Anomalous and rare top quarks in CMS

Giovanni Zevi Della Porta,
on behalf of the CMS Collaboration

LPCC Seminar - 3 July 2018
indico.cern.ch/event/719632/

The Top Quark

The heaviest fundamental particle, so far

$m_{top} \sim 173$ GeV

The only naked quark, decays weakly before hadronizing

$\tau \sim 5*10^{-25}$ s

- Allows to probe quark properties directly: mass, couplings, spin, charge

Strongly interacting with the electroweak sector and the Higgs

$m_{top} = y_t\, v / \sqrt{2} \;\rightarrow\; y_t \sim 1$

- Direct top-Higgs coupling in ttH observed by both CMS and ATLAS!

Inspiring us to look Beyond the Standard Model

Hierarchy problem: divergent top corrections to the Higgs mass

- Supersymmetry, vector-like fermions

First place to look for new particles that couple to mass

- Heavy partners of the Higgs

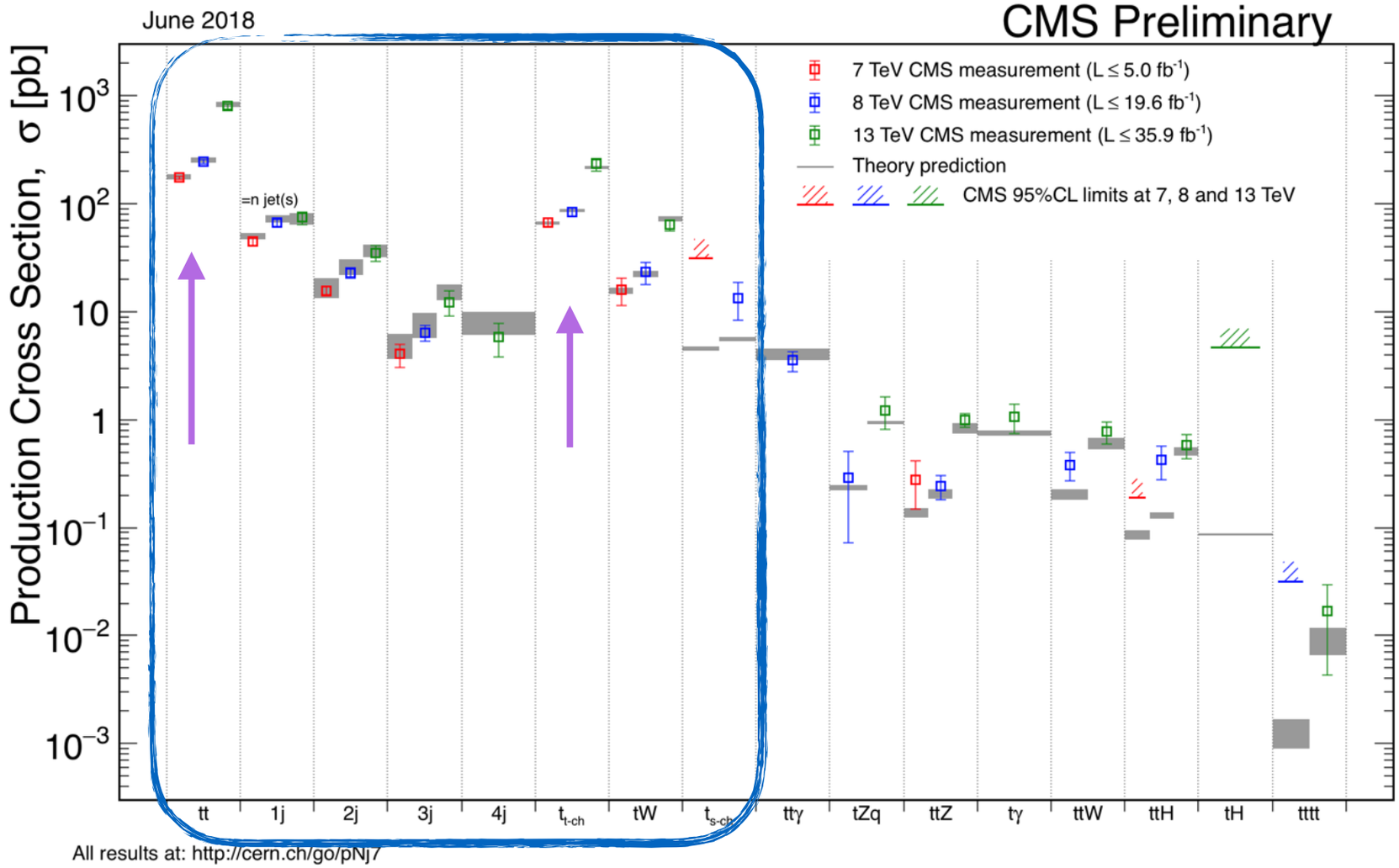
How does the top quark interact with other SM particles?

What is the strength of the top quark coupling with the gluon and the W?

- Measure tt and single-top cross-sections [not discussed today]

What is the structure of its weak coupling, the Wtb vertex?
Is it SM-like (left-handed vector), or does it have BSM components?

- Study W helicity in tt, search among angular correlations in single-top



20 fb^{-1}, 8 TeV

How does the top quark interact with other SM particles?

How does it couple to the Z/H/γ?

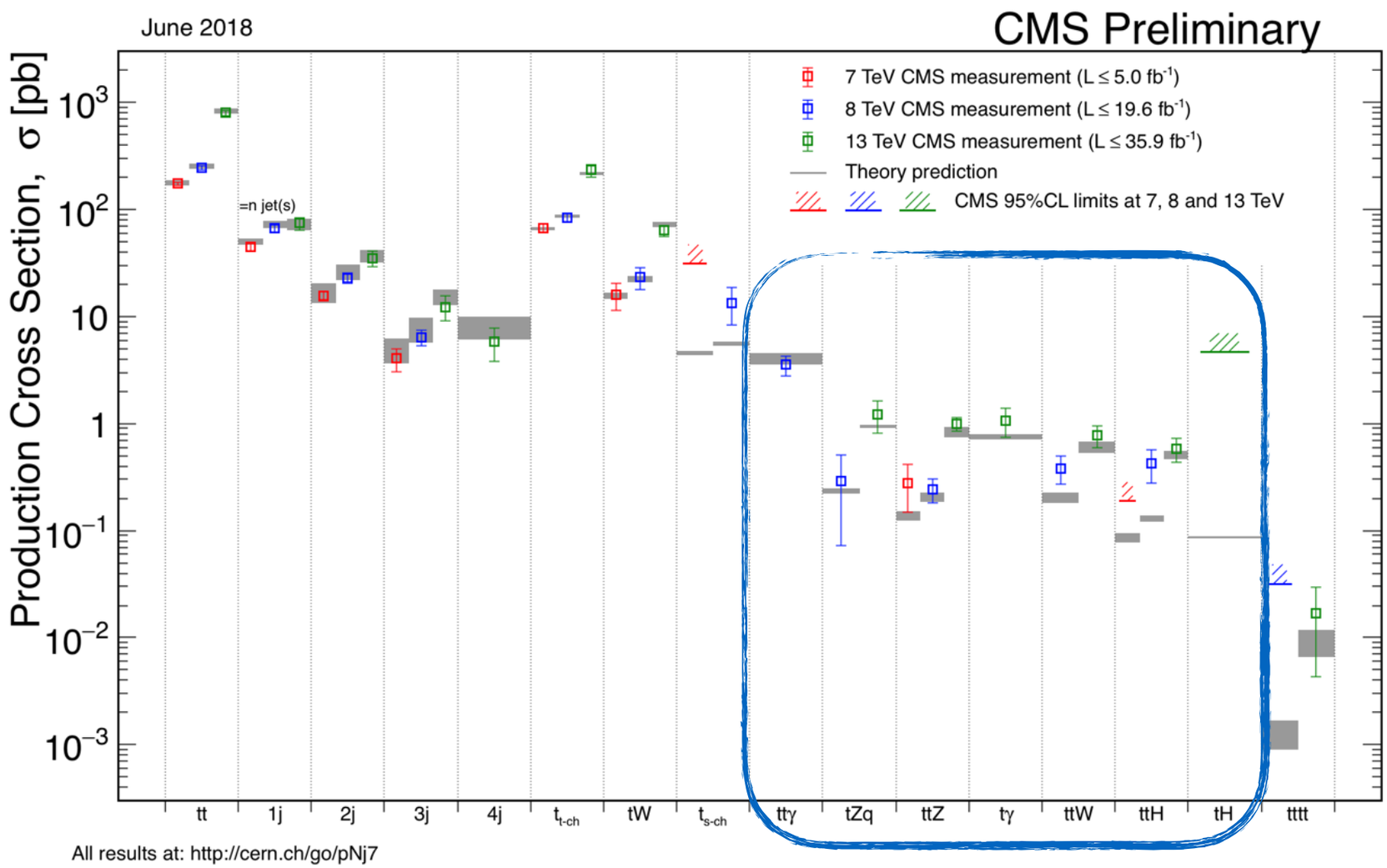
… when does the top quark radiate Z/H/γ?

- Measure (SM) ttZ, tZ, ttγ, tγ. [For ttH and tH, see recent CMS LPCC seminar by A. Gilbert]
- Constrain coefficients of Effective Field Theory couplings (ttW, ttZ)

… or can it decay to Z/H/γ in a Flavor Changing Neutral Current?

- Search for (BSM) FCNC decays in tt and single top (t→H, Z, γ, g)

20 fb^{-1}, 8 TeV
36 fb^{-1},13 TeV

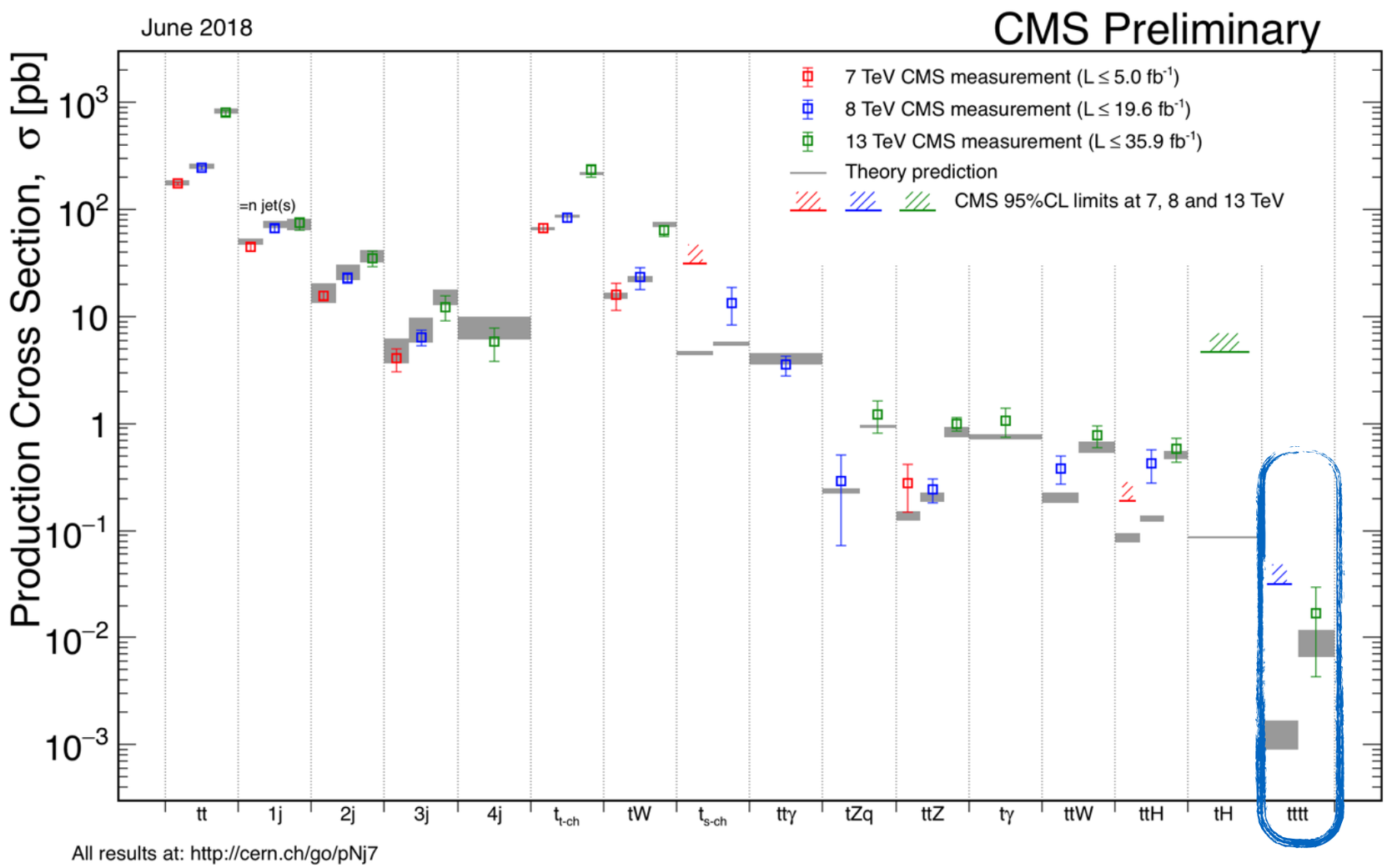


How does the top quark interact with other SM particles?

How do these interactions affect the t-t coupling at high energies?

- Measure the SM four top process (pp→tttt), where LO electroweak corrections can become as large as NLO strong corrections

These fundamental questions define a rich research program!



20 fb^{-1}, 8 TeV
36 fb^{-1},13 TeV

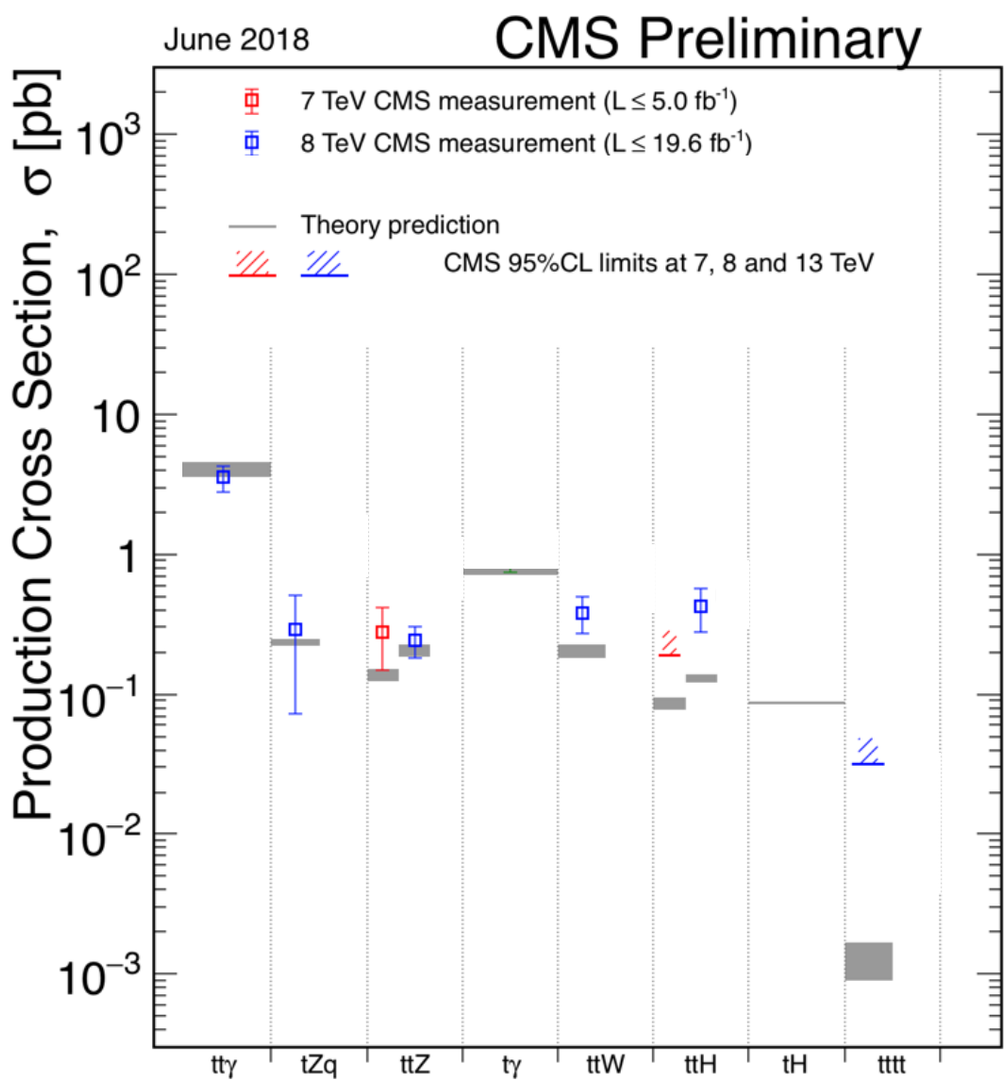
Status after LHC Run 1: Rare Top

Rare, but within LHC reach: SM cross section larger than O(fb)

- Measurements: ttW (±30%), ttZ (±27%), ttγ (±22%), tZ (±80%)
- Limits: tttt (95% CL upper limit: $\sigma_{tttt} < 25 * \sigma_{SM}$)

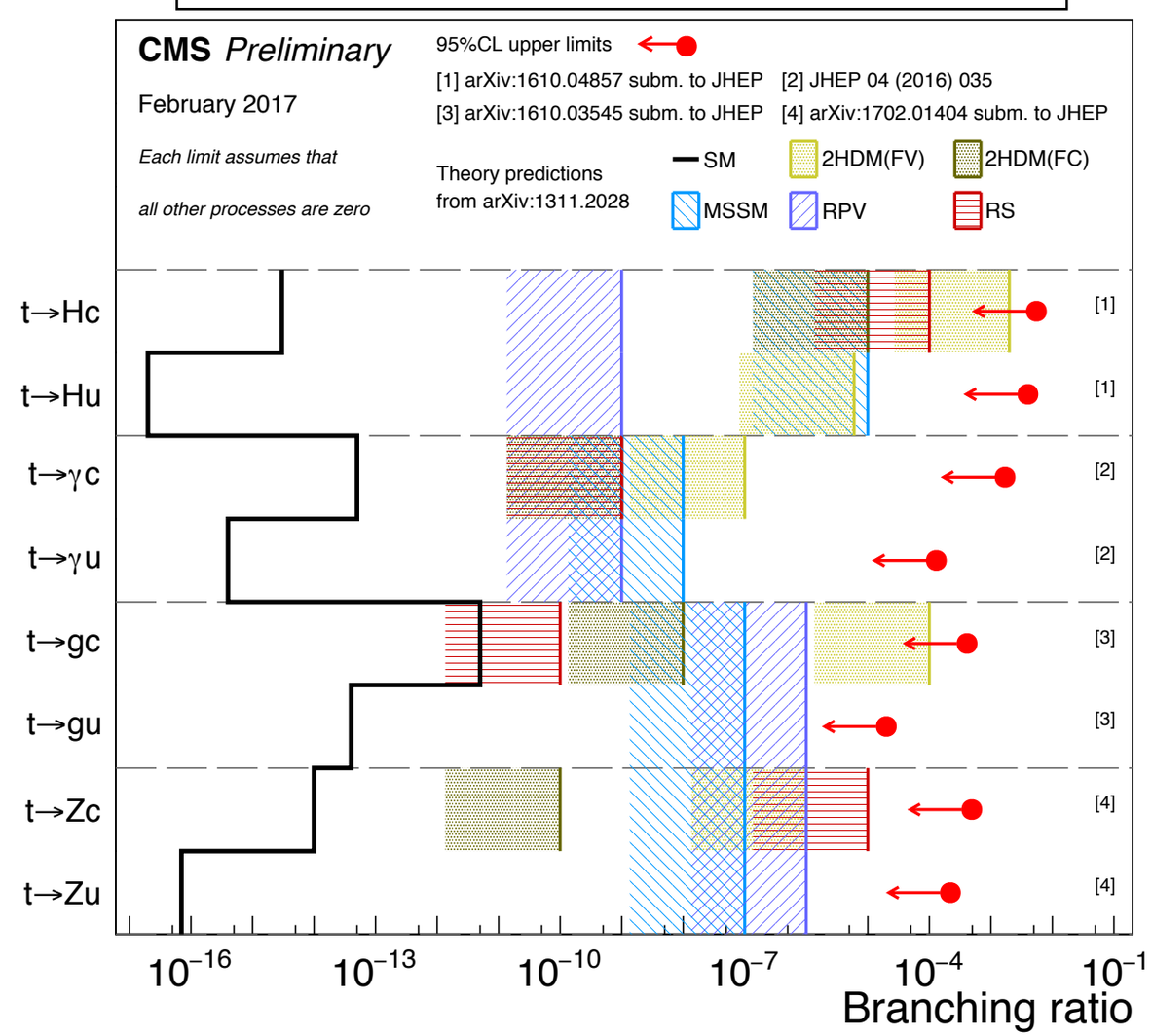
Very Rare: FCNC, σ_{SM} smaller than O(10^{-6} fb), but large BSM enhancements

- Limits on top BR (t→H, γ, g, Z) between 10^{-2} and 10^{-5}



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

Flavor Changing Neutral Currents



Status after LHC Run 1: Anomalous Top

Anomalous couplings: Wtb vertex can include BSM terms

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + \text{h.c.}$$

$$P_{L,R} \equiv \left(1 \mp \gamma^5\right)/2$$
$$\sigma_{\mu\nu} = i(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$$

- Left-handed vector: $f_V^L = V_L = V_{tb} \sim 1$ in the Standard Model
- Right-handed vector, and left/right-handed tensors: f_V^R, f_T^L, f_T^R (aka V_R, g_L, g_R). 0 in SM.

Two 8 TeV analyses: t-channel single top and top pair

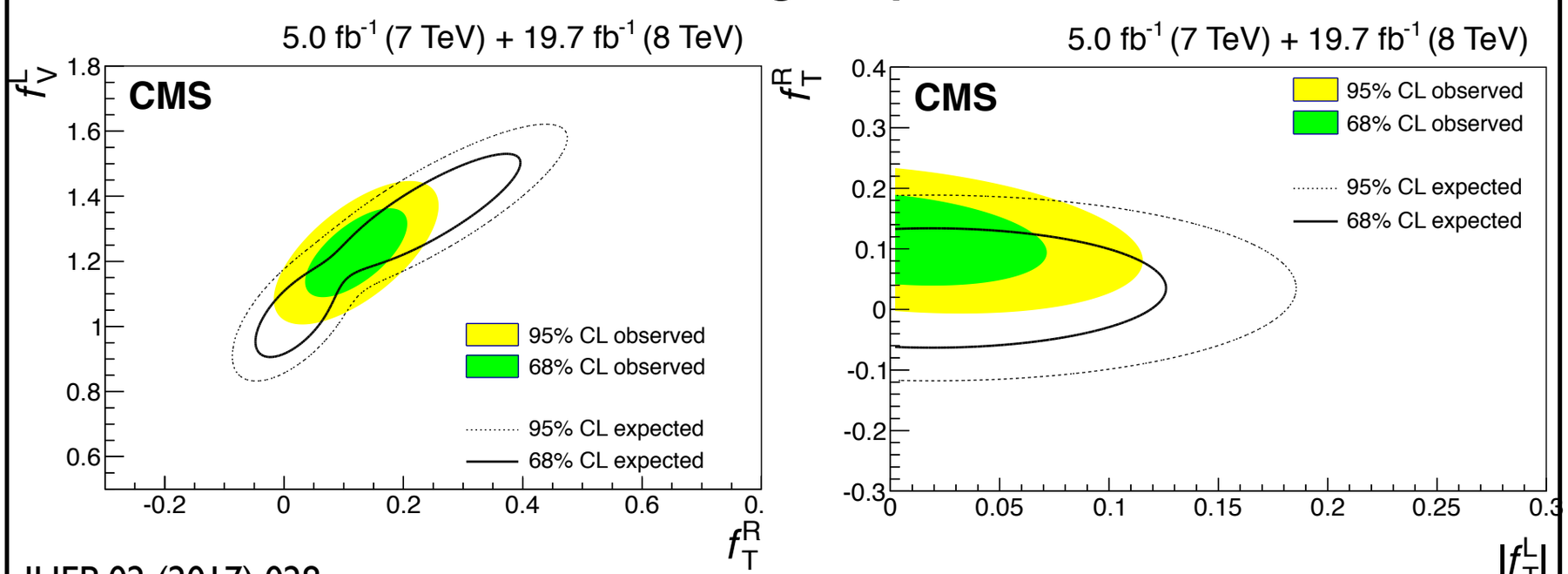
single top: generate samples with anomalous couplings (f_V^R, f_T^L, f_T^R), train Neural Networks on each

- Assume real couplings, and constrain (f_V^L, f_V^R, f_T^L, f_T^R) in 2D or 3D

top pair: measure helicity fractions of the W (F_0, F_L, F_R)

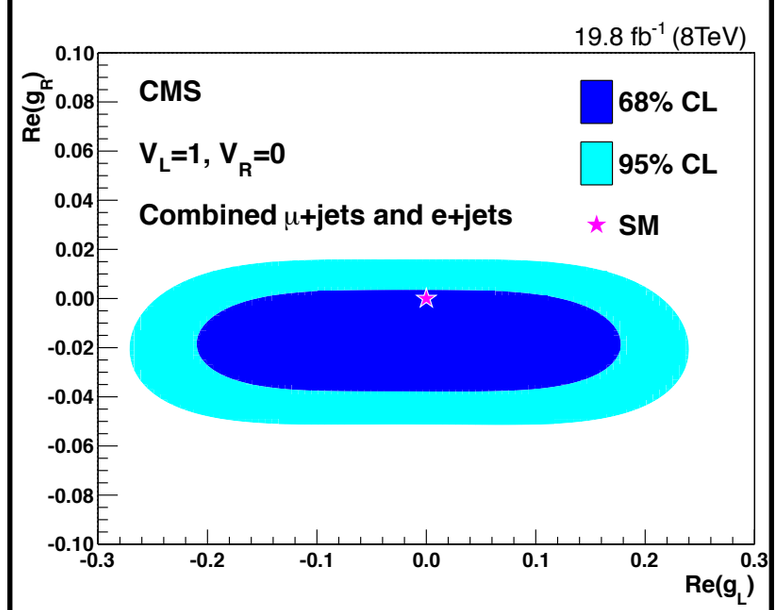
- Assume real couplings, $f_V^L = 1$ and $f_V^R = 0$. Constrain (f_T^L, f_T^R)

single top



JHEP 02 (2017) 028

W helicity in top pair



Phys. Lett. B 762 (2016) 512

Today: Results with 36 fb^{-1} of 13 TeV data

Run 2 results in Rare top:

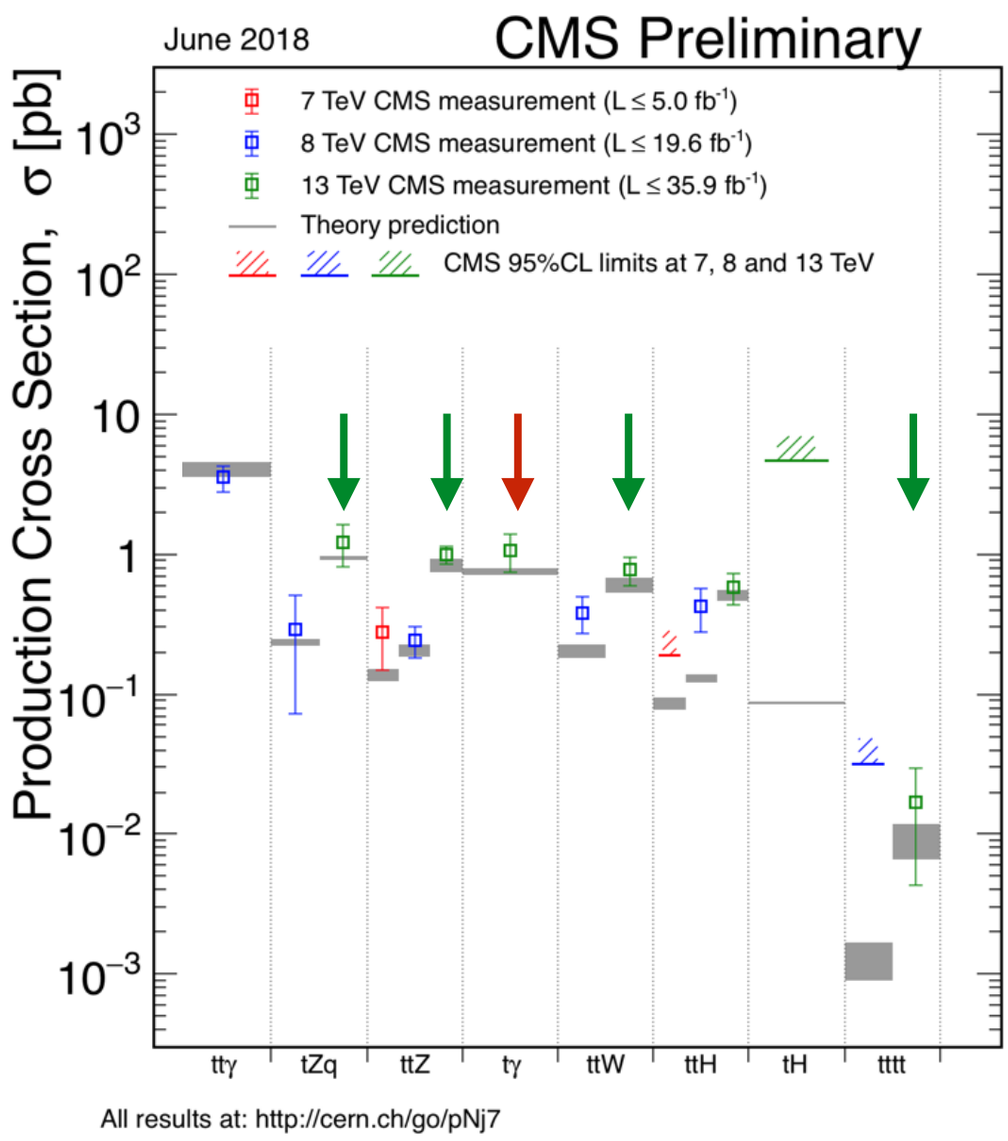
Newest (June 2018)

ttW (5σ), ttZ (5σ), tγ (4.4σ), tZ (3.7σ), tttt (1.6σ)

Highest luminosity results on these processes @ 13 TeV LHC

Run 2 results in Very Rare (FCNC) top:

t→H (H→bb) and t→Z



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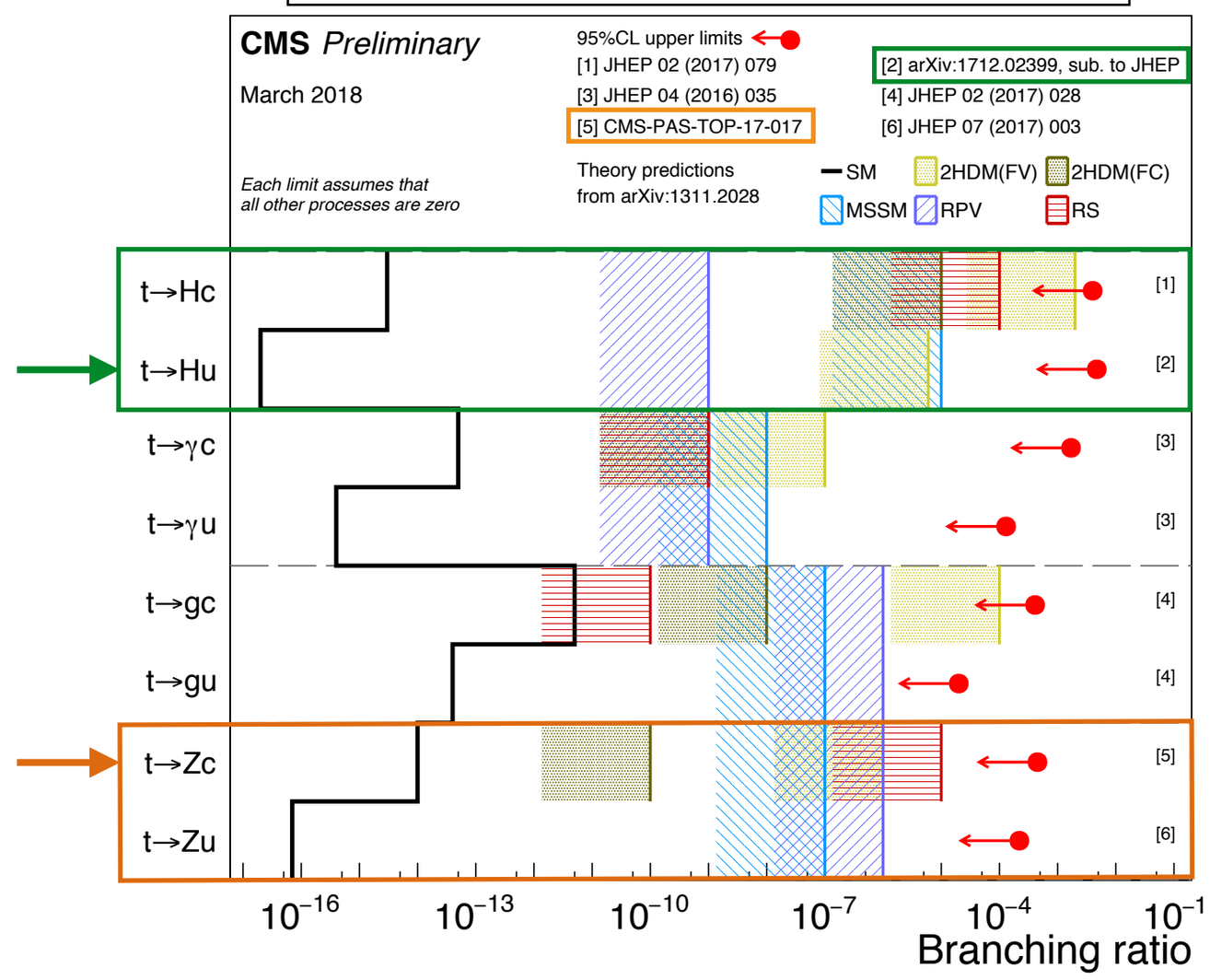
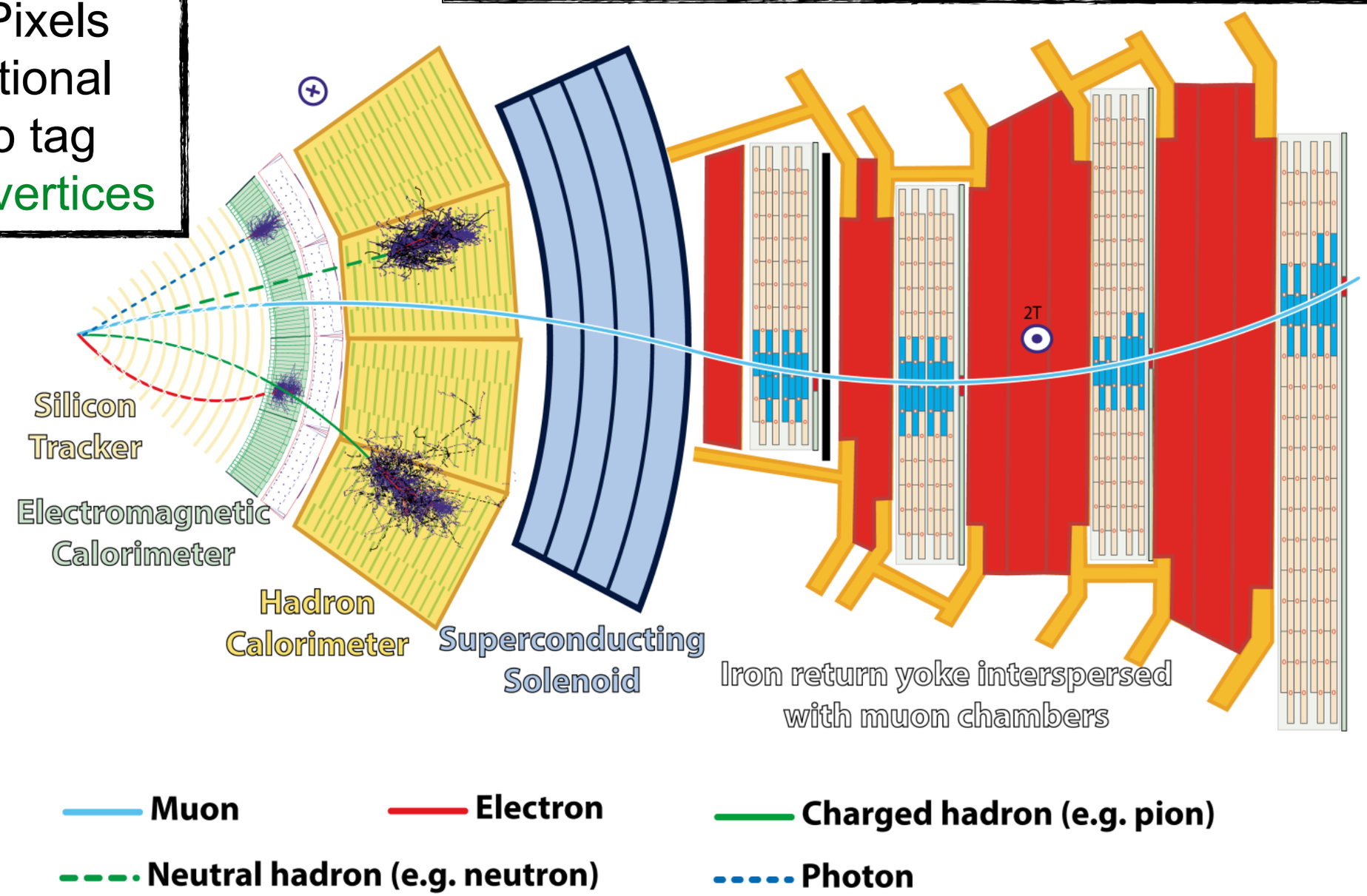


