

CMS tttt: recent results

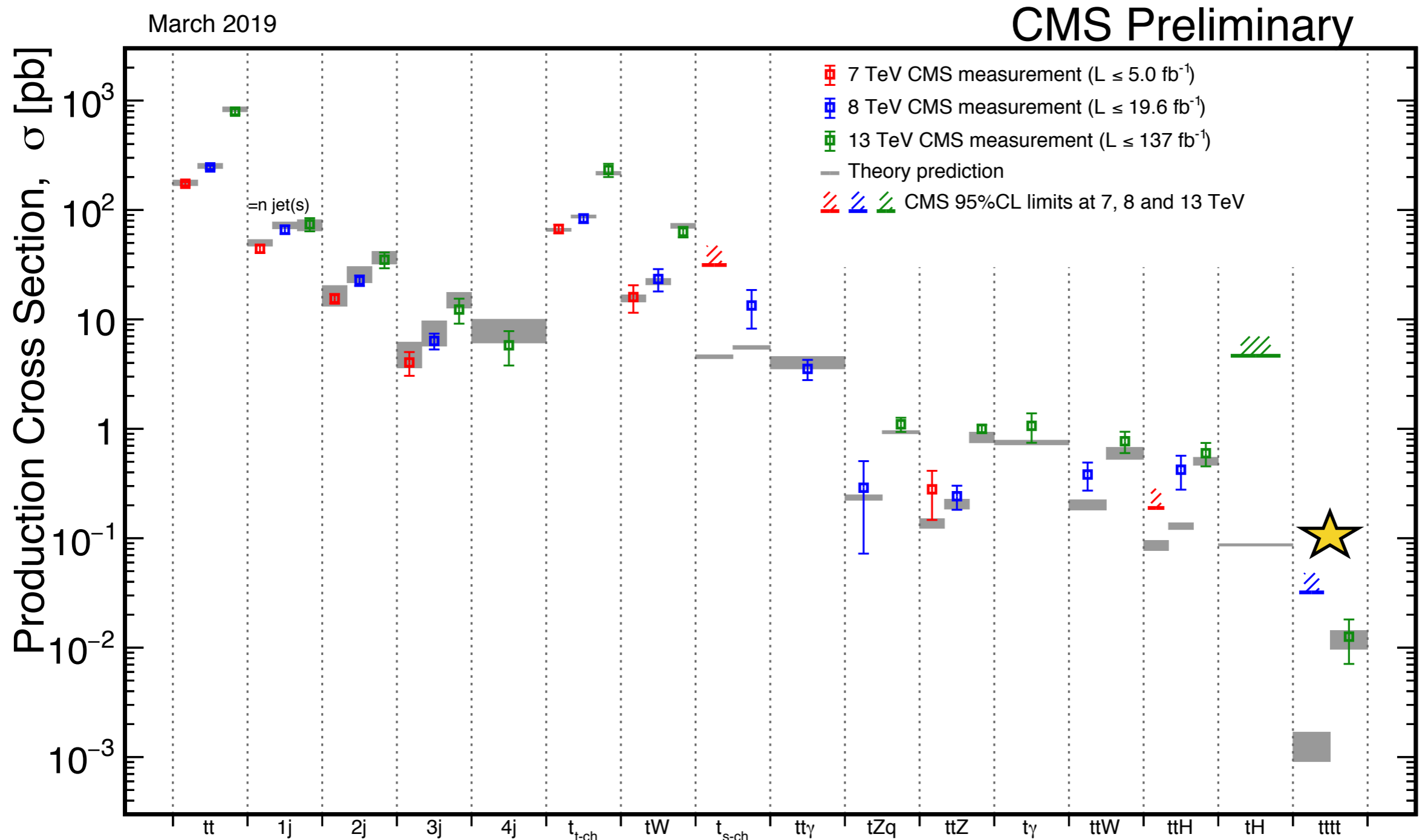
CMS-TOP-17-019: 36 fb⁻¹ @ 13 TeV
CMS-TOP-18-003: 137 fb⁻¹ @ 13 TeV

Giovanni Zevi Della Porta on behalf of CMS

Open LHC TOP WG meeting
28 May 2019

tttt: the next frontier ★

Top quark *pair pair* production: a complex QCD process with large sensitivity to new physics effects



All results at: <http://cern.ch/go/pNj7>

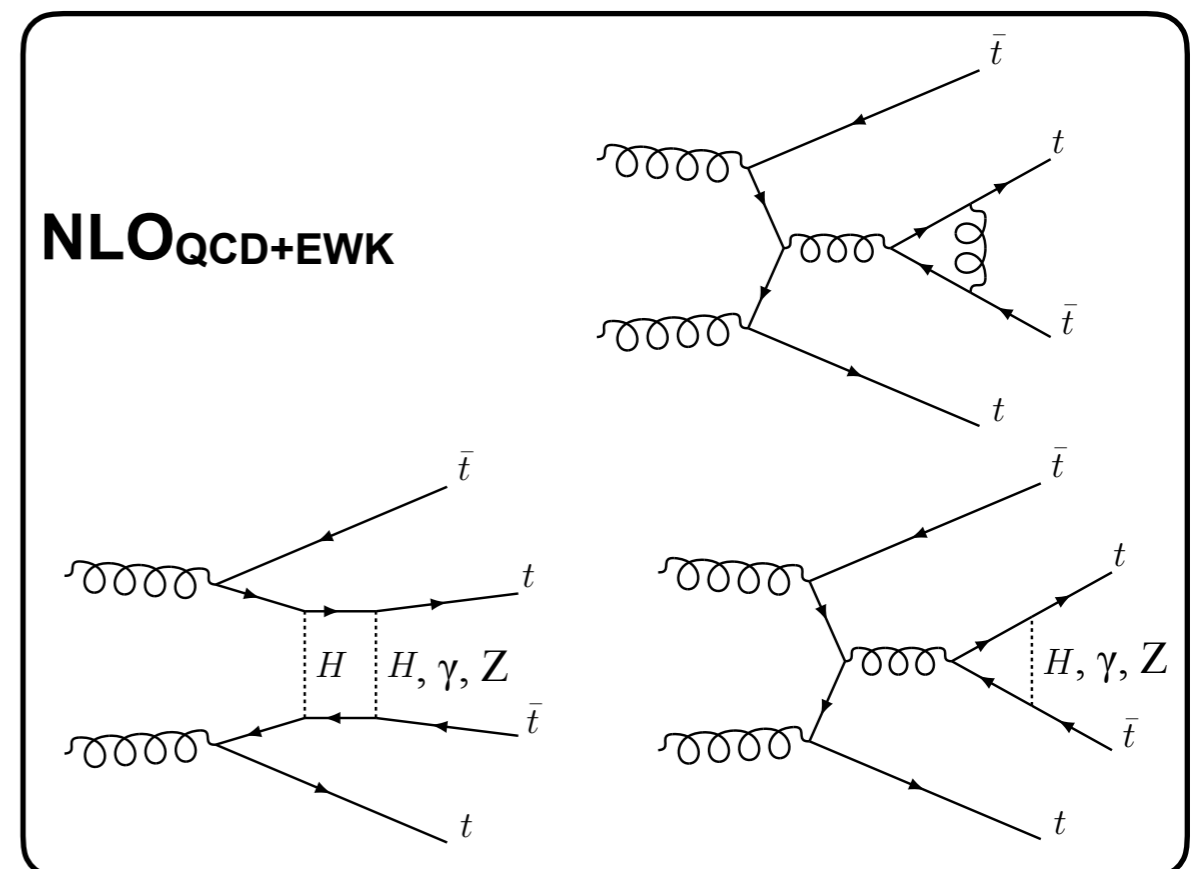
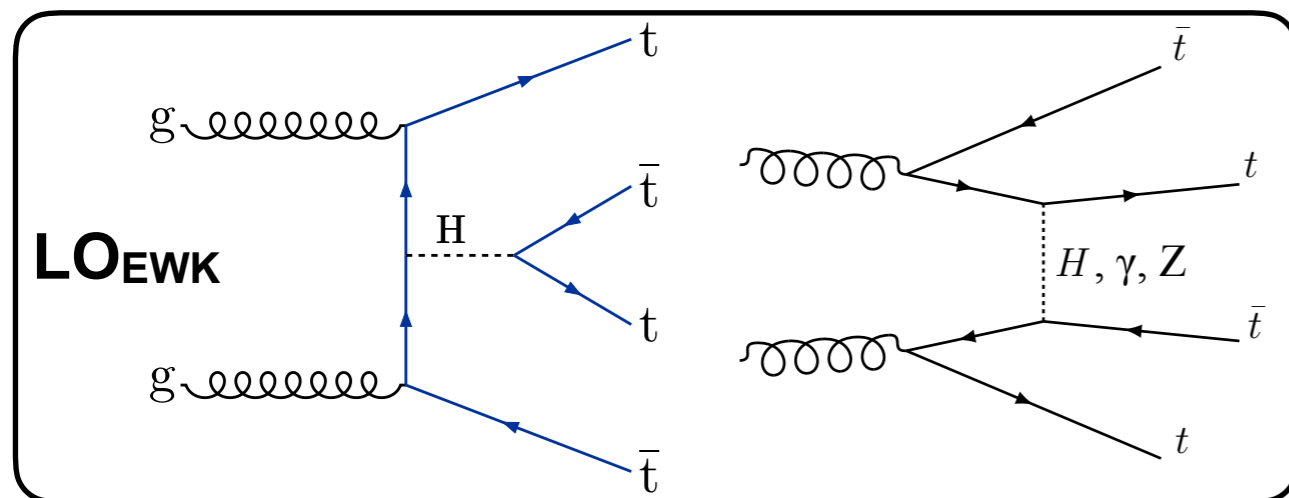
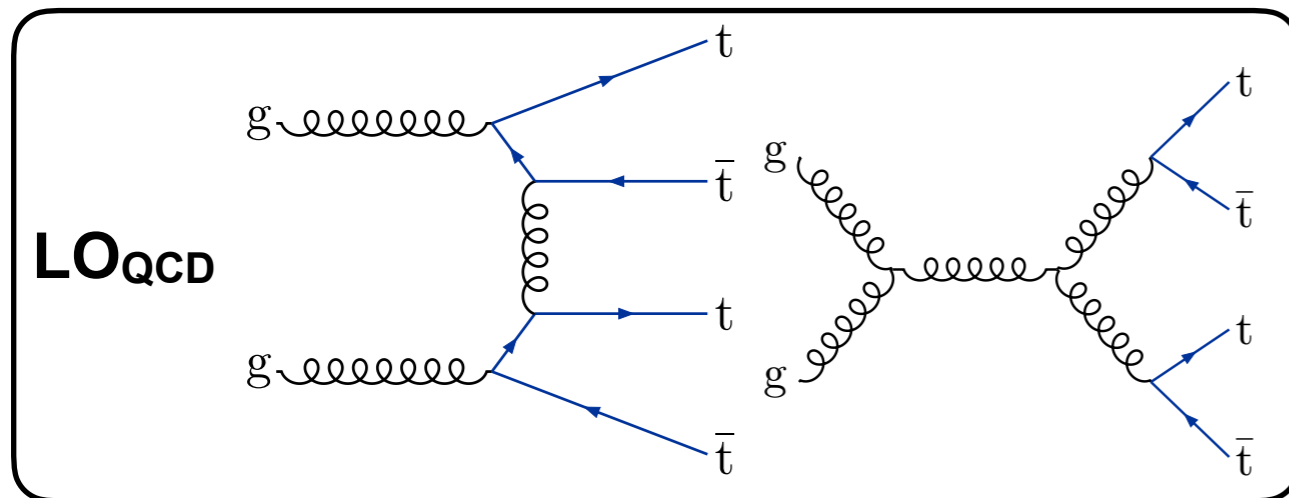
Standard Model prediction

