Summary of single top measurements in CMS

5th CMS Single Top Workshop

Karlsruher Institut für Technologie

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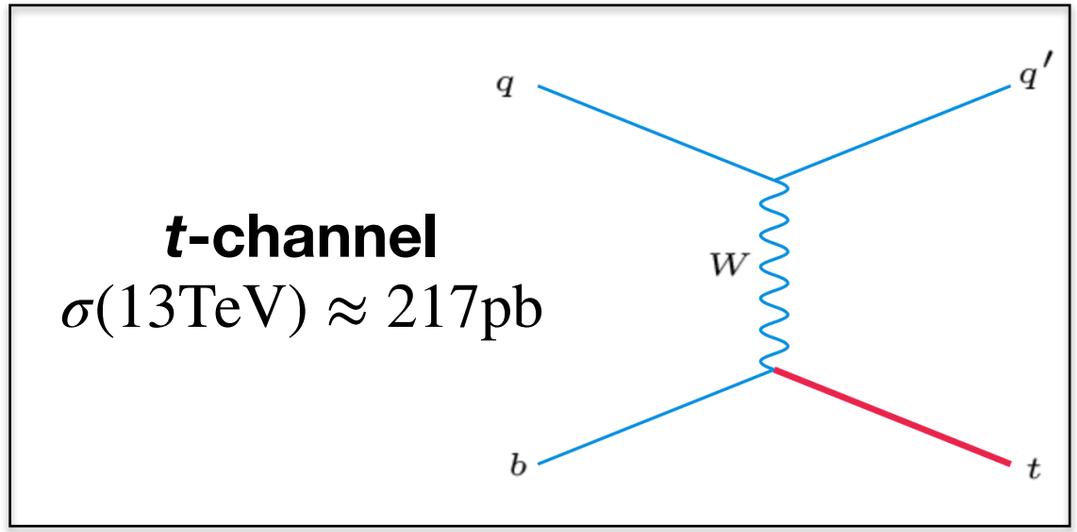
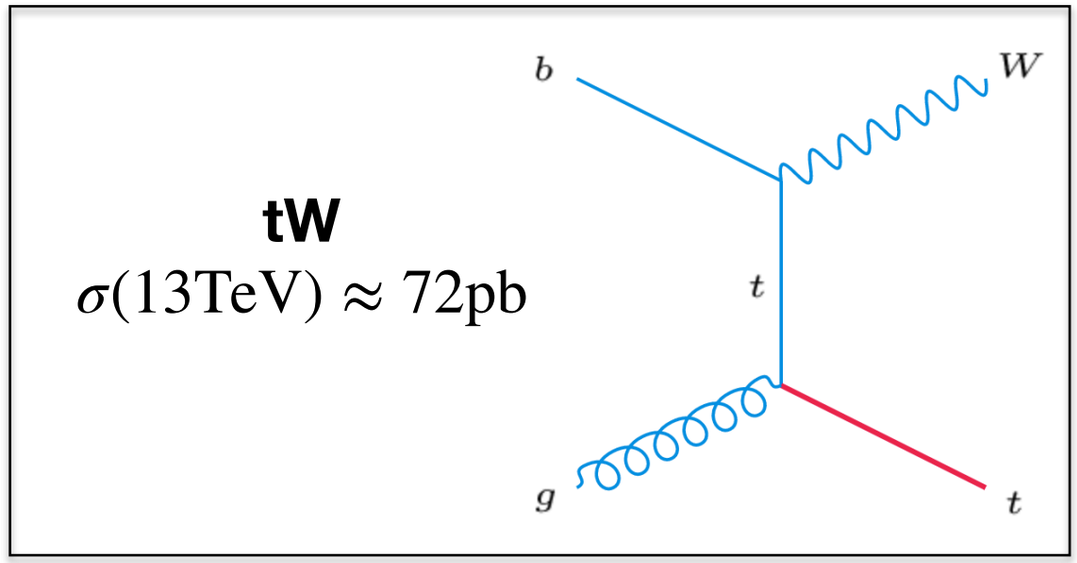
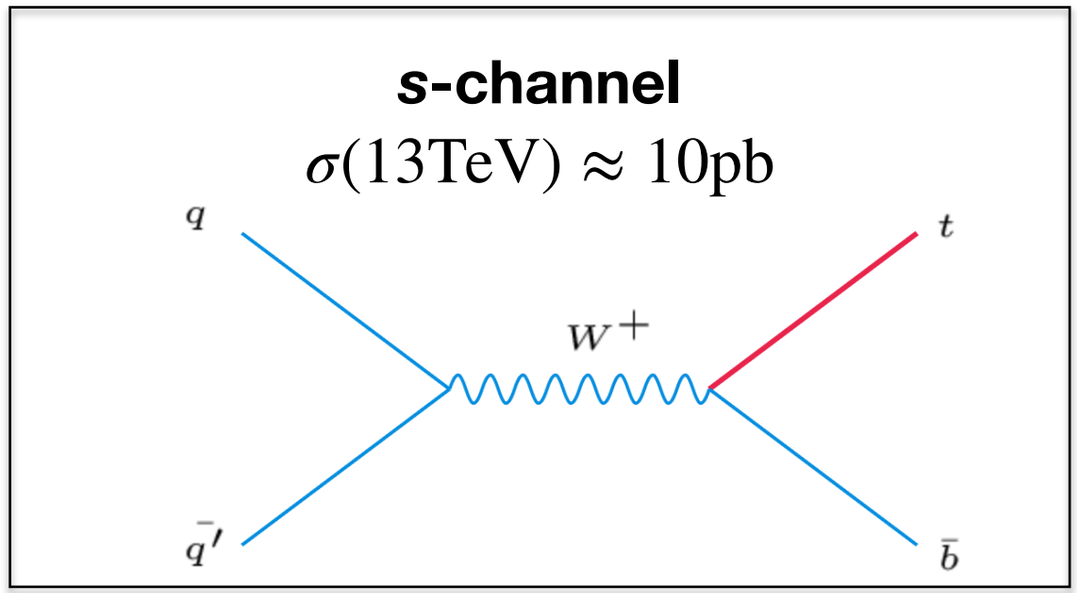
on behalf of the CMS collaboration