Taking full advantage of the CMS detector: the ingredients for rare/anomalous top

Lepton triggers:
e (Tracker and ECAL)
μ (Tracker and Muon Chambers)

Full event reconstruction: rely on high granularity to identify and reconstruct each individual particle, classified into mutually exclusive categories. Ingredients to define e, μ, γ, jets and MET

b-tagging: Pixels supply additional resolution to tag secondary vertices

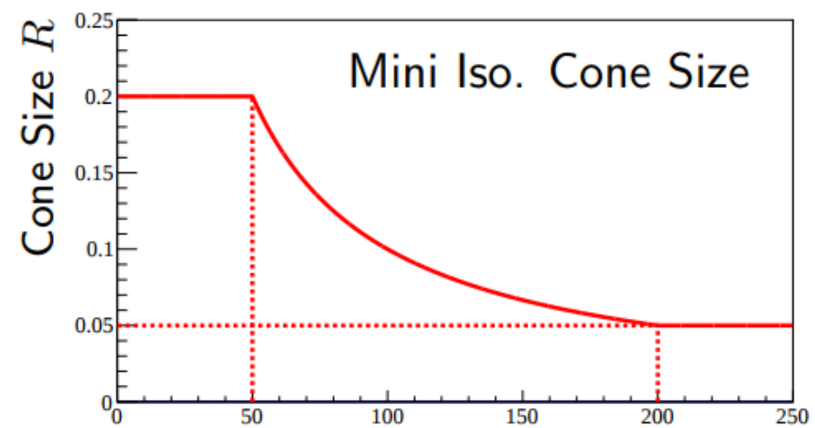


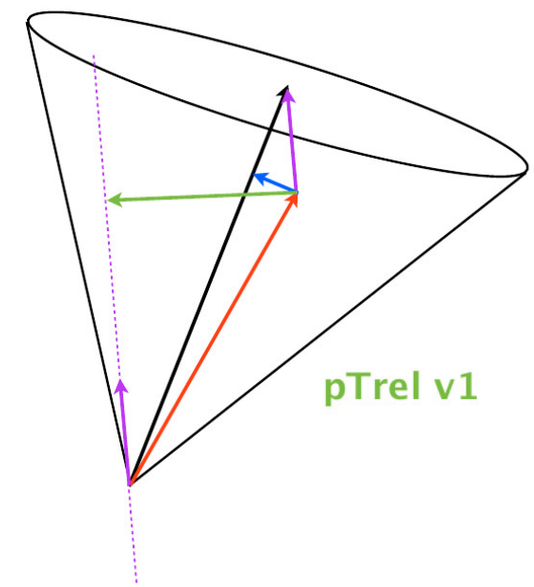
New at 13 TeV: leptons and b-jets

Lepton selection optimized for high multiplicity environments

Combine three simple variables with square cuts

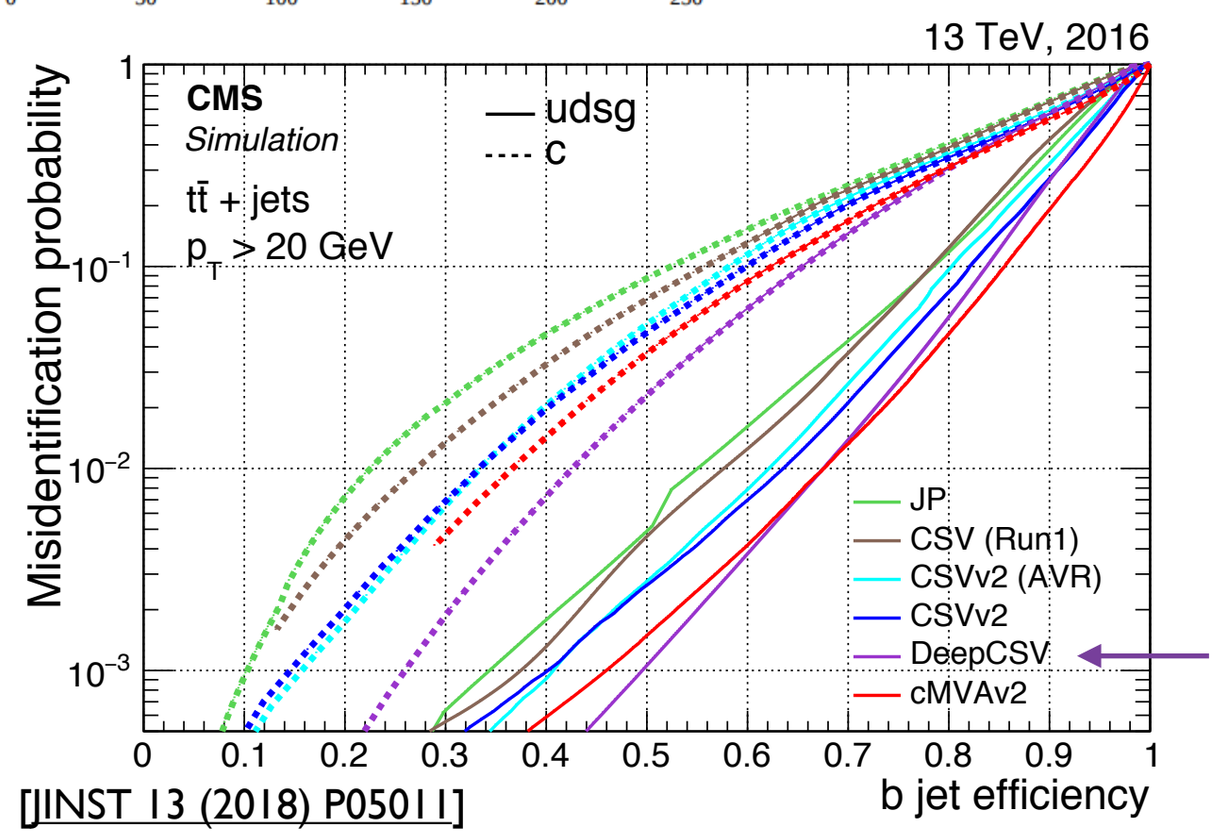
- (i) Large cone isolation: strongest background rejection, but loses efficiency in dense environments
- (ii) Small cone isolation and (iii) lepton momentum w.r.t. surrounding jet: recover leptons overlapping with jets due to boost or multiplicity





Update b-tagging of jets, using deep learning

Based on Run 1 tagger ("CSV"), but using more tracks and featuring 4 hidden layers



[JINST 13 (2018) P05011]

New at 13 TeV: background estimates

Many rare top analyses reject tt by requiring 2 same-sign or ≥ 3 leptons

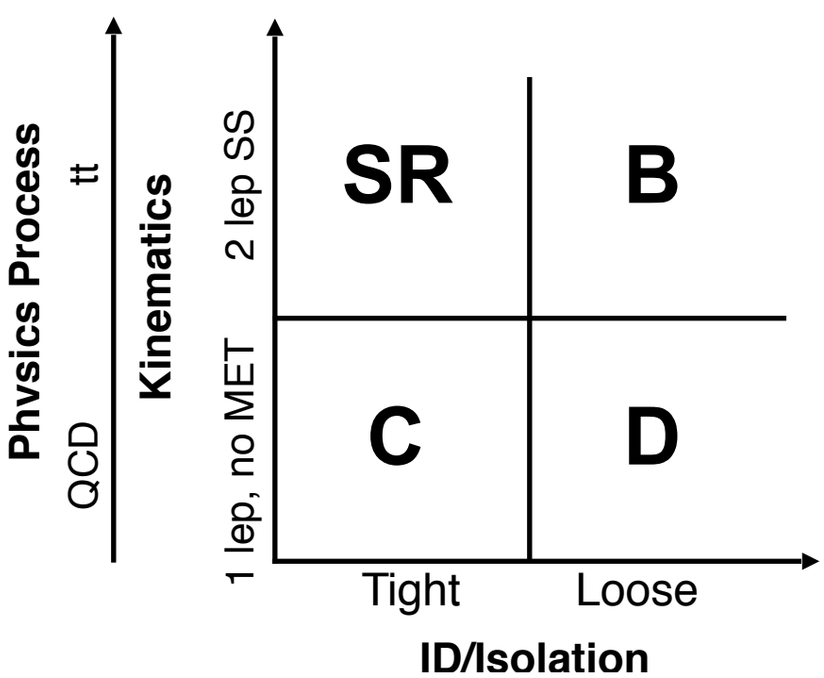
tt events can still pass the selection, due to different sources of "nonprompt" leptons

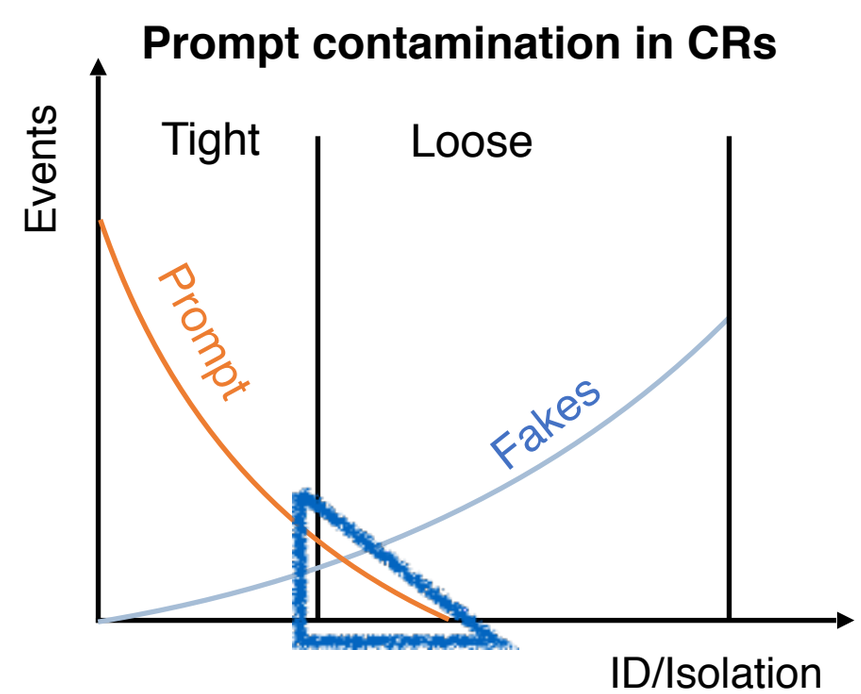
- Leptons from decays of heavy-flavor and light-flavor hadrons
- Hadrons misidentified as leptons
- Conversions of γ in jets

Even after strongly <u>reducing it</u>, still need dedicated methods to <u>estimate it</u>

Basic estimate is based on "fake rate" method (aka ABCD)

- Measure a Tight/Loose ratio in a control region, apply it to signal region

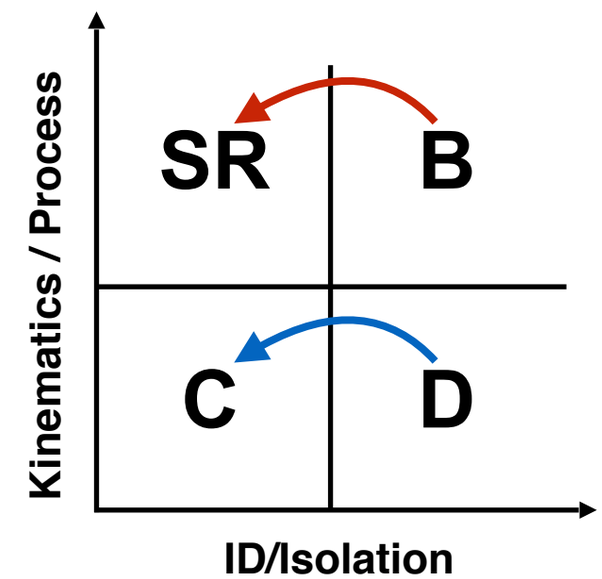




New at 13 TeV: background estimates

ABCD works well, as long as two axes are uncorrelated, i.e. the transfer factor applies to SR:

$$TF \equiv \frac{C}{D} \stackrel{?}{=} \frac{SR}{B}$$



Any biases should be understood and parametrized

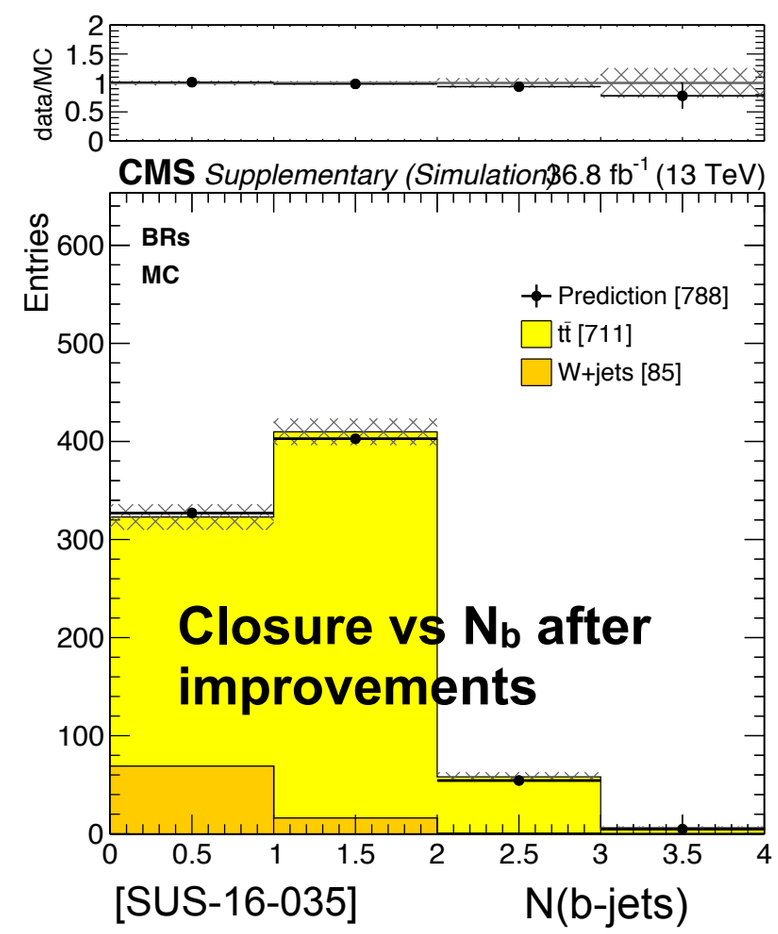
- 1st order bias (well understood): lepton kinematics
- 2nd: p_T and flavor (b/c/light) of lepton's parton parent (p)

Two strategies to avoid the "2nd order" effects:

- Tune the Loose selection to avoid the flavor bias
- Combine p_T^{lepton} and p_T^{parton}: $p_T^{cone} = p_T^l(1 + \mathrm{RelIso})$

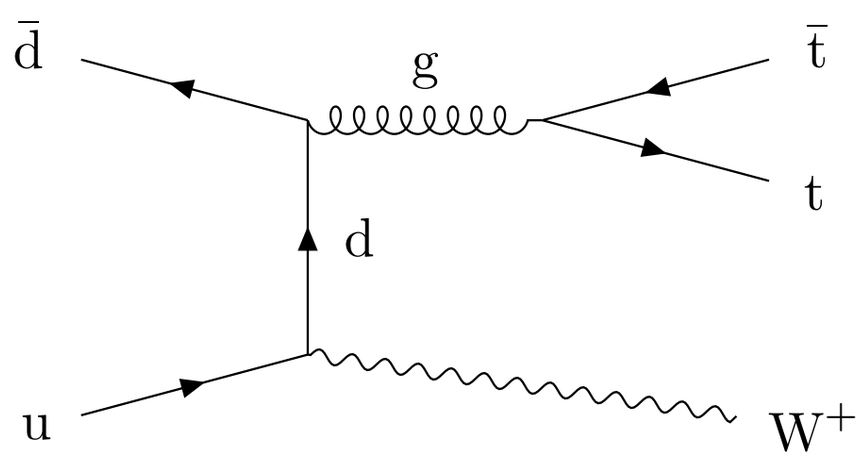
With these improvements, ABCD works out of the box across samples with different kinematics and flavor compositions

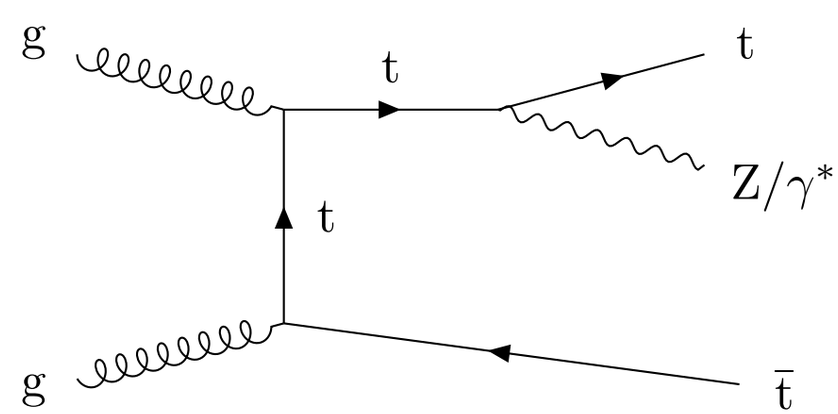
- Left: measure TF in QCD MC, and apply it to tt MC



Measurement of the cross section for top quark pair production in association with a W or Z boson in pp collisions at $\sqrt{s}$ = 13 TeV

The CMS Collaboration
arXiv:1711.02547, submitted to JHEP





ttW, ttZ: analysis strategy

arXiv:1711.02547

Use same-sign dileptons (ttW) and 3 or 4-lepton (ttZ) to reject most of the tt background

Train a kinematic BDT ("D") to separate ttW from nonprompt leptons

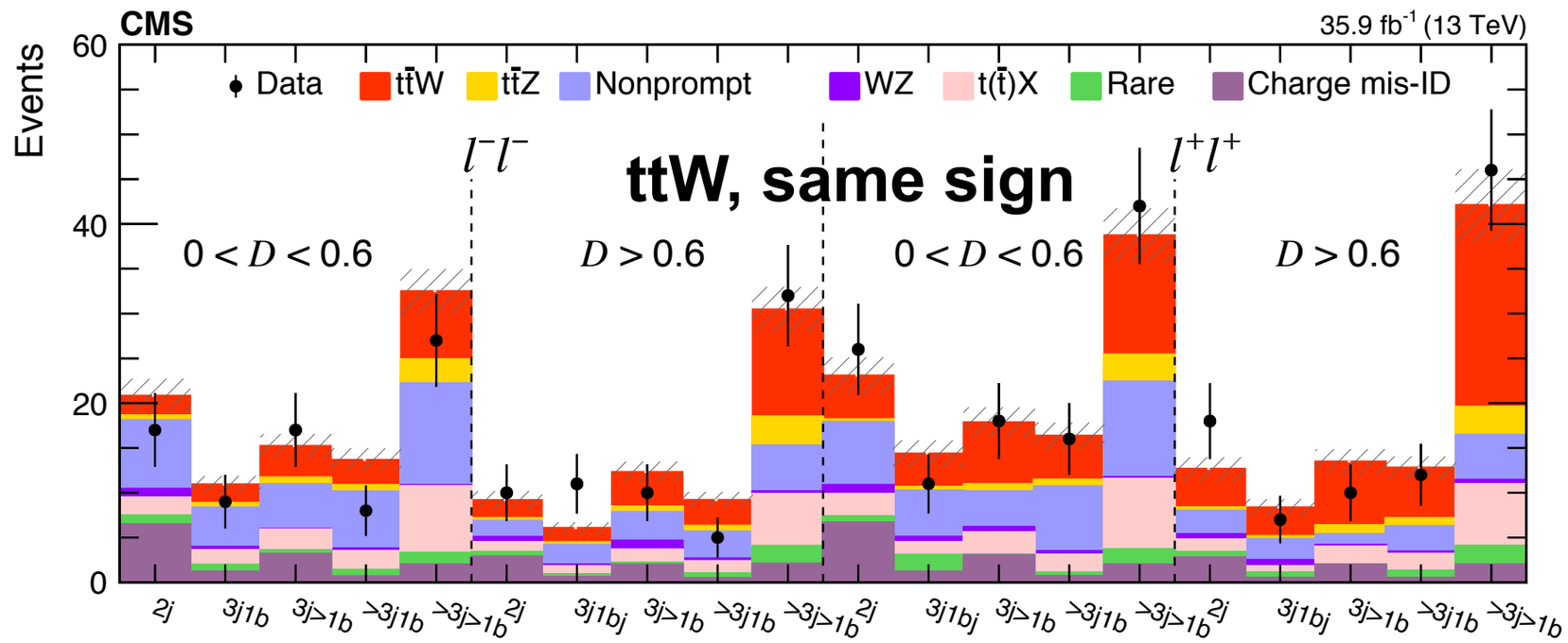
- Variables: N_{jets}, $N_{b\text{-}tags}$, H_T, p_T^{lep1}, p_T^{lep2}, MET, $m_T(W)$, p_T^{j1}, p_T^{j2}, $\Delta R(lep2, j)$

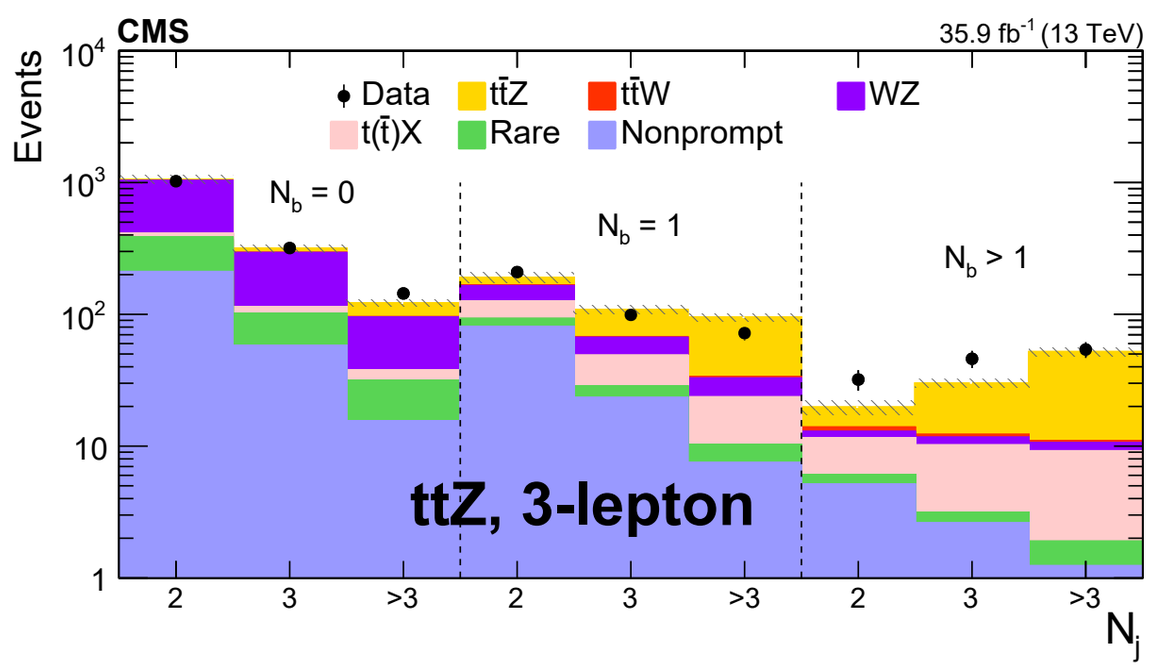
Categorize in $N_{b\text{-}jets}$, N_{jets} to reject prompt backgrounds

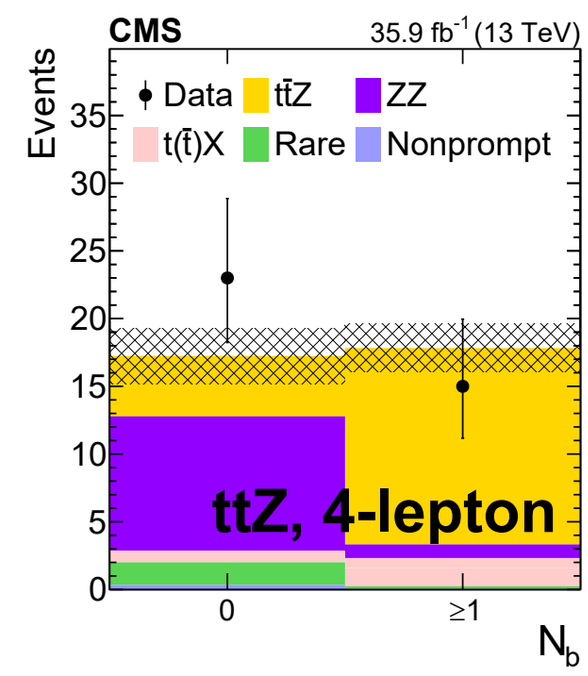
Main backgrounds:

Nonprompt leptons: data-driven

WZ, ZZ: control regions







ttW, ttZ: results

arXiv:1711.02547

Good agreement with theory prediction

- 5 std. dev. significance in both ttW and ttZ

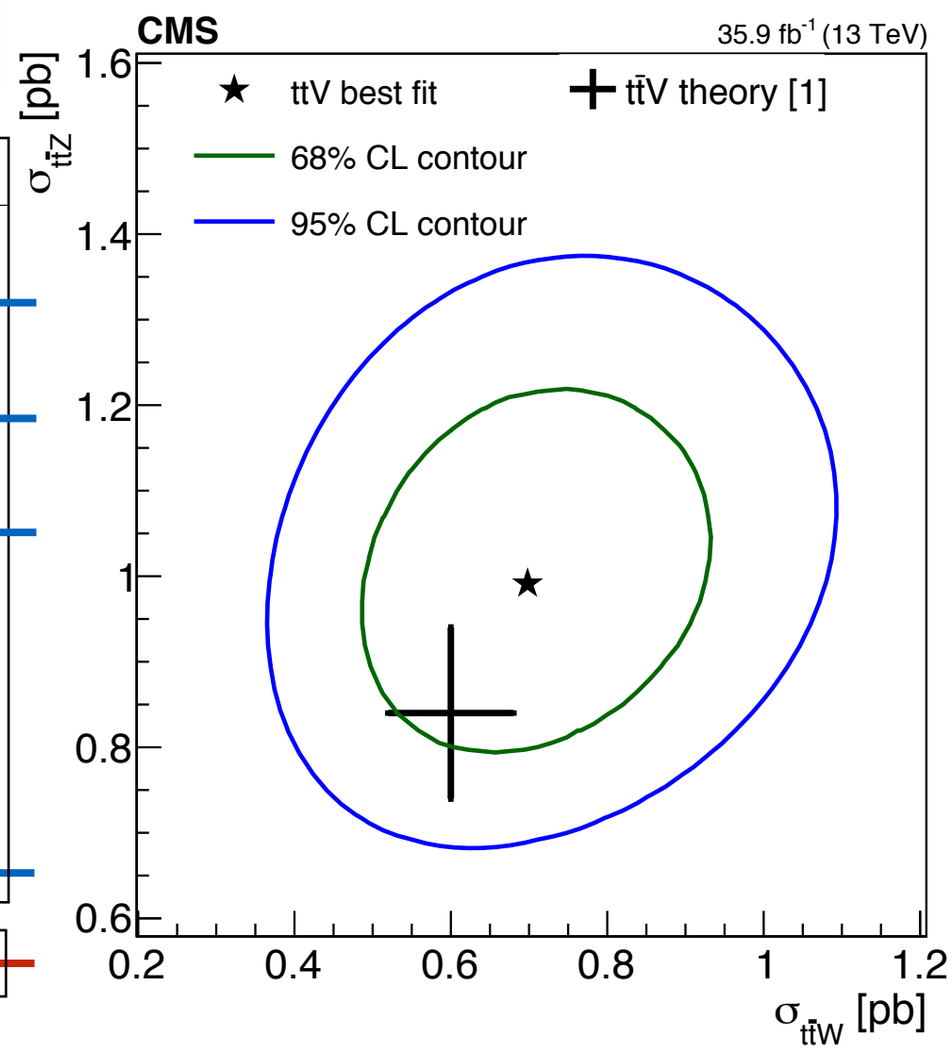
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.13}_{-0.12}\,(\mathrm{syst})\,\mathrm{pb},$$

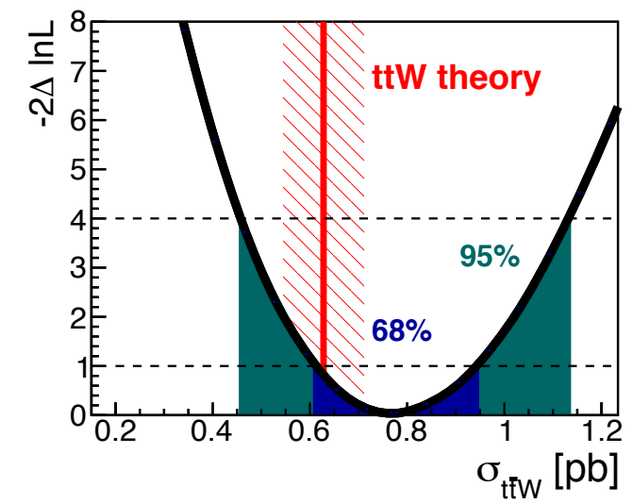
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}.$$

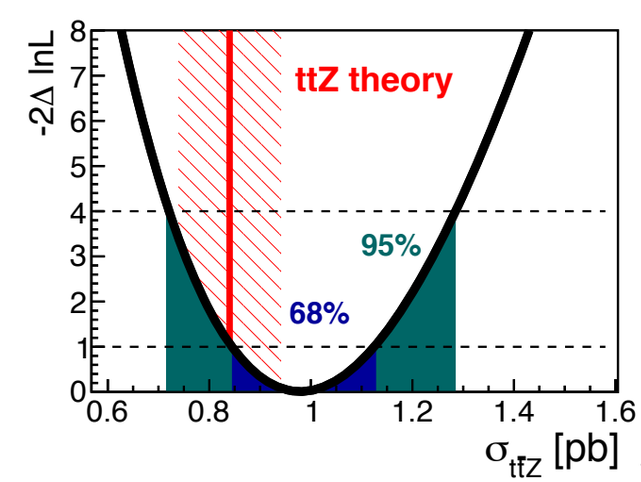
Stat. and syst. uncertainties smaller than 15%

Dedicated developments needed to improve uncertainties further.

Source	σ_{ttZ} (%)	σ_{ttW} (%)
Integrated luminosity	3	4
Jet energy scale and resolution	3	3
Trigger	5	4–5
B tagging	4–5	2–5
PU modeling	1	1
Lepton ID efficiency	6–7	3
Choice in μ_{R} and μ_{F}	1	<1
PDF	1	<1
Nonprompt background	<2	4
WZ cross section	2	<1
ZZ cross section	1	—
Charge misidentification	—	3
Rare SM background	2	2
$\mathrm{t(\bar{t})X}$ background	3	4
Stat. unc. in nonprompt background	2	4
Stat. unc. in rare SM backgrounds	<1	1
Total systematic uncertainty	12	14
Statistical uncertainty	12	15





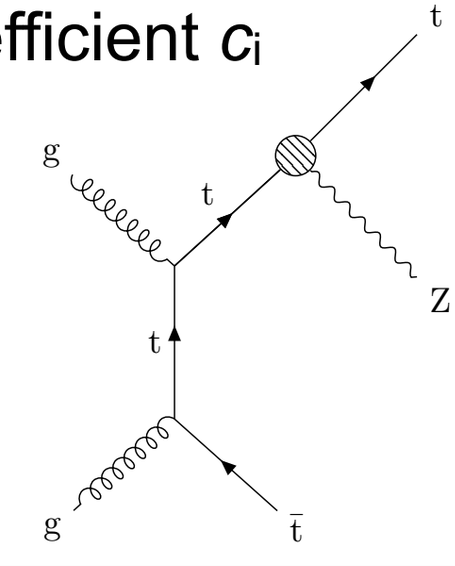


ttW/Z and Effective Field Theory

BSM physics at energy scale Λ may alter cross-sections and kinematics

Parametrize as a function of dimension-6 operators, $\mathcal{O}_i$ with coefficient c_i

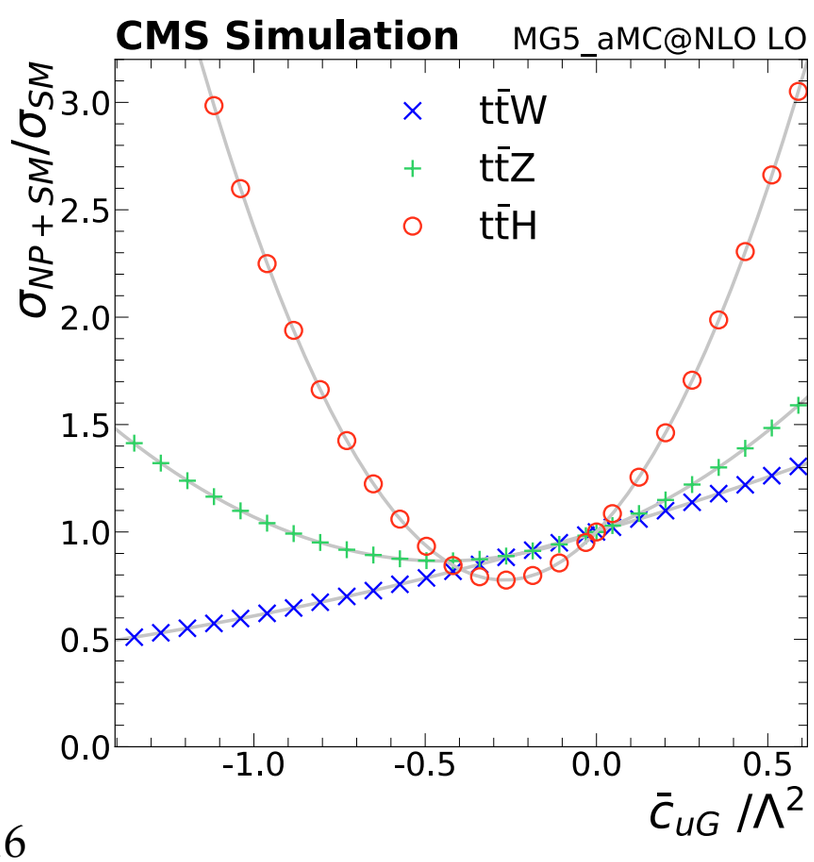
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$



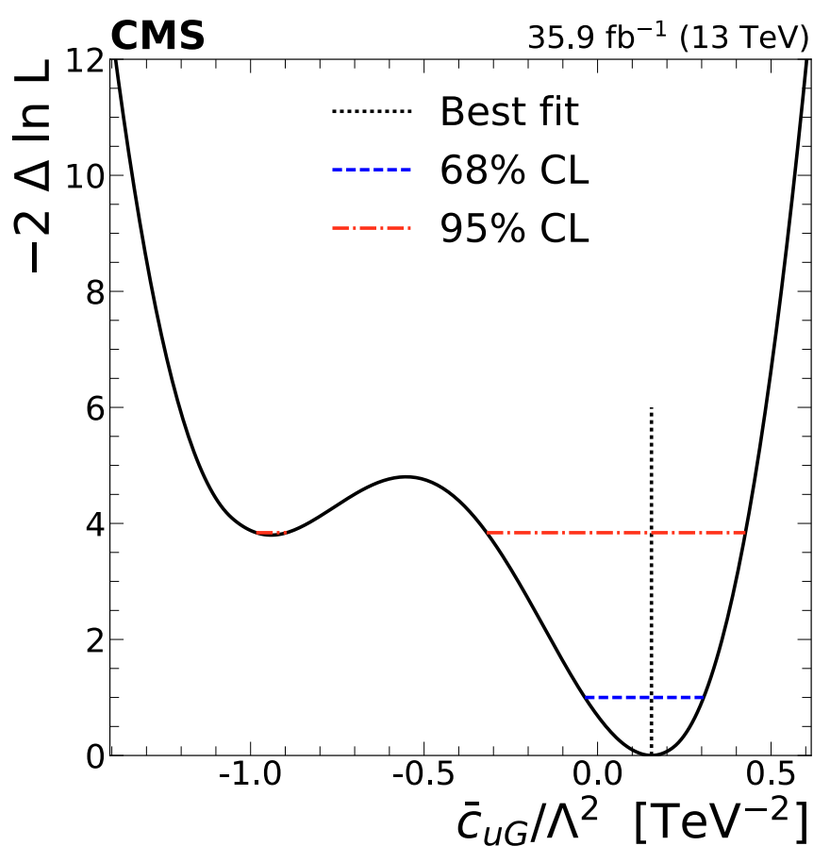
Identify 8 EFT operators mainly affecting σ(ttW) and σ(ttZ)