Large theoretical uncertainties in inclusive cross section

QCD NLO/LO k-factor ranges between 1.2 and 2.0, depending on scale and PDF choices
Large effects (up to 40%) from Leading Order EWK diagrams

13 TeV prediction used by ATLAS and CMS with 2016 data: $\sigma_{\text{NLO}}(\text{tttt}) = 9.2^{+2.9}_{-2.4} \text{ fb}$ [1]

Most recent, with EWK NLO effects, used by CMS for full Run 2 analysis: $12^{+2.2}_{-2.5} \text{ fb}$ [2]



- [1] J. Alwall et al., JHEP 1407, 079 (2014) [arXiv:1405.0301]
[2] R. Frederix, et al., JHEP 1802 (2018) 031 [arXiv:1711.0211]

Beyond the Standard Model

Several new physics couplings and particles can affect $t\bar{t}t\bar{t}$ production

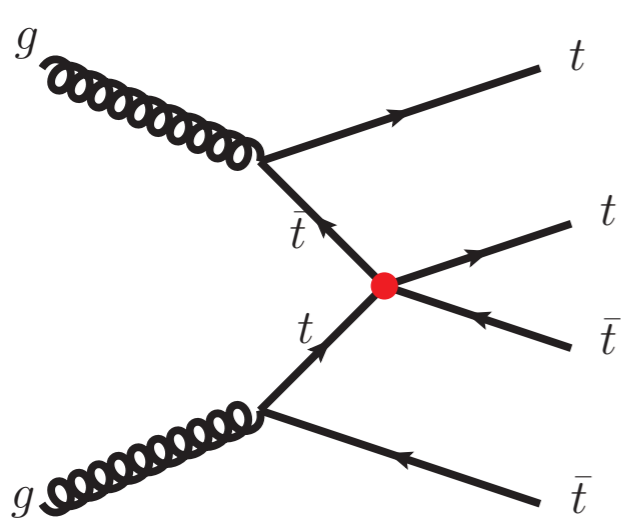
EFTs, including four-fermion **contact interactions**

New particles coupling to top quark (see next slide)

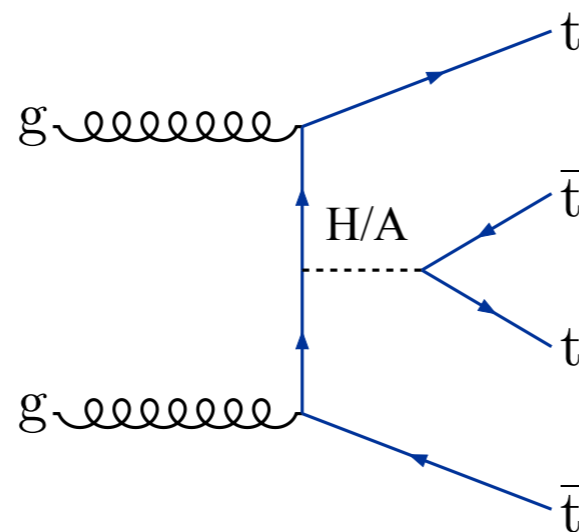
Higgs physics: **Top-Higgs yukawa coupling**, **Higgs oblique parameter**

And more: gluinos, sgluons, ...

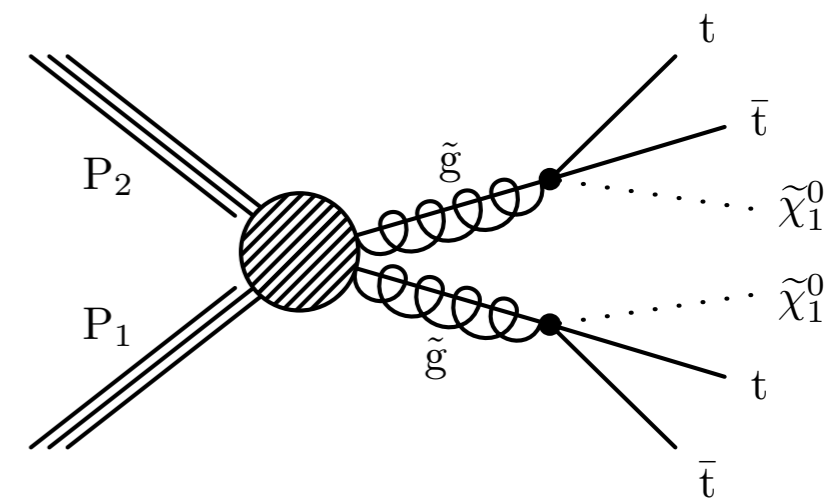
Some of these models generate SM-like kinematics, and can be probed with a cross section limit/measurement. Others have harder kinematics.



Four-fermion contact interaction



2HDM scalar/pseudoscalar



SUSY gluinos

New particles coupling to top quarks

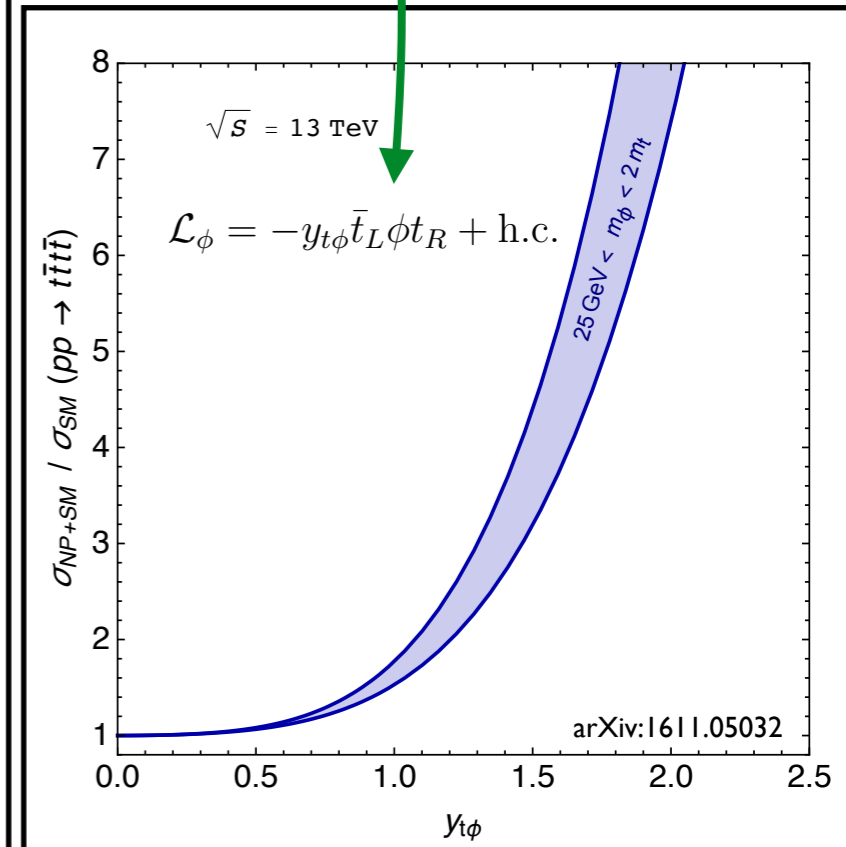
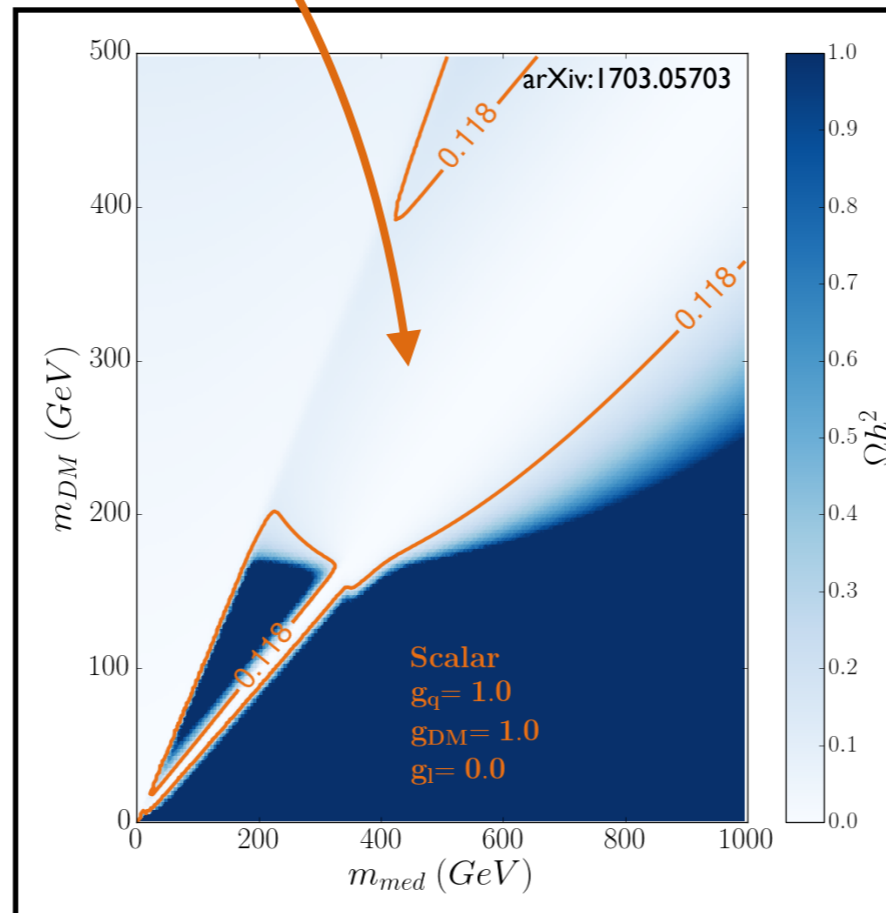
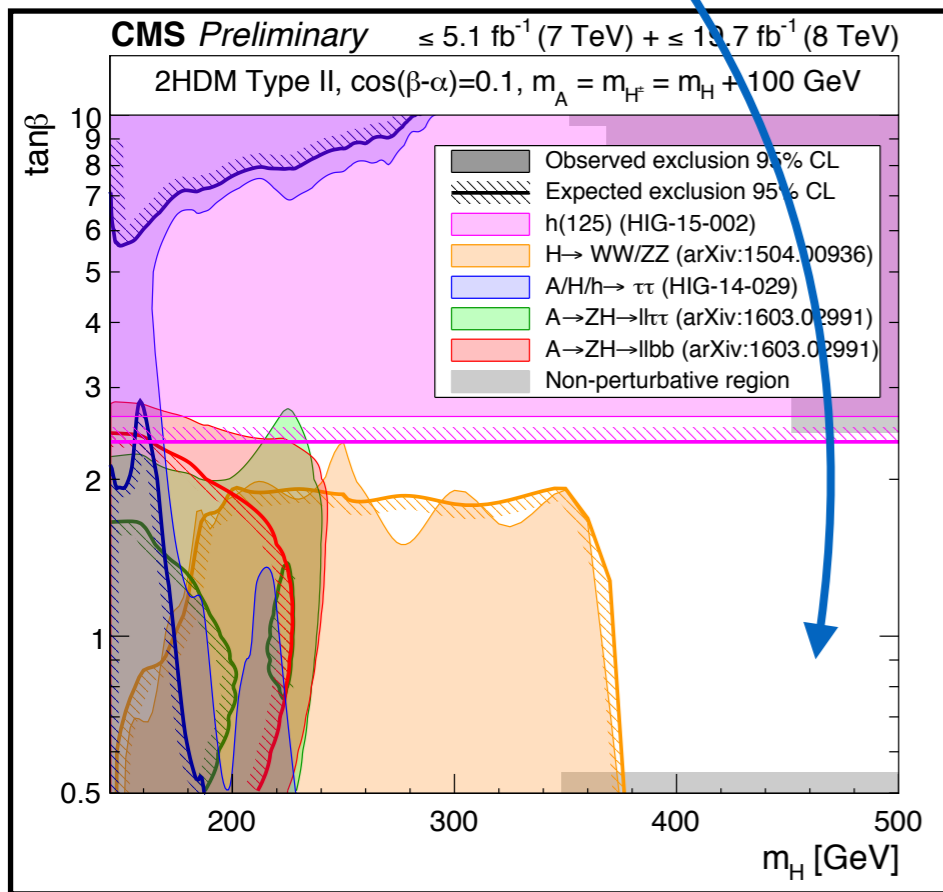
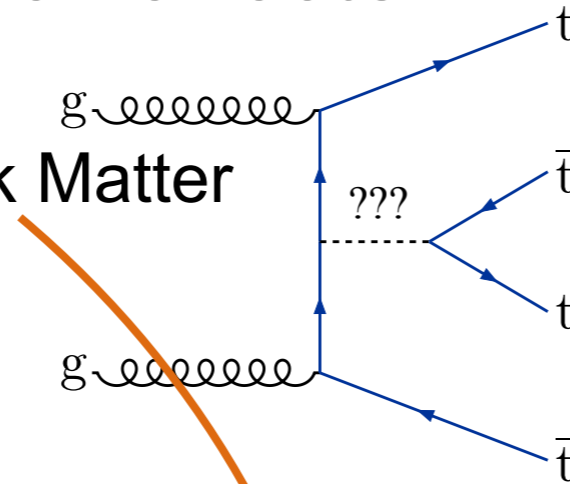
High mass ($>2m_t$), on-shell effects