Introduction

- Single top quark production occurs via electroweak interaction
- Interesting for various reasons
  - ➤ Precision measurement of SM parameters:
    - ➛ $|V_{tb}|$
    - ➛ m_{top}
  - ➤ Sensitive to u/d quark ratio in proton PDFs
  - ➤ Powerful probe for BSM physics:
    - ➛ anomalous tWb coupling
    - ➛ FCNC in production
    - ➛ new resonances (W', $H^{\pm}$)
  - ➤ Important to understand rare processes:
    - ➛ Single top + X , where X = Z, γ, H
  - ➤ Factory to tune MC generators:
    - ➛ unfolded distributions
    - ➛ fiducial measurements
- In this talk ➛ recent results from CMS (Run -II)



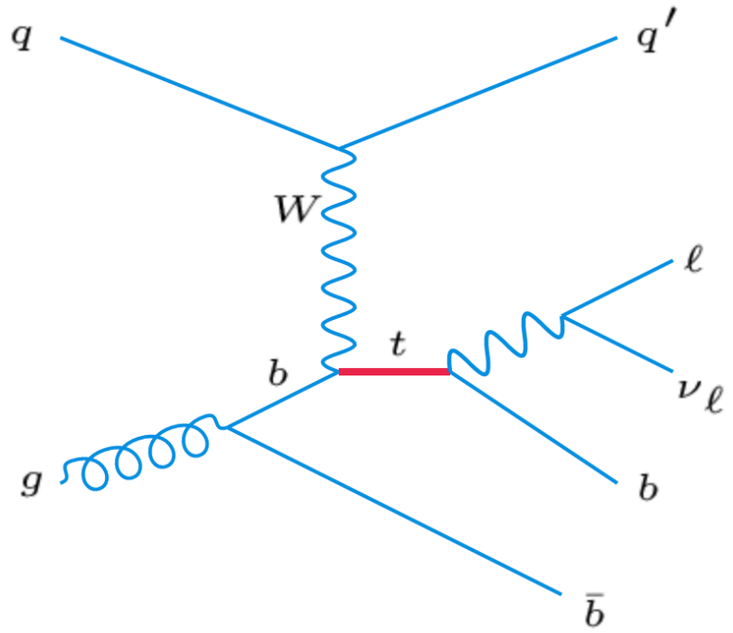




t-channel

Topology

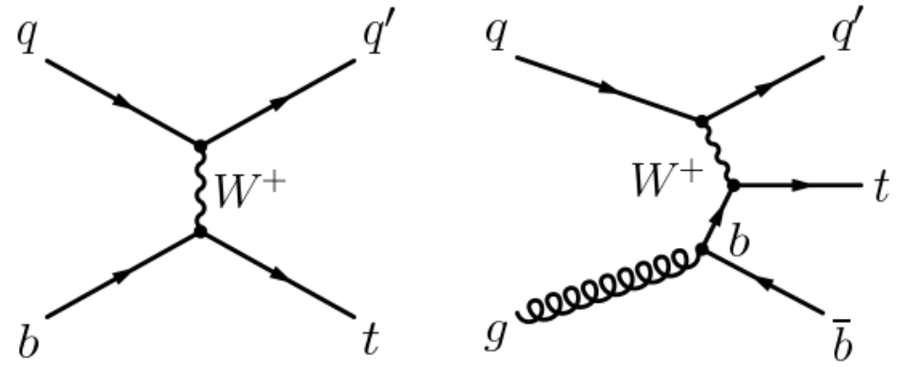
- Spectator jet with high |η|
- 1 isolated high-p_T lepton
- high-p_T, central b-jet
- Missing p_T



$$t-\text{ch} : \sigma(13\text{TeV}) = 217.0^{+9.1}_{-7.7}\text{pb}$$

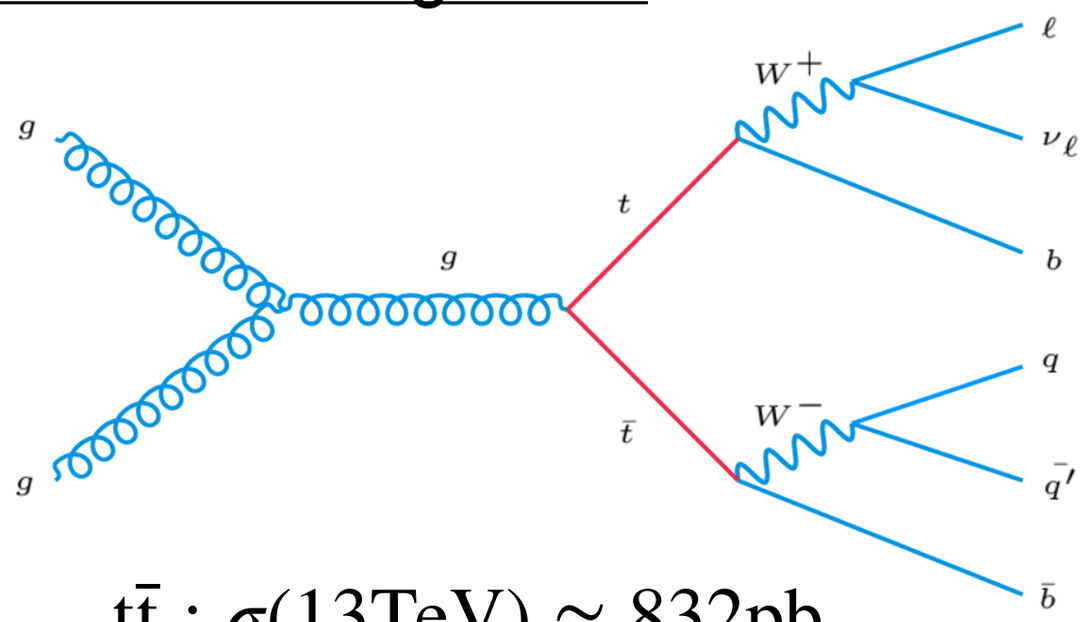
Modeling

5FS : 2➛2 process; b-quark from proton
4FS : 2➛3 process; gluon in the initial state