Use inclusive cross sections to set limits (individually) on c_i/Λ^2

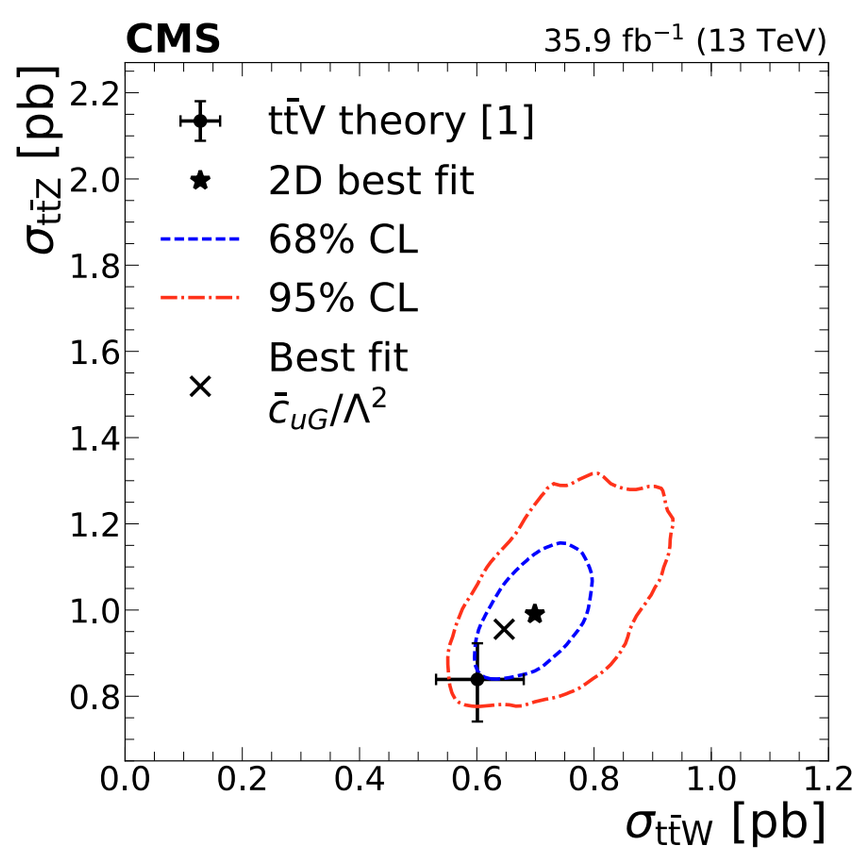
σ(ttX) vs c_{uG}



Fit c_{uG} to $\sigma_{observed}$



Compare $\sigma_{best\ fit}$ with σ_{obs}



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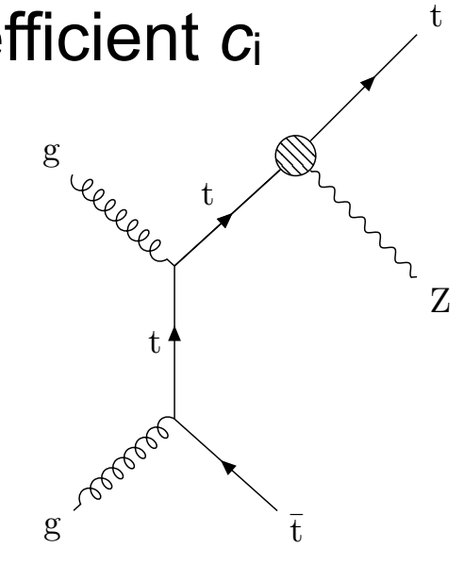

Identify 8 EFT operators mainly affecting σ(ttW) and σ(ttZ)

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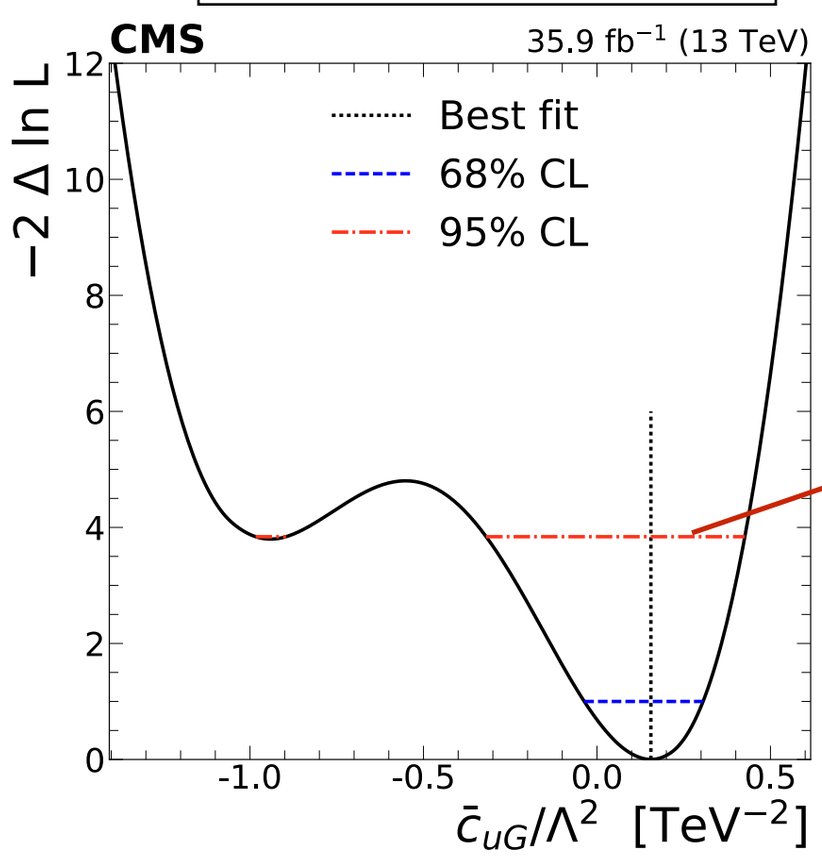
Fit c_{uG} to $\sigma_{observed}$

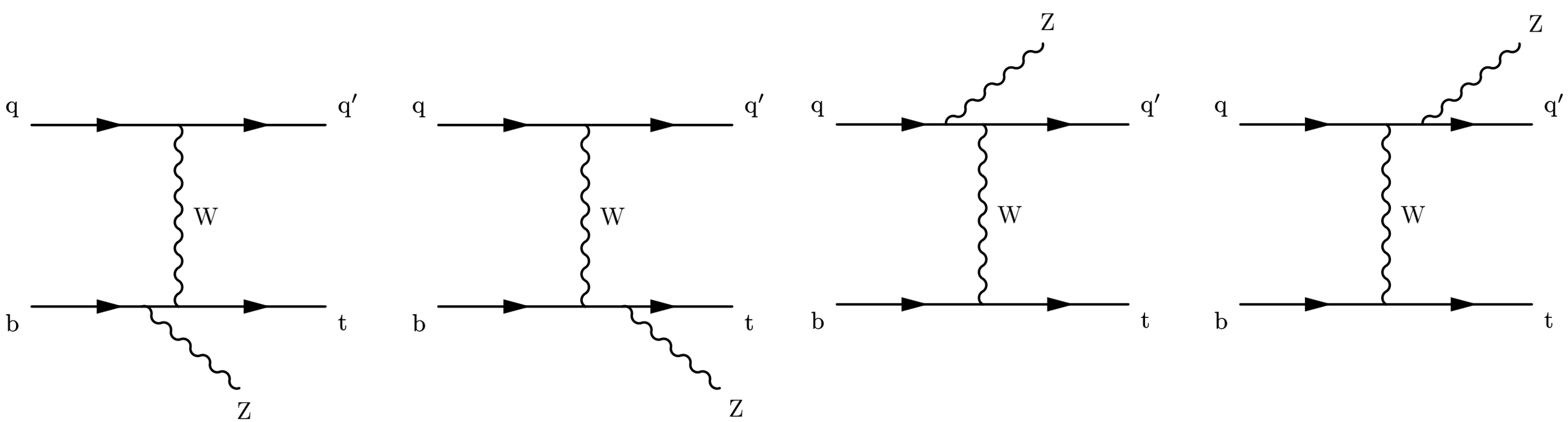


Limits on individual coefficients

Wilson coefficient	95% CL [TeV^{-2}]
$\bar{c}_{\text{uW}}/\Lambda^2$	$[-2.9, 2.9]$
$\lvert\bar{c}_{\text{H}}/\Lambda^2 - 16.8\ \text{TeV}^{-2}\rvert$	$[0, 28.5]$
$\lvert\widetilde{c}_{\text{3G}}/\Lambda^2\rvert$	$[0, 0.9]$
$\bar{c}_{\text{3G}}/\Lambda^2$	$[-0.7, 1.0]$
$\bar{c}_{\text{uG}}/\Lambda^2$	$[-1.0, -0.9]$ and $[-0.3, 0.4]$
$\lvert\bar{c}_{\text{uB}}/\Lambda^2\rvert$	$[0, 2.7]$
$\bar{c}_{\text{Hu}}/\Lambda^2$	$[-11.1, -6.5]$ and $[-1.6, 3.0]$
$\bar{c}_{\text{2G}}/\Lambda^2$	$[-1.1, 0.8]$

Measurement of the associated production of a single top quark and a Z boson in pp collisions at $\sqrt{s}$ = 13 TeV

The CMS Collaboration
Phys. Lett. B 779 (2018) 358, arXiv:1712.02825



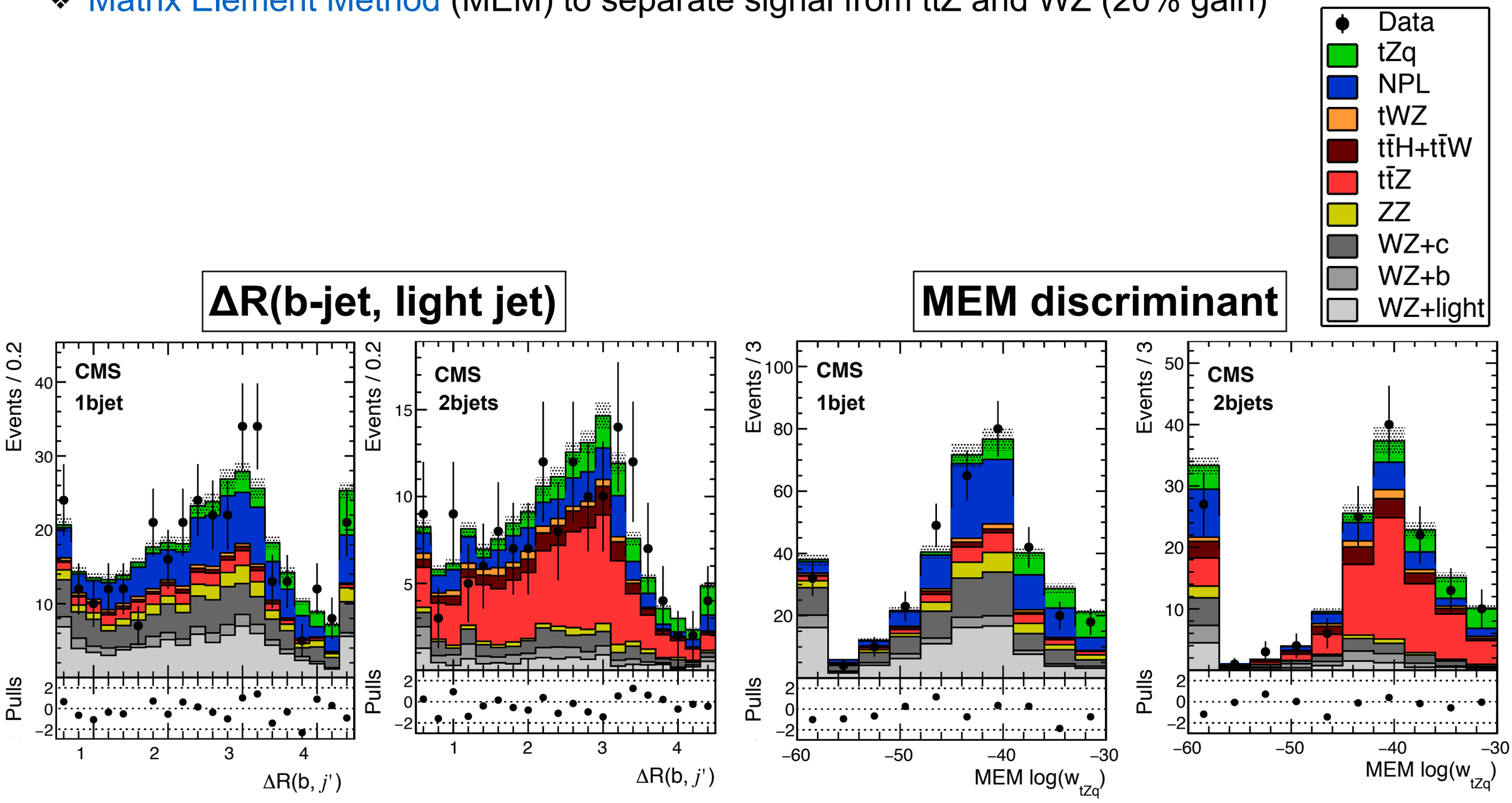
tZ: analysis strategy

Phys. Lett. B 779 (2018) 358

Signature: 3 leptons, one Z candidate, at least 2 jets of which 1 or 2 b-tagged

Use 2 BDTs (for 1bjet and 2bjet regions) to separate signal and sum of backgrounds

- Kinematics: lepton, jet, Z, reconstructed top quark, b-tagging discriminants
- Matrix Element Method (MEM) to separate signal from ttZ and WZ (20% gain)



tZ: results

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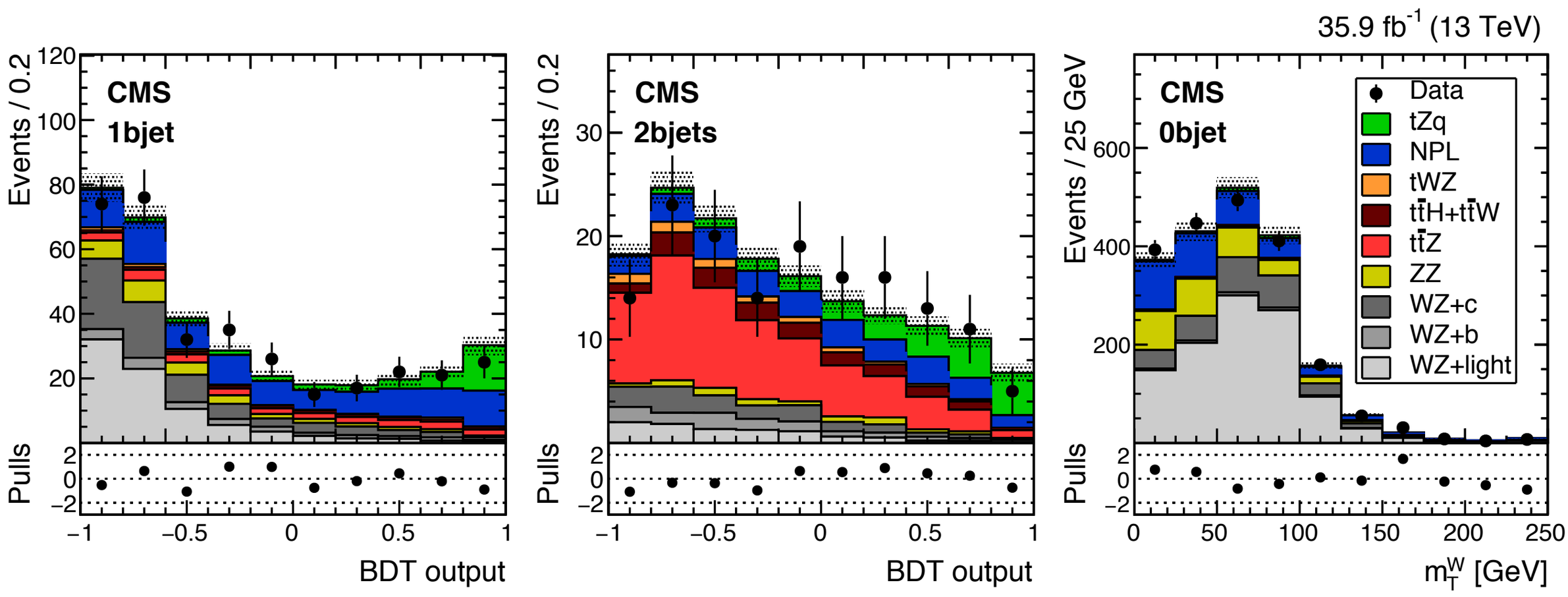
Background normalizations based on a simultaneous fit in 3 regions

- $N_{b\text{-jets}} = 1$, BDT distribution: extract signal
- $N_{b\text{-jets}} = 2$, BDT distribution: constrain ttZ, some signal
- $N_{b\text{-jets}} = 0$, $m_T(W)$ distribution: constrain WZ and nonprompt leptons



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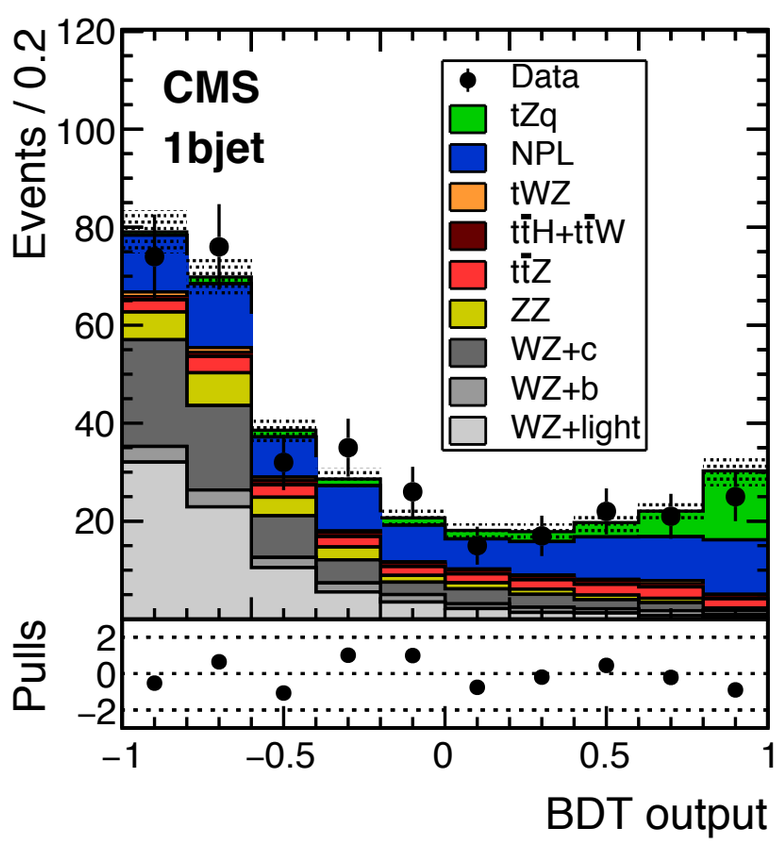
- $N_{b\text{-jets}} = 2$, BDT distribution: constrain ttZ, some signal
- $N_{b\text{-jets}} = 0$, $m_T(W)$ distribution: constrain WZ and nonprompt leptons



Main systematics:

Backgrounds: nonprompt lepton and ttZ

Detector effects: b-tagging

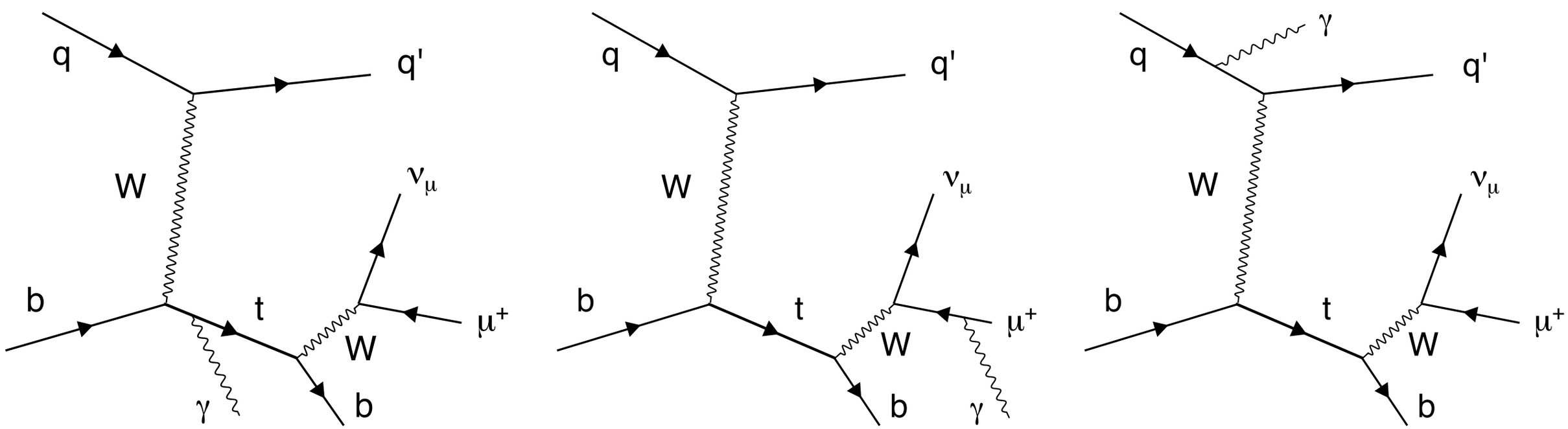
Signal modelling: parton shower scales

	Significance	$\sigma(pp \to tZq \to t\ell\ell q)$, with $m_{\ell\ell} > 30$ GeV [fb]
Pred.	3.1	94.2 ± 3.1
Meas.	3.7	$123\ ^{+33}_{-31}$ (stat) $^{+29}_{-23}$ (syst)

Search for top+photon production in pp collisions at 13 TeV in the muon+jets channel

The CMS Collaboration
CMS-PAS-TOP-17-016

First Evidence!!



tγ: analysis strategy

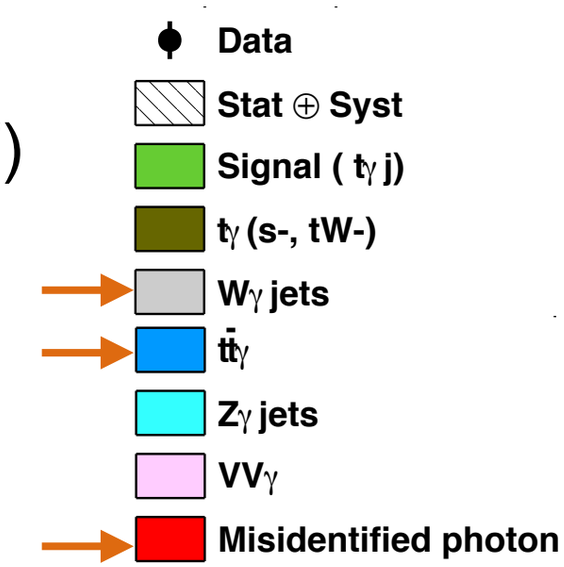
Signature: 1 isolated γ, 1 μ, 1 b-tagged jet and 1 untagged jet

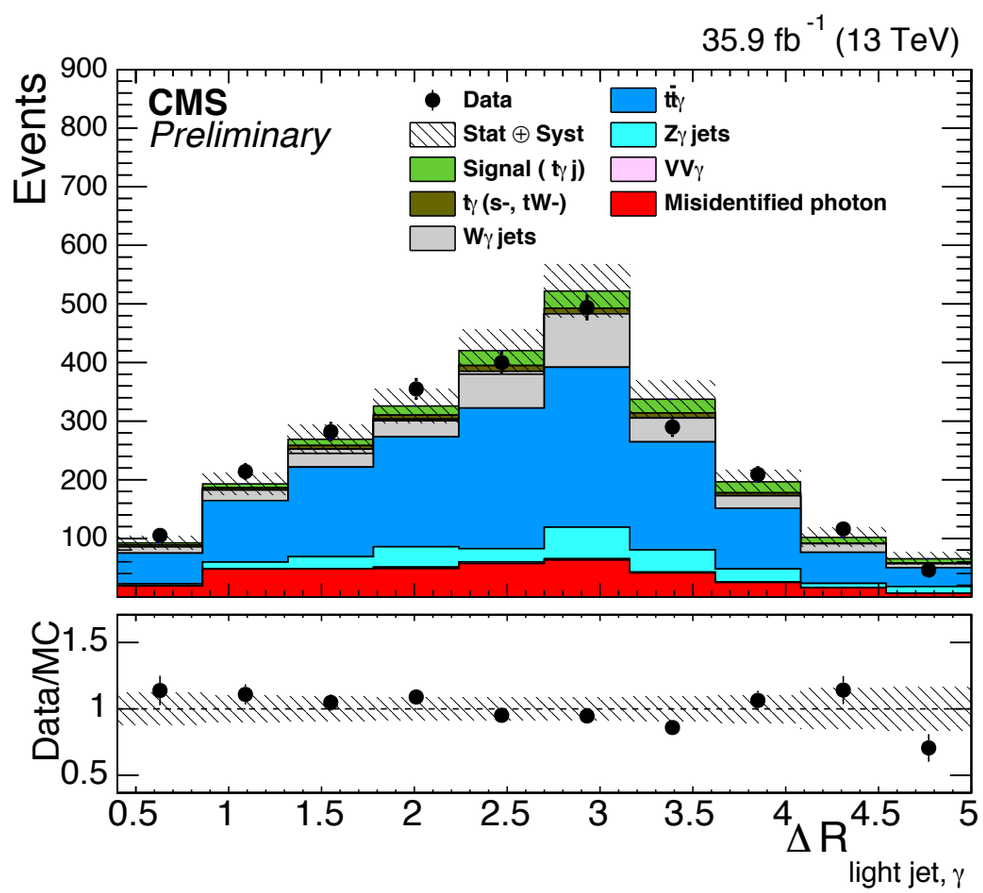
Use a BDT to separate signal and sum of backgrounds

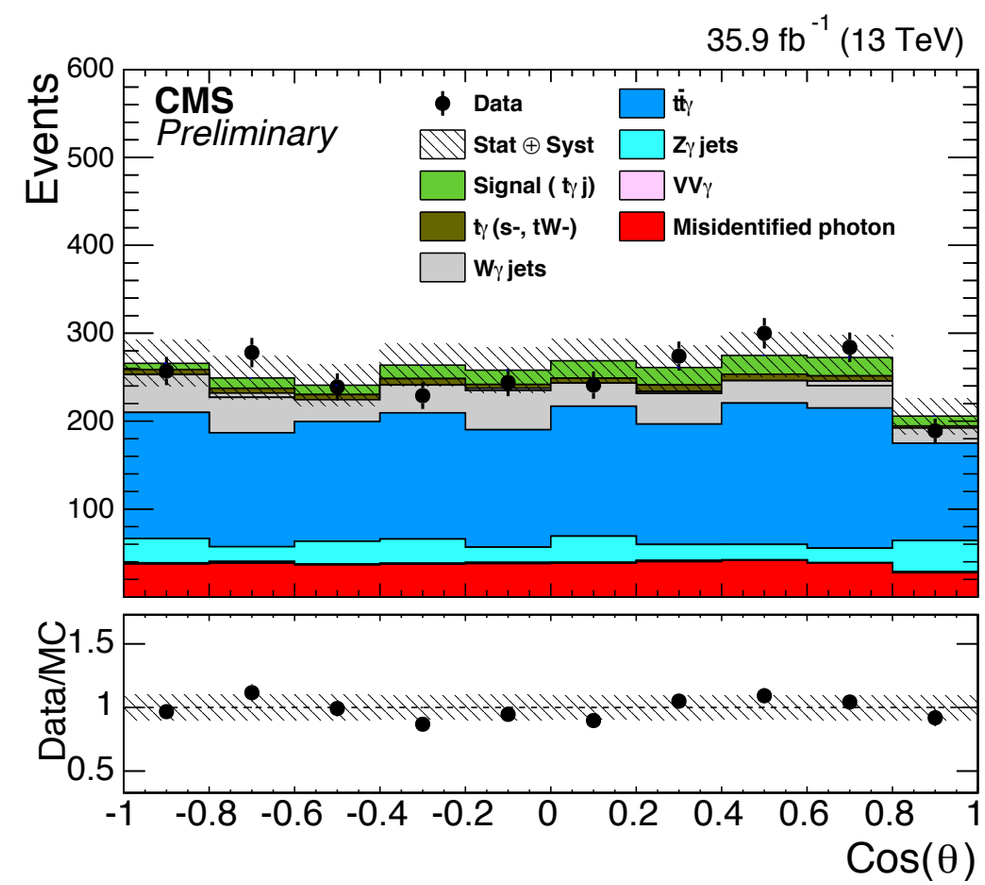
- Kinematics: $\eta^{\text{light jet}}$, η^{μ}, ΔR(light jet, γ), cos(θ), $m_{\mu\nu b}$, N_{jets}, $m_T(W)$
- No b-tagging information: use $N_{b\text{-jets}}$ to build control regions

Background normalization and shapes from data:

- Fake photons: use photon ID/isolation sidebands
- $t\bar{t}\gamma$: use data with $N_{b\text{-jets}}=2$







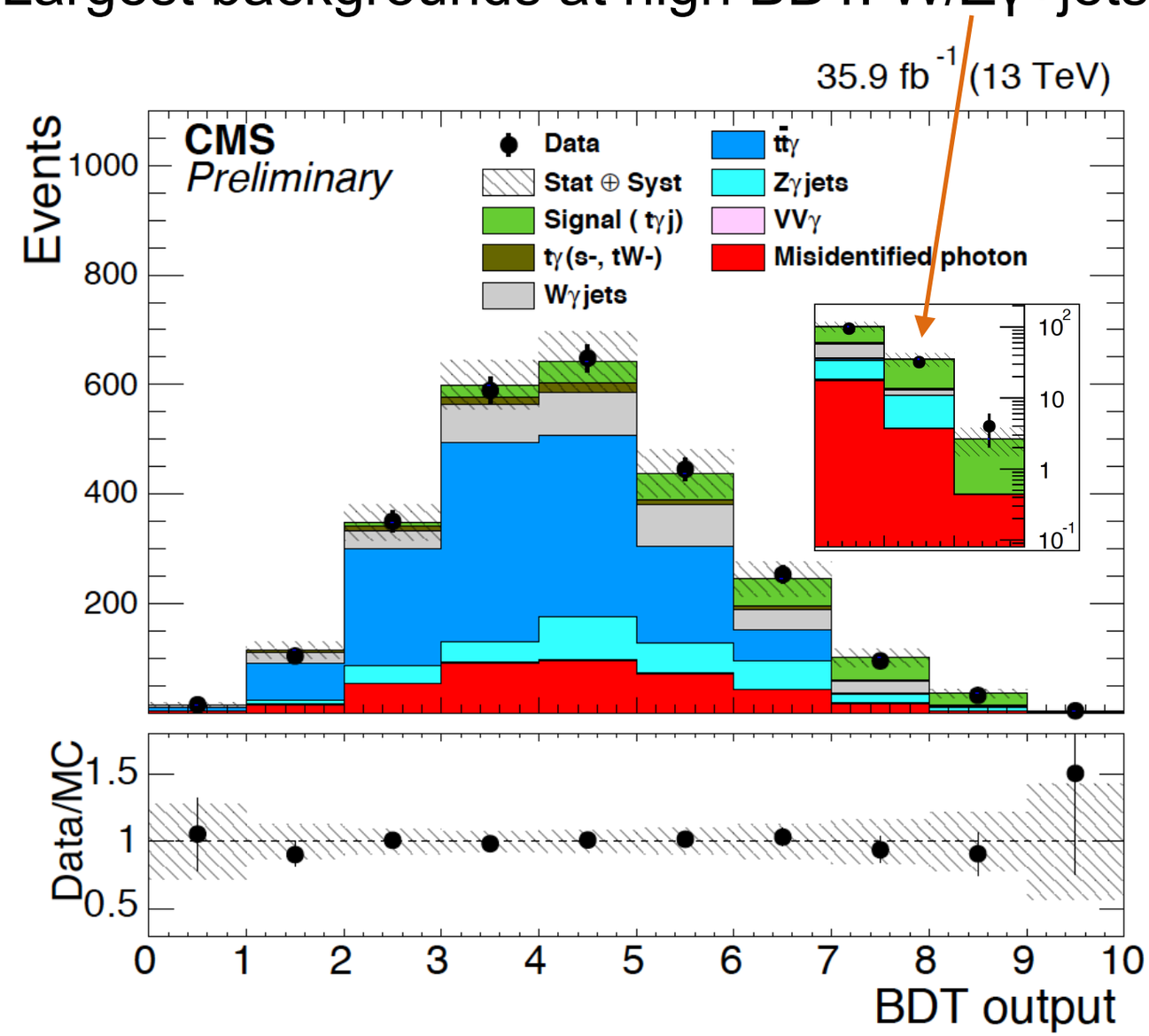
θ = angle btw μ and light jet in t frame

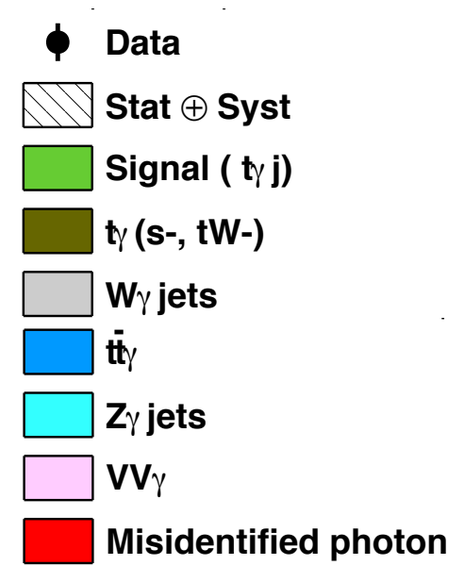
tγ: results

Uncertainties dominated by systematics

- jet energy (12%), b-tagging (7%)
- tγ modeling (9%): scale, PDF, hadronization/showering
- Zγ+jets (8%)

Largest backgrounds at high BDT: W/Zγ+jets



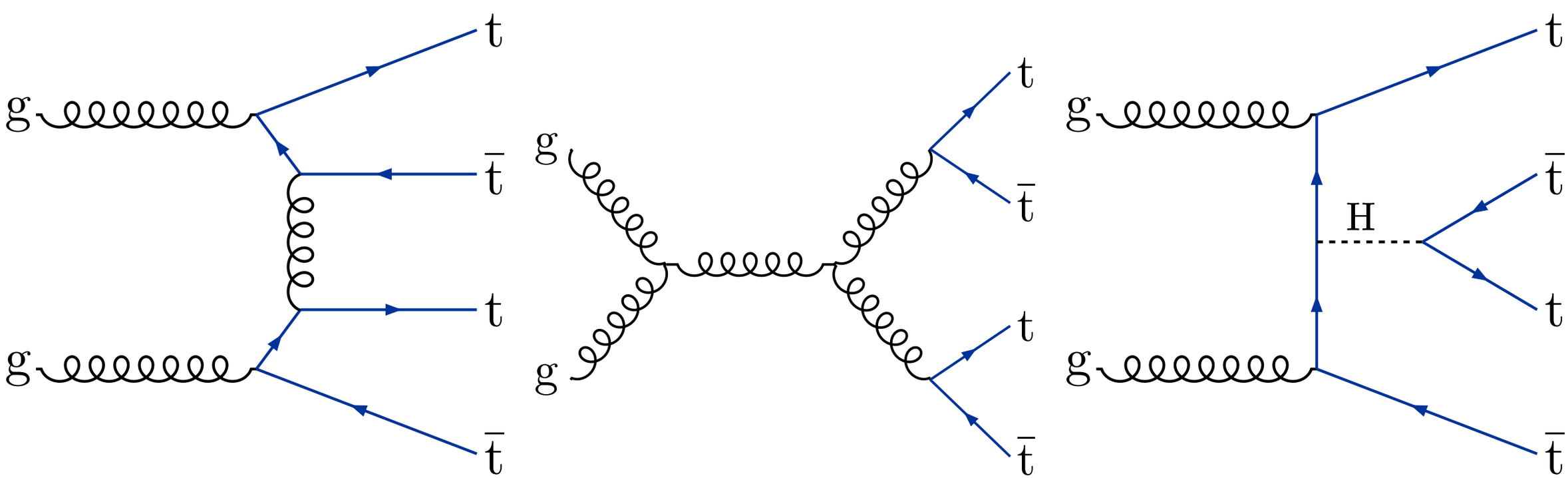


	Significance	σ(tγ)*B(t→μνb) [fb]
Pred.	3.0	81 ± 4
Meas.	4.4	115 ± 17 (stat) $^{+33}_{-27}$ (syst)

First Evidence!!

Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV

The CMS Collaboration
Eur. Phys. J. C 78 (2018) 140, arXiv:1710.10614



tttt: status of SM calculation

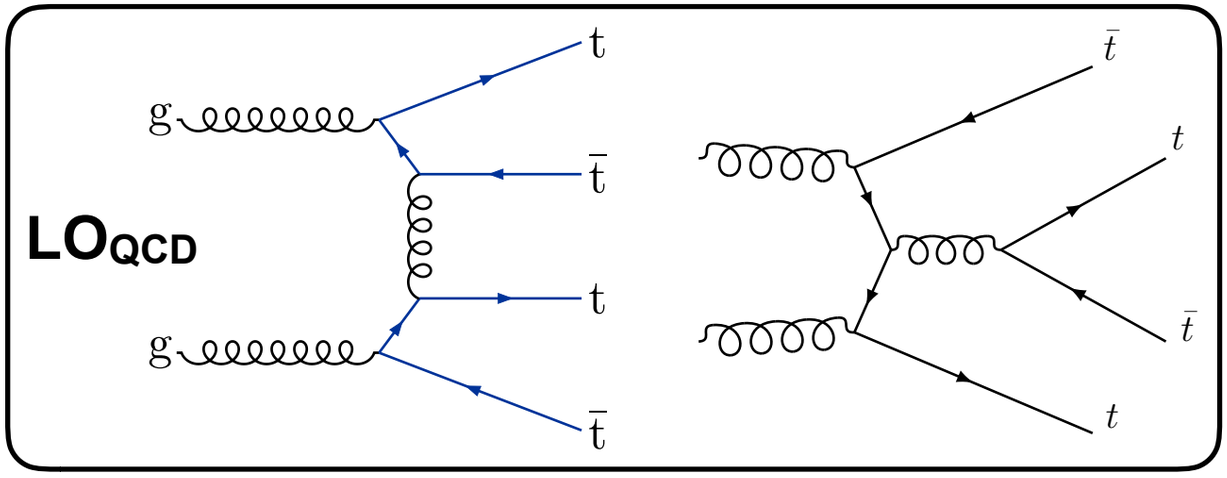
Large theoretical uncertainties in tttt inclusive cross section

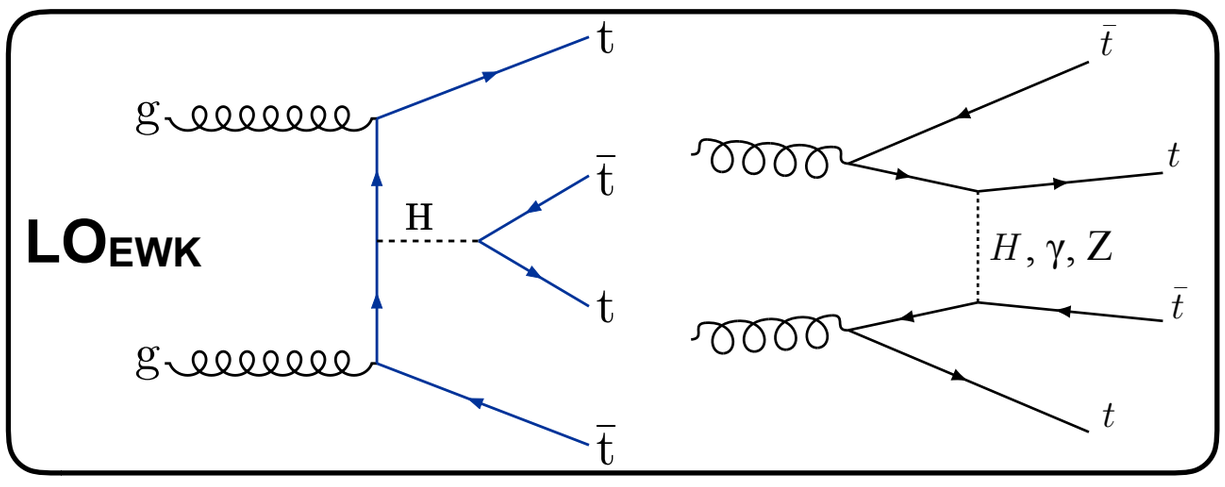
QCD NLO/LO k-factor ranges between 1.2 and 2.0, depending on scale and PDF choices

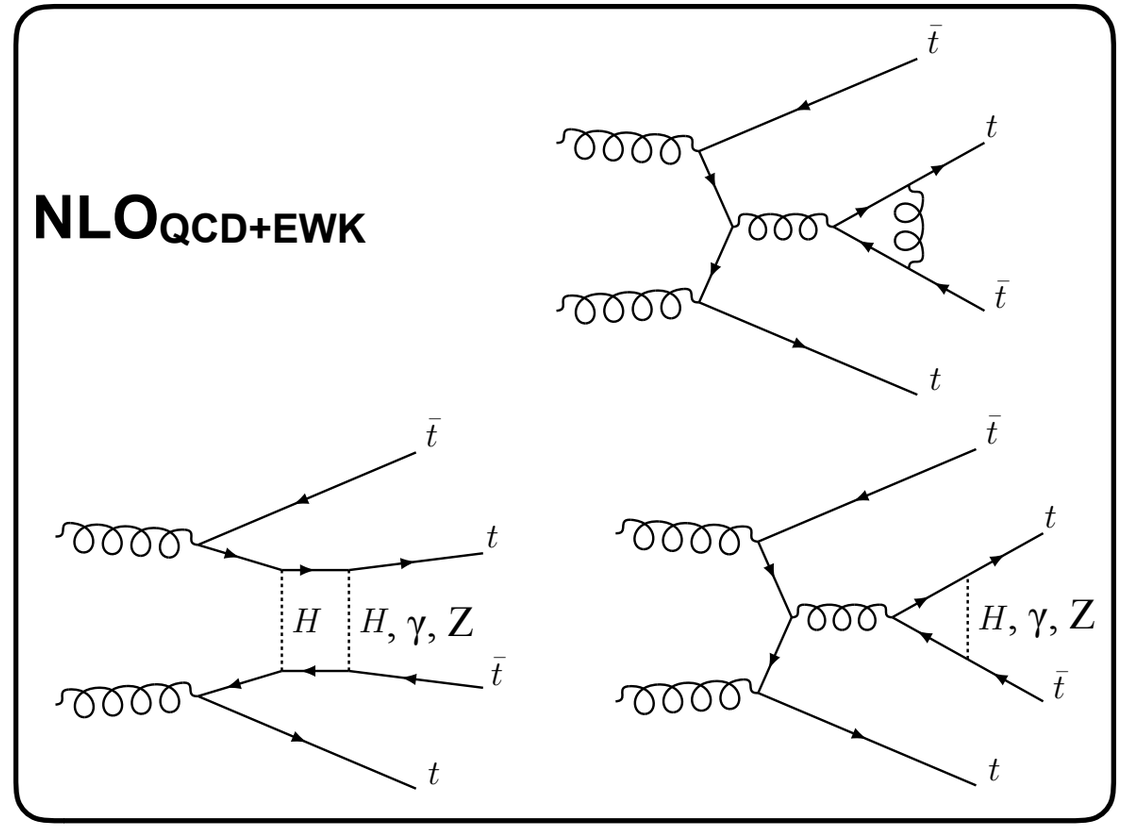
Large effects (up to 40%) from Leading Order EWK diagrams

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

Most recent prediction, including EWK NLO effects: $12^{+2.2}_{-2.5}$ 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]

tttt: analysis strategy

All-hadronic

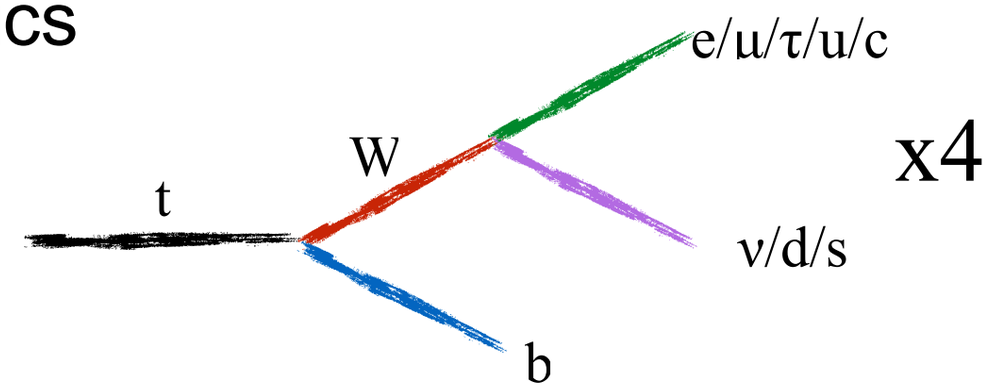
Powerful in boosted searches for new physics

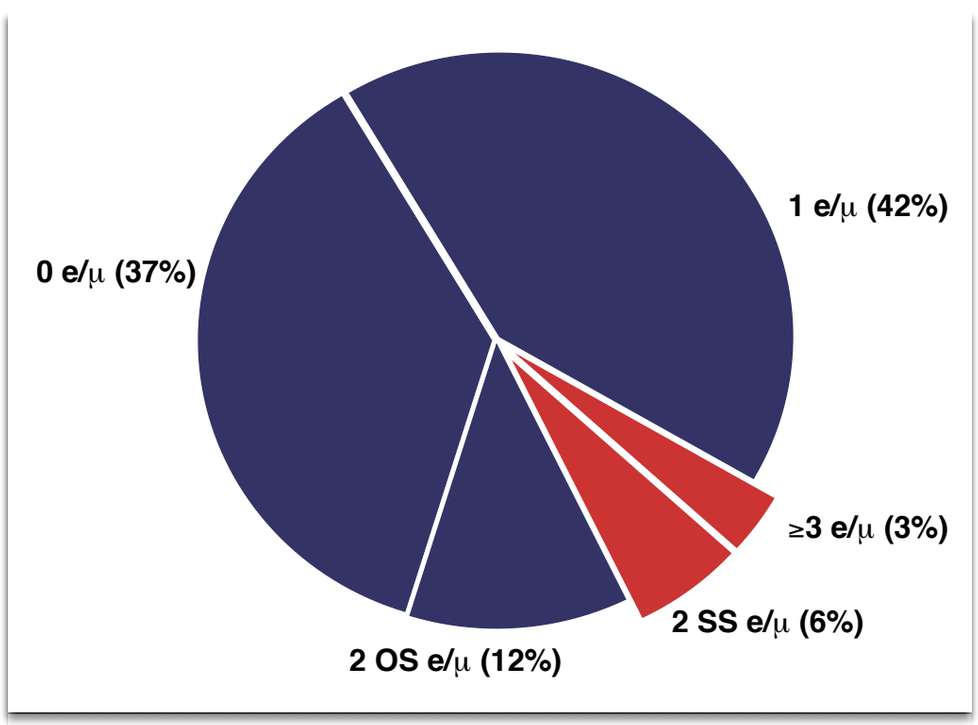
1 lepton and opposite-sign 2 leptons

Large tt pair-production background

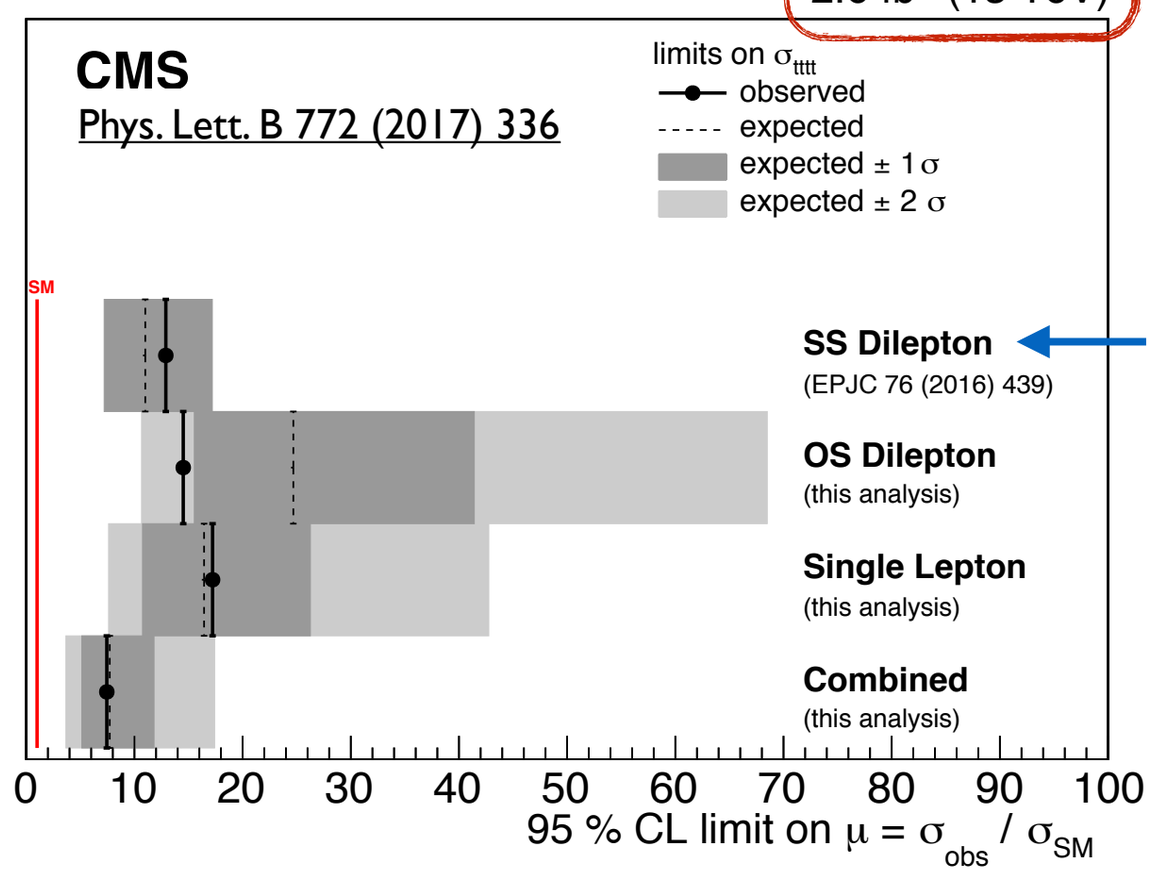
2 same-sign or ≥ 3 leptons

Comparable branching to OS2L, reject tt background





Latest CMS combination: 2.6 fb^{-1} (13 TeV)



tttt: analysis strategy

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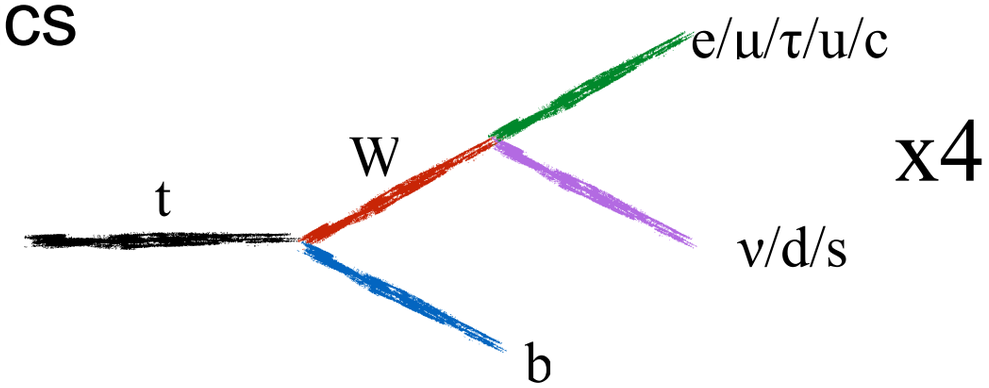


Total branching ratio: 9%

Baseline selection

- ✦ Tight lepton identification
- ✦ $N_{jets} \geq 2$, $N_{b\text{-}jets} \geq 2$
- ✦ $H_T > 300$, MET > 50 GeV
- ✦ DY veto, down to $p_T^{lep3} >$ 5(7) GeV for e(μ)

Total BR * acceptance * efficiency after baseline selection: 1.5%

tttt: main backgrounds

Rare top processes with $W^{\pm}W^{\pm}$ (or WZ with a lost Z lepton) and b-jets

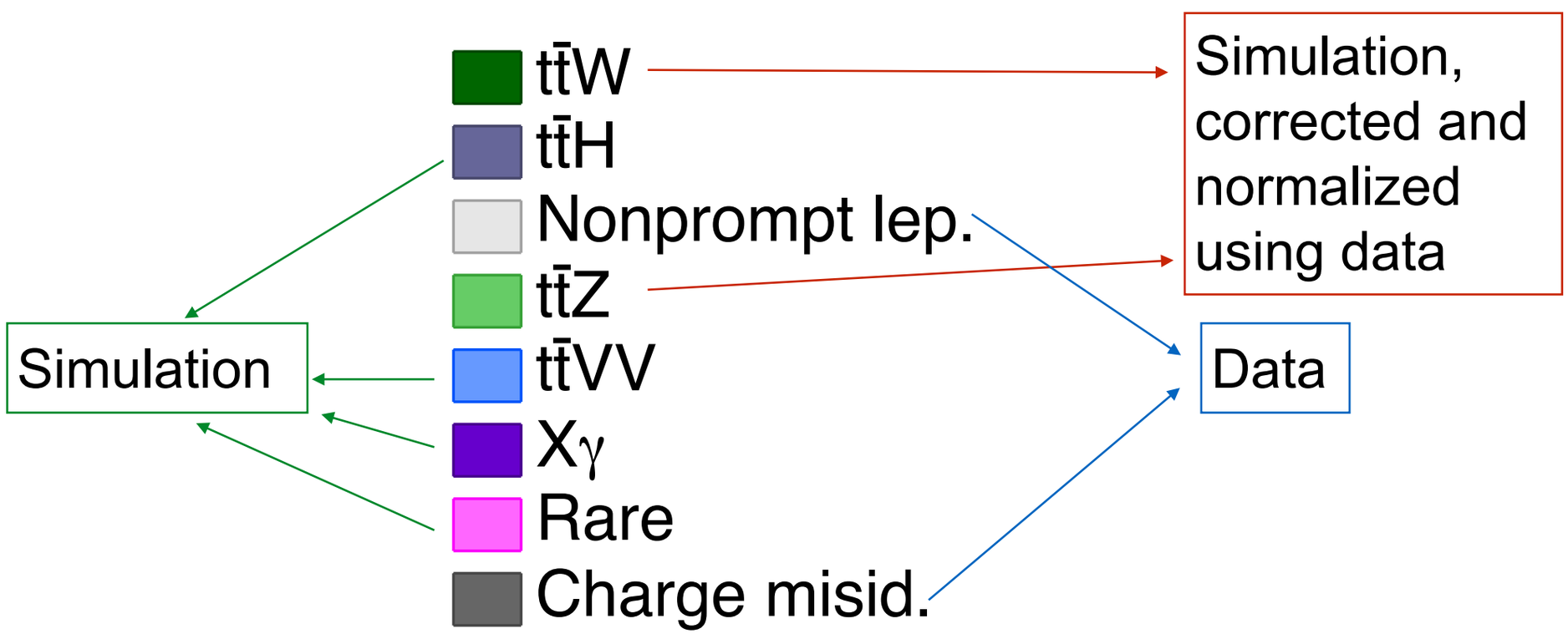
tt+X: ttW, ttZ, ttH (mainly H→WW), ttVV

Single-lepton tt with an additional fake/nonprompt lepton

- ✦ Reduction and estimate discussed earlier

Opposite-sign dilepton tt with a charge-misidentified electron

- ✦ Reduced to a rate of 10^{-5}-10^{-3} with track-quality criteria
- ✦ Estimated by reconstructing $Z \to e^{\pm}e^{\pm}$



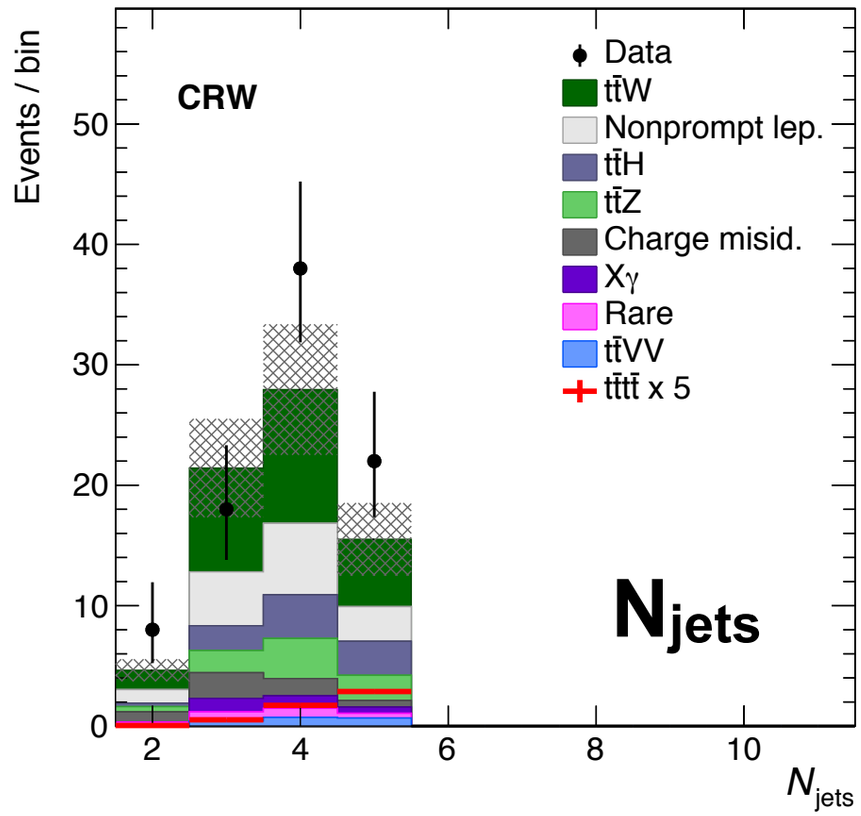
tttt: ttW and ttZ control regions

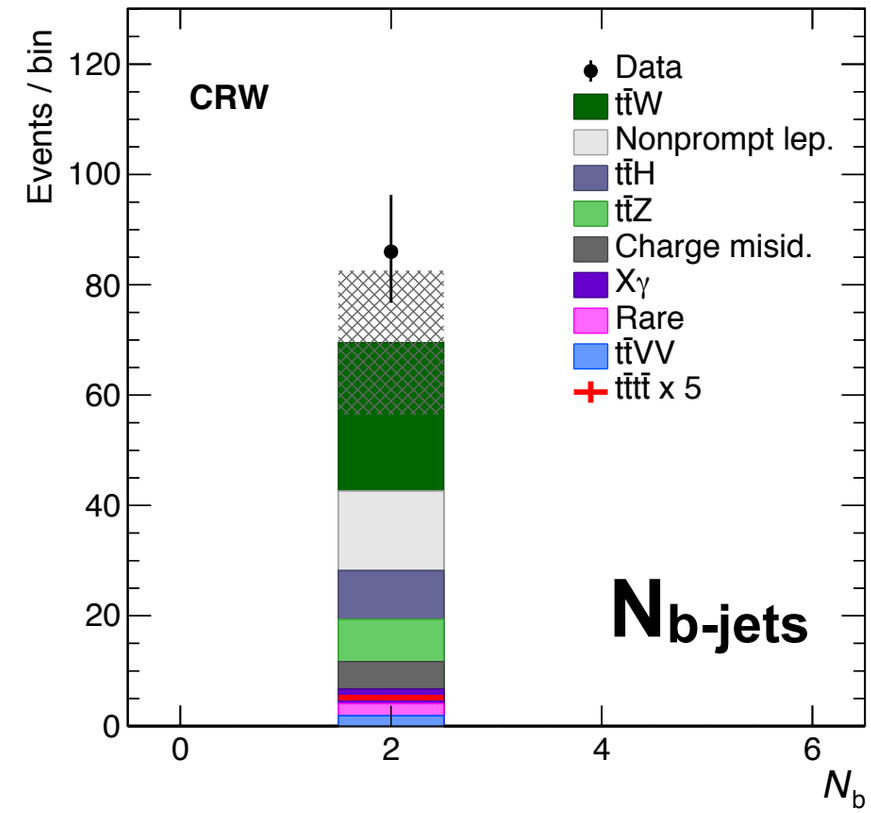
ttW CR:

$N_{jets} \leq 5$, $N_b = 2$

40% ttW

ttW scale: 1.2 ± 0.3



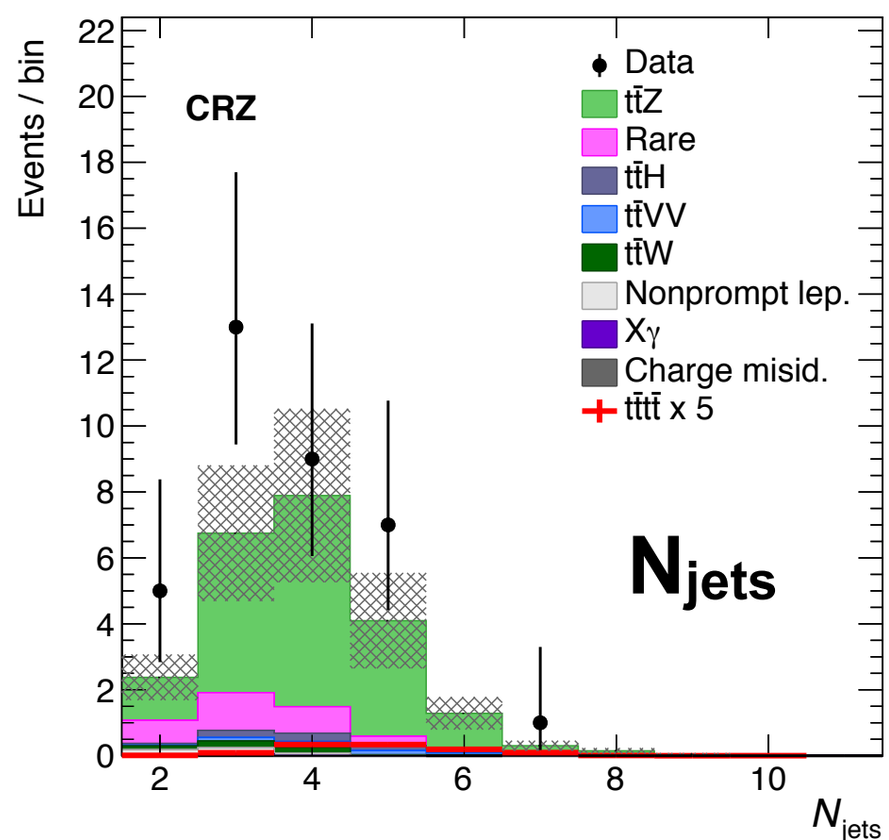


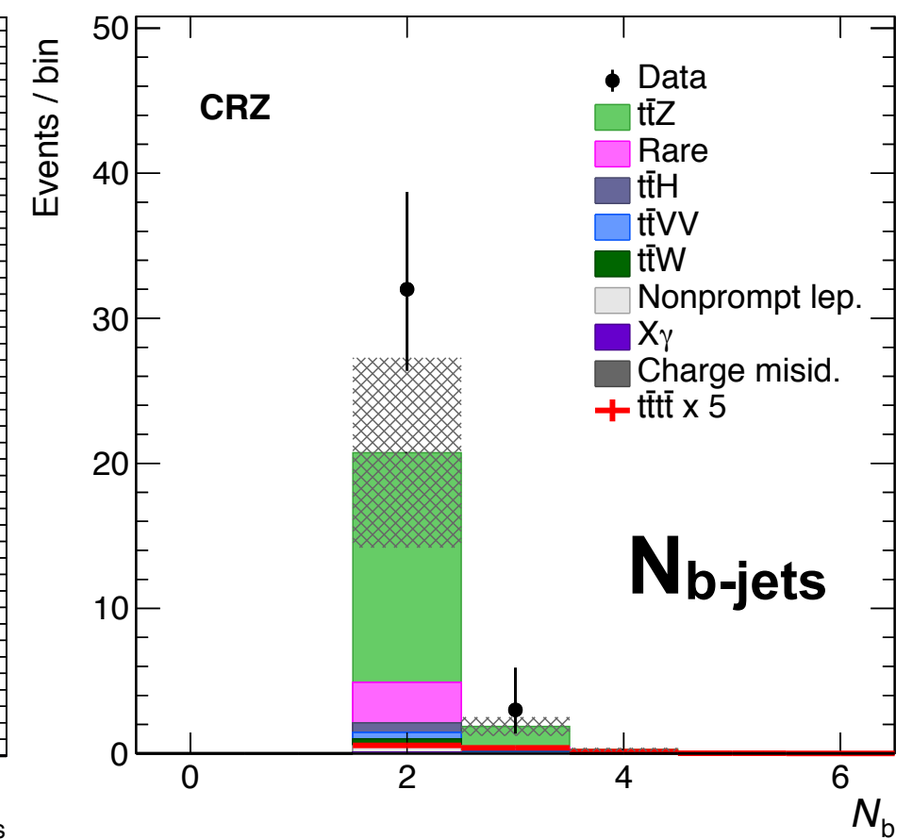
ttZ CR:

3 lep, $m_{ll} \sim m_Z$

75% ttZ

ttZ scale: 1.3 ± 0.3



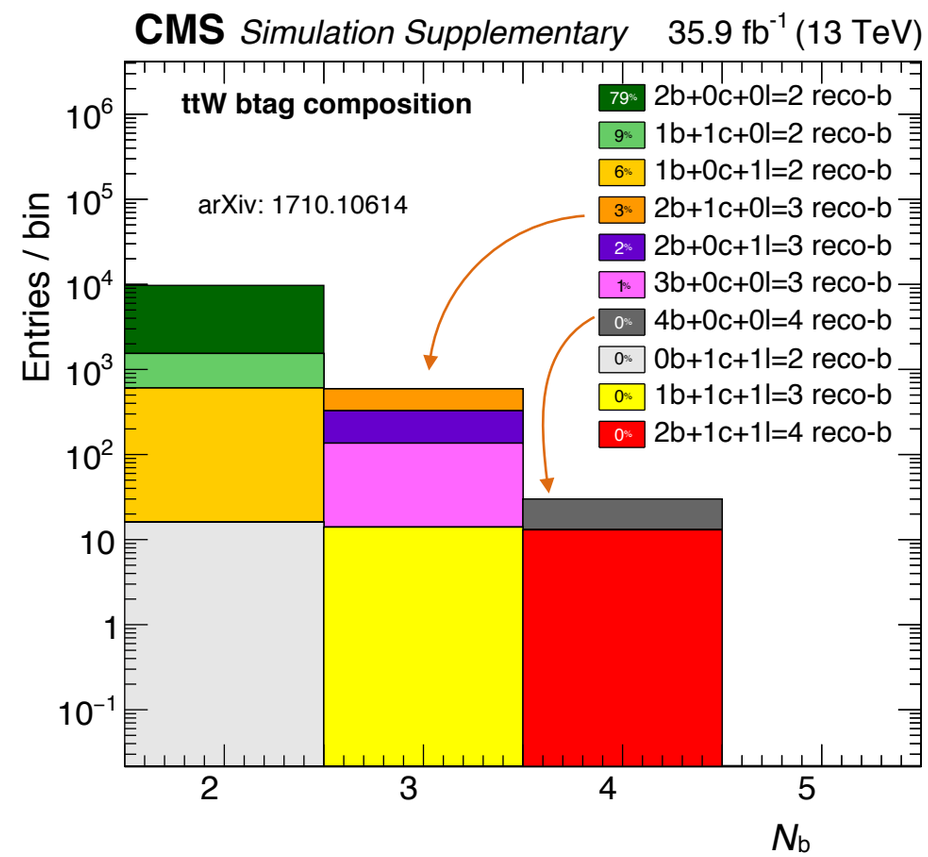


tttt: where do the extra (b-)jets come from?

Main backgrounds, ttW, ttZ, ttH(WW) have 2 b-jets: why 3 b-tags?

Check ttW at generator level:

- $N_b = 3$ region dominated by W→c
- $N_b = 4$ region dominated by ttW+bb

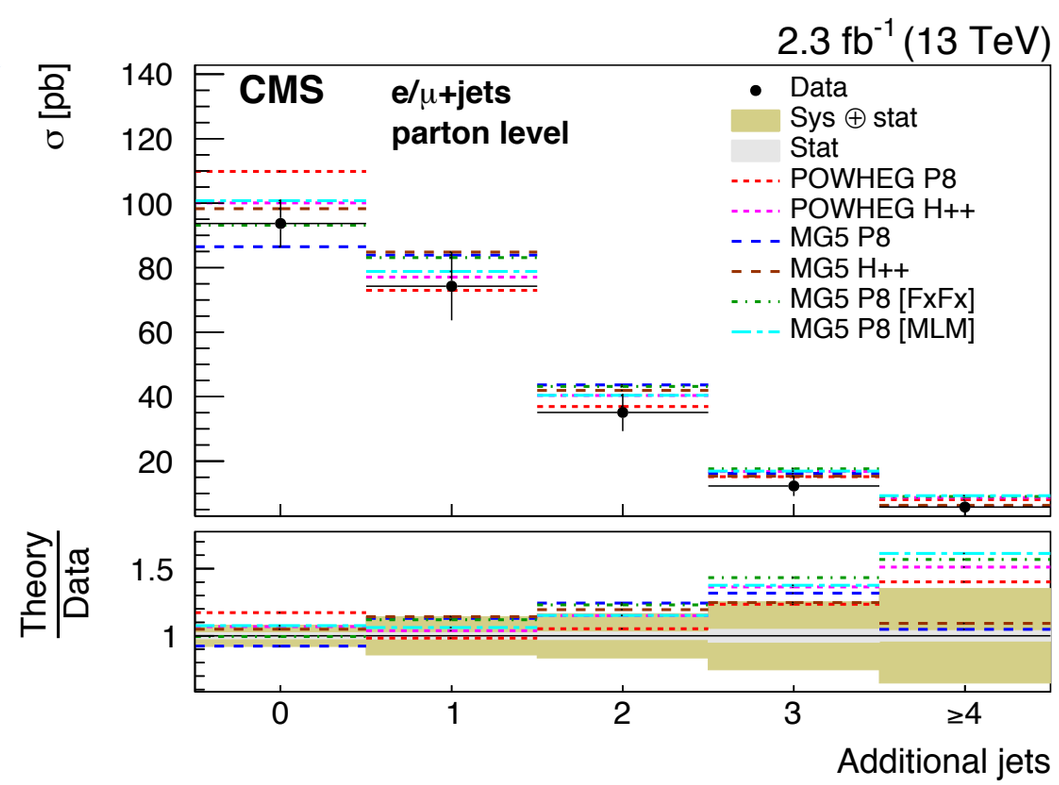


Are ttV+jets and ttV+bb well understood?

