	0.2911	0.2777

Table 7. The same as Table 6 but for the $t\bar{t}g\gamma$ channel.

$t\bar{t}g\gamma$