Heavy spin-0 particles

- Mediator for Simplified Dark Matter
- Two Higgs Doublet Model

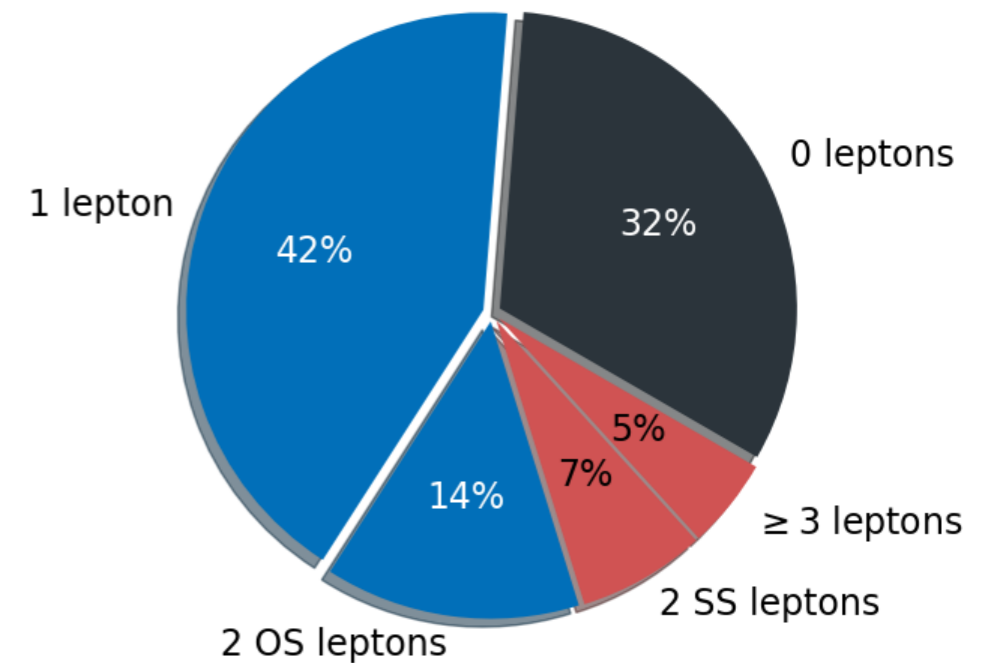
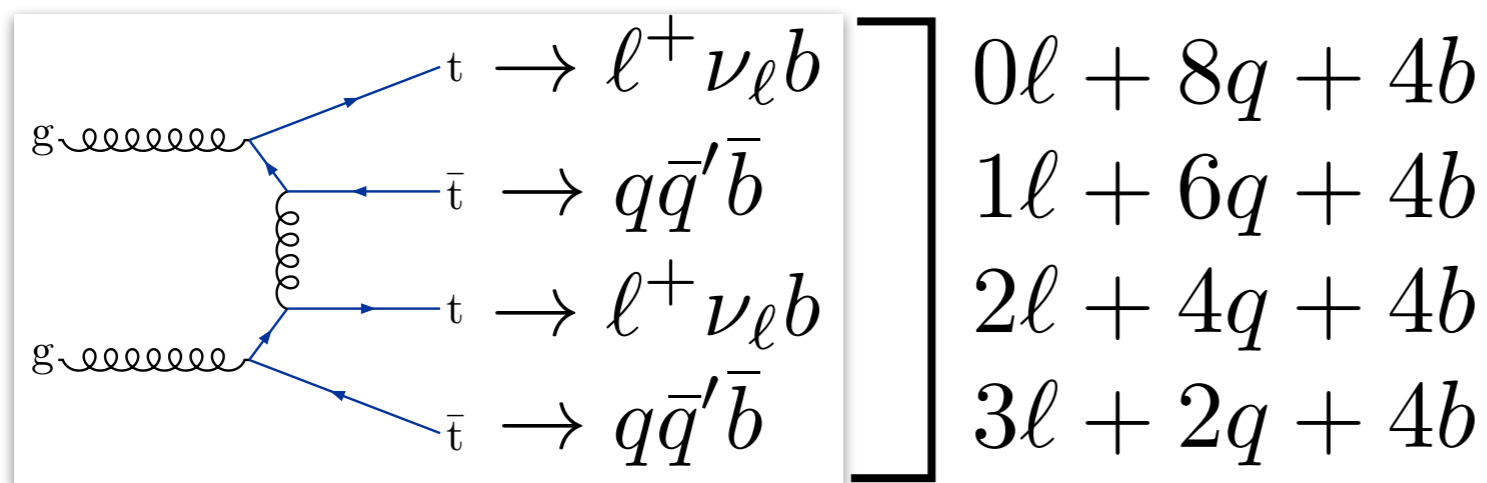
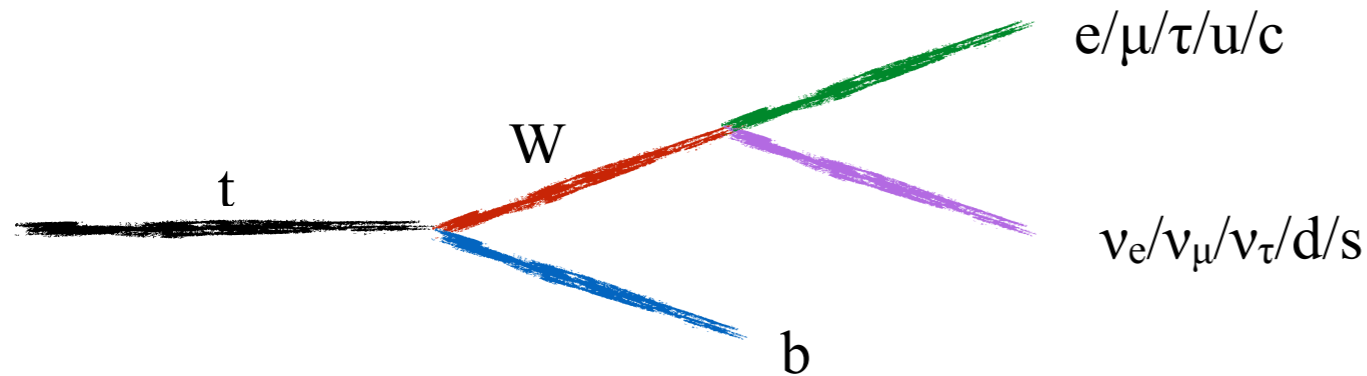
Low mass ($<2m_t$), off-shell

- Modified coupling with H
- But also other new particles (scalar or vector) with top-philic couplings



Searches in other channels ($pp \rightarrow X \rightarrow tt$, $pp \rightarrow ttX \rightarrow ttYY$) possible, but have larger interference and/or require assumptions on couplings and total width of new particle

Final States



All-hadronic

Powerful with massive new particles (gluons), not yet explored with SM kinematics

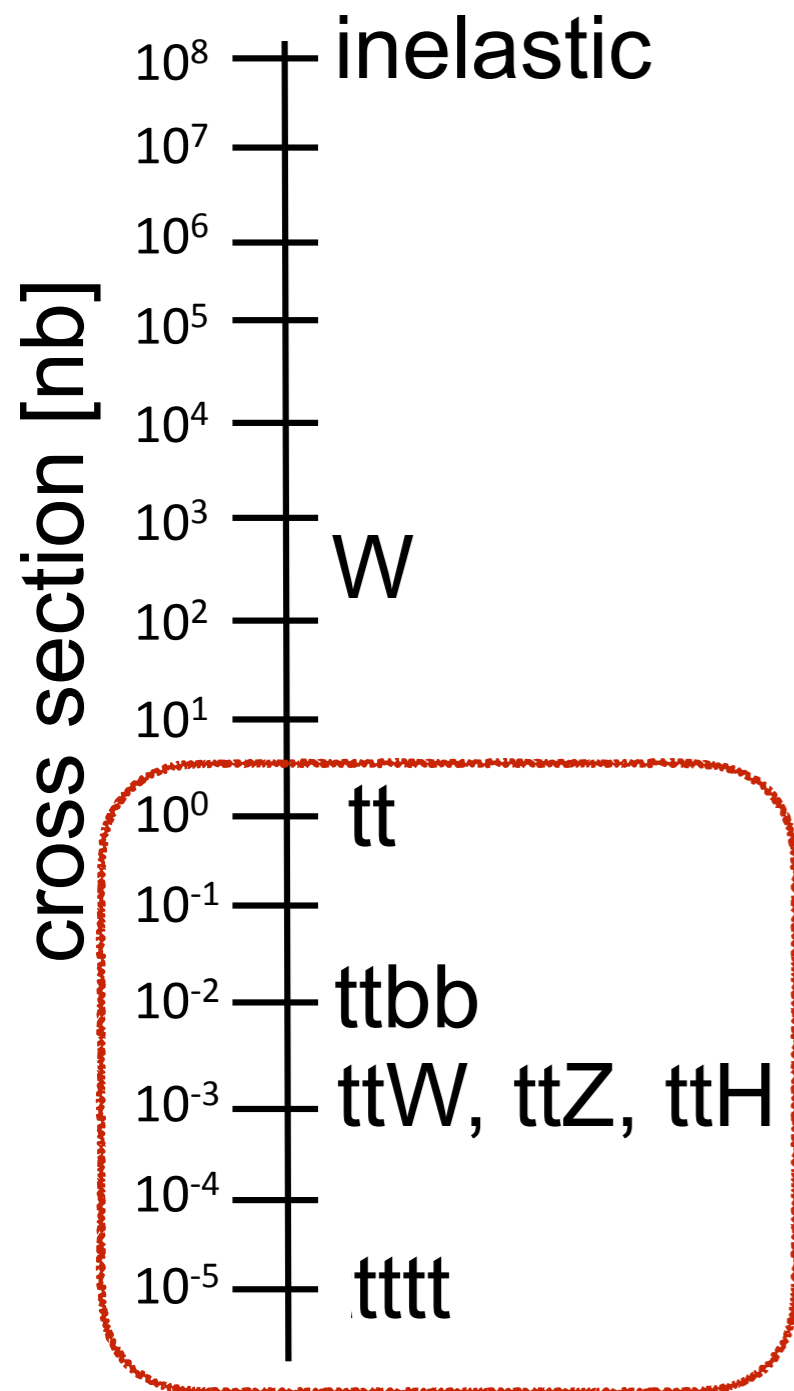
1 lepton and opposite-sign 2 lepton (1L/2LOS)