Use tt+jets and tt+bb as proxy for ttV

- tt+jets measurement is below simulation
- σ(ttbb)/σ(ttjj) measurement is 1 σ above simulation (1.7 ± 0.6) [arXiv:1705.10141]

Correct ttV simulation using tt Data/MC

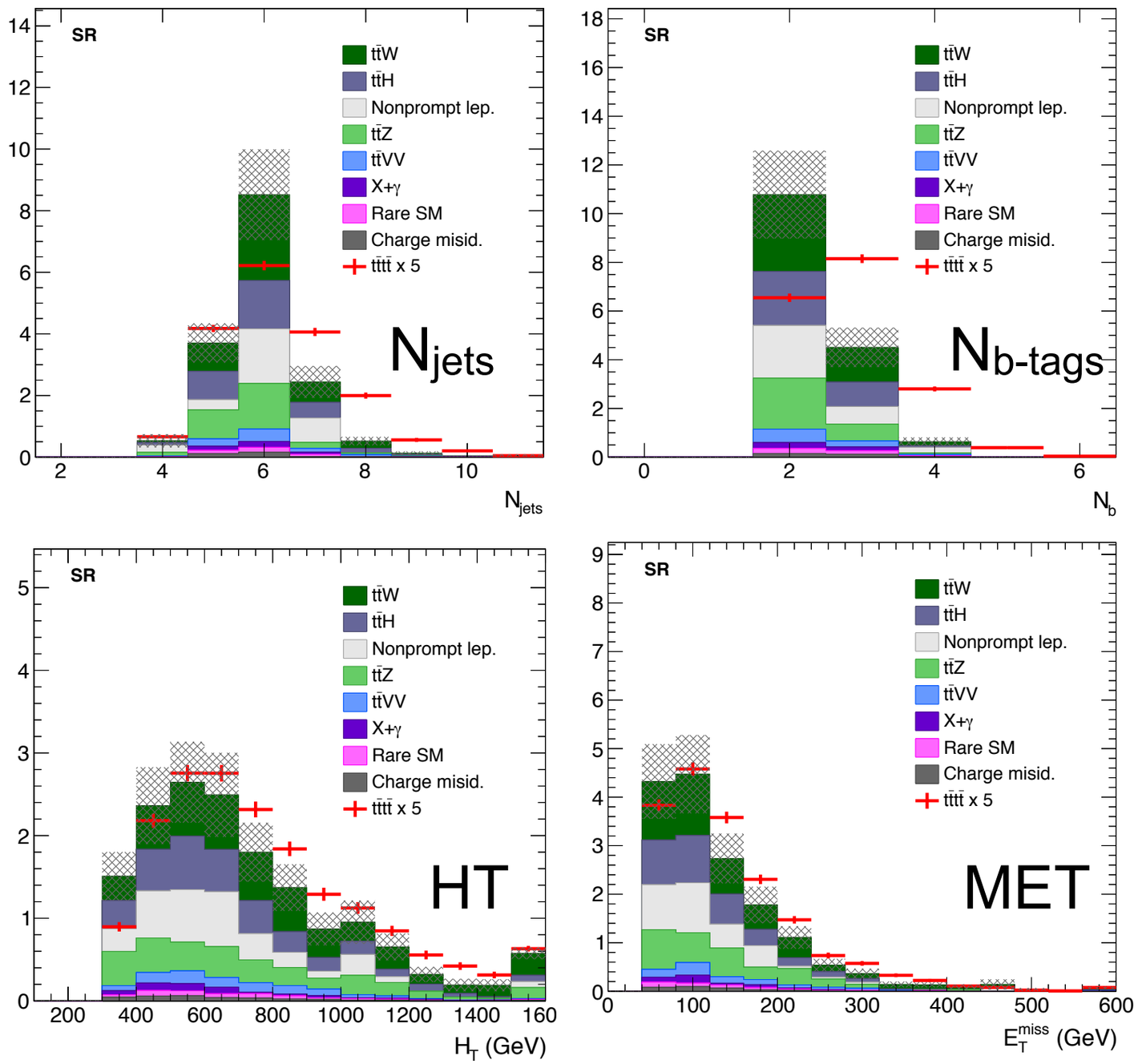


[tt+bb: arXiv:1705.10141, tt+jets: arXiv:1610.04191]
[36 fb^{-1} tt+jets, newer tune: arXiv:1803.08856]

tttt: Signal Regions definitions

tttt at generator level: 2(3) leptons, 8(6) jets of which 4 b-jets

Most discriminant variables: N_{jets}, $N_{b\text{-}tags}$, $N_{leptons}$

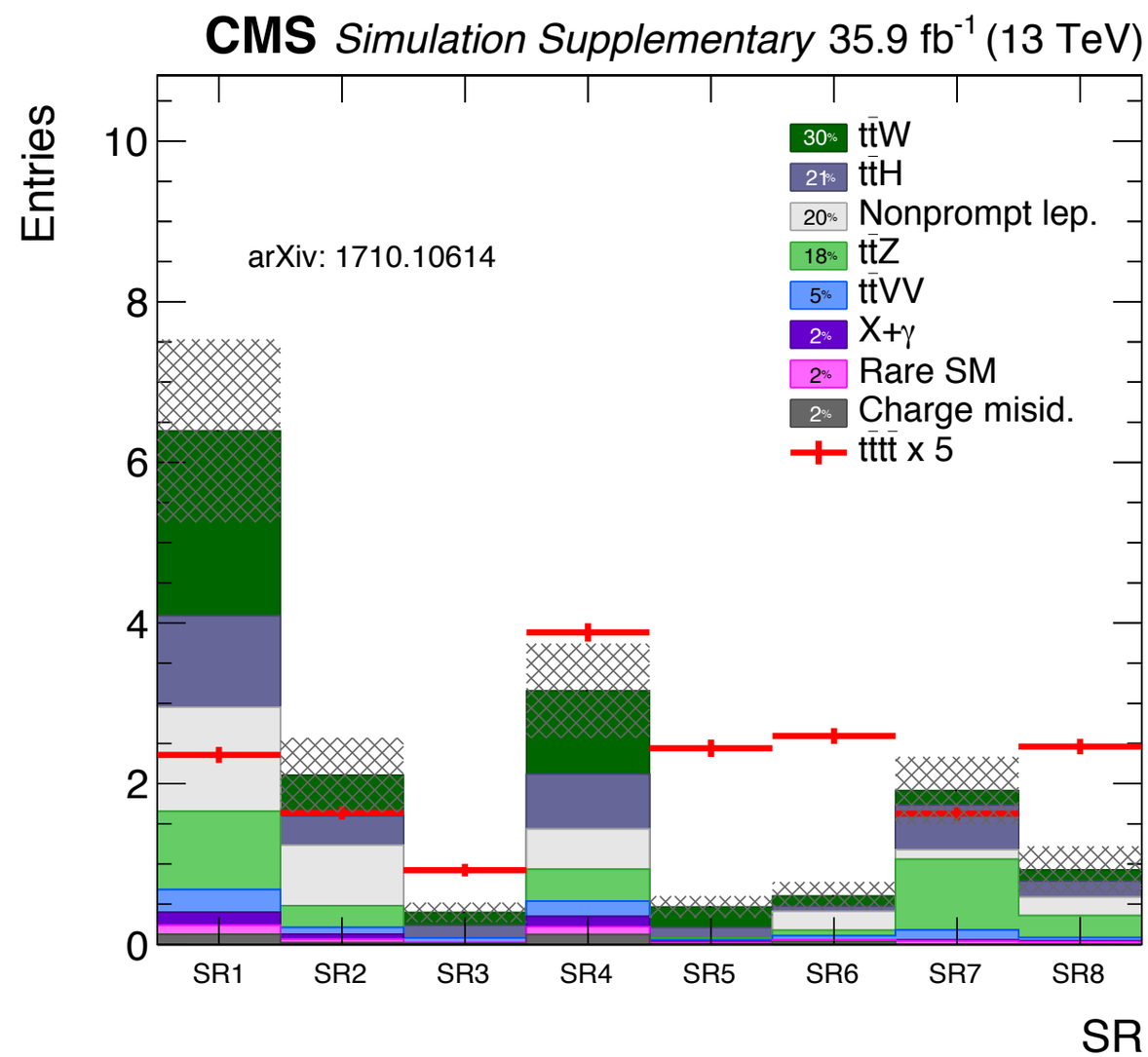


tttt: Signal Regions definitions

Use N_{jets}, $N_{b\text{-}tags}$, and separate 2 lepton and ≥3 lepton events

Group regions with similar S/B, avoid regions with << 1 event

N_{leps}	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
inverted Z-veto			CRZ



tttt: Uncertainties

Large total uncertainty (±100%)

Expect ~5 signal, ~15 background events

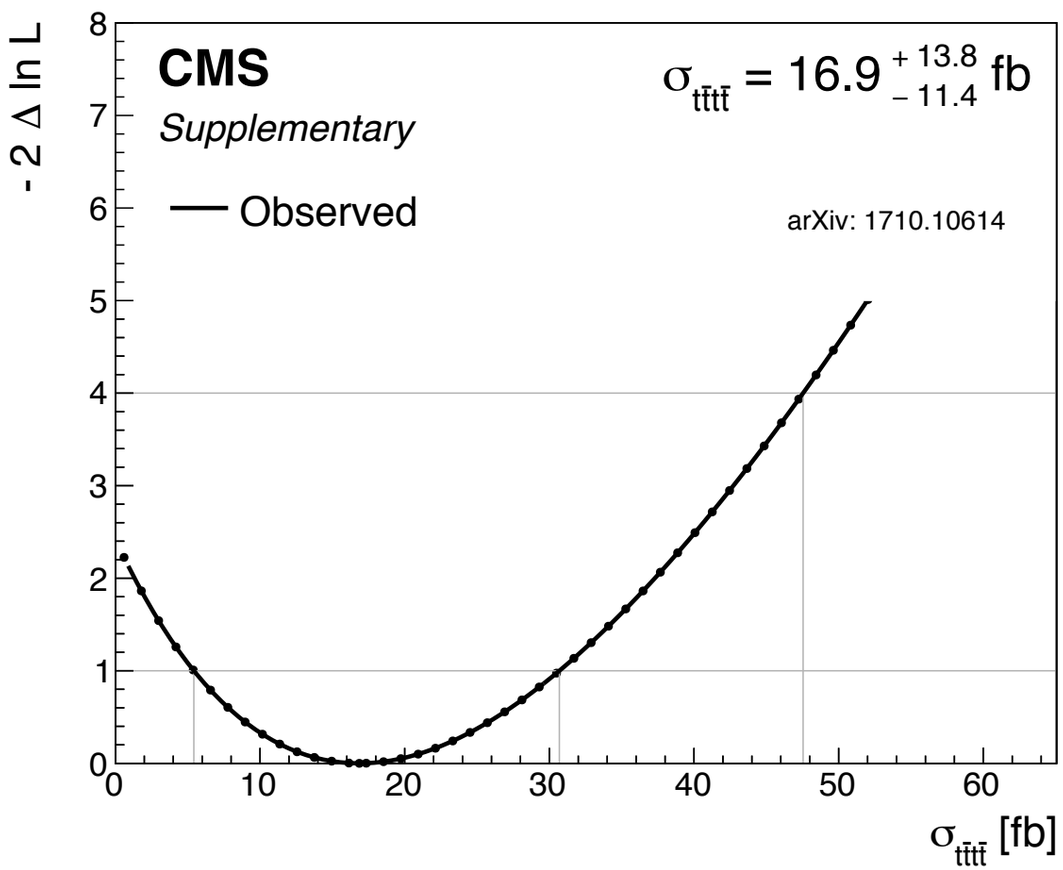
Statistically limited analysis

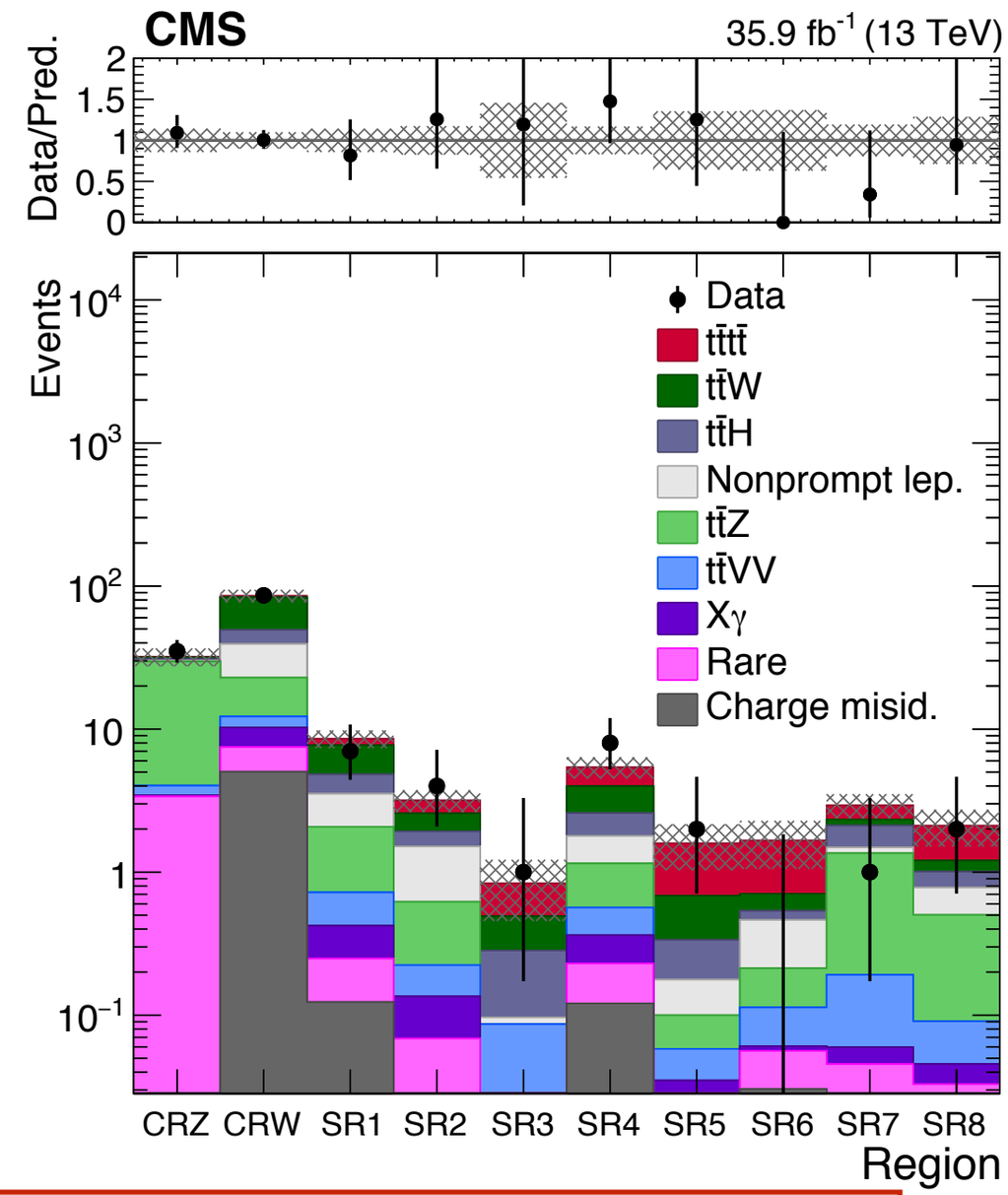
	Source	Uncertainty (%)
Signals and Backgrounds	Integrated luminosity	2.5
	Pileup	0–6
	Trigger efficiency	2
	Lepton selection	4–10
	Jet energy scale	1–15
	Jet energy resolution	1–5
	b tagging	1–15
	Size of simulated sample	1–10
	Scale and PDF variations	10–15
	ISR/FSR (signal)	5–15
Backgrounds	$t\bar{t}H$ (normalization)	50
	Rare, $X\gamma$, $t\bar{t}VV$ (norm.)	50
	$t\bar{t}Z$, $t\bar{t}W$ (normalization)	40
	Charge misidentification	20
	Nonprompt leptons	30–60

Combined effect of systematic uncertainties only increases total uncertainty by ~10%

Main background uncertainties constrained by control region statistics

tttt results: Standard Model





Results:

- Upper limit: $20.8^{+11.2}_{-6.9}$ fb expected (bkg only), 42 fb observed
- 1.6 sigma significance observed (1.0 expected)
- σ(tttt) = $16.9^{+13.8}_{-11.4}$ fb (σ_{SM} = 9.2±3 fb or 12 ± 2 fb)

tttt: Higgs and BSM interpretations

Constrain the top-Higgs Yukawa coupling [Cao et al., arXiv:1602.01934]

Higgs diagrams are a small contribution O(10%), but proportional to y_t^4

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

$$\kappa_t \equiv y_{Htt}/y^{\rm SM}_{Htt}$$

Probe Two-Higgs-doublet models (2HDM) [Craig et al., arXiv:1605.08744]

Introduce a scalar (H) and a pseudoscalar (A), in addition to the SM Higgs (h)

Top-associated production (pp →ttH/A), followed by H/A →tt

Constraining the four fermion EFT operators [ATLAS, arXiv:1803.09678]

Recent ATLAS limits on $\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2}(\bar{t}_{\rm R}\gamma^\mu t_{\rm R})\left(\bar{t}_{\rm R}\gamma_\mu t_{\rm R}\right)$: $c_{4t}/\Lambda^2 < 1.6$ TeV^{-2}

… and more recent proposals from theory community:

Comprehensive EFT constraints from tttt [C. Zhang, arXiv:1708.05928]

Top dipole moments with tttt [M. Malekhosseini et al., arXiv:1804.05598]

tttt results: Top-Higgs Yukawa

Compare UL with predicted σ(tttt) as a function of $\kappa_t = |y_t/y_t^{SM}|$

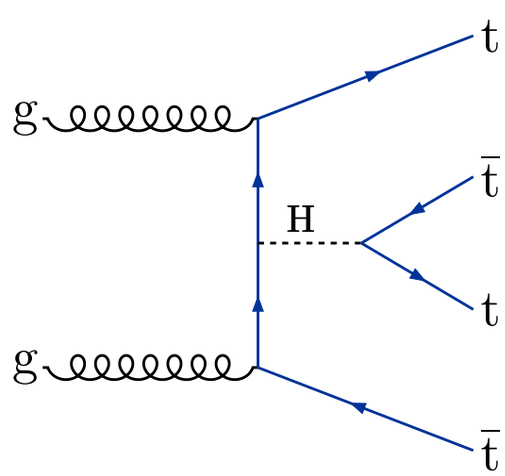
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma_{\mathrm{int}}^{\mathrm{SM}} + \kappa_t^4\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$$

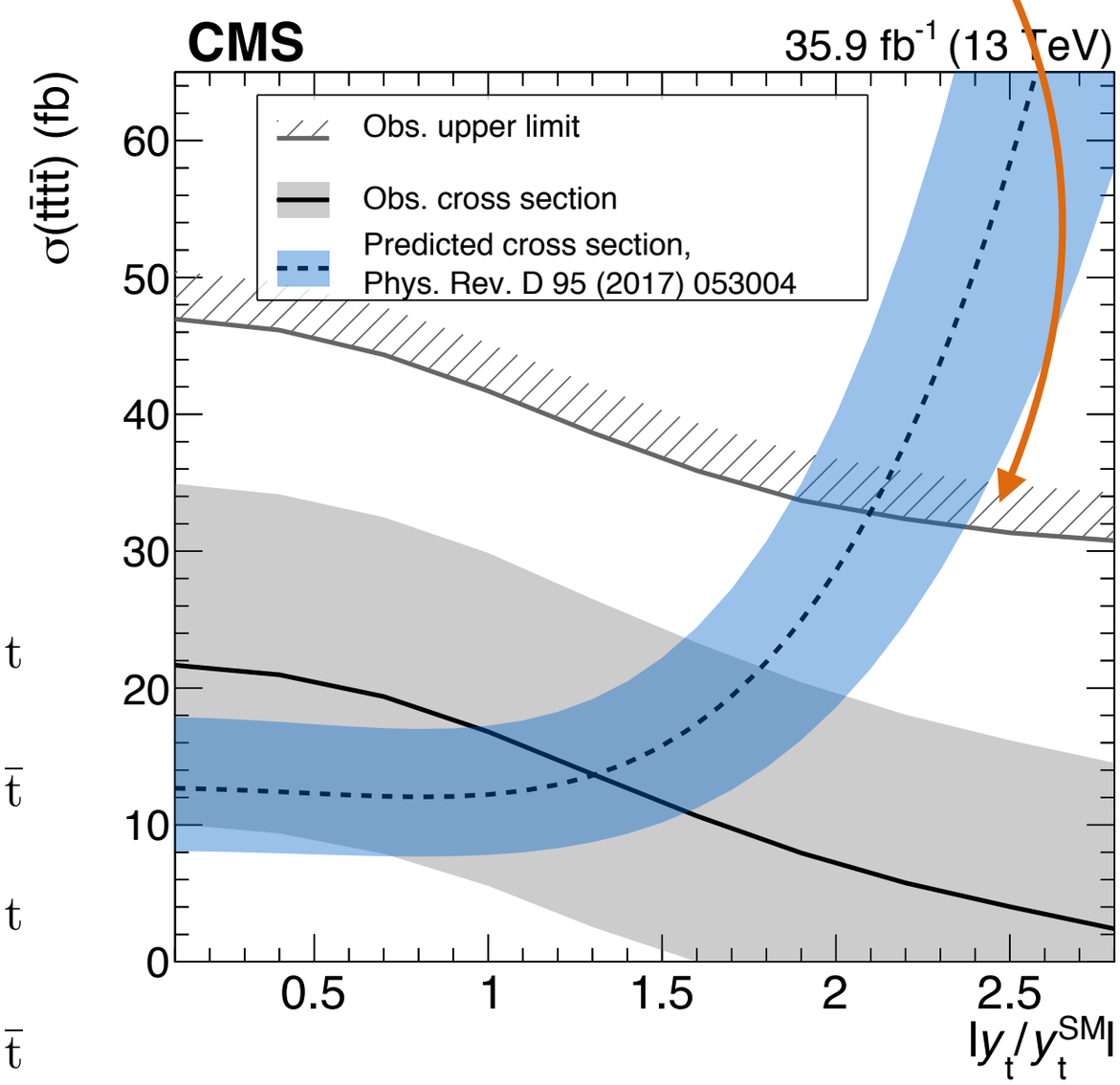
- ttH background also depends on y_t, so σ(tttt) upper limit improves at large y_t

Result:

- $|y_t| < 2.1$ at 95% CL
- Differences w.r.t. ttH measurement
  - probe a higher center of mass
  - no assumption on total Higgs width

Leading Order	13 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	9.997 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$:	1.168 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−1.547 fb,





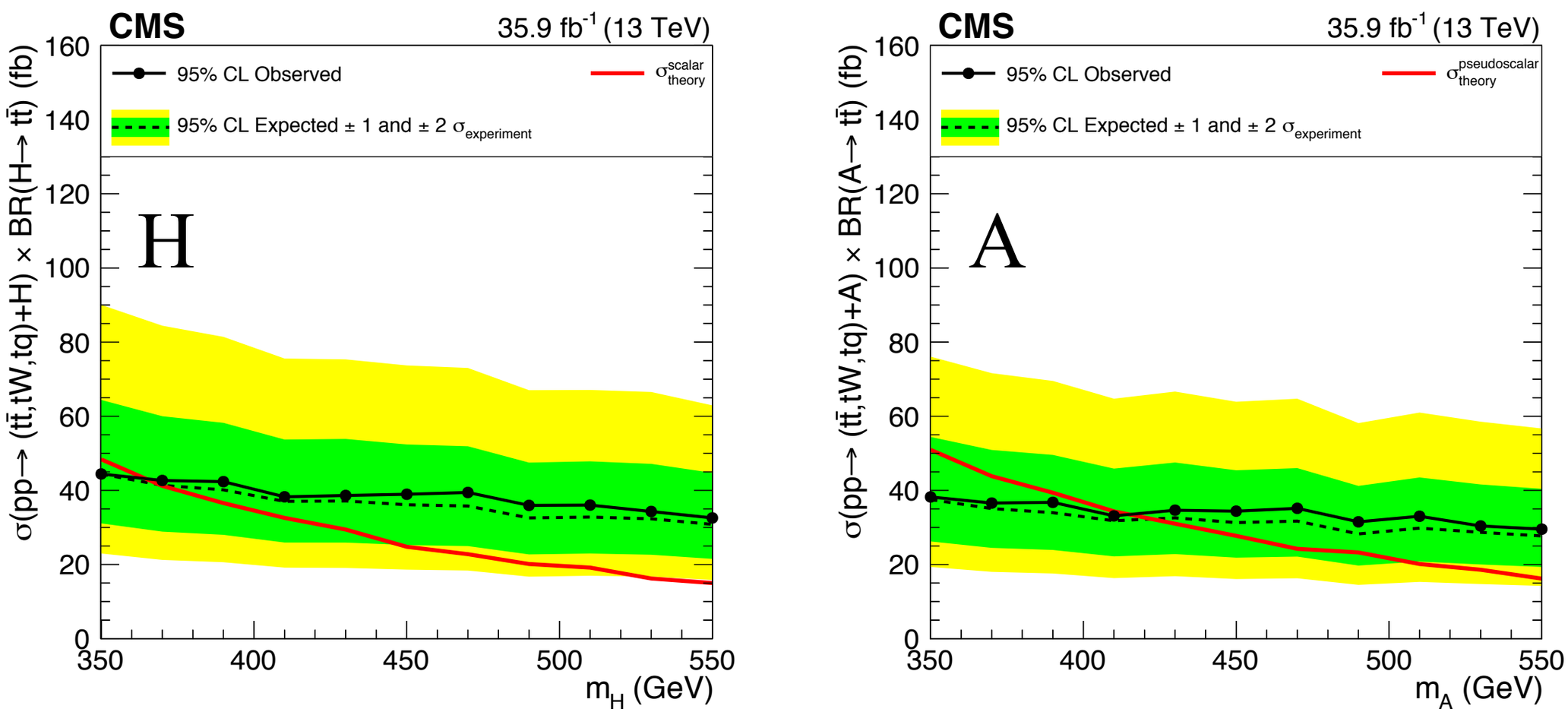
tttt results: 2HDM heavy (pseudo)scalar *

Compare UL with prediction of top-associated H/A production (ttH / ttA)

Heavy H/A can generate large enhancement (low tanβ, mH/A ≳ 2*mt) where H/A → tt

Exclude $m_{A(H)}$ < 430 (360) GeV for tanβ = 1

- With respect to direct searches for pp→H/A→tt resonances, this strategy has no dependence on the H/A width and does not suffer from large SM interference

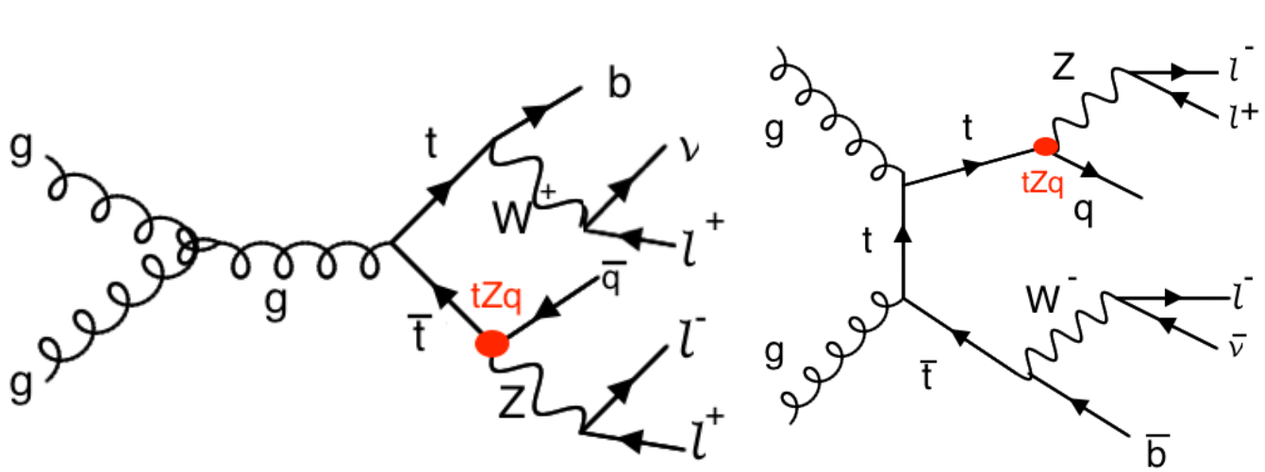


* From inclusive 2016 same-sign analysis, arXiv:1704.07323, which inspired the dedicated tttt analysis

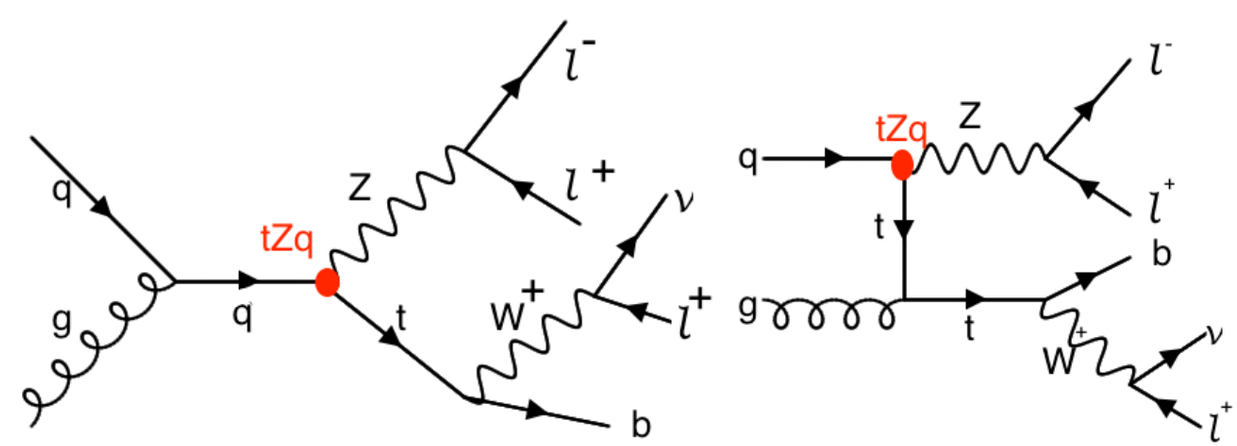
Search for flavour changing neutral currents in top quark production and decays with three-lepton final state using the data collected at √s = 13 TeV

The CMS Collaboration
CMS-PAS-TOP-17-017

top pair production, tZq decay



tZq single-top production



FCNC t→Zq

CMS-PAS-TOP-17-017

Signature: 3 leptons, one Z candidate, ≥1 b-jets, 1-3 jets

2 signal regions: "TT" for tZq decay (2-3 jets) and "ST" for tZq production (1 jet)

Use BDTs to separate signal from prompt lepton backgrounds

- Variables: object kinematics, angles, b-tag discriminant
- Separate trainings for each SRs and each lepton channels (μμμ, μμe, …)
- Separate trainings for t→Zu and t→Zc

Control regions

"WZ": estimate WZ and DY+nonprompt

"TT" and "ST": estimate tt+nonprompt for respective SRs

	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{\mathrm{reco}}) - M_{\mathrm{Z}}\rvert < 7.5$ GeV	Yes	Yes	Yes	No	No

FCNC t→Zq

CMS-PAS-TOP-17-017

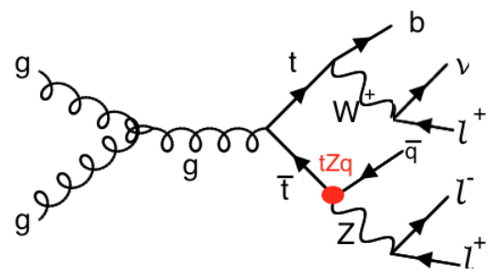
Signature: 3 leptons, one Z candidate, ≥1 b-jets, 1-3 jets

2 signal regions: "TT" for tZq decay (2-3 jets) and "ST" for tZq production (1 jet)

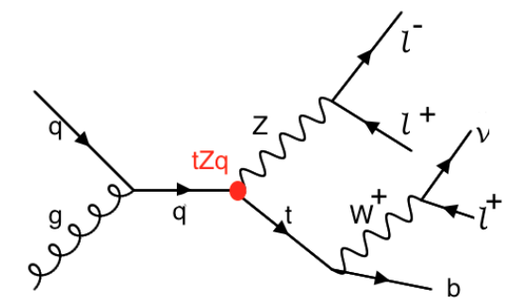
Use BDTs to separate signal from prompt lepton backgrounds

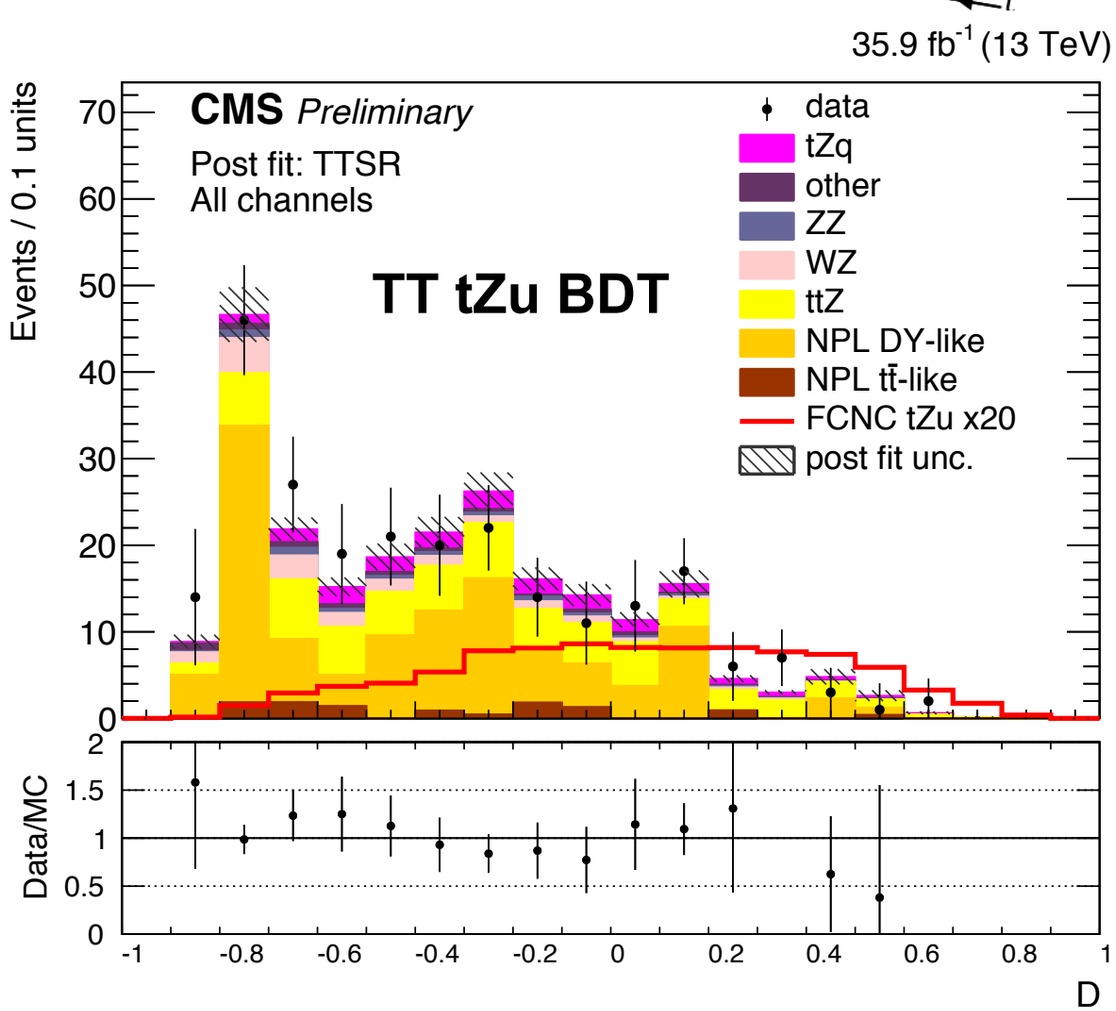
Main background: nonprompt ('NPL')

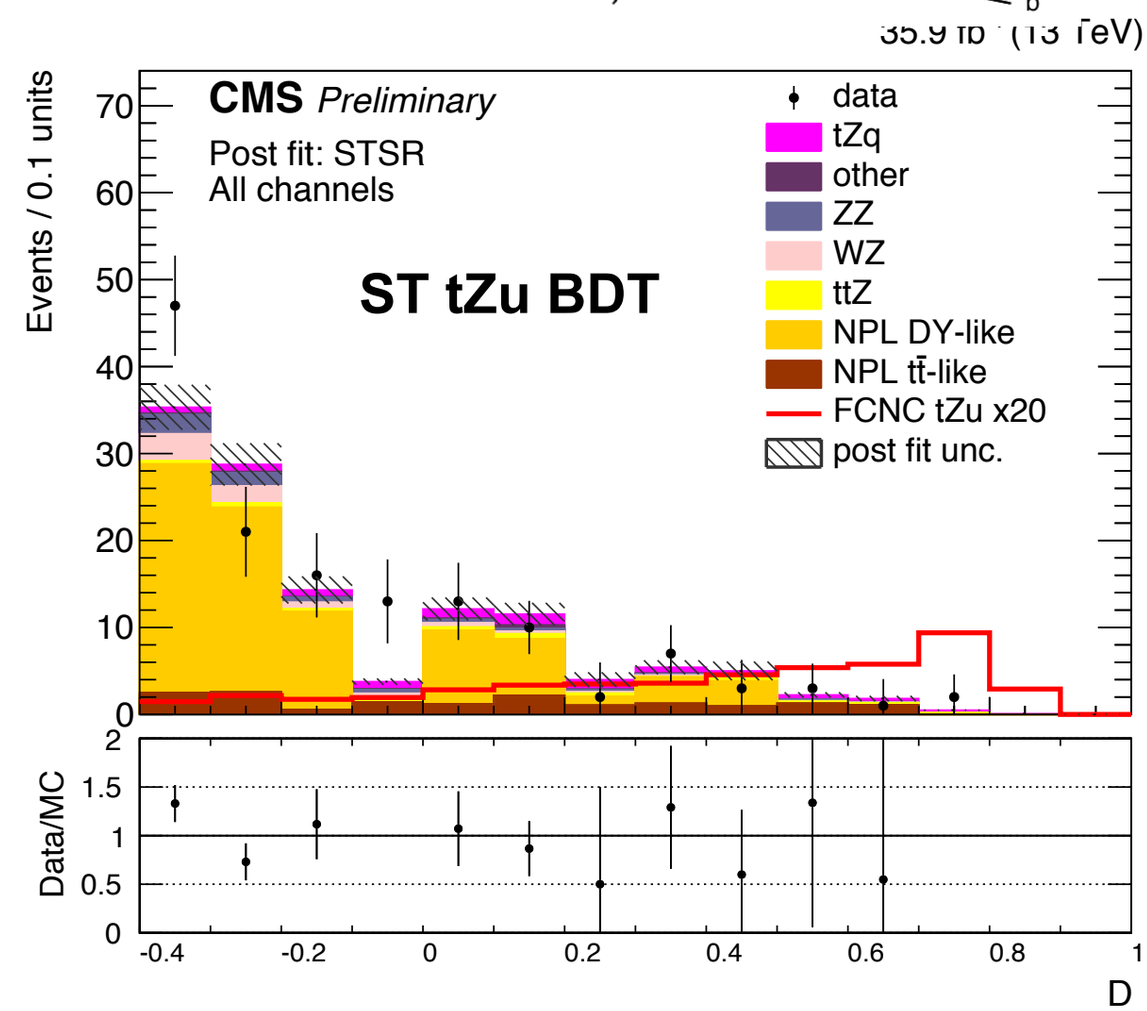
tt production, tZq decay



tZq single-top production



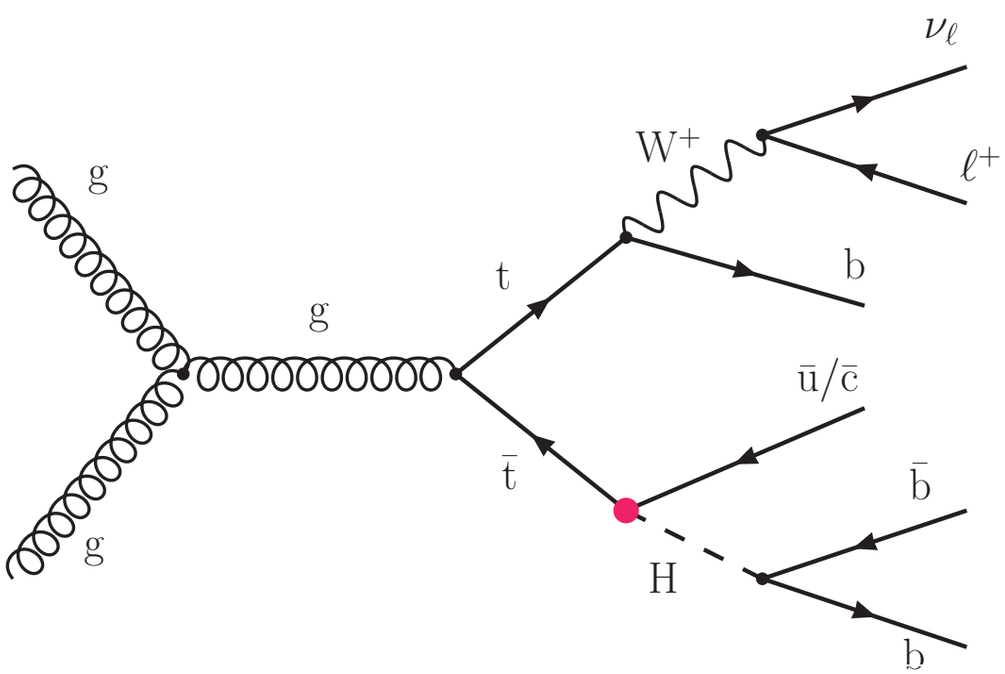




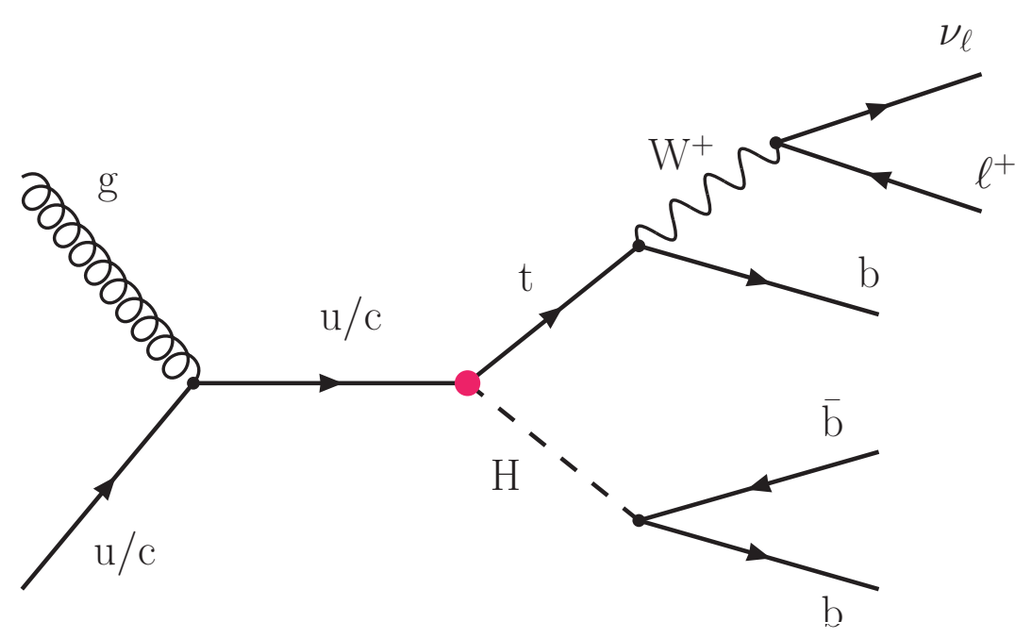
Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s}$ = 13 TeV