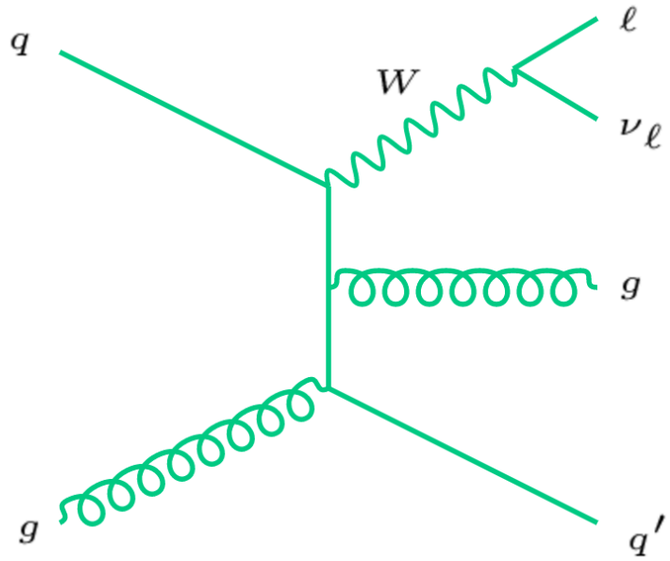


Normalization from 5FS calculation
Modeling from 4FS simulation

Dominant Backgrounds



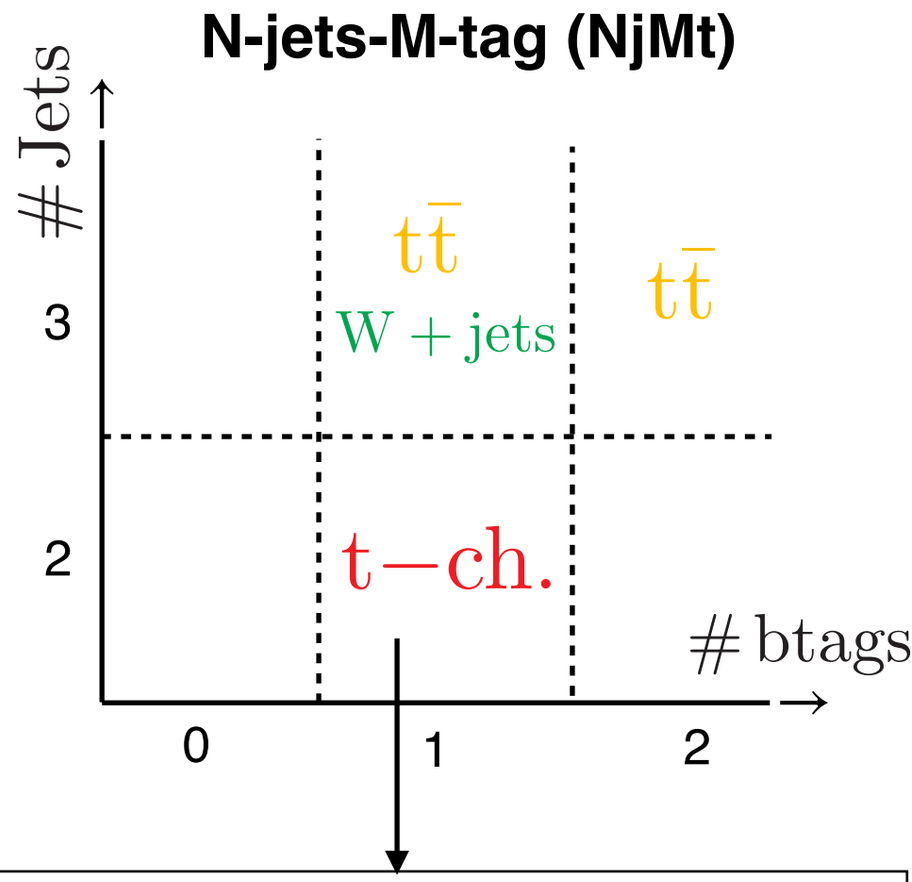
$$t\bar{t} : \sigma(13\text{TeV}) \approx 832\text{pb}$$