Dominant BR, large $t\bar{t}$ pair-production background (systematics limited)

2 same-sign or ≥ 3 leptons (2LSS)

Comparable branching to OS2L, but reject the $t\bar{t}$ background (statistically limited)

Backgrounds



Two categories of backgrounds:

tt (including ttbb):

1L/2LOS: main background

2LSS: only with a 'fake' or 'charge flip' lepton

ttW, ttZ, ttH, ttVV:

1L/2LOS: small but tttt-like background

2LSS: main background

1L/2LOS: Analysis Strategy

Main background: $t\bar{t}$

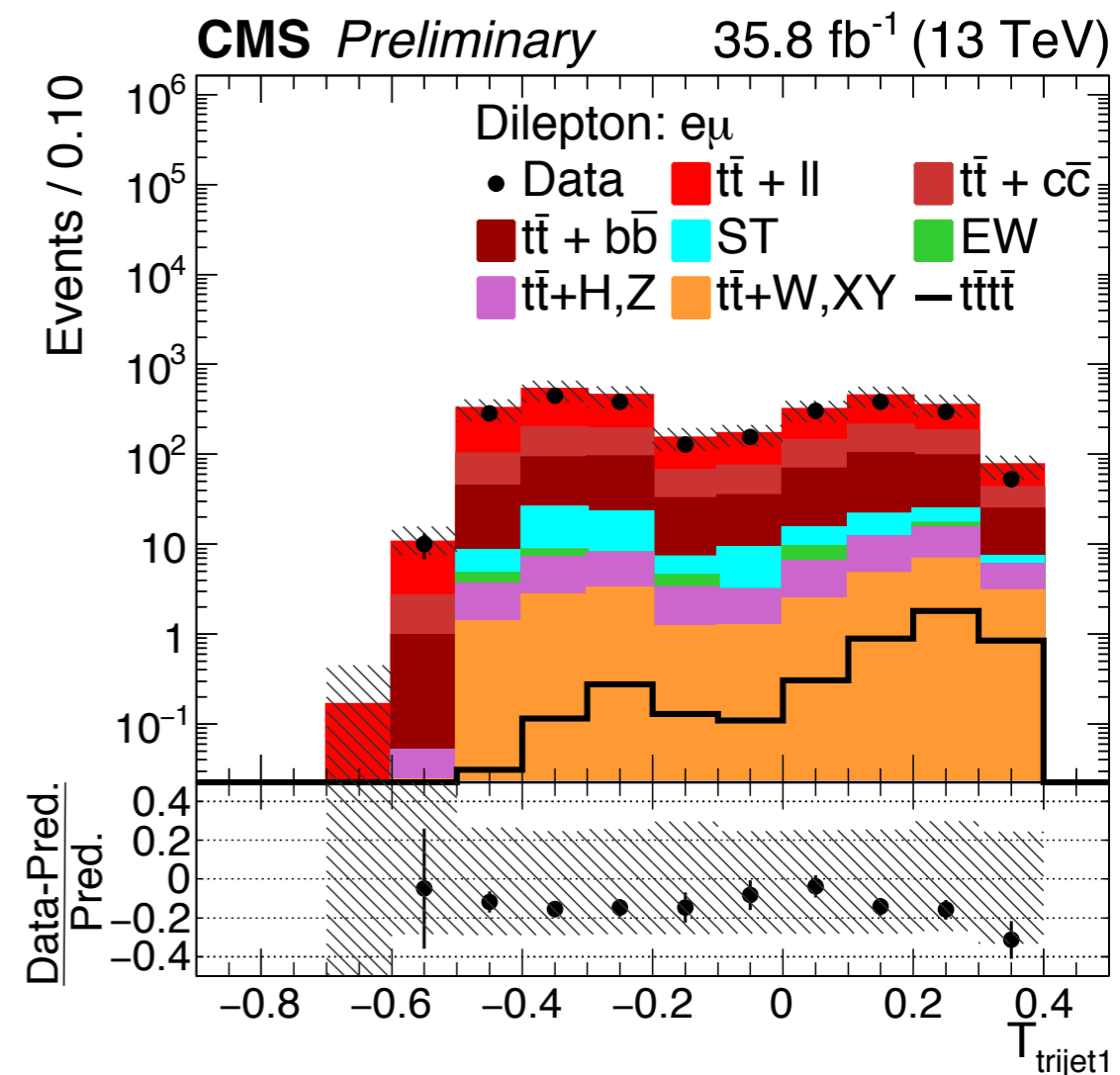
Estimate from simulation, with reconstruction and theory uncertainties

- Use data (bulk of $t\bar{t}$ sample) to profile uncertainties

Analysis strategy

1) Reconstruct (i.e. tag) **hadronic top** decays

- BDT to find the best (for 2LOS) or second best (for 1L) **triplet of $R=0.4$ jets**
- BDT variables: $m(jj)$, $m(jjj)$, b-tag, $\Delta R(jjj)$, “W”), $\Delta R(jjj)$, “b”), $p_{T^{jjj}} / (\Sigma p_{T^j})$
- BDT score: T_{trijet}



1L/2LOS: Analysis Strategy

Main background: $t\bar{t}$

Estimate from simulation, with reconstruction and theory uncertainties

- Use data (bulk of $t\bar{t}$ sample) to profile uncertainties

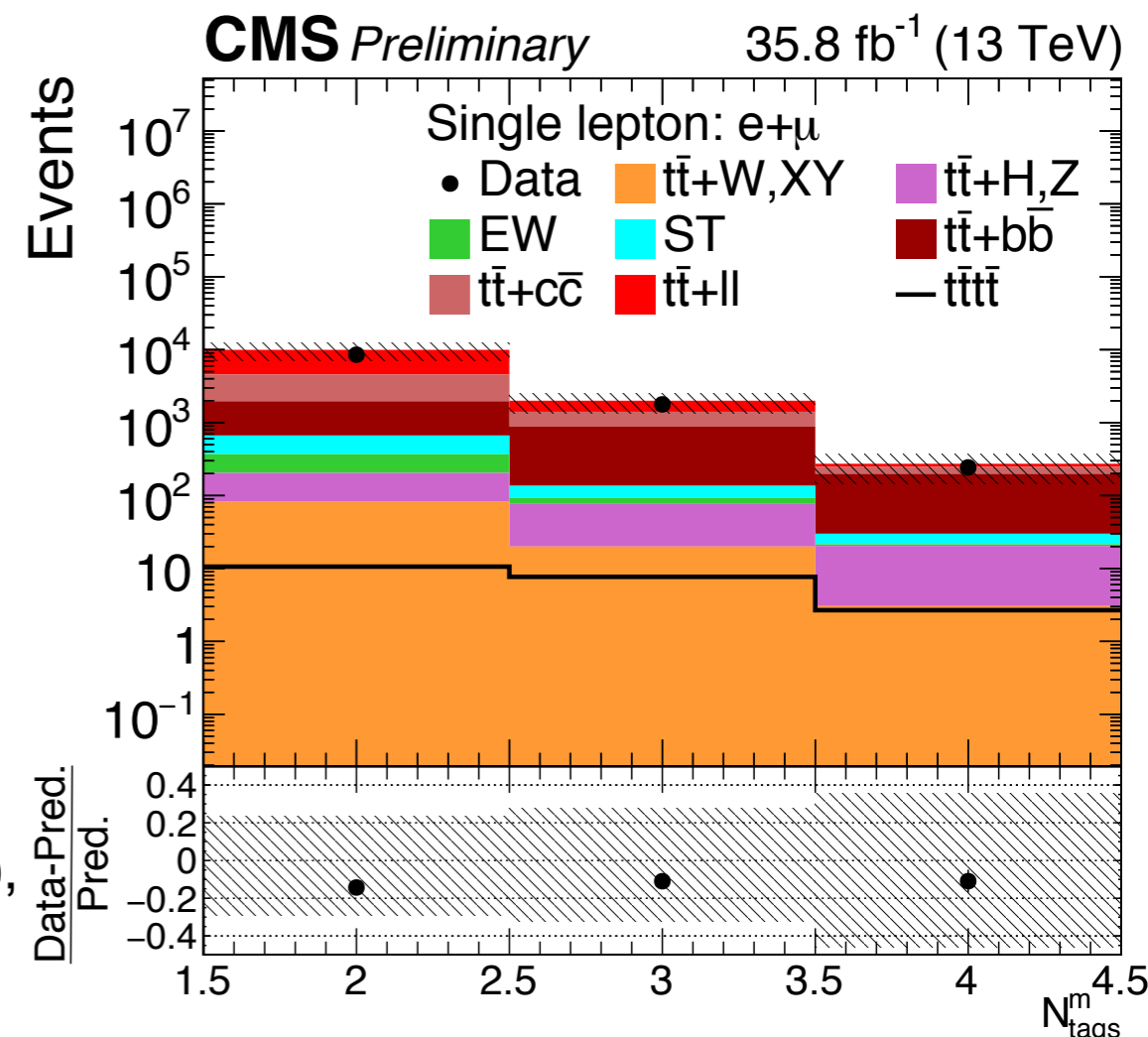
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- BDT score: T_{trijet}

2) Use **event kinematics** to separate $t\bar{t}t\bar{t}$ from $t\bar{t}+(b)\text{jets}$

- Categorize events based on N_{jets} , N_b , N_{lep}
- Train BDT in each category
- **BDT** variables: T_{trijet} , HT, $HT_{b\text{-jets}}$, $(HT - p_{T^{b1}} - p_{T^{b2}})$, $p_{T^{j3}}$, $p_{T^{j4}}$, centrality, sphericity, p_T^l , ΔR_{ll} , ΔR_{bb} , $(HT - p_{T^{\text{trijet}}})$, inv. mass of jets excluding trijet...