The CMS Collaboration
arXiv:1712.02399, submitted to JHEP

top pair production, tHq decay



tHq single-top production



t→Hq, H→bb

arXiv:1712.02399

Single lepton events, classify in N_{jets}, $N_{b\text{-}jets}$

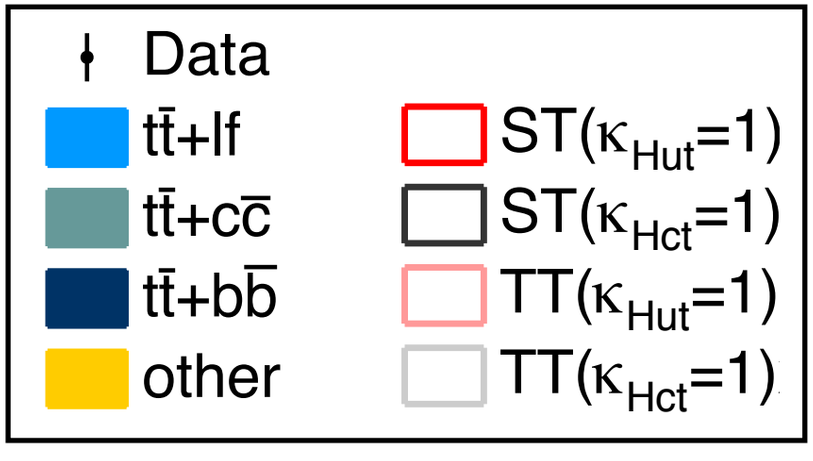
Main backgrounds: tt+bb/cc/light

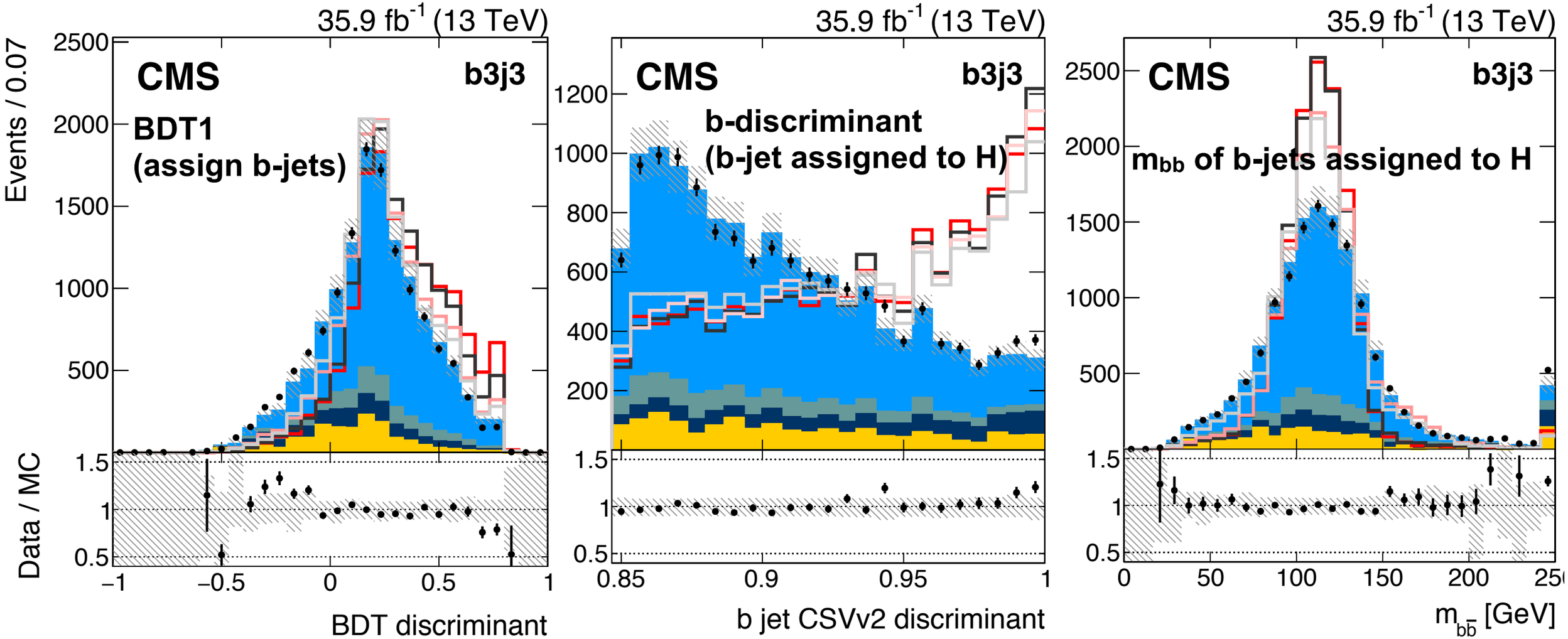
BDT1: assign b-jets to initial particles (top or Higgs)

- ~75% correct assignment

BDT2: (t→Hu or t→Hc) vs sum of backgrounds

- Most important variables: BDT1, b-jet discriminant and m_{bb} of b-jets assigned to H, lepton charge





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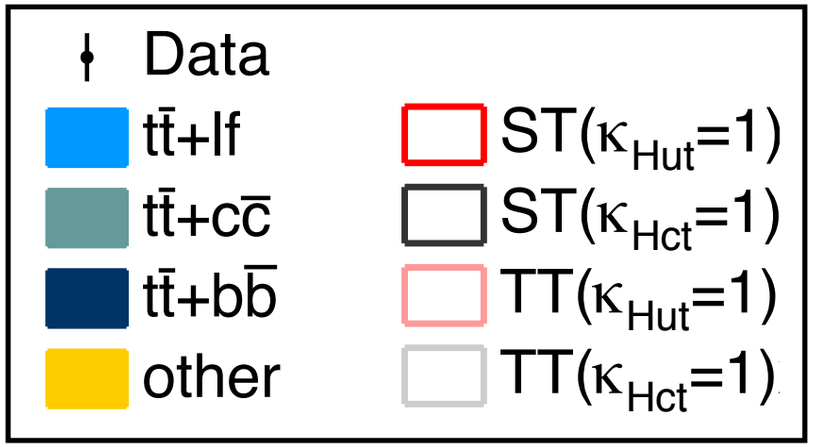
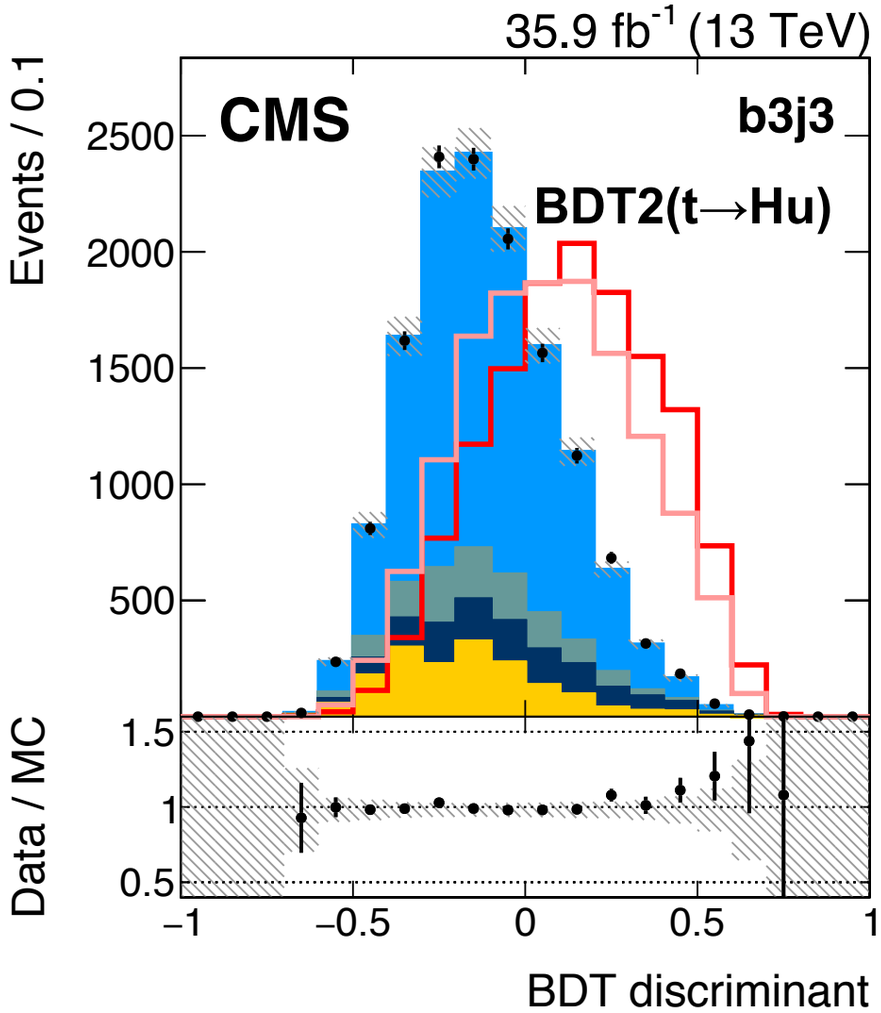
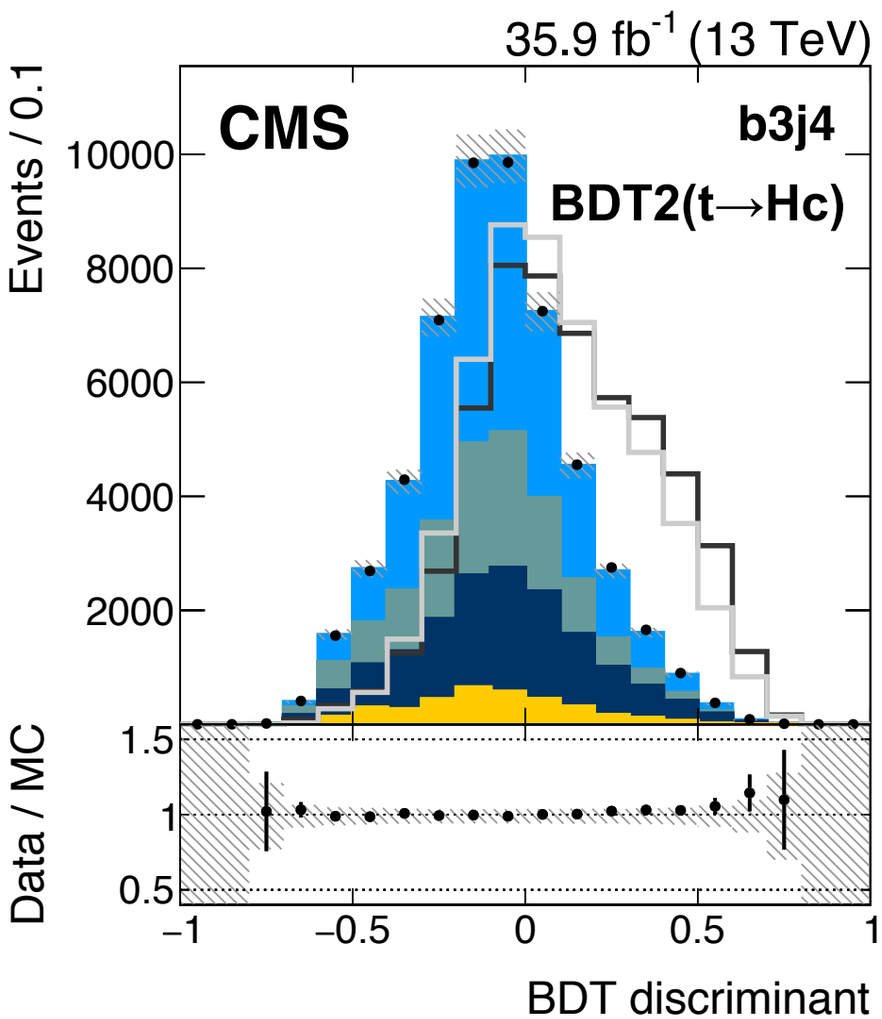






t→Zq and t→Hq Results

Good agreement with SM, interpreted as 95% CL limits on top branching fractions

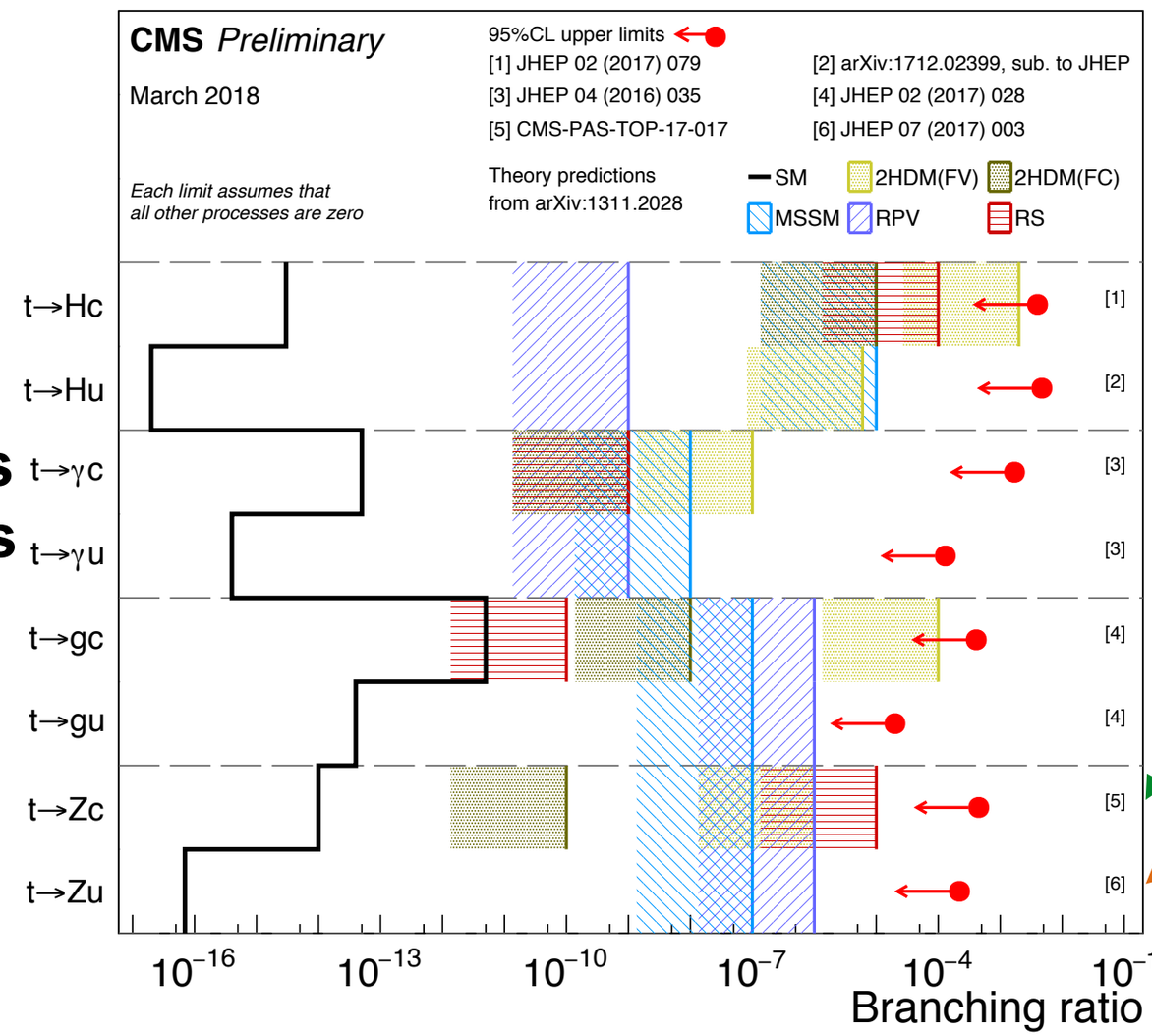
t→Zq: significant improvement in expected limits, observed comparable with Run 1

t→Hq: H→bb Run2 result is comparable to full Run1 combination (multilepton, bb, γγ)

	Branching (%)	t→Zu	t→Zc	t→Hu	t→Hc
Run 2	Obs (Exp)	0.024(0.015)	0.045(0.037)	0.47(0.34) (bb)	0.47(0.44) (bb)
Run 1	Obs (Exp)	0.022(0.027)	0.049(0.118)	0.55(0.40) (VV, ττ, γγ, bb)	0.40(0.43) (VV, ττ, γγ, bb)

Large FCNC program for Run 2 has just started.

Already surpassing Run 1, with several more channels to explore, and x4 statistics expected.



Run 2

Run 1

Summary

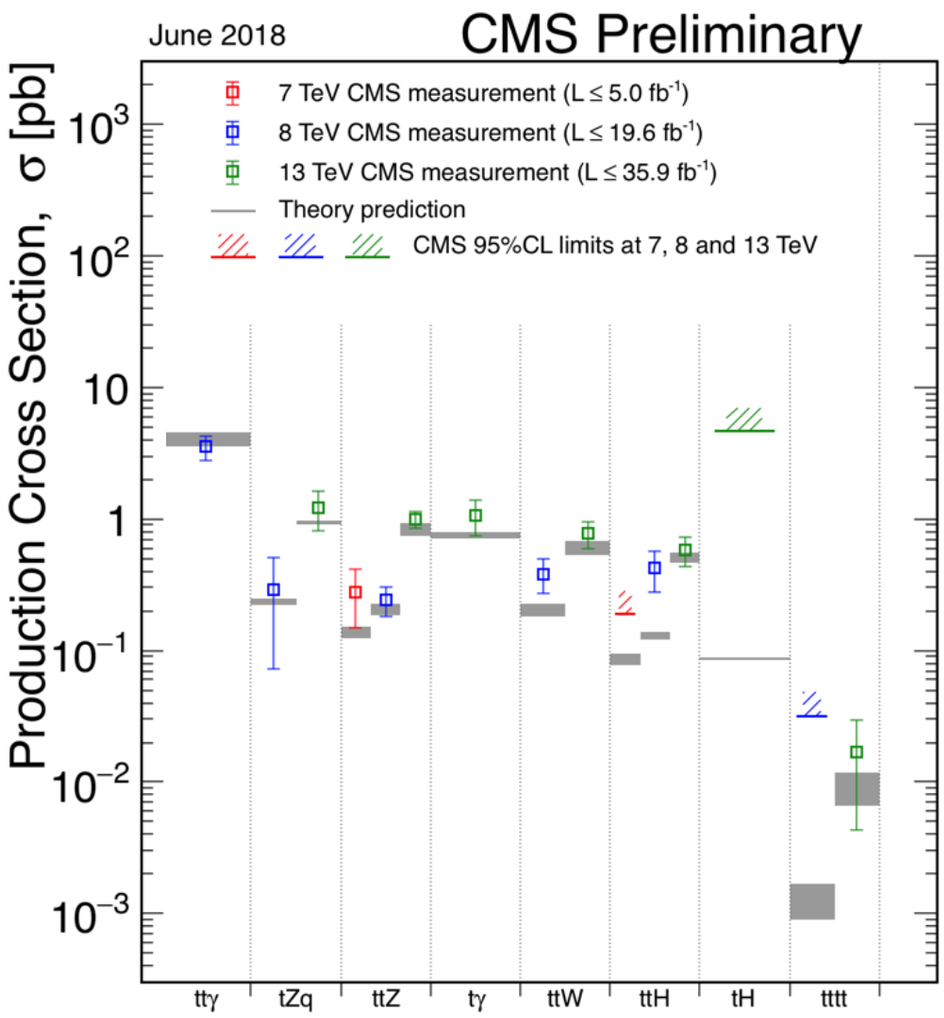
CMS has taken advantage of the first 36 fb^{-1} of Run 2 data to explore rare SM top processes, reaching new frontiers and finding good agreement with SM predictions

- New results in ttW (5σ), ttZ (5σ), tγ (4.4σ), tZ (3.7σ), tttt (1.6σ)
- Several results systematics limited → strategies will need to evolve to keep improving

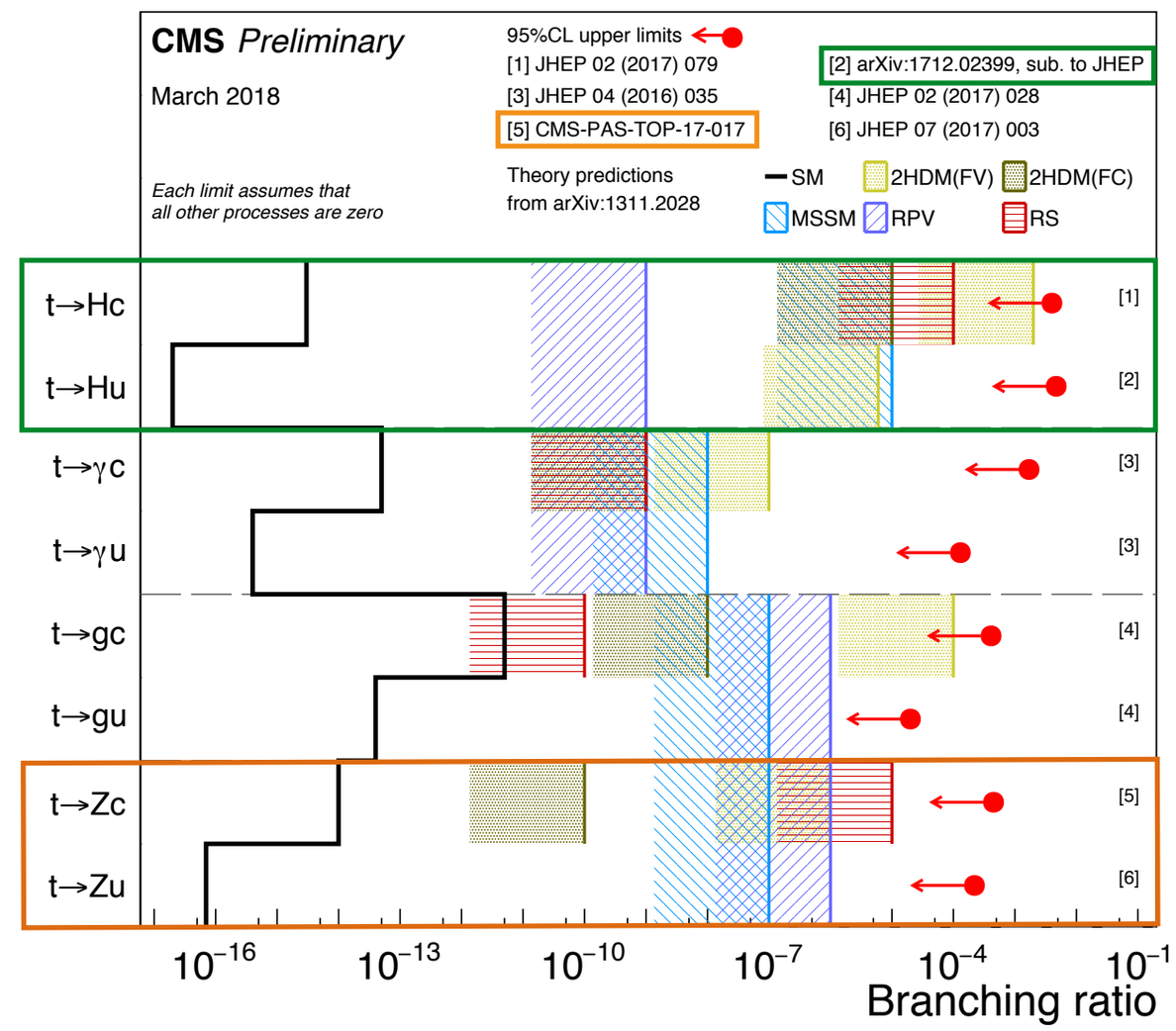
The search for Flavor Changing Neutral Currents at 13 TeV has started

- New results in t→Zq and t→Hq with H(bb), already surpassing Run 1

Rare and anomalous top offer a complementary program to direct searches for BSM



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



Backup

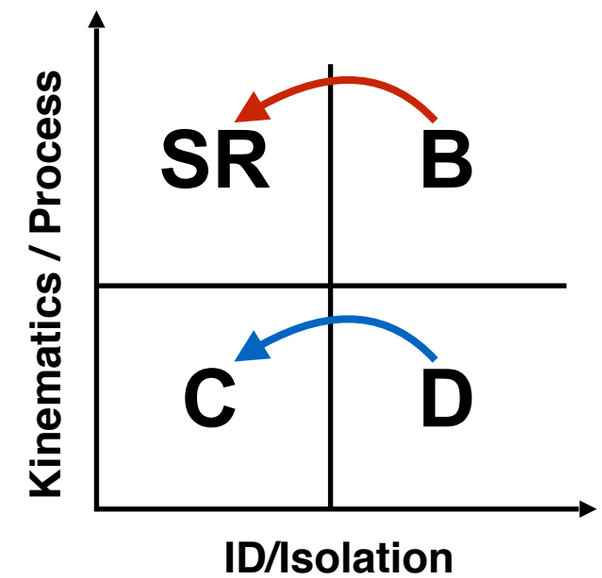
CMS and ATLAS analyses

	ATLAS		CMS	
	Dataset	Analysis	Dataset	Analysis
ttW and ttZ	3.6 fb^{-1}, 13 TeV	Eur. Phys. J. C (2017) 77:40	36 fb^{-1}, 13 TeV	arXiv:1711.02547
ttγ	20 fb^{-1}, 8 TeV	JHEP 11 (2017) 086 (J. Caudron)	20 fb^{-1}, 8 TeV	JHEP 10 (2017) 006 (P. David)
tttt	3.6 fb^{-1}, 13 TeV	ATLAS-CONF-2016-020, 032	36 fb^{-1}, 13 TeV	Eur. Phys. J. C 78 (2018) 140
	36 fb^{-1}, 13 TeV	arXiv:1803.09678 (BSM only)		
FCNC: $t \to Zq$	36 fb^{-1}, 13 TeV	arXiv:1803.09923	36 fb^{-1}, 13 TeV	CMS-PAS-TOP-17-017
FCNC: $t \to Hq$	36 fb^{-1}, 13 TeV	arXiv:1805.03483, H(WW)	36 fb^{-1}, 13 TeV	arXiv:1712.02399, H(bb)
	36 fb^{-1}, 13 TeV	arXiv:1707.01404, H(γγ)		
Wtb anomalous couplings	20 fb^{-1}, 8 TeV	JHEP 12 (2017) 017	20 fb^{-1}, 8 TeV	JHEP 02 (2017) 028
		Eur. Phys. J. C 77 (2017) 264		Phys. Lett. B 762 (2016) 512

New at 13 TeV: background estimates

ABCD works well, as long as two axes are uncorrelated, i.e. the transfer factor applies to SR:

$$TF \equiv \boxed{\frac{C}{D}} \stackrel{?}{=} \boxed{\frac{SR}{B}}$$



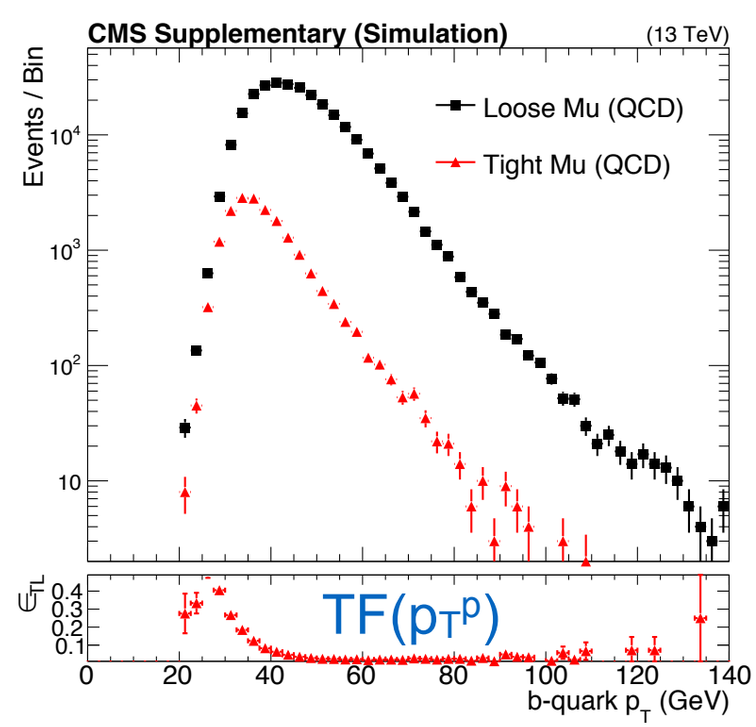
Differences can be understood and parametrized

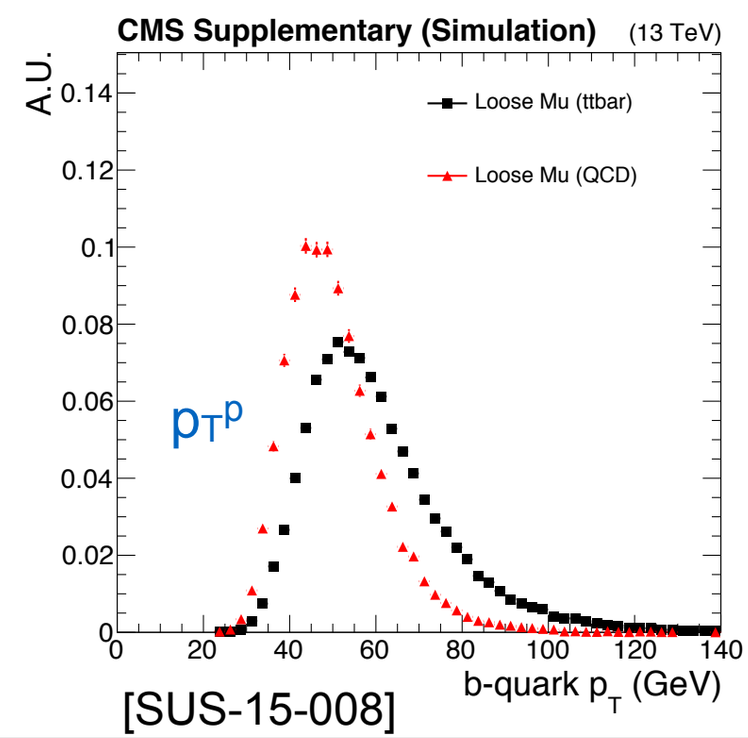
- 1st cause of difference: lepton kinematics: $TF(p_T^l, \eta^l)$
- 2nd: p_T and flavor (b/c/light) of lepton's parton parent (p)
  - Could be solved by: $TF(p_T^l, \eta^l, p_T^p, f^p)$

Example: pick muons with: $20 < p_T^l < 25 \text{ GeV}, \ |\eta^l| < 0.9, \ f^p = b$

$TF(p_T^p)$ plot shows clear dependence

And p_T^p is different for QCD and tt

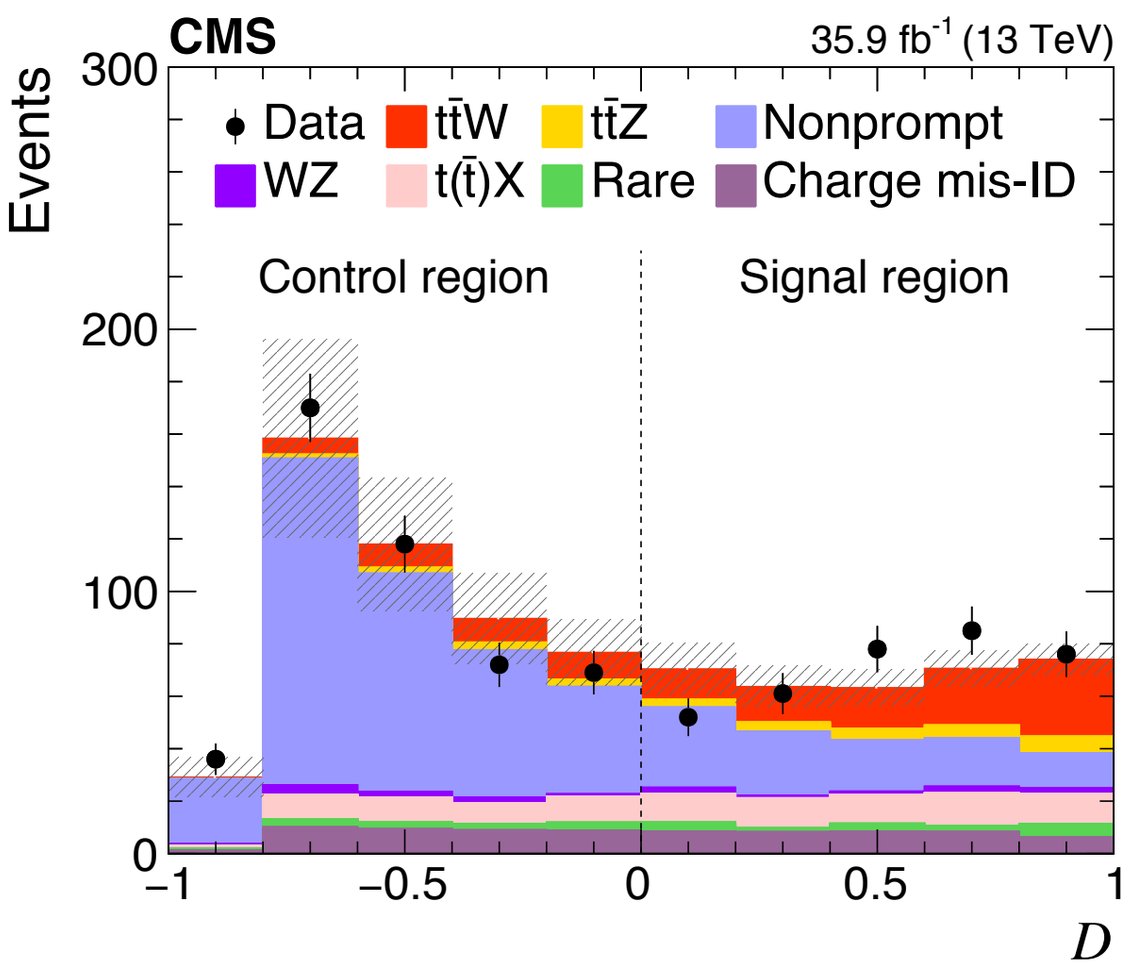




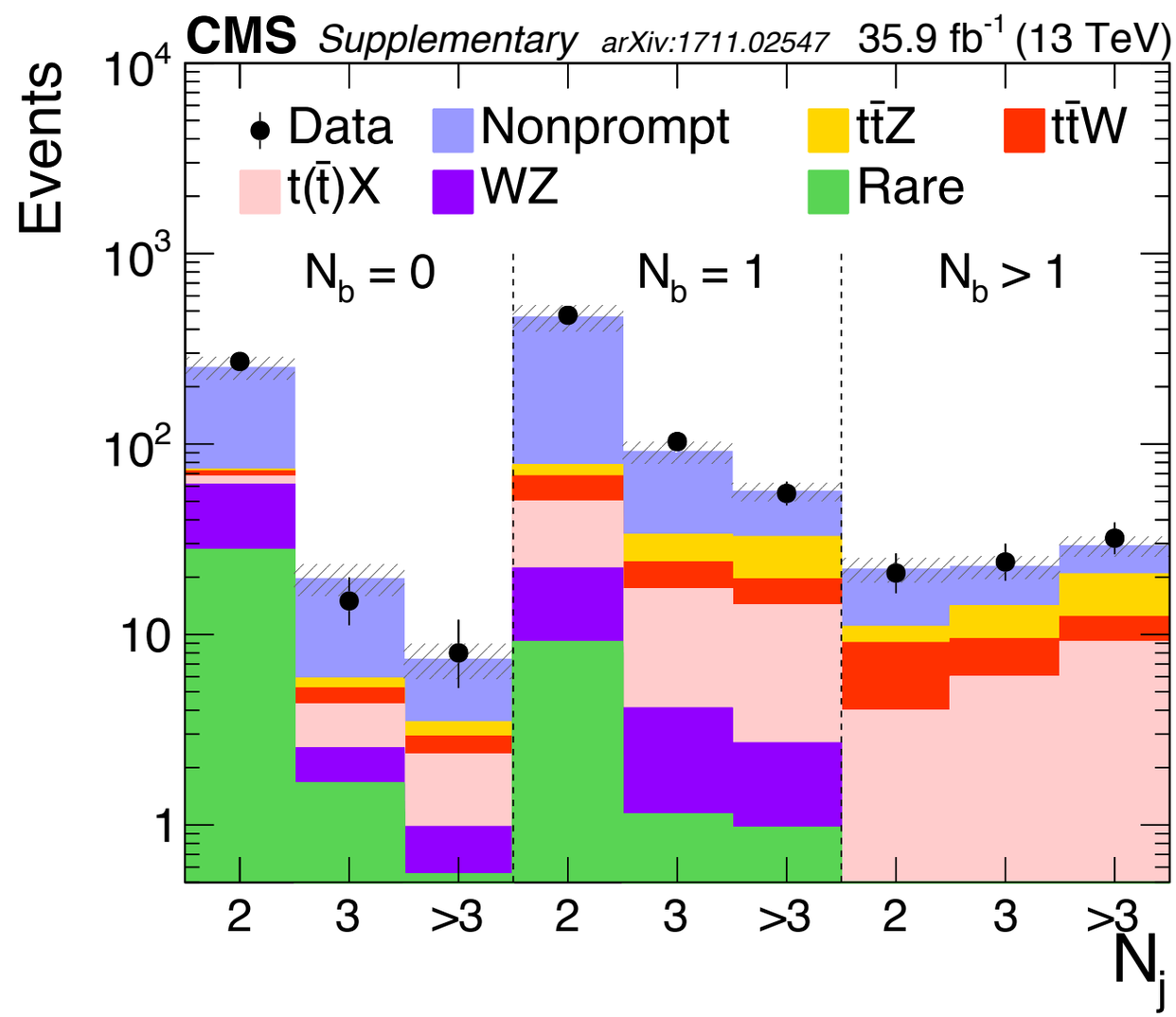
[SUS-15-008]

ttW/ttZ: nonprompt lepton control regions

2 same-sign leptons:
BDT determining signal and control regions



3-lepton, nonprompt-enriched:
Either no OSSF pair or $|m_{ll} - m_Z| > 10$ GeV



Anomalous Couplings (single top). ATLAS/CMS

Wtb vertex general form includes anomalous couplings

- Left-handed vector: $f_V^L = V_L = V_{tb} \sim 1$ in the Standard Model
- Right-handed vector, and left/right-handed tensors: f_V^R, f_T^L, f_T^R (aka V_R, g_L, g_R). 0 in SM.