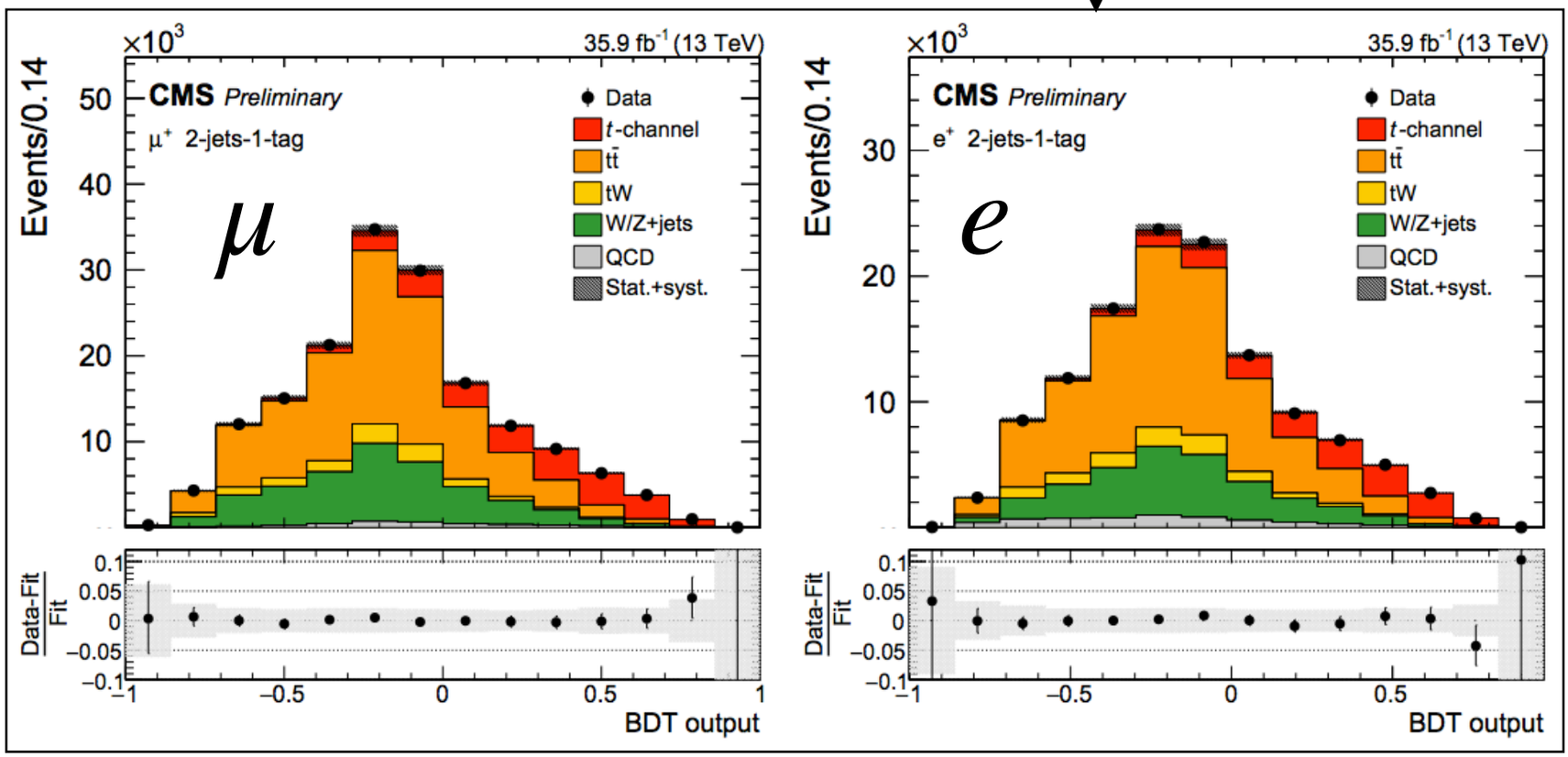


$$W + \text{jets} : \sigma(13\text{TeV}) \approx 61527\text{pb}$$

t-channel @13 TeV - Inclusive (CMS-PAS-TOP-17-011)

- Analysis with 2016 data (35.9 fb^{-1})
- Event Selection
  - ➤ **Exactly 1 isolated *μ* (*e*)** with **p_T > 26 (35) GeV** , **|*η*| < 2.4 (2.1)**
  - ➤ **Additional lepton veto: p_T > 10 GeV** & **relaxed isolation**
  - ➤ **2 - 3 jets** with **p_T > 40 GeV , |*η*| < 4.7**
  - ➤ **1- 2 b-tags** corresponding to **"tight" WP** (light quark mistag prob. = 0.1%)
  - ➤ **m_T(W) > 50 GeV (*μ*)** and **Missing p_T > 30 GeV (*e*)** to **reject QCD**
- **QCD estimate** from **SB data** ➤ inverting **lepton Iso / ID**
- Separate **BDTs for *μ* and *e***
  - ➤ **trained** in **2j1t**
  - ➤ **evaluated** in **2j1t, 3j1t** & **3j2t**





t-channel @13 TeV - Inclusive (CMS-PAS-TOP-17-011)