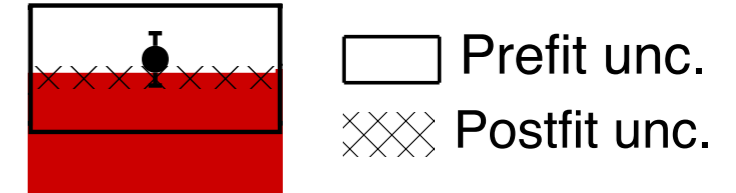


1L/2LOS: Signal Regions

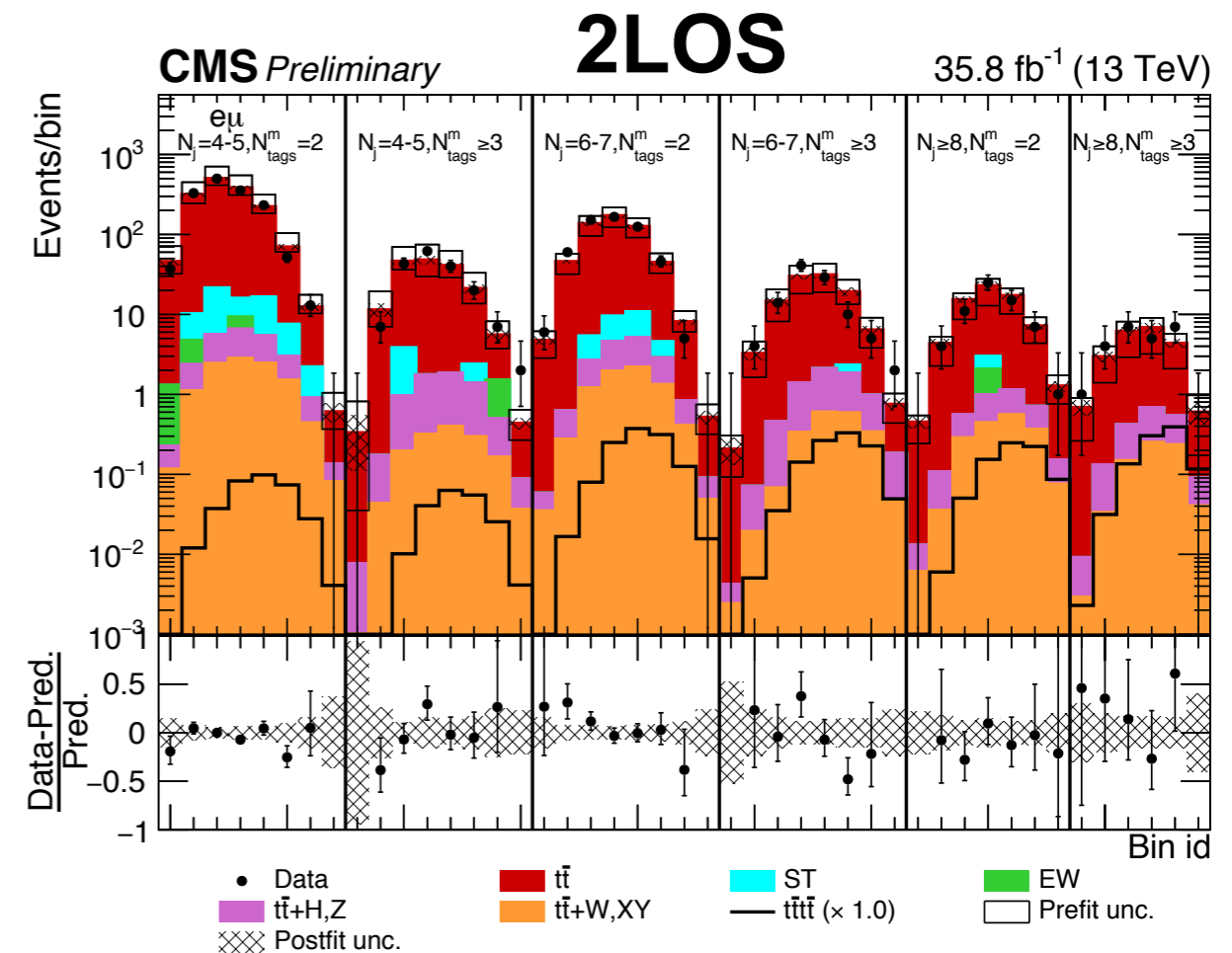
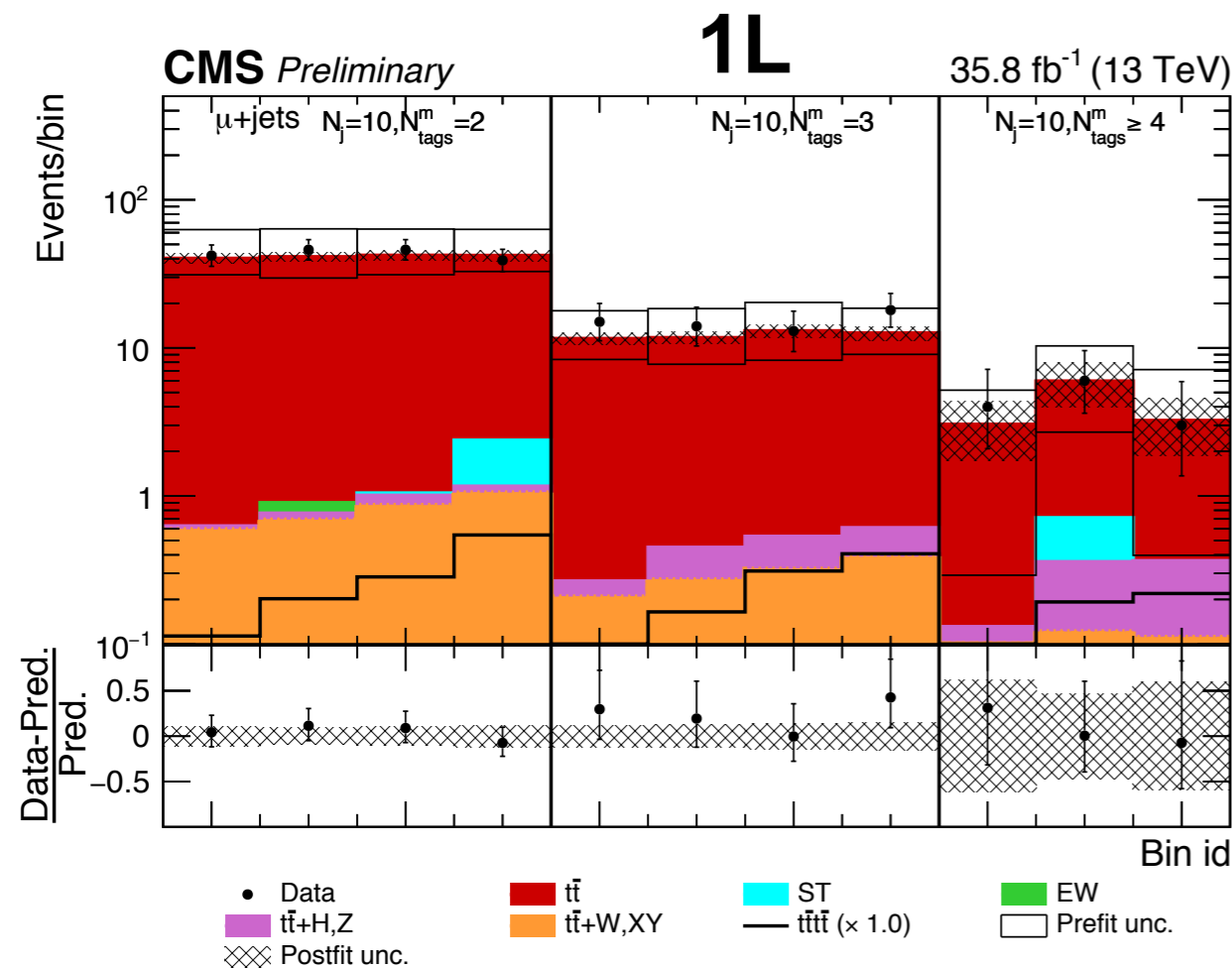
Signal regions for 1L (left) and 2LOS (right) analyses

Post-fit distribution shown, good agreement with predictions

- Fit: Difference between 'box' and 'shaded' uncertainty



Distributions agree well with SM, but fit scales $t\bar{t}t\bar{t}$ to zero in 2LOS





2LSS: Analysis Strategy

Several main backgrounds: ttW, ttZ, ttH, nonprompt leptons

- **Nonprompt leptons**: data-driven estimate ('fake rate' method)
- **ttW and ttZ**: correct N_{jets} and N_b using tt data, then normalize in control regions
- **ttH**: correct N_b using tt data, and apply a large normalization uncertainty

Strategy: BDT analysis, cut-based cross-check

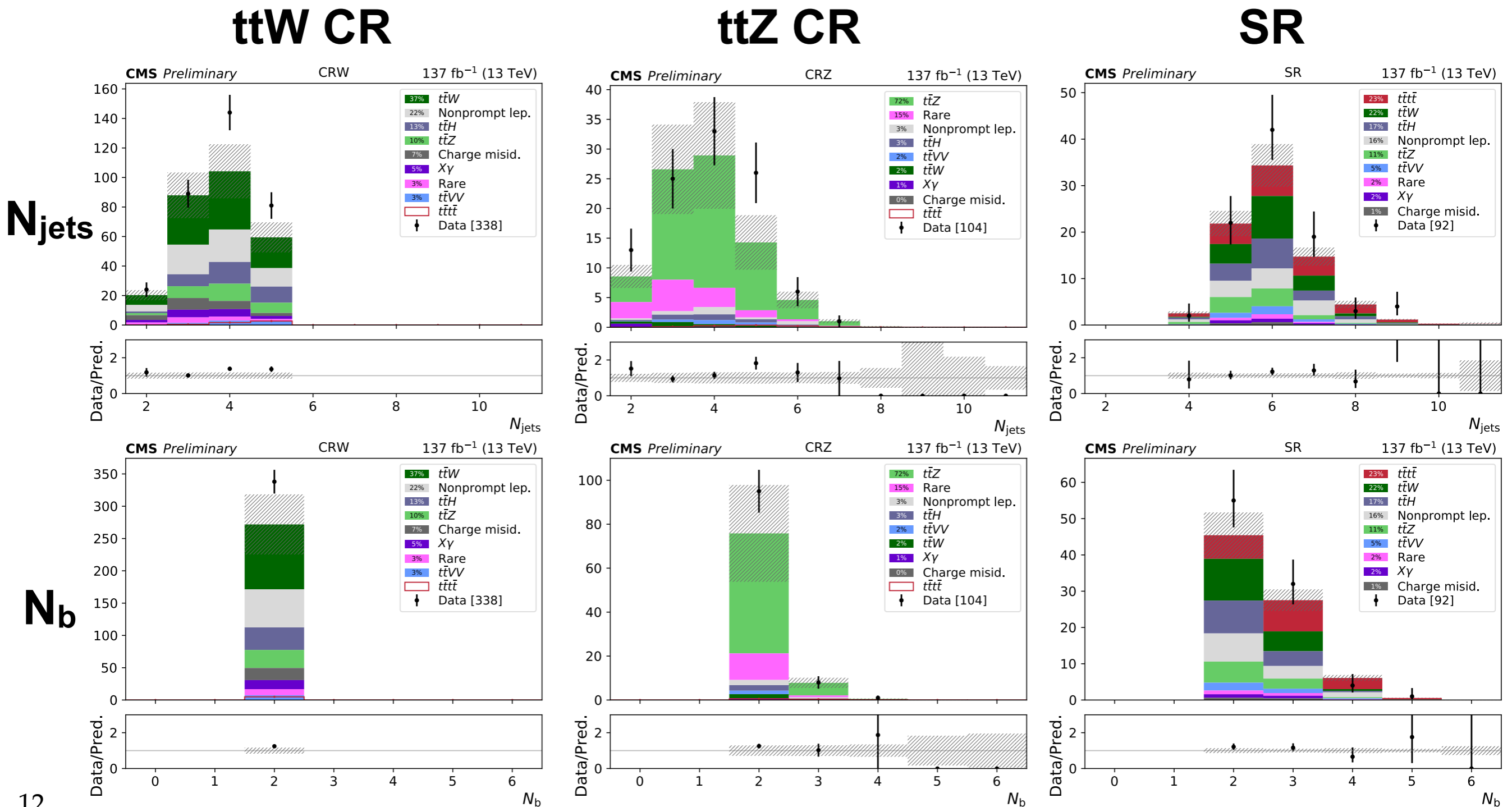
- **Cut-based**: number of jets, b-jets and leptons 
- **BDT**: 19 variables, separate tttt from $\Sigma(\text{bkg})$ 