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu\left(f_V^L P_L + f_V^R P_R\right) t W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_\nu W_\mu^-}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + \text{h.c.}$$

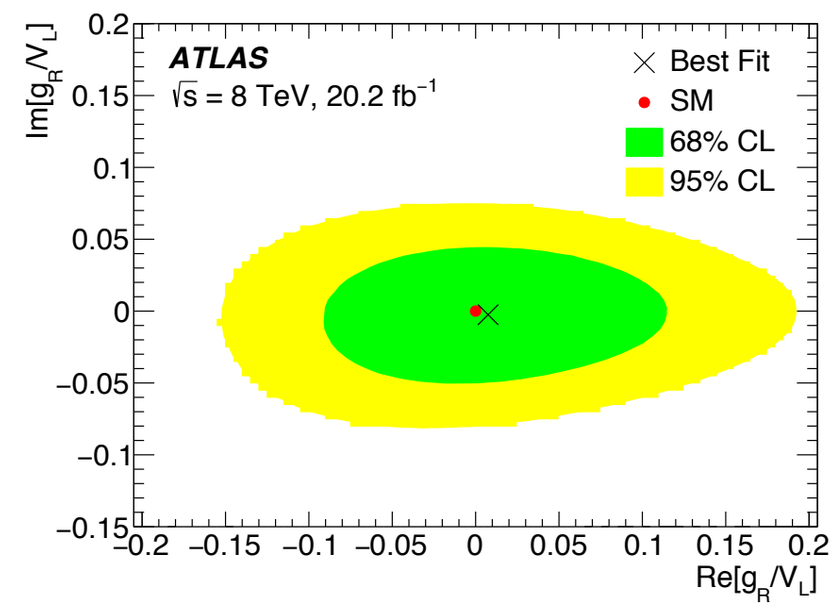
8 TeV analyses in t-channel single top in ATLAS and CMS

ATLAS CMS

- Use Neural Networks trained on dedicated samples
- Assume real couplings, constrain (f_V^L, f_V^R, f_T^L, f_T^R) in 2D or 3D

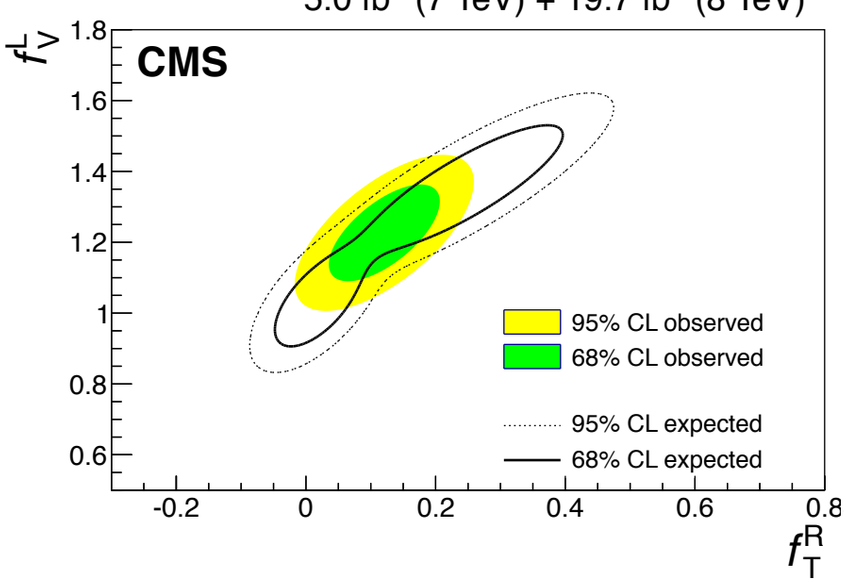
Measure angles in t decays to extract helicities and phases

- Allow complex (CP-violating) couplings, constrain ratios



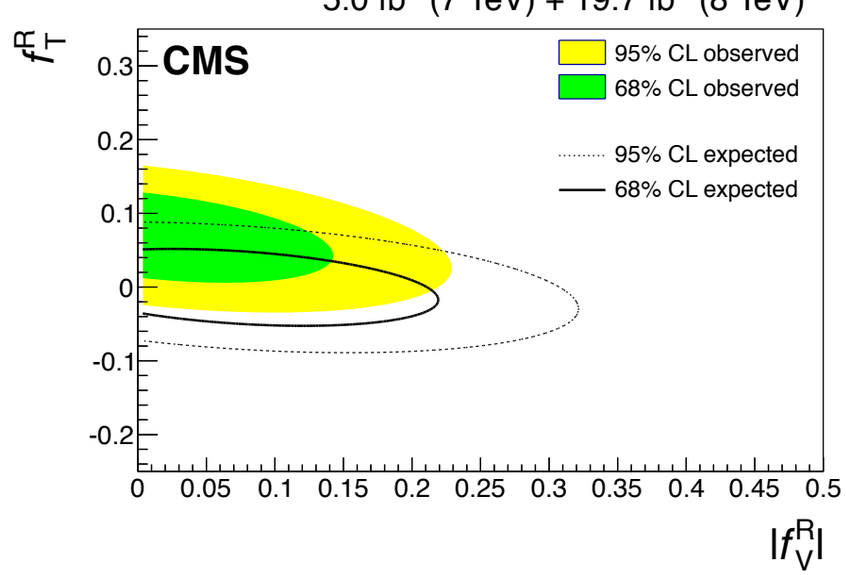
2D limit

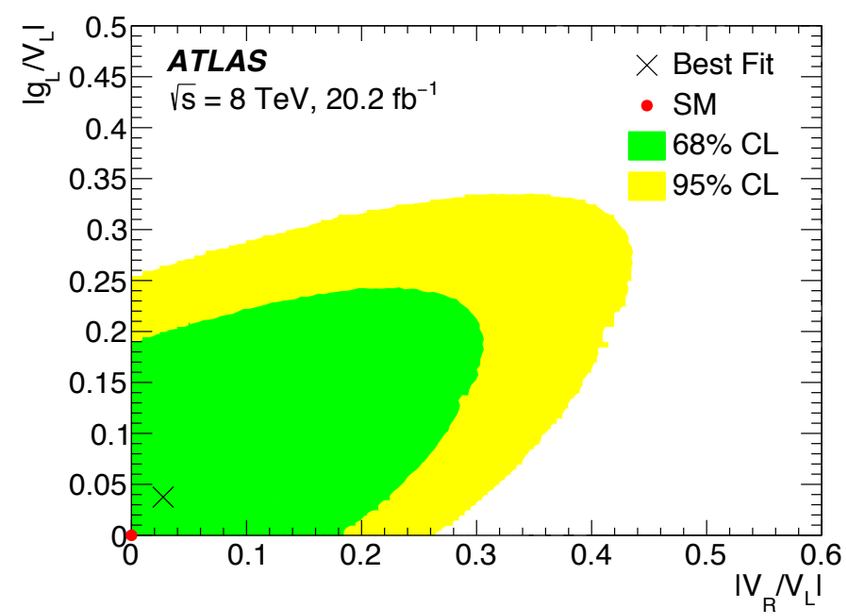
5.0 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)



2D projection of 3D limit (including f_V^L)

5.0 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)





ttW, ttZ: results. ATLAS/CMS

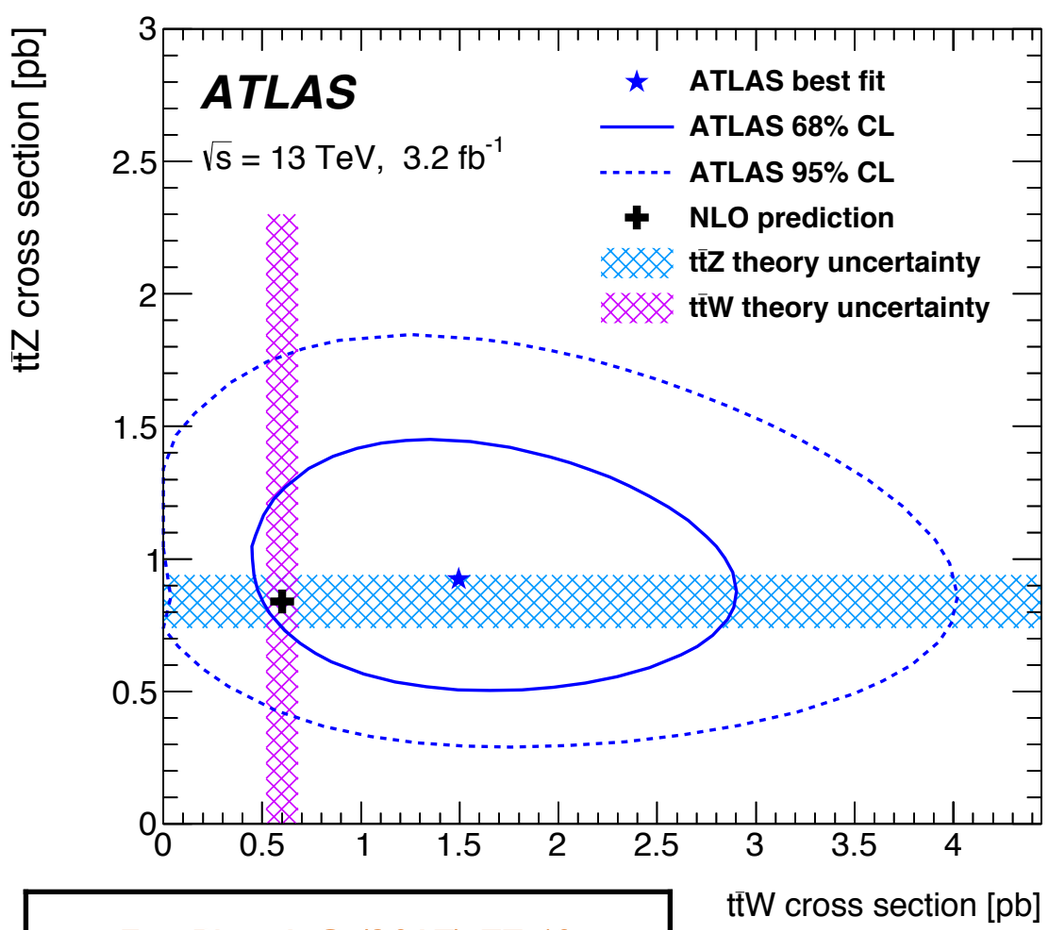
Simultaneous 2D fits to ttW and ttZ

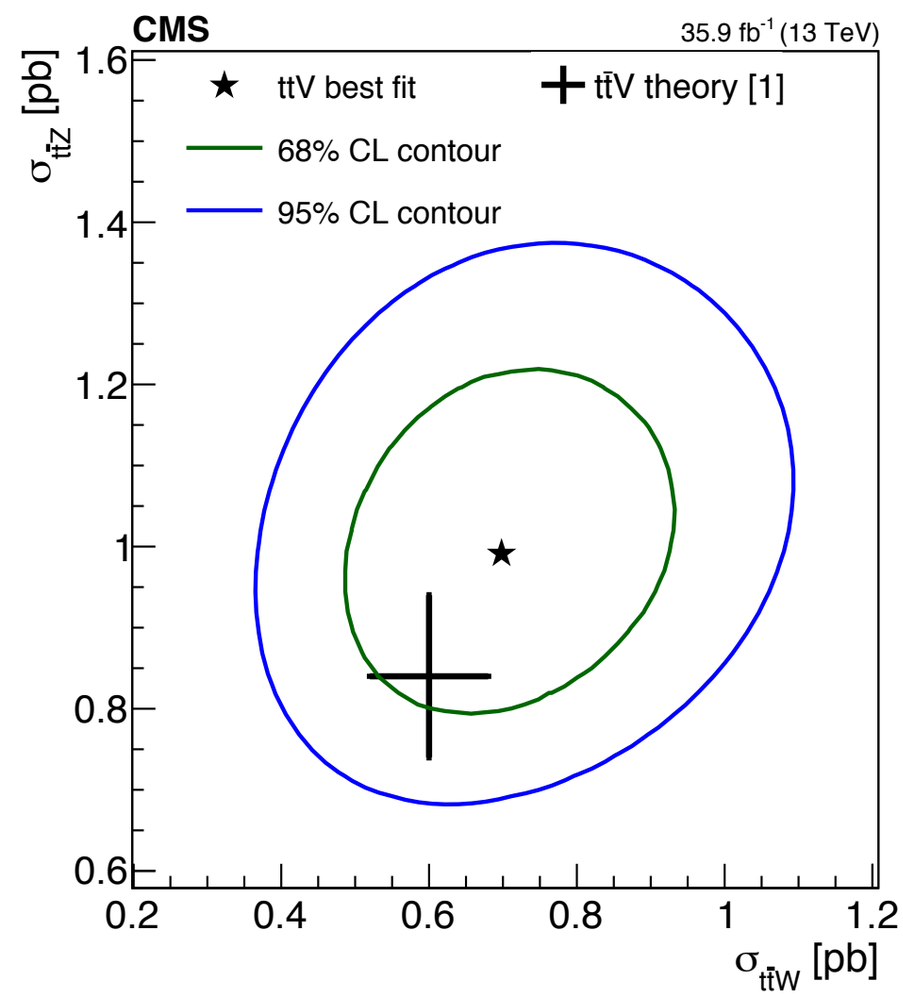
Good agreement with theory prediction (also ATLAS 3.2 fb^{-1} analysis)

- CMS reaches 5 std. dev. significance in both ttW and ttZ
- About 1 std. dev. higher than σ_{SM}

$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(stat)^{+0.13}_{-0.12}\,(syst)\,pb,$$

$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}\,(stat)^{+0.12}_{-0.10}\,(syst)\,pb.$$





Eur. Phys. J. C (2017) 77:40

tttt: status of SM calculation

Scale/PDF choices lead to different NLO/LO k-Factors:

[1] 14 TeV, NLO: $\sigma_{NLO}(tttt) = 15.3^{+4.0}_{-3.8}$ fb

- NLO/LO k-factor: 1.27

[2] 13 TeV, NLO: $\sigma_{NLO}(tttt) = 9.2^{+2.9}_{-2.4}$ fb ← Commonly used as default for 13 TeV

- NLO/LO k-factor: 2.04

[3] 13 TeV, LO: $\sigma_{LO}(tttt) = 9.6^{+3.9}_{-3.5}$ fb

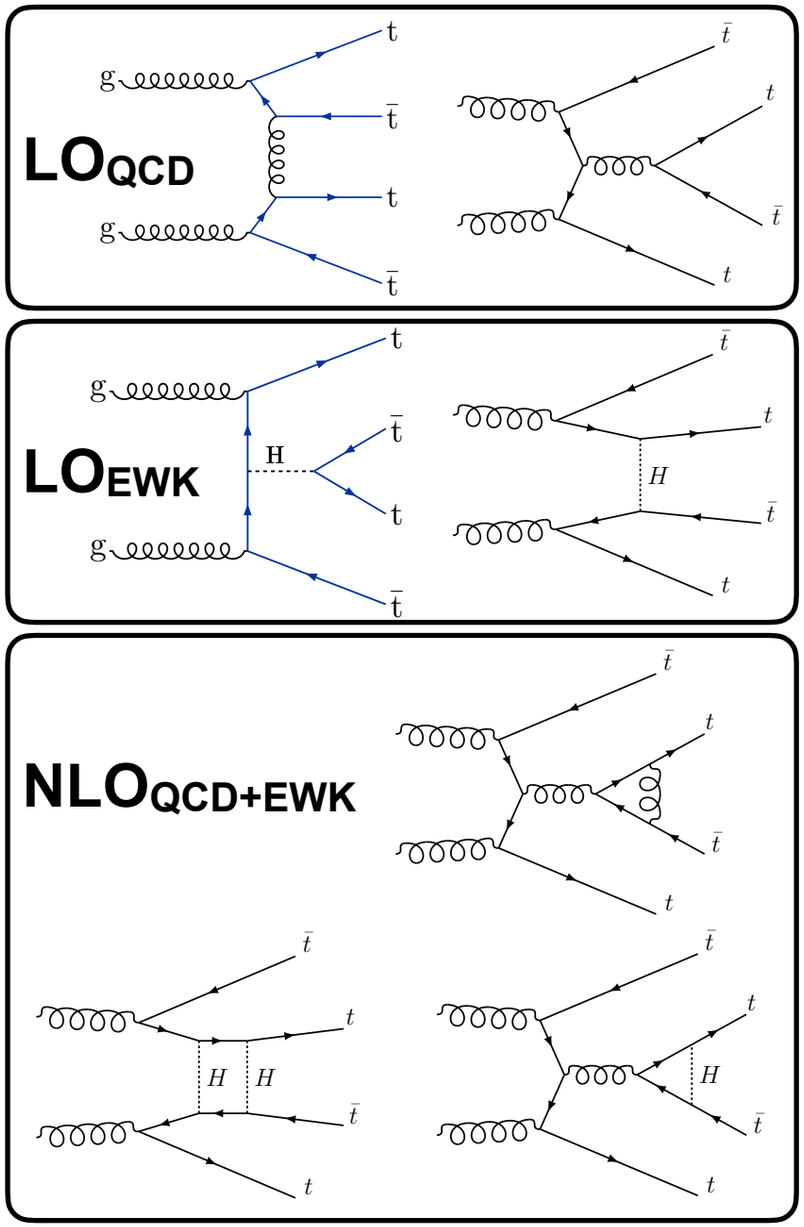
- explicitly separate the Higgs diagrams
- authors apply the 1.27 k-factor from [1] to get: $12.2^{+5.0}_{-4.4}$ fb

Used in top yukawa interpretation

Latest calculation with NLO (QCD) and NLO (EWK):

[4] 13 TeV, NLO(QCD+EWK): $12^{+2.2}_{-2.5}$ fb ← The next standard?

- NLO/LO k-factor: 1.57



Summary:

1) Prediction has strong dependence on scale, PDF, EWK diagrams
2) Range of NLO/LO k-factor: 1.27 to 2.04
3) Range of NLO ±1 sigma: 6.8 to 14.2 fb

[1] G. Bevilacqua and M. Worek, JHEP 1207, 111 (2012) [arXiv:1206.3064].
[2] J. Alwall et al., JHEP 1407, 079 (2014) [arXiv:1405.0301]
[3] Q.-H. Cao, et al., Phys. Rev. D 95 (2017) 053004 [arXiv:1602.01934]
[4] R. Frederix, et al., JHEP 1802 (2018) 031 [arXiv:1711.0211]

tttt: NLO EWK+QCD

[4] R. Frederix, et al., JHEP 1802 (2018) 031 [arXiv:1711.0211]

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}} + \mathrm{NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{+19\%}_{-23\%}$	$7.59^{+64\%}_{-36\%}$	$11.97^{+18\%}_{-21\%}$	1.11 (1.08)

Table 5. Cross section for $pp \to t\bar{t}t\bar{t}$ at 13 TeV in various approximations.

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−26.0	−28.3	−30.5
$\mathrm{LO_3}$	32.6	39.0	45.9
$\mathrm{LO_4}$	0.2	0.3	0.4
$\mathrm{LO_5}$	0.02	0.03	0.05
$\mathrm{NLO_1}$	14.0	62.7	103.5
$\mathrm{NLO_2}$	8.6	−3.3	−15.1
$\mathrm{NLO_3}$	−10.3	1.8	16.1
$\mathrm{NLO_4}$	2.3	2.8	3.6
$\mathrm{NLO_5}$	0.12	0.16	0.19
$\mathrm{NLO_6}$	< 0.01	< 0.01	< 0.01
$\mathrm{NLO_2} + \mathrm{NLO_3}$	−1.7	−1.6	0.9

Table 7. $t\bar{t}t\bar{t}$: $\sigma_{(\mathrm{N})\mathrm{LO}_i}/\sigma_{\mathrm{LO_{QCD}}}$ ratios at 13 TeV, for different values of $\mu = \mu_r = \mu_f$.

$$\Sigma^{t\bar{t}t\bar{t}}_{\mathrm{LO}}(\alpha_s, \alpha) = \alpha_s^4 \Sigma^{t\bar{t}t\bar{t}}_{4,0} + \alpha_s^3 \alpha \Sigma^{t\bar{t}t\bar{t}}_{4,1} + \alpha_s^2 \alpha^2 \Sigma^{t\bar{t}t\bar{t}}_{4,2} + \alpha_s^3 \alpha \Sigma^{t\bar{t}t\bar{t}}_{4,3} + \alpha^4 \Sigma^{t\bar{t}t\bar{t}}_{4,4}$$
$$\equiv \Sigma_{\mathrm{LO}_1} + \Sigma_{\mathrm{LO}_2} + \Sigma_{\mathrm{LO}_3} + \Sigma_{\mathrm{LO}_4} + \Sigma_{\mathrm{LO}_5} \,.$$

$$\Sigma^{t\bar{t}t\bar{t}}_{\mathrm{NLO}}(\alpha_s, \alpha) = \alpha_s^5 \Sigma^{t\bar{t}t\bar{t}}_{5,0} + \alpha_s^4 \alpha^1 \Sigma^{t\bar{t}t\bar{t}}_{5,1} + \alpha_s^3 \alpha^2 \Sigma^{t\bar{t}t\bar{t}}_{5,2} + \alpha_s^2 \alpha^3 \Sigma^{t\bar{t}t\bar{t}}_{5,3} + \alpha_s^1 \alpha^4 \Sigma^{t\bar{t}t\bar{t}}_{5,4} + \alpha^5 \Sigma^{t\bar{t}t\bar{t}}_{5,5}$$
$$\equiv \Sigma_{\mathrm{NLO}_1} + \Sigma_{\mathrm{NLO}_2} + \Sigma_{\mathrm{NLO}_3} + \Sigma_{\mathrm{NLO}_4} + \Sigma_{\mathrm{NLO}_5} + \Sigma_{\mathrm{NLO}_6} \,.$$

tttt: Top Yukawa and Higgs Width

σ(tttt) includes diagrams with off-shell Higgs bosons

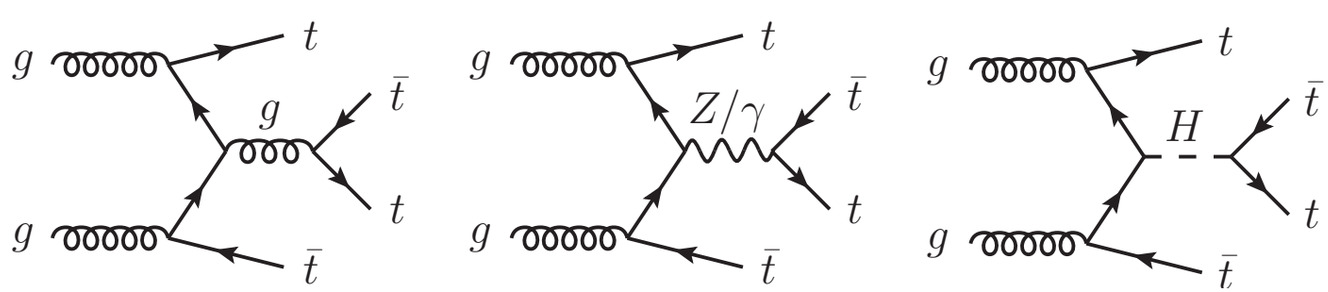
Small, but proportional to 4th power of top-Higgs coupling

$$\kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

- Unique: production and decay through same Yukawa
- $|y_t| > |y_t^{SM}|$ would significantly enhance tttt cross section

Proposal from Cao et al. [PRD 95, 053004 (2017) and FCC Yellow Report]

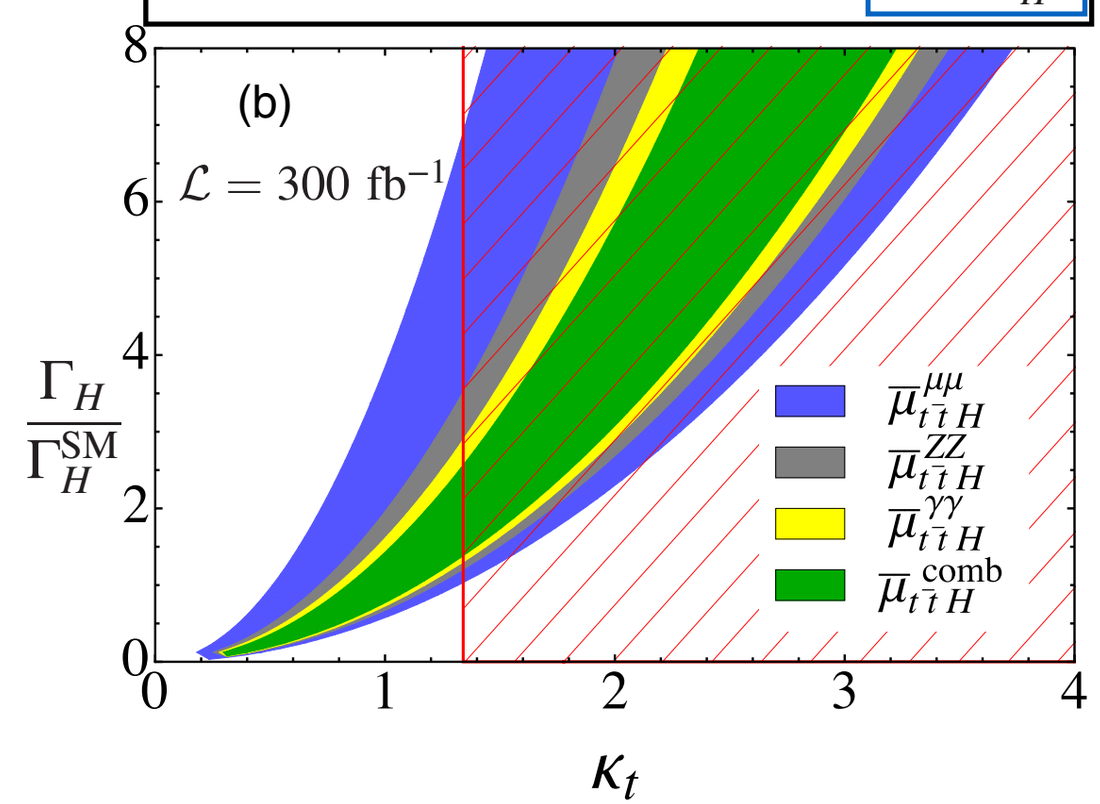
Combine tttt and ttH measurements to constrain total Higgs width, assuming SM branching ratio to μμ/ZZ/γγ, or vice-versa



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

	8 TeV	13 TeV	14 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.344 fb,	9.997 fb,	13.140 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$:	0.171 fb,	1.168 fb,	1.515 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−0.224 fb,	−1.547 fb,	−2.007 fb.

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx) = \sigma^{\rm SM}(pp \to t\bar{t}H \to t\bar{t}xx) \times \kappa_t^2\kappa_x^2\frac{\Gamma_H^{\rm SM}}{\Gamma_H}$$



tttt: H/A resonant search (ATLAS)

Two-Higgs-doublet models (2HDM)

Realized in many new physics scenarios, such as SUSY

Lowest mass scalar can match the SM Higgs ("h"), in the "alignment limit"

Introduce a scalar (H) and a pseudoscalar (A)

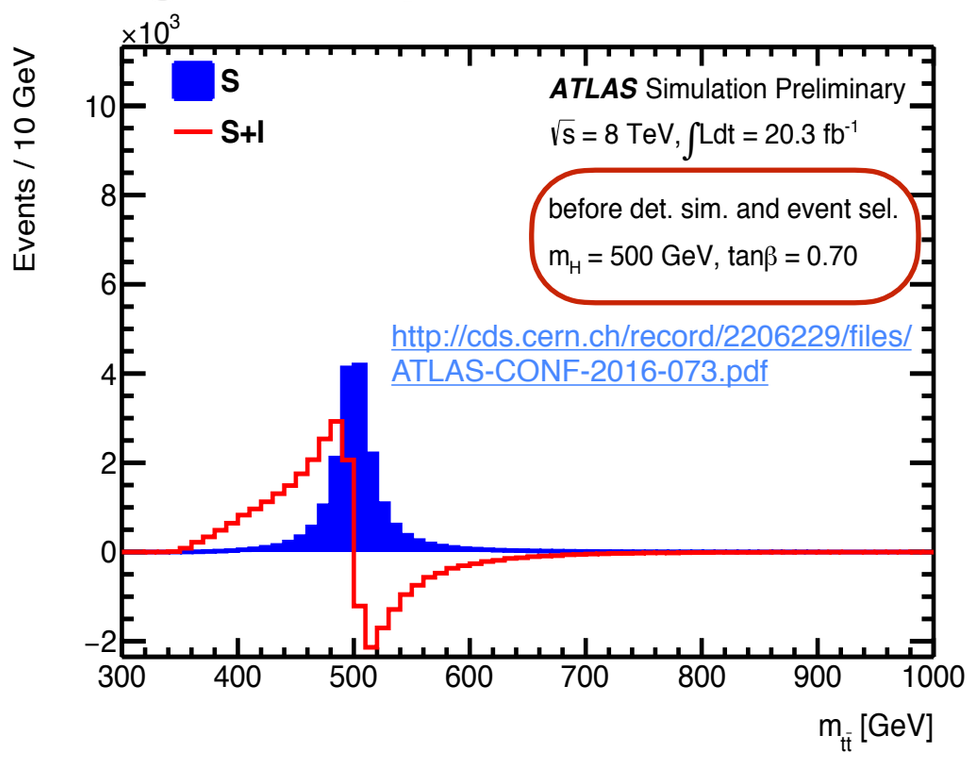
Currently unprobed region (alignment limit, low tanβ, $m_{H/A} \gtrsim 2*m_t$) where bb/WW couplings are suppressed, and H/A decays preferentially to tt

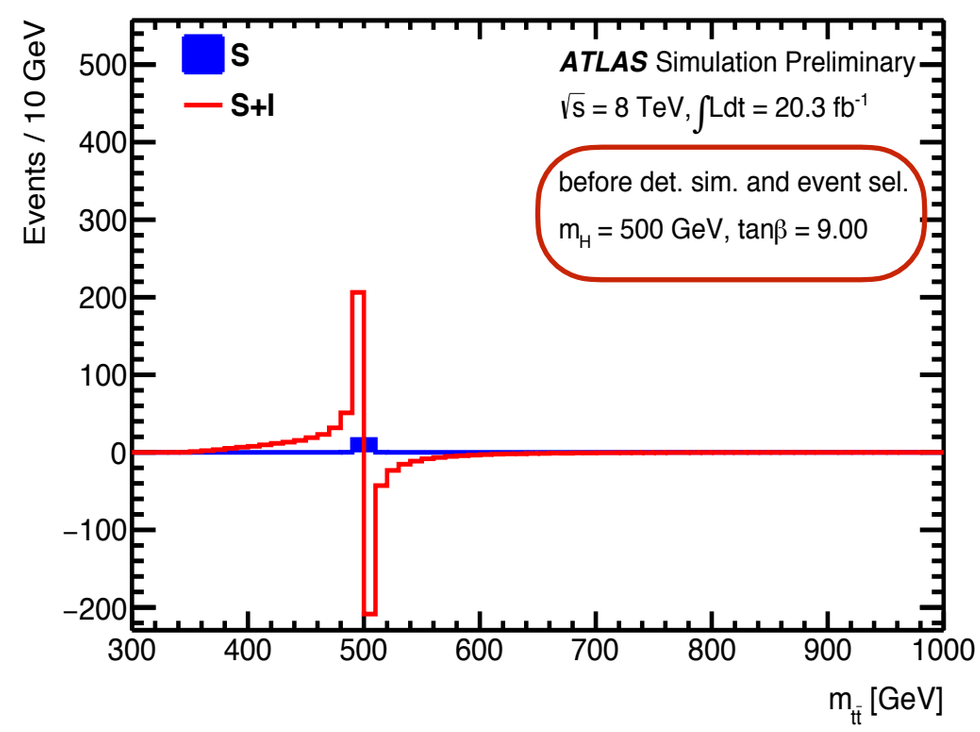
Largest cross section is direct production pp→H/A→tt

Problem 1: large background (and interference with) QCD tt production

Problem 2: shape of signal mass peak depends on coupling

Signal shape in m_{tt} for different assumptions of signal strength





tttt: H/A resonant search (ATLAS)

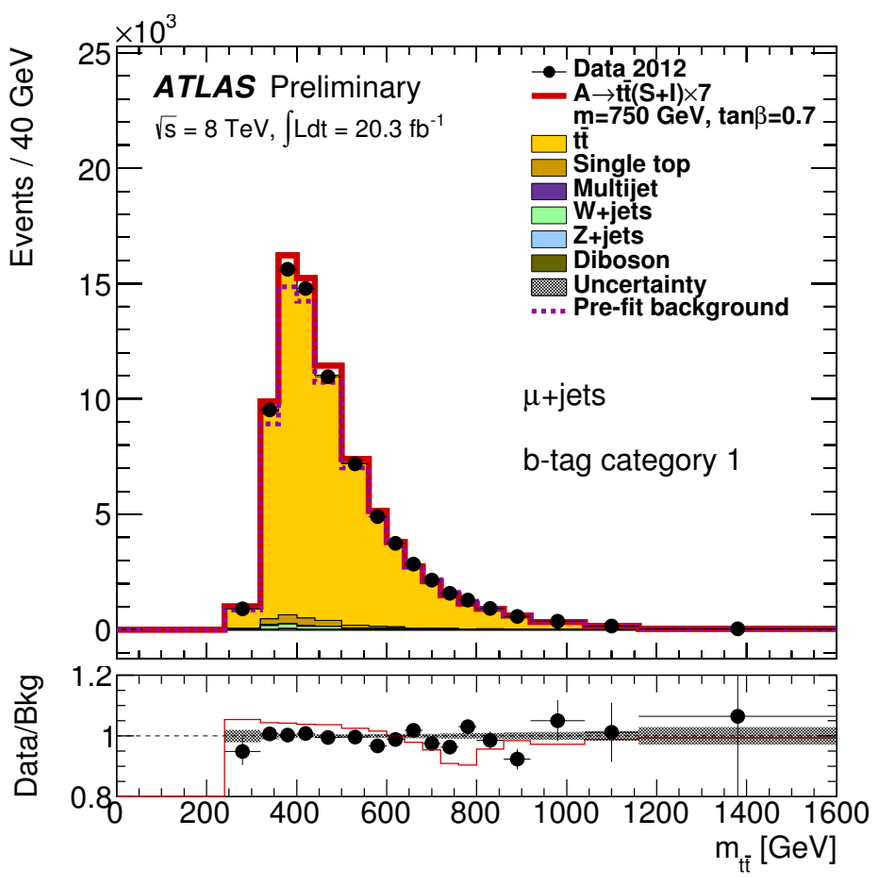
ATLAS search for m_{tt} features in 8 TeV data [CONF-2016-073]

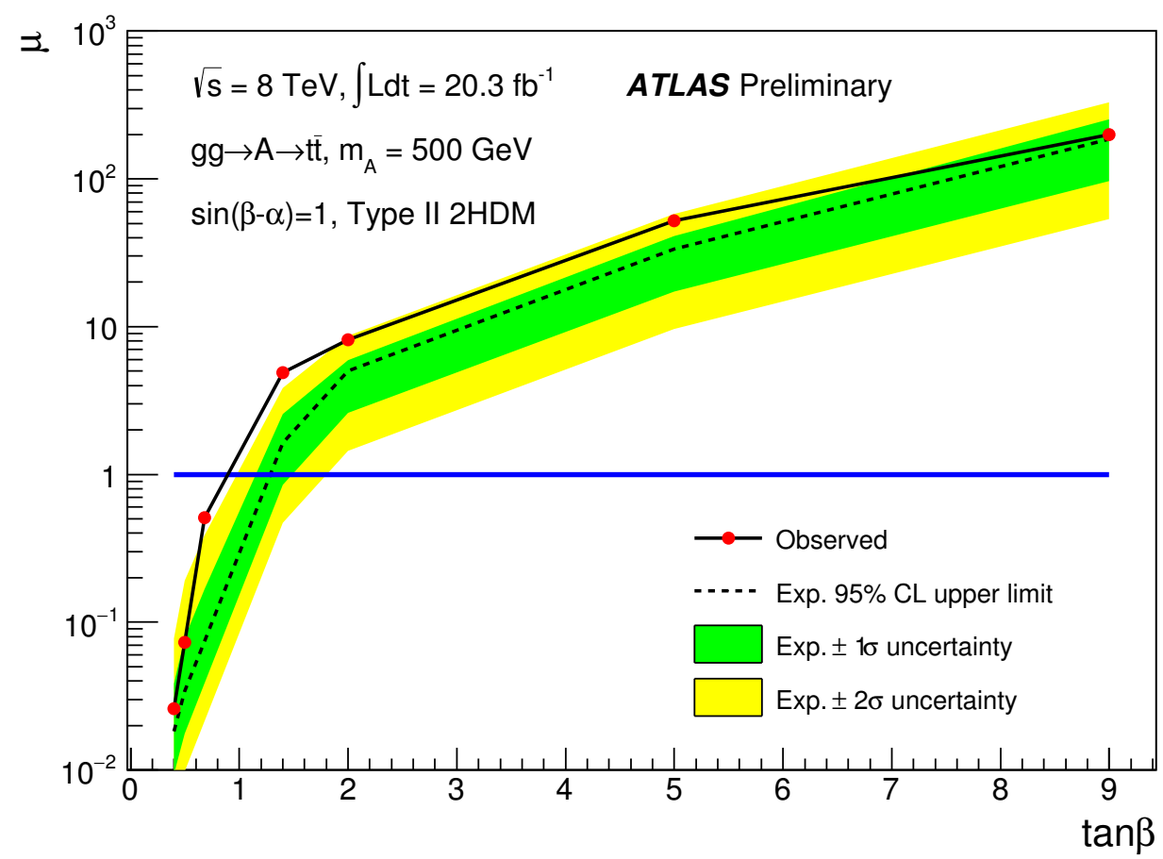
Exclude $m_{A(H)}$~500 GeV for very small values of tanβ<0.85 (0.45)

- Expected sensitivity for tanβ ≲ 1.2 (1.0).