- Simultaneous ML fit in SR and CR
  - ➤ **# BDT distributions:** $12 = 3(\text{2j1t,3j1t,3j2t}) \times 2(\mu, e) \times 2(+, -)$
- Free Parameters: $\sigma_{t-\text{ch,t}}$, $\sigma_{t-\text{ch,}\bar{\text{t}}}$, $\text{R}_{t-\text{ch}} = \sigma_{t-\text{ch,t}}/\sigma_{t-\text{ch,}\bar{\text{t}}}$
  - ➤ **Any 2 of the 3 allowed to float** during fit ➤ **correlations taken into account**
- Uncertainty sources:

Externalized
➤ Fit performed with varied templates

Profiled
➤ Included in fit as nuisance parameters

	$\Delta R/R$	$\Delta\sigma/\sigma(\text{t})$	$\Delta\sigma/\sigma(\bar{\text{t}})$
PDF t channel	1.4	0.7	0.6
PS-scale t channel	1.1	12.5	13.8
ME-PS scale matching t channel	0.2	1.5	1.8
$\mu_\text{R}/\mu_\text{F}$ scale t channel	0.1	6.3	6.2
QCD normalization	2.1	1.7	3.8
JES	1.9	6.6	8.4
$\text{t}\bar{\text{t}}$ modeling and normalization	1.9	0.8	3.2
Top quark p_T	1.2	4.0	5.2
MC sample size	0.9	1.8	0.5
$\mu_\text{R}/\mu_\text{F}$ scale	0.8	1.0	0.3
Pileup	0.4	1.4	1.8
Muon and electron efficiencies	0.3	0.1	0.5
JER	0.2	0.4	0.7
b tagging	0.2	1.2	1.4
PDF	0.1	0.1	0.2
Unclustered energy	0.1	0.4	0.6
W/Z+jets normalization	0.1	0.9	0.9
tW normalization	< 0.1	0.2	0.2

t-channel @13 TeV - Inclusive (CMS-PAS-TOP-17-011)

meas.

$$\sigma_{t-\mathrm{ch,t}} = 136.3 \pm 1.1(\mathrm{stat}) \pm 3.4(\mathrm{prof}) \pm 19.4(\mathrm{ext}) \pm 3.4(\mathrm{lumi})\mathrm{pb} = 136.3 \pm 20.0\mathrm{pb}$$

$$\sigma_{t-\mathrm{ch,\bar{t}}} = 82.7 \pm 1.1(\mathrm{stat}) \pm 2.7(\mathrm{prof}) \pm 12.6(\mathrm{ext}) \pm 2.1(\mathrm{lumi})\mathrm{pb} = 82.7 \pm 13.1\mathrm{pb}$$

$$\sigma_{t-\mathrm{ch,t+\bar{t}}} = 219.0 \pm 1.5(\mathrm{stat}) \pm 6.1(\mathrm{prof}) \pm 32.0(\mathrm{ext}) \pm 5.5(\mathrm{lumi})\mathrm{pb} = 219.0 \pm 33.1\mathrm{pb}$$

$$\mathrm{R}_{t-\mathrm{ch}} = 1.65 \pm 0.02(\mathrm{stat}) \pm 0.03(\mathrm{prof}) \pm 0.03(\mathrm{ext}) = 1.65 \pm 0.05$$

theory

$$\sigma_{t-\mathrm{ch,t}} = 136.0^{+4.1}_{-2.9}(\mathrm{scale}) \pm 3.5(\mathrm{PDF} + \alpha_s)\mathrm{pb}$$