- | | |
|------------------------------------|------------------------------------|
| • (a) Nbtags | • (k) $p_T(j_6)$ |
| • (b) Njets | • (l) $\max(m(j) / p_T(j))$ |
| • (c) Nlooseb | • (m) Nleps |
| • (d) MET | • (n) $p_T(\ell_1)$ |
| • (e) Ntightb | • (o) $\Delta\eta(\ell_1, \ell_2)$ |
| • (f) $p_T(\ell_2)$ | • (p) $p_T(j_8)$ |
| • (g) $m(\ell_1, j_1)$ | • (q) H_T^b |
| • (h) $p_T(j_1)$ | • (r) $p_T(\ell_3)$ |
| • (i) $p_T(j_7)$ | • (s) q_1 |
| • (j) $\Delta\phi(\ell_1, \ell_2)$ | |

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥ 8	SR7
	≥ 4	≥ 5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥ 7	SR11
	≥ 3	4	SR12
		5	SR13
		≥ 6	SR14
inverted Z-veto			CRZ

2LSS: Control Regions and Distributions

Well behaved control regions, visible $t\bar{t}t$ signal in signal region
Pre-fit distribution shown, with normalizations based on theory prediction



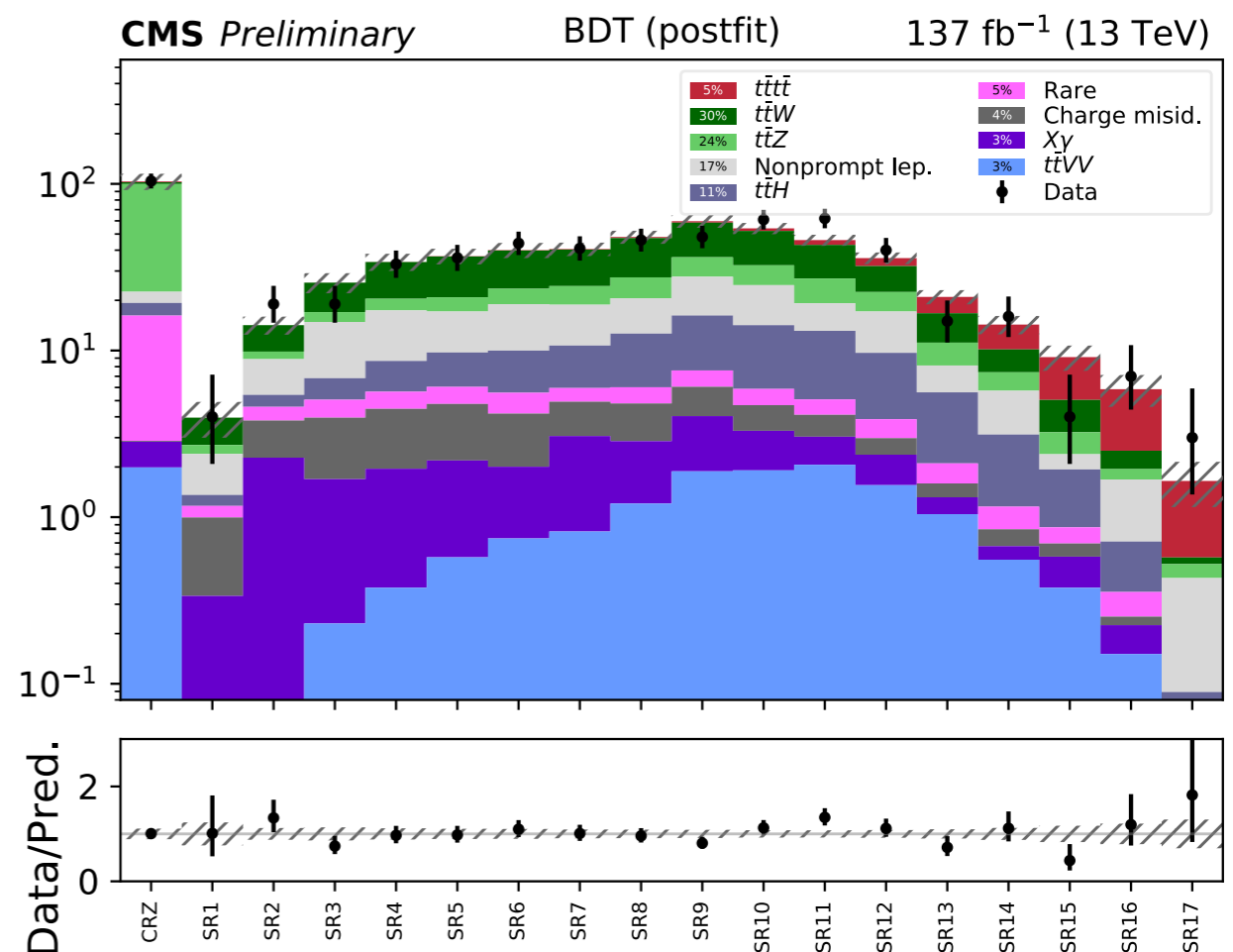
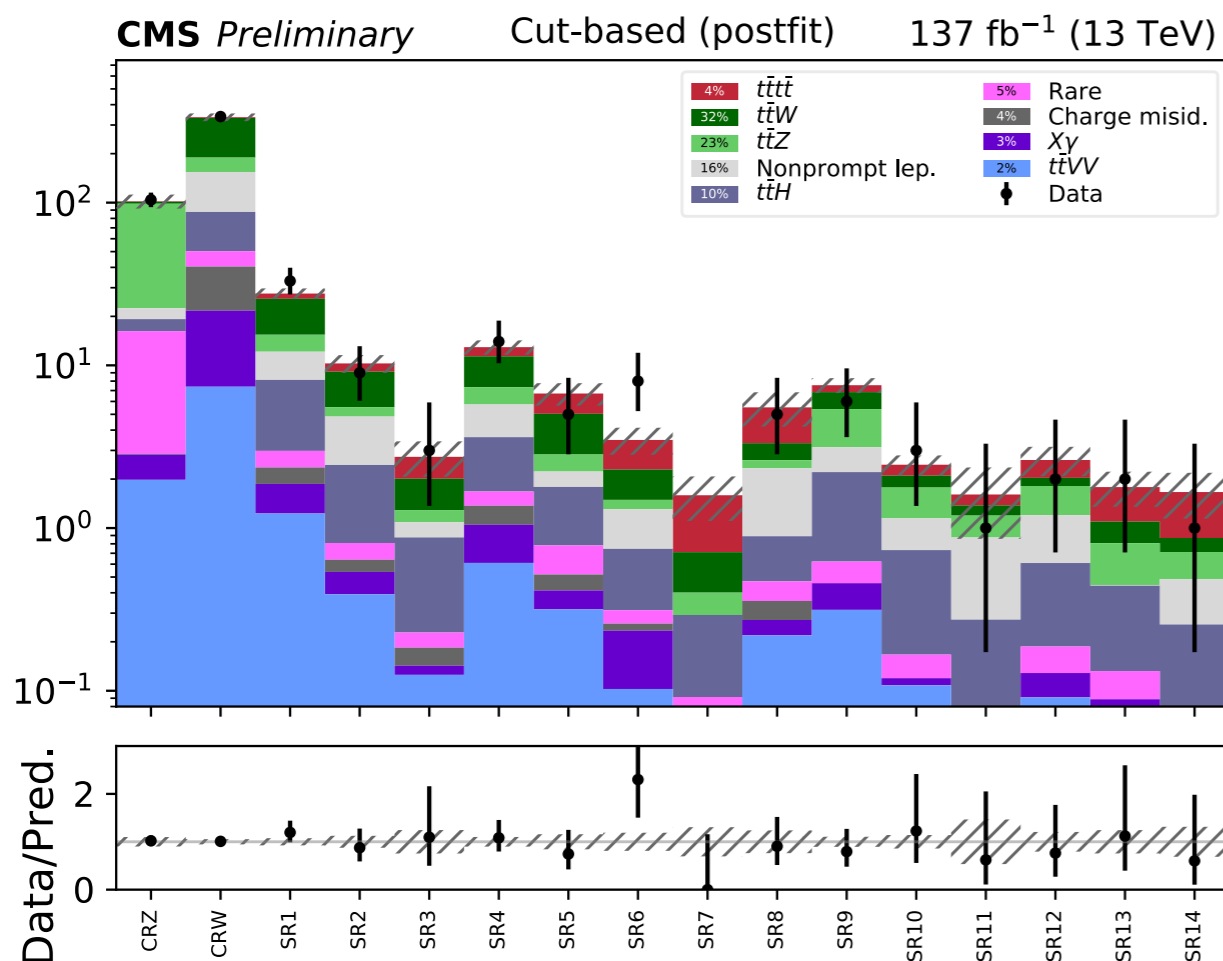
2LSS: Signal Regions

Signal regions for cut-based (left) and BDT (right) analyses

Post-fit distribution shown, good agreement with predictions

- $t\bar{t}W$ and $t\bar{t}Z$ scaled to 1.3 ± 0.2 , $t\bar{t}H$ to 1.1 ± 0.3
- $t\bar{t}t\bar{t}$ scaled to 0.8 (cut-based) and 1.0 (BDT)
- BDT and cut-based analyses agree

Distributions agree well with SM including $t\bar{t}t\bar{t}$



Uncertainties

1L/2LOS: total systematic uncertainty ~ total stat. uncertainty

Largest syst.: tt modeling, fraction of ttbb, b-tagging

2LSS: total systematic uncertainty ~ half of stat. uncertainty

Largest syst.: fraction of ttW/Z/H events with additional bb, jet scale, ttH

Systematic uncertainty	Source	Uncertainty (%)	Impact on the $t\bar{t}t\bar{t}$ cross section (%)
Integrated luminosity	Integrated luminosity	2.3–2.5	3
Pileup modeling	Pileup	0–5	1
Lepton reconstruction and identification	Trigger efficiency	2–7	2
Jet energy corrections	Lepton selection	2–10	2
b tagging	Jet energy scale	1–15	9 ←
Ren. and fact. scales	Jet energy resolution	1–10	6
PS scales ←	b tagging	1–15	6
ME-PS matching	Size of simulated sample	1–25	<1
UE ←	Scale and PDF variations †	10–15	2
Jet multiplicity correction	ISR/FSR (signal) †	5–15	2
Parton distribution functions	$t\bar{t}H$ (normalization) †	25	5 ←
Top quark p_T reweighting	Rare, $X\gamma$, $t\bar{t}VV$ (norm.) †	11–20	<1
Heavy-flavor reweighting ←	$t\bar{t}Z$, $t\bar{t}W$ (norm.) †	40	3–4
Rare process	Charge misidentification †	20	<1
	Nonprompt leptons †	30–60	3
	$N_{\text{jets}}^{\text{ISR/FSR}} \dagger$	1–30	2
	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}j\bar{j}) \dagger$	35	11 ←