Search loses sensitivity quickly as higher tanβ reduces cross section and narrows width

- Searches for this signature are constrained by systematics on reconstructed m_{tt}
- Difficult to probe 350-450 GeV region due to background shape



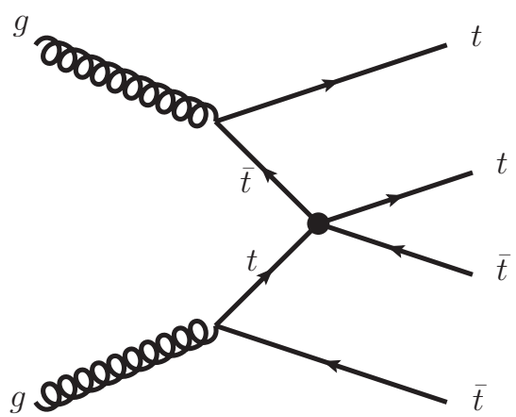


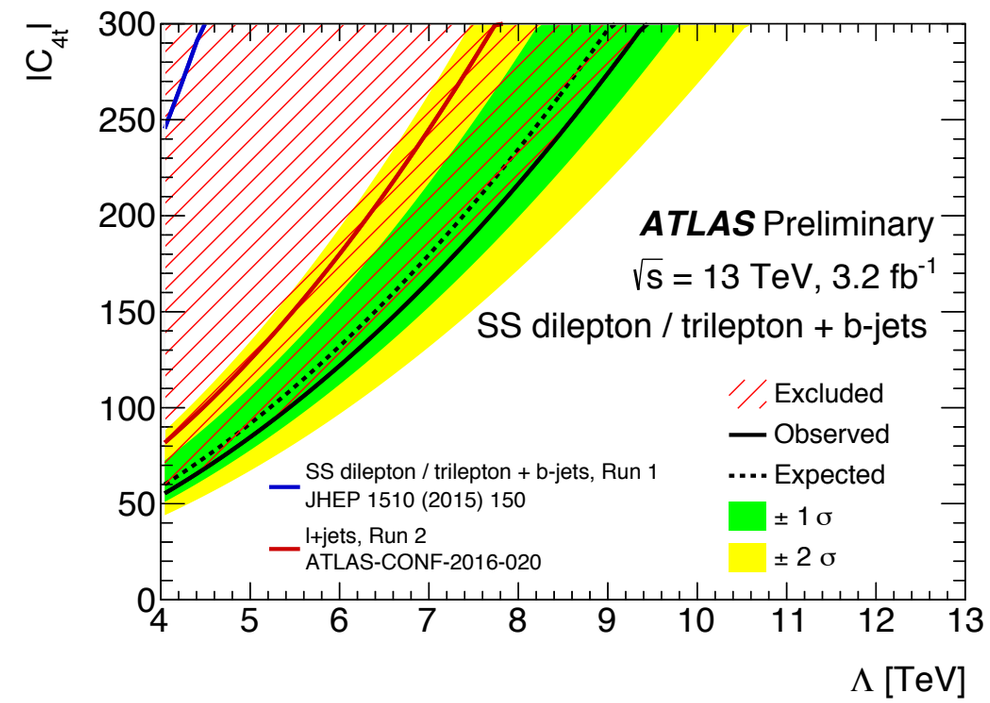
tttt EFTs (ATLAS)

Contact interactions (explored by ATLAS-CONF-2016-020 and 032)

Generic non-resonant tttt production, as long as Λ is much larger than the scale of the process

$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} \left(\bar{t}_R \gamma^\mu t_R\right) \left(\bar{t}_R \gamma_\mu t_R\right)$$





Even more generic: Effective Field Theory operators

- http://feynrules.irmp.ucl.ac.be/wiki/4topEFT

First: can set limits based on cross-section enhancement

Next (300 fb^{-1}): can start studying kinematics

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

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

$$\mathcal{O}_L^{(8)} = \left(\bar{Q}_L \gamma^\mu T^A Q_L\right)\left(\bar{Q}_L \gamma_\mu T^A Q_L\right)$$

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

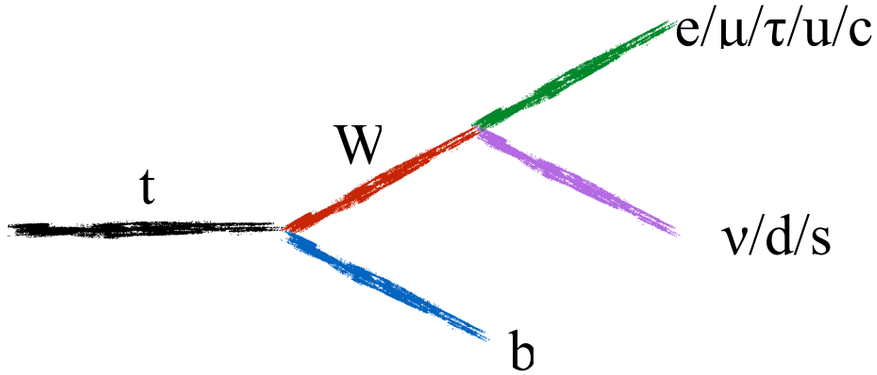
$$\mathcal{O}_B^{(8)} = \left(\bar{Q}_L \gamma_\mu T^A Q_L\right)\left(\bar{t}_R \gamma_\mu T^A t_R\right)$$

tttt: trigger and Baseline selection

Dilepton triggers: ee, μμ, eμ

Use non-isolated triggers with p_T^{lep} > 8 GeV, H_T > 300 GeV

- > 95% (92%) for ee, eμ (μμ)



Object kinematics:

Object	p_T	η
Electrons	$p_T > 20\,\text{GeV}$	$\lvert\eta\rvert < 2.5$
Muons	$p_T > 20\,\text{GeV}$	$\lvert\eta\rvert < 2.4$
Jets	$p_T > 40\,\text{GeV}$	$\lvert\eta\rvert < 2.4$
b-tagged jets	$p_T > 25\,\text{GeV}$	$\lvert\eta\rvert < 2.4$

Baseline selection:

tttt: Branching Ratio ~ 9% Baseline selection ~ 1.5%

tttt: ttVV

$t\bar{t}VV$

Several not-yet-observed rare backgrounds with t's and V's

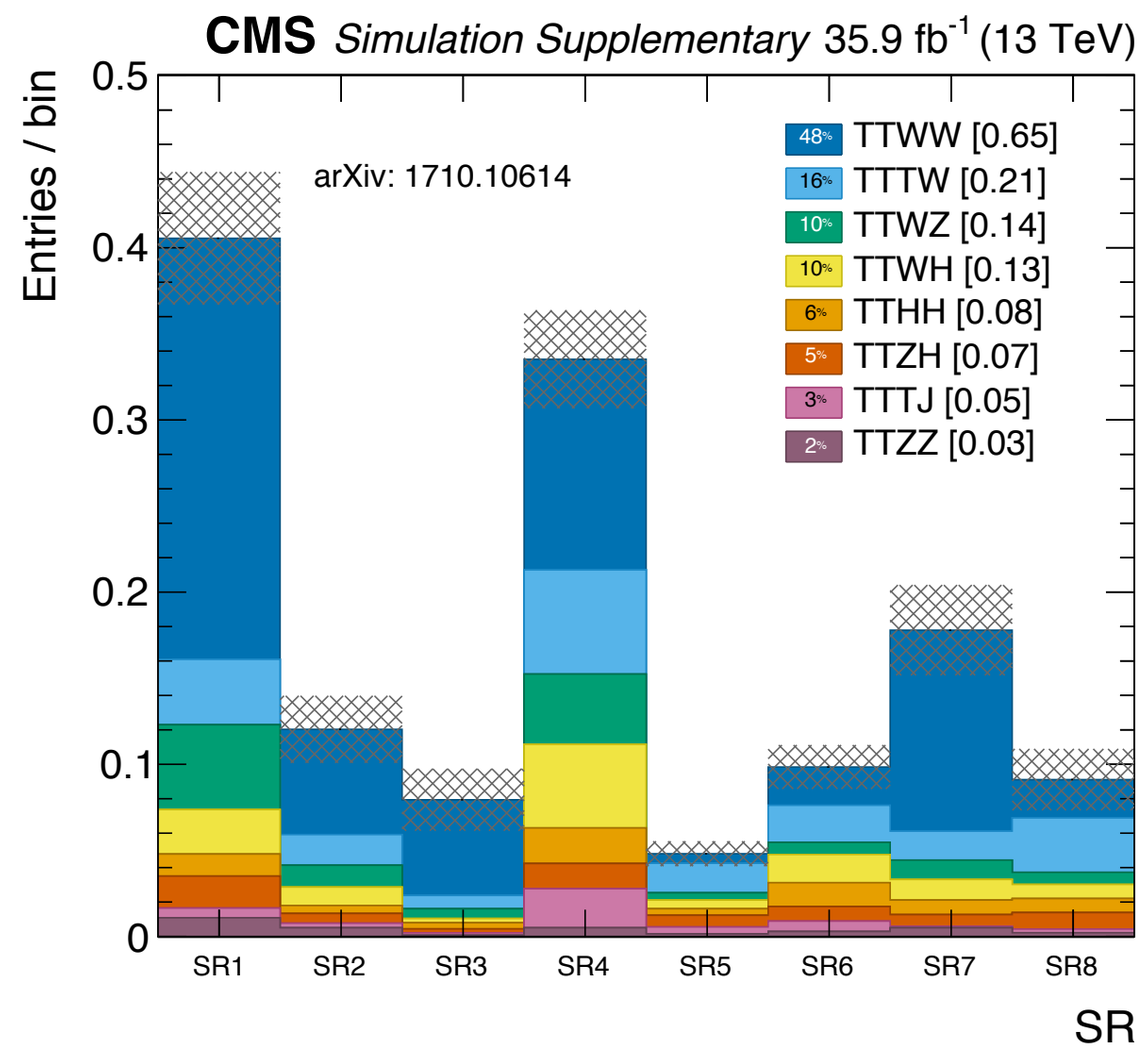
Generate LO samples, use NLO cross-sections

- Largest contribution: ttWW (σ ~ 10 fb)

Interesting measurements for Run 3 and beyond!

13 TeV σ [ab]	$t\bar{t}W^+Z$	$t\bar{t}W^-Z$	$t\bar{t}ZZ$
NLO QCD	$2705(3)^{+9.9\%}_{-10.6\%}{}^{+2.7\%}_{-2.7\%}$	$1179(2)^{+11.2\%}_{-11.2\%}{}^{+3.7\%}_{-3.7\%}$	$1982(2)^{+5.2\%}_{-9.0\%}{}^{+2.6\%}_{-2.6\%}$
LO	$1982(2)^{+28.4\%}_{-20.6\%}{}^{+3.3\%}_{-3.3\%}$	$839.4(6)^{+28.2\%}_{-20.5\%}{}^{+4.2\%}_{-4.2\%}$	$1611(1)^{+31.4\%}_{-22.1\%}{}^{+2.7\%}_{-2.7\%}$
K-factor	1.36	1.40	1.23
13 TeV σ [ab]	$t\bar{t}W^+H$	$t\bar{t}W^-H$	$t\bar{t}ZH$
NLO QCD	$1089(1)^{+1.8\%}_{-5.9\%}{}^{+2.6\%}_{-2.6\%}$	$493.0(5)^{+2.6\%}_{-6.4\%}{}^{+3.4\%}_{-3.4\%}$	$1535(2)^{+1.9\%}_{-6.8\%}{}^{+3.0\%}_{-3.0\%}$
LO	$997.0(9)^{+26.9\%}_{-19.8\%}{}^{+3.0\%}_{-3.0\%}$	$440.0(4)^{+26.9\%}_{-19.8\%}{}^{+3.8\%}_{-3.8\%}$	$1391(1)^{+32.2\%}_{-22.6\%}{}^{+2.8\%}_{-2.8\%}$
K-factor	1.09	1.12	1.10
13 TeV σ [ab]	$t\bar{t}W^+W^-$	$t\bar{t}W^+W^-$ (4f)	$t\bar{t}HH$
NLO QCD	–	$11500(10)^{+8.1\%}_{-10.9\%}{}^{+3.0\%}_{-3.0\%}$	$756.5(7)^{+1.1\%}_{-4.4\%}{}^{+3.3\%}_{-3.3\%}$
LO	$8380(5)^{+33.2\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$8357(5)^{+33.3\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$765.4(5)^{+31.8\%}_{-22.4\%}{}^{+2.9\%}_{-2.9\%}$
K-factor	–	1.38	0.99

arXiv:1610.07922 (Handbook of LHC cross-sections 4)



tttt: X+γ and Rares

Xγ
Rare

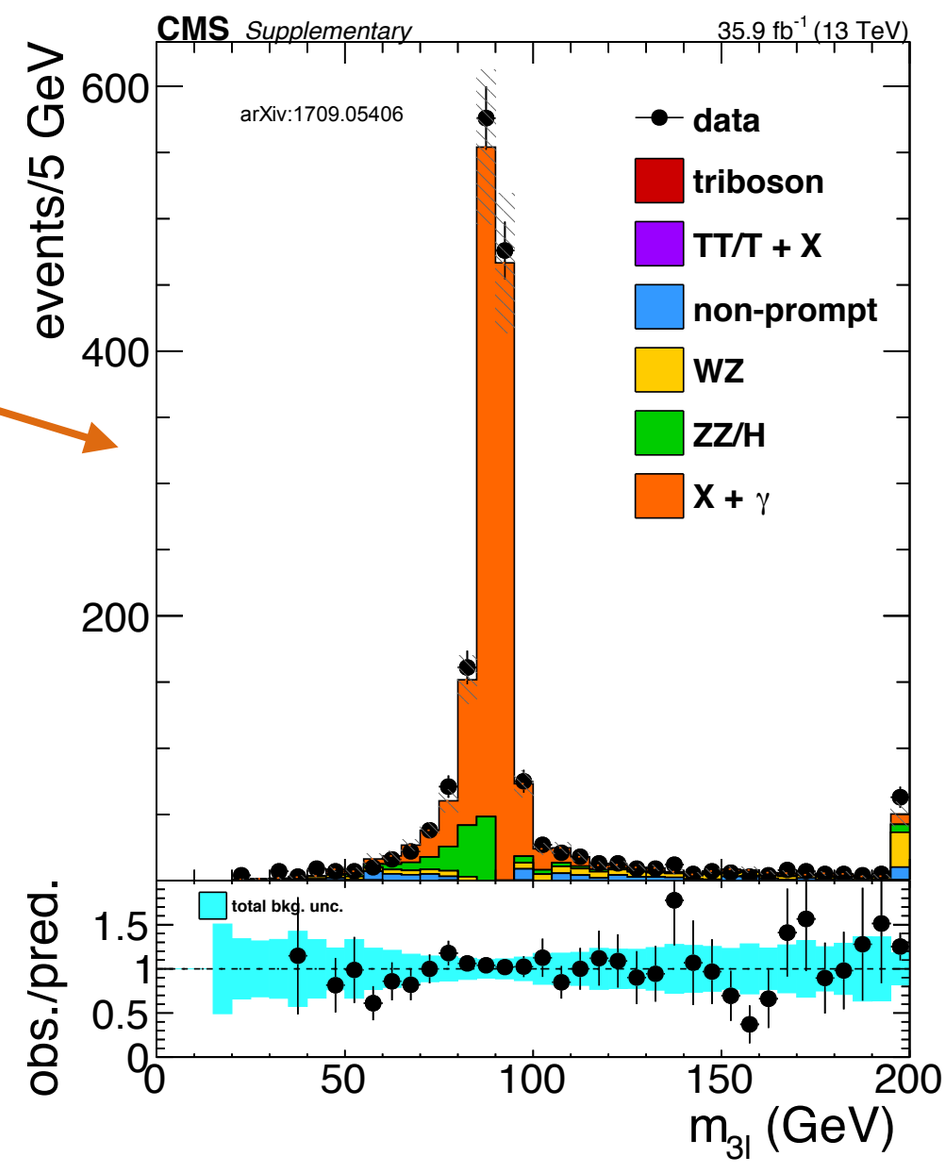
X+γ: ttγ, tγ

Asymmetric prompt γ —> dilepton, with one lepton lost

- Internal conversions: $\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$
- External conversions: $\gamma \rightarrow e^+e^-$ interacting with the detector

Estimated from simulation in tttt analysis

- But could also define a Z—>llγ* and γ*—> ll CR, as in arXiv:1709.05406
- CR: $N_{lep} = 3$, $m_{ll} < 75$ GeV, MET < 50 GeV



Rares:

- VVV: WWW, WWZ, WZZ, ZZZ, WWγ, WZγ
- tZq, ggH, WH, ZH, $W^\pm W^\pm$, tttV, tttq
- Estimated from simulation

tttt: charge misidentification

Charge misid.

Charge misidentification is negligible for muons, and for electrons we reduce it by requiring "triple-charge agreement"

Agreement between 3 available charge measurements

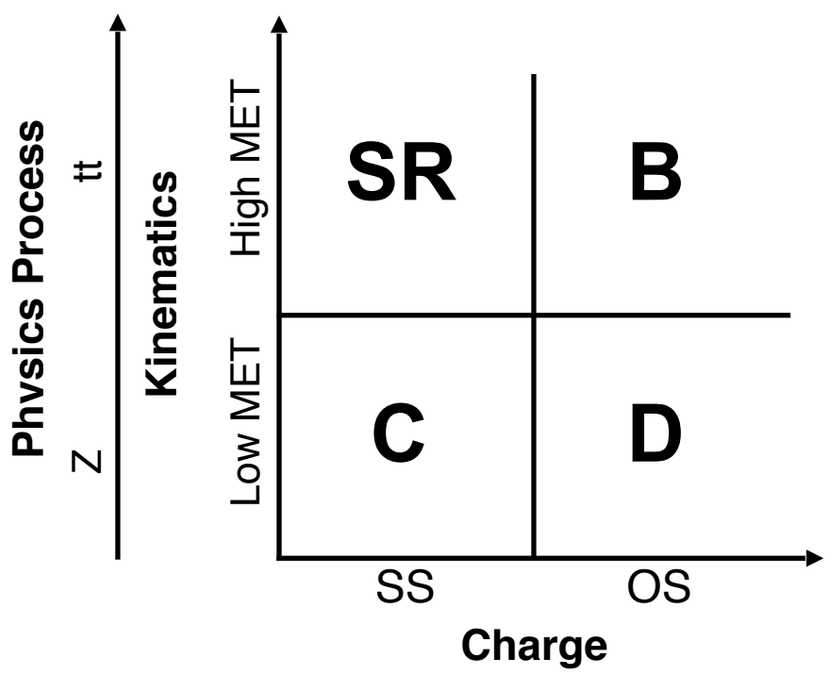
- Pion-like track, Electron-like track (with Brehm), Δφ(Pixel hits, Supercluster)

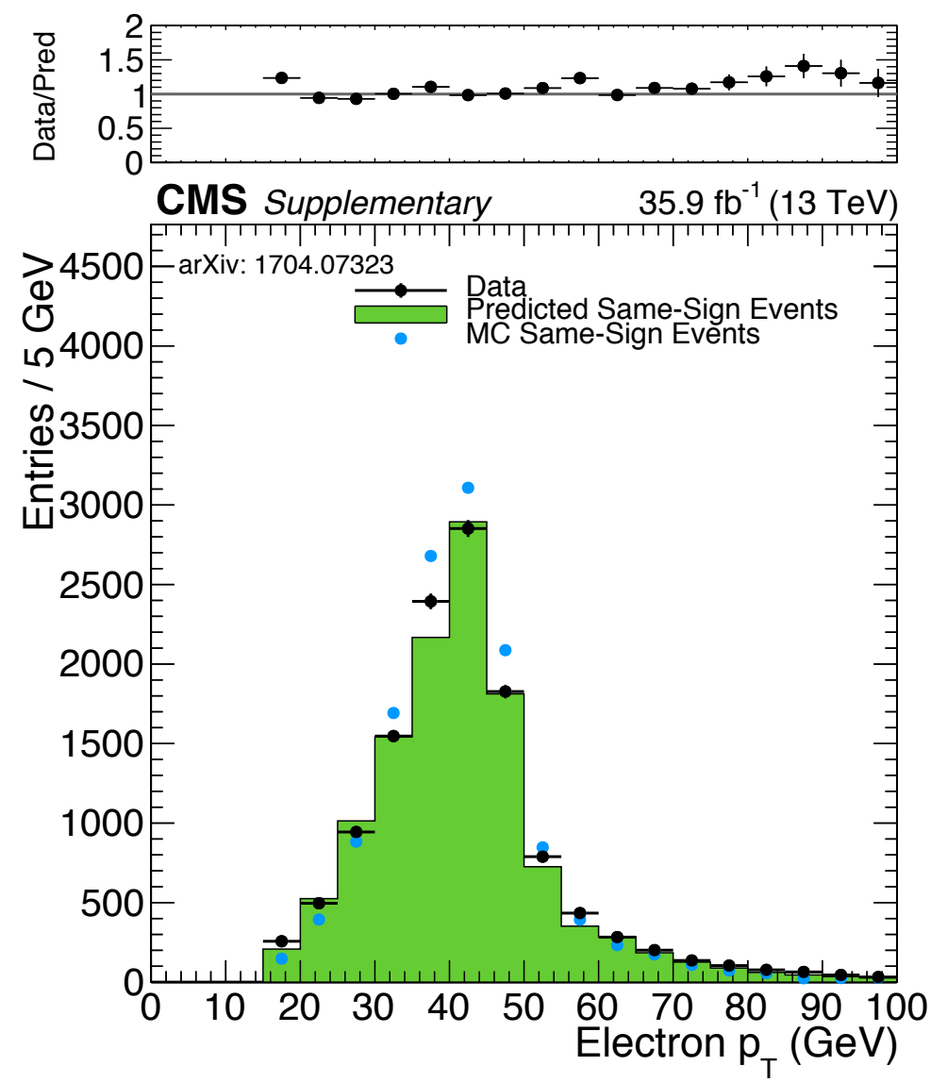
Estimate based on "ABCD-like" method

Use Z MC to estimate $TF(p_T^l, \eta^l)$

- Validate TF in Z-enriched (low-MET) data

Apply TF to OS events in data



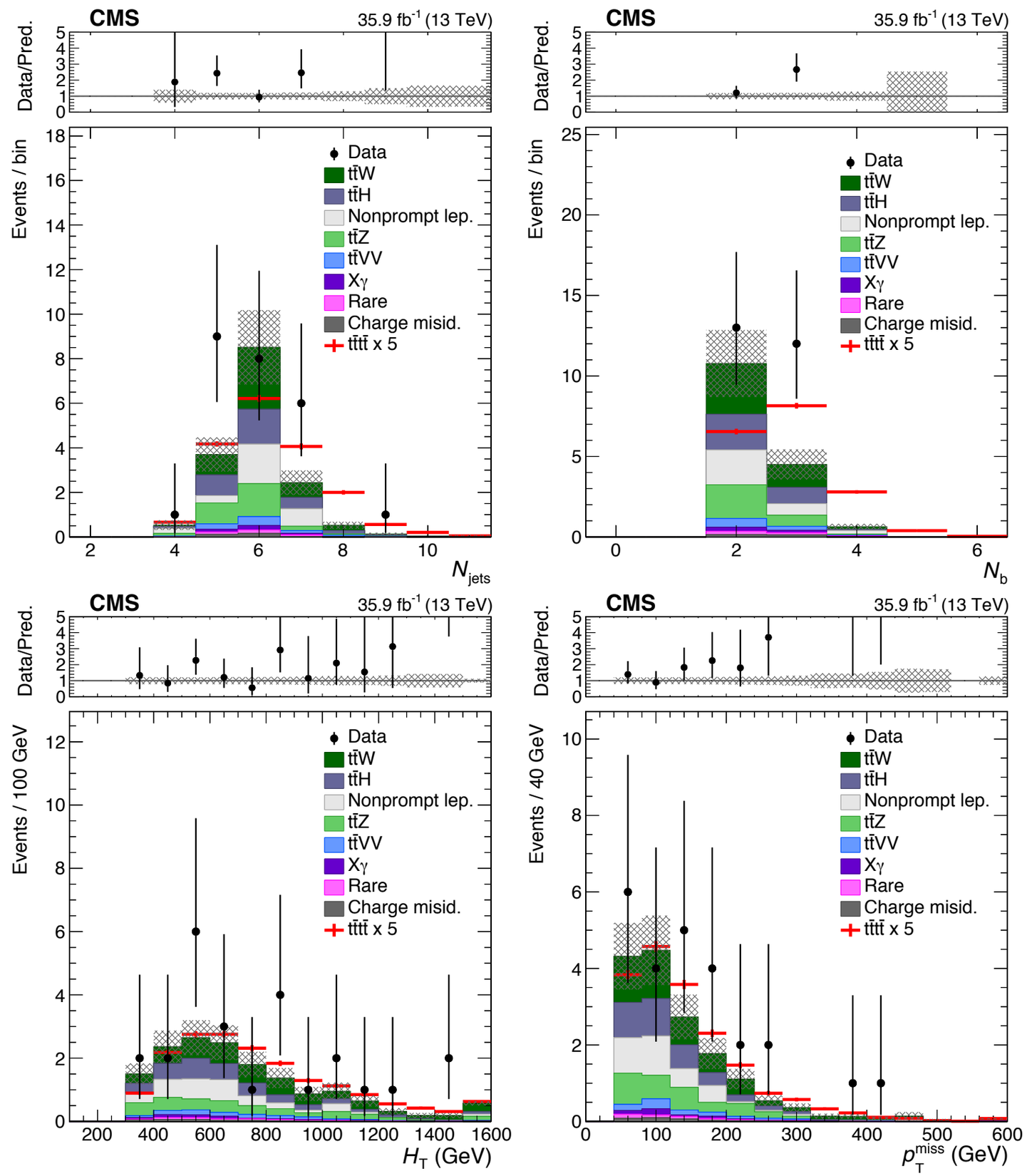


tttt: pre-fit kinematics

Small underestimate when using pre-fit ttW, ttZ

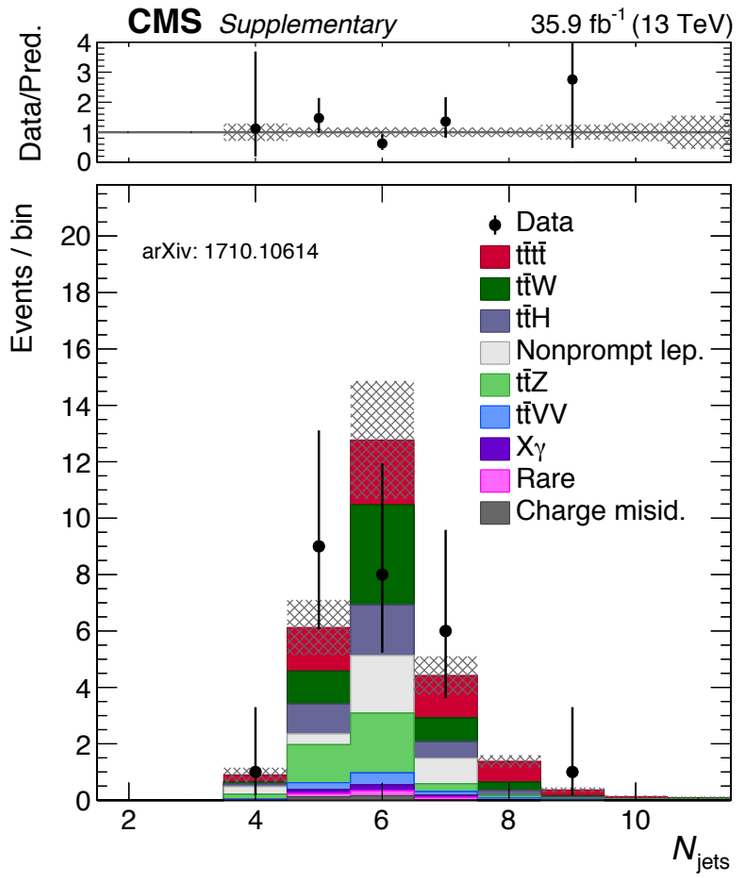
Interesting excess in $N_b = 3$ bin

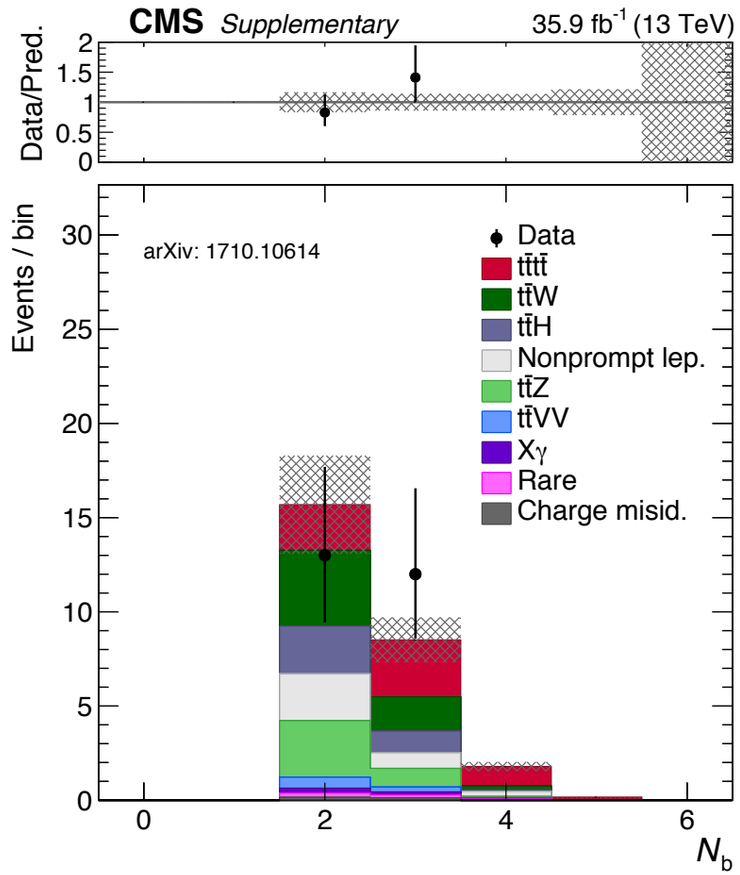
Checked individual events, found no suspicious behavior

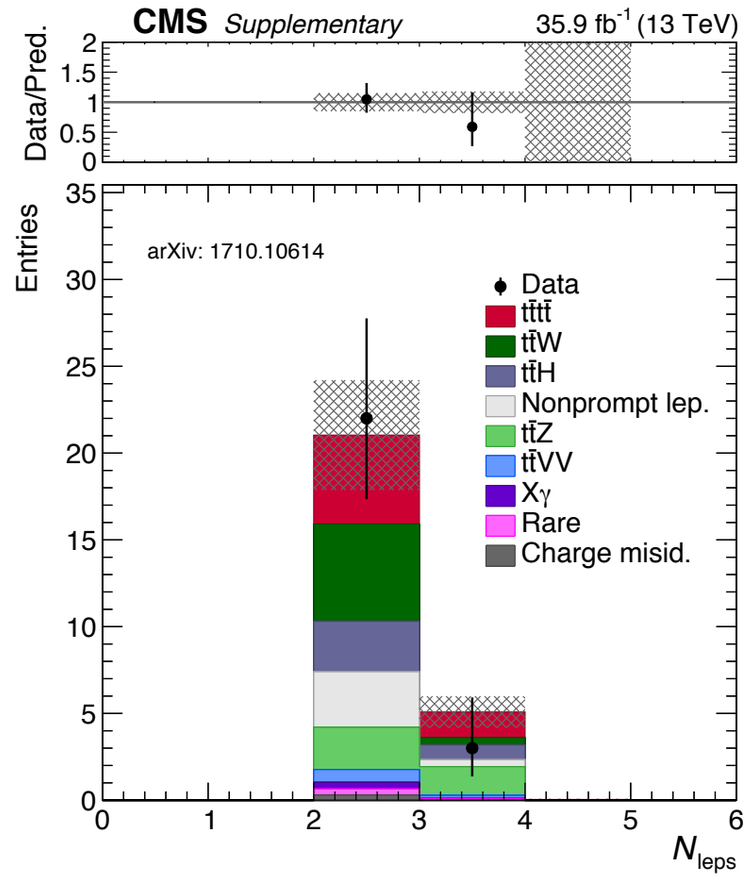


tttt: post-fit kinematics

Reduced tension in Nb=3 region. Good agreement for leptons.







μμ μe eμ ee