Results: SM

1L/2LOS 36 fb⁻¹, and 36 fb⁻¹ combination with 2LSS

1L/2LOS: No deviation from SM background prediction

Combination with 36 fb⁻¹ 2LSS, which had 1.6σ significance

2LSS 137 fb⁻¹

2.5σ significance, good agreement with $12^{+2.2}_{-2.5}$ fb theory prediction

	Lumi	Significance	95% UL [fb]	σ(tttt) [fb]
1L/2LOS	36 fb ⁻¹	0.0 (0.4)	48 (52 ⁺²⁶ ₋₁₇)	0 ⁺²⁰
2LSS	36 fb ⁻¹	1.6 (1.0)	42 (23 ⁺¹² ₋₈)	17 ⁺¹⁴ ₋₁₁
Combination	36 fb ⁻¹	1.4 (1.1)	33 (20 ⁺¹⁰ ₋₆)	13 ⁺¹¹ ₋₉
2LSS	137 fb ⁻¹	2.5 (2.7)	23 (9 ⁺⁴ ₋₃)	13 ⁺⁶ ₋₅

Note: expected UL assumes no SM tttt

Results: BSM (1)

Effective Field Theory (36 fb⁻¹)

Consider 4 operators, assume they affect $\sigma(tttt)$ and not kinematics

- Parametrize their impact on $\sigma(tttt)$

$$\mathcal{O}_{tt}^1 = (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R)$$

$$\mathcal{O}_{QQ}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{Q}_L \gamma_\mu Q_L)$$

$$\mathcal{O}_{Qt}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{t}_R \gamma_\mu t_R)$$

$$\mathcal{O}_{Qt}^8 = (\bar{Q}_L \gamma^\mu T^A Q_L) (\bar{t}_R \gamma_\mu T^A t_R)$$

$$\sigma_{t\bar{t}t\bar{t}} = \sigma_{t\bar{t}t\bar{t}}^{\text{SM}} + \frac{1}{\Lambda^2} \vec{C}^T \cdot \vec{\sigma}^{(1)} + \frac{1}{\Lambda^4} \vec{C}^T \sigma^{(2)} \vec{C},$$

Operator	$\sigma_k^{(1)}$
\mathcal{O}_{tt}^1	0.39
\mathcal{O}_{QQ}^1	0.47
\mathcal{O}_{Qt}^1	0.03
\mathcal{O}_{Qt}^8	0.28

Operator	\mathcal{O}_{tt}^1	\mathcal{O}_{QQ}^1	\mathcal{O}_{Qt}^1	\mathcal{O}_{Qt}^8
\mathcal{O}_{tt}^1	5.59	0.36	-0.39	0.3
\mathcal{O}_{QQ}^1		5.49	-0.45	0.13
\mathcal{O}_{Qt}^1			1.9	-0.08
\mathcal{O}_{Qt}^8				0.45

Convert 95% UL on $\sigma(tttt)$ to limits on coefficients (marginalizing others)

Operator	Expected C_k / Λ^2 (TeV ⁻²)	Observed (TeV ⁻²)
\mathcal{O}_{tt}^1	[-1.5, 1.4]	[-2.2, 2.1]
\mathcal{O}_{QQ}^1	[-1.5, 1.4]	[-2.2, 2.0]
\mathcal{O}_{Qt}^1	[-2.5, 2.4]	[-3.7, 3.5]
\mathcal{O}_{Qt}^8	[-5.7, 4.5]	[-8.0, 6.8]

Results: BSM (2)

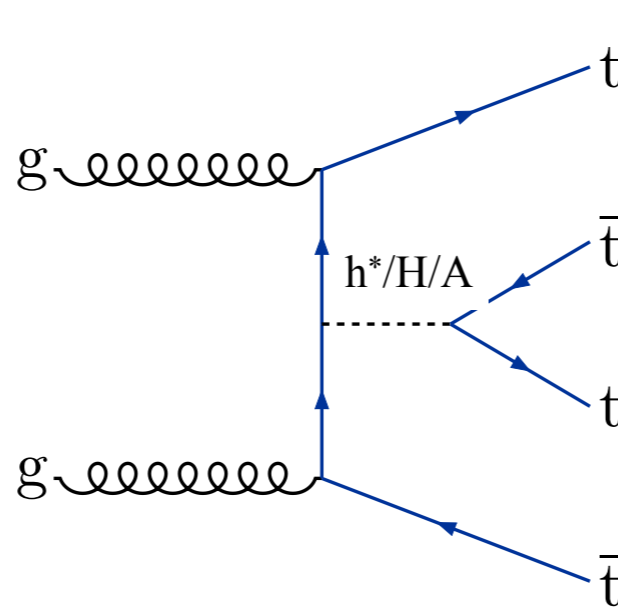
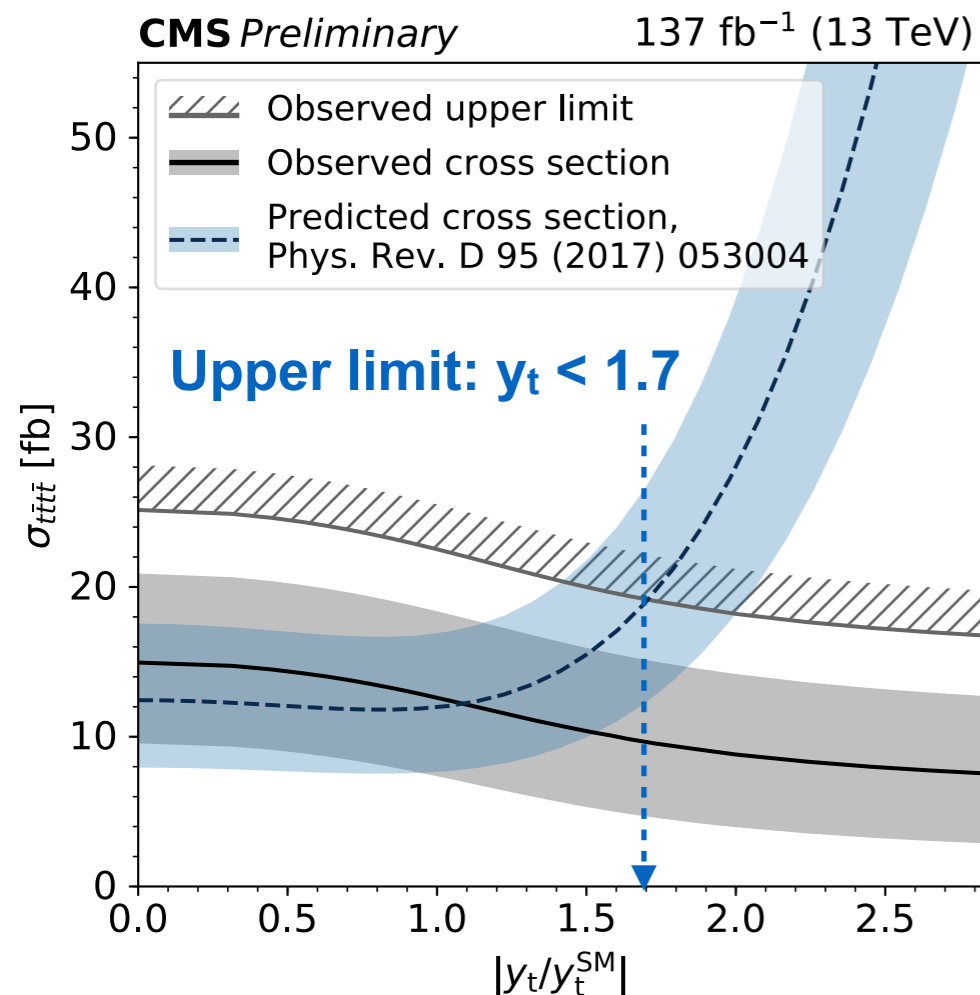
Top-Higgs Yukawa coupling (y_t)

Off-shell Higgs has a $\sim 10\%$ contribution to $t\bar{t}t\bar{t}$, which grows as y_t^4

$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\text{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma_{\text{int}}^{\text{SM}} + \kappa_t^4 \sigma^{\text{SM}}(t\bar{t}t\bar{t})_H$$

$$\kappa_t = |y_t/y_t^{\text{SM}}|$$

- Different approach w.r.t extracting y_t from ggH and $t\bar{t}H$, which requires assumption on total width of the Higgs

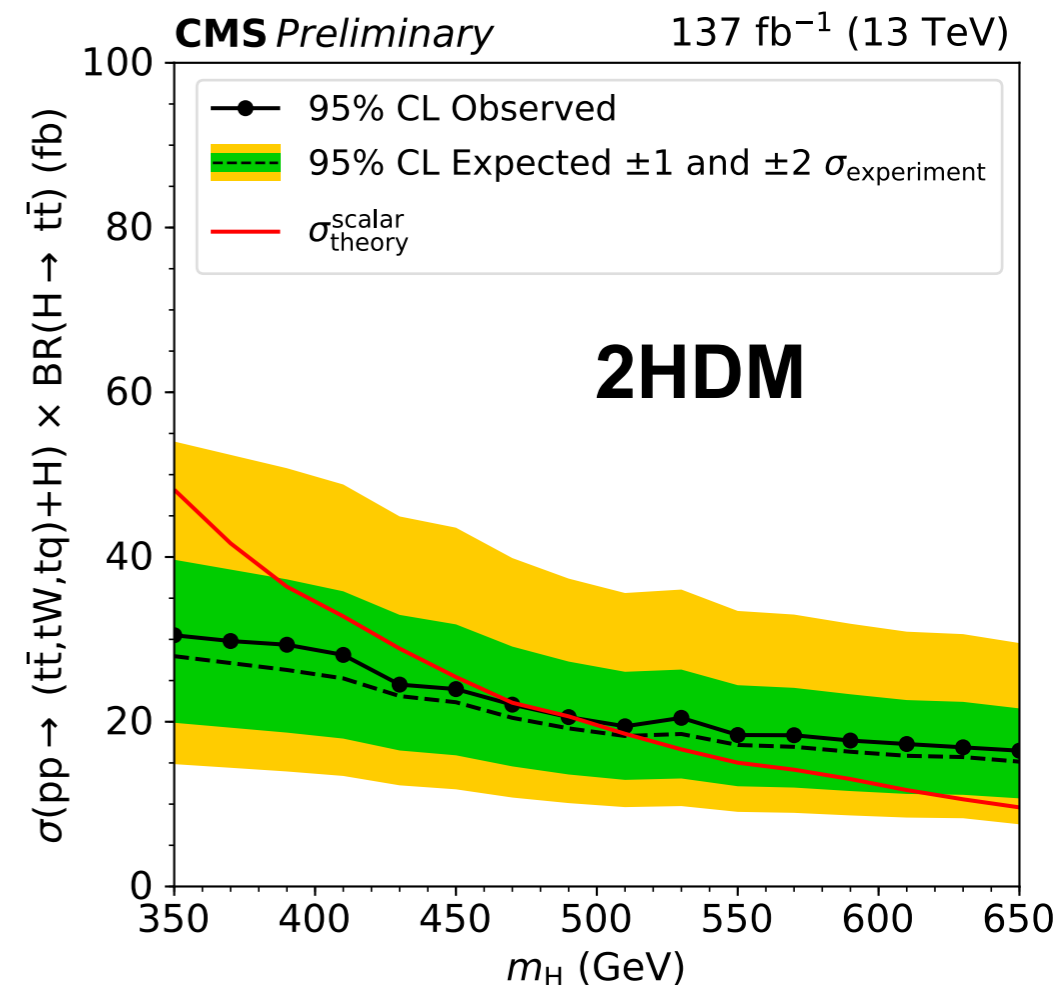


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Two Higgs doublet model (2HDM)

On-shell scalar/pseudoscalar with $m_{H/A} > 2m_t$: $(t\bar{t}, t)+H/A$, with $H/A \rightarrow t\bar{t}$

- 2HDM samples and cross sections based on alignment limit and $\tan\beta=1$
- Different approach w.r.t. resonant $pp \rightarrow H/A \rightarrow t\bar{t}$ search, which suffers from width-dependent interference



Summary

Two recent CMS results

2016 data analysis (36 fb⁻¹) combining 1L/2LOS/2LSS

2LSS analysis of the full Run 2 dataset (137 fb⁻¹)

- 2.5 sigma, $\sigma(t\bar{t}t\bar{t}) = 13^{+6}_{-5}$ fb, expected upper limit (assuming no signal) is now below σ_{SM}

Interest in $t\bar{t}t\bar{t}$ continues to grow

Active communities in both CMS and ATLAS

Many BSM models, only a few interpretations explored

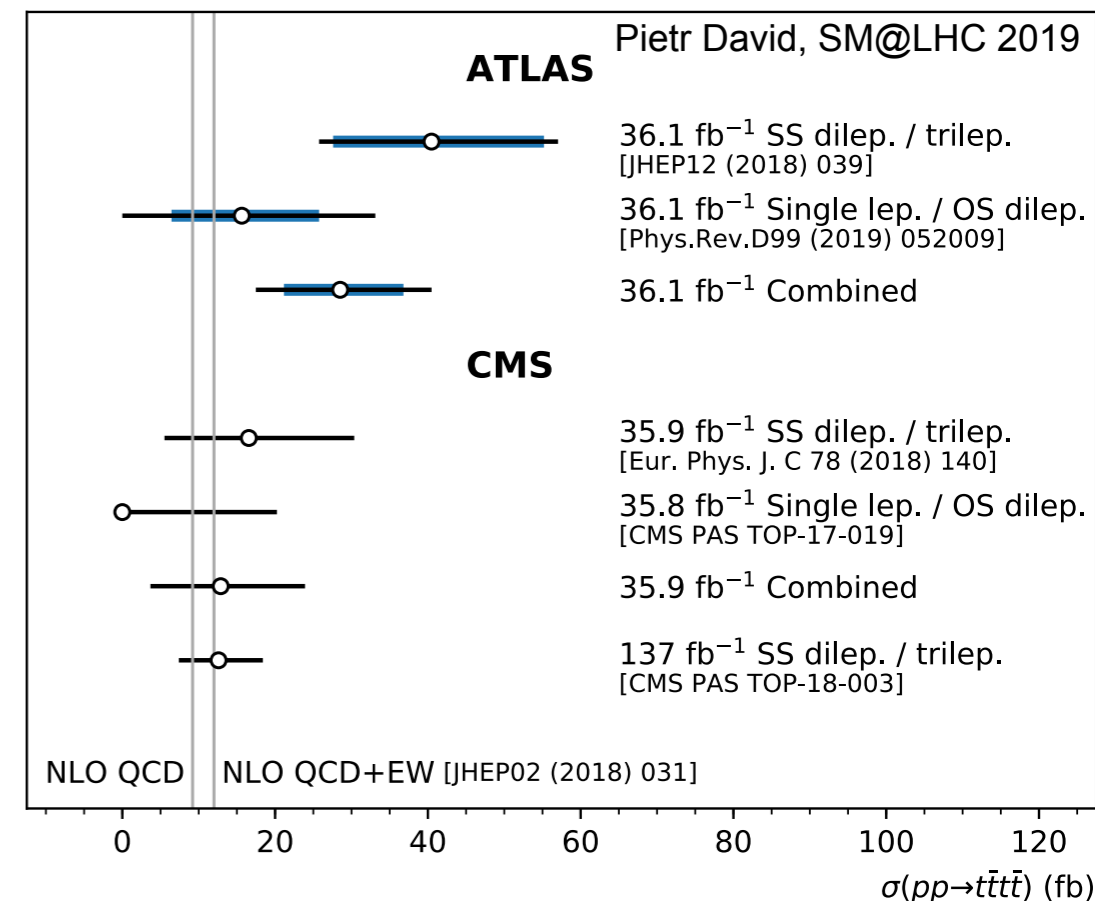
Run 2 analyses ongoing

The majority of $t\bar{t}t\bar{t}$ events still on disk

Stand to benefit from 14 TeV in Run 3

Detailed comparison with ATLAS $t\bar{t}t\bar{t}$, from last LHC TOP WG meeting

indico.cern.ch/event/746611/



Backup

Comparison with SMEFiT (arXiv:1901.05965)

Operator	Observed (TeV ⁻²)
\mathcal{O}_{tt}^1	$[-2.2, 2.1]$ ←
\mathcal{O}_{QQ}^1	$[-2.2, 2.0]$ ←
\mathcal{O}_{Qt}^1	$[-3.7, 3.5]$ ←
\mathcal{O}_{Qt}^8	$[-8.0, 6.8]$ ←

SMEFiT uses the 36 fb⁻¹ 2LSS results, not yet the 1L/2LOS of TOP-17-019

Both CMS and arXiv:1901.05965 use MC@NLO, with NLO SM tttt and LO EFT up to O(Λ⁴)

Wilson coefficients are constrained using the one-sided asymptotic CLs upper limit (CMS) or the measured cross section with NNPDF-like MC replica approach (SMEFiT)

SMEFiT constrains other operators, but the right table shows the results of fits to constrain individual operators

SMEFiT individual bounds (single-operator fits)				
Notation	DoF	Baseline	$\mathcal{O}(\Lambda^{-2})$ only	LO QCD
0QQ1	c_{QQ}^1	$[-5.2, 4.9]$ ←	$[-54, 83]$	$[-5.4, 5.2]$
0QQ8	c_{QQ}^8	$[-14, 12]$	$[-200, 18]$	$[-21, 16]$
0Qt1	c_{Qt}^1	$[4.5, 4.5]$ ←	$[-610, 210]$	$[-4.9, 4.9]$
0Qt8	c_{Qt}^8	$[-10, 8.1]$ ←	$[-69, 28]$	$[-11, 8.7]$
0Qb1	c_{Qb}^1	$[6.9, 6.7]$	$[-1.9 \cdot 10^3, -110]$	$[-6.1, 6.0]$
0Qb8	c_{Qb}^8	$[-16, 12]$	$[-260, -14]$	$[-15, 11]$
0tt1	c_{tt}^1	$[-2.9, 2.7]$ ←	$[-26, 41]$	$[-3.4, 3.2]$
0tb1	c_{tb}^1	$[-6.8, 6.8]$	$[-2.1 \cdot 10^4, -1.4 \cdot 10^3]$	$[-6.1, 6.1]$
0tb8	c_{tb}^8	$[-17, 12]$	$[-270, -15]$	$[-15, 11]$
0QtQb1	c_{QtQb}^1	$[-5.4, 5.5]$	$[160, 2.8 \cdot 10^3]$	$[-4.8, 4.9]$
0QtQb8	c_{QtQb}^8	$[-14, 14]$	$[910, 1.6 \cdot 10^4]$	$[-13, 13]$
081qq	$c_{Qq}^{1,8}$	$[-0.6, 0.1]$	$[-1.2, 0.3]$	$[-0.6, 0.07]$
011qq	$c_{Qq}^{1,1}$	$[-0.2, 0.02]$	*	$[-0.2, 0.03]$
083qq	$c_{Qq}^{3,8}$	$[-0.5, 0.4]$	$[-3.3, -0.08]$	$[-0.7, 0.2]$
013qq	$c_{Qq}^{3,1}$	$[-0.1, 0.09]$	$[-0.1, 0.2]$	$[-0.1, 0.09]$
08qt	c_{tq}^8	$[-1.3, 0.4]$	$[-2.1, 1.5]$	$[-0.7, 0.09]$
01qt	c_{tq}^1	$[-0.3, 0.02]$	*	$[-0.3, 0.03]$
08ut	c_{tu}^8	$[-1.1, 0.04]$	$[-2.0, 0.09]$	$[-0.9, 0.03]$
01ut	c_{tu}^1	$[-0.2, 0]$	*	$[-0.4, 0.03]$
08qu	c_{Qu}^8	$[-2.6, 0.2]$	$[-4.4, 0.3]$	$[-2.6, 0.1]$
01qu	c_{Qu}^1	$[-0.5, 0.02]$	*	$[-0.4, 0.03]$
08dt	c_{td}^8	$[-2.5, -0.01]$	$[-4.6, -0.2]$	$[-1.6, 0.02]$
01dt	c_{td}^1	$[-0.8, 0]$	*	$[-0.6, 0.03]$
08qd	c_{Qd}^8	$[-2.7, 0.3]$	$[-3.7, 0.9]$	$[-1.9, 0.07]$
01qd	c_{Qd}^1	$[-0.9, -0.01]$	*	$[-0.9, 0.05]$
0tG	c_{tG}	$[-0.08, 0.03]$	$[-0.08, 0.03]$	$[-0.1, 0.04]$
0tW	c_{tW}	$[-0.4, 0.2]$	$[-0.3, 0.1]$	$[-0.4, 0.2]$
0bW	c_{bW}	$[-0.6, 0.2]$	*	$[-0.7, 0.2]$
0tZ	c_{tZ}	$[-2.8, 4.5]$	$[-17, 4.6]$	$[-6.3, 7.4]$
0ff	$c_{\varphi tb}$	$[-9.4, 9.5]$	*	$[-9.7, 9.8]$
0fq3	$c_{\varphi Q}^3$	$[-0.9, 0.6]$	$[-1.0, 0.6]$	$[-1.0, 0.6]$
0pQM	$c_{\varphi Q}^-$	$[-4.2, 3.9]$	$[-4.2, 3.8]$	$[-5.1, 4.6]$
0pt	$c_{\varphi t}$	$[-6.4, 7.3]$	$[-6.9, 7.8]$	$[-7., 8.0]$
0tp	$c_{t\varphi}$	$[-5.3, 1.6]$	$[-5.1, 1.6]$	$[-5.4, 1.6]$

Table 5.4. Same as Table 5.3, now for the results of individual fits when only one operator is constrained at a time. The bounds in italics have been obtained from the analytical minimisation of the χ^2 rather than using the SMEFiT numerical approach, see text for more details.

Thanks to D. Lontkovsyi for discussion