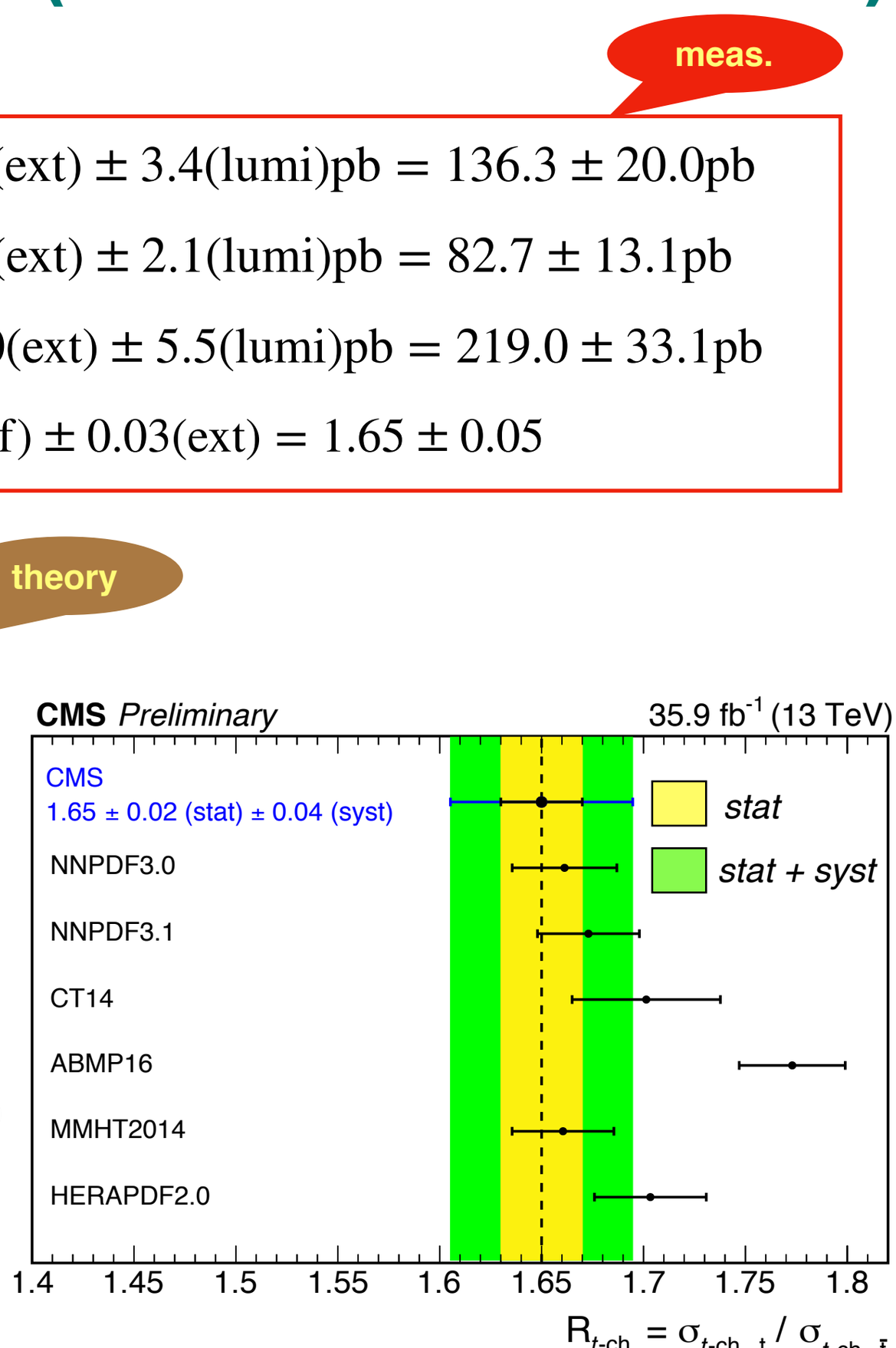
$$\sigma_{t-\mathrm{ch,\bar{t}}} = 81.0^{+2.5}_{-1.7}(\mathrm{scale}) \pm 3.2(\mathrm{PDF} + \alpha_s)\mathrm{pb}$$

$$\sigma_{t-\mathrm{ch,t+\bar{t}}} = 217.0^{+6.6}_{-4.6}(\mathrm{scale}) \pm 6.2(\mathrm{PDF} + \alpha_s)\mathrm{pb}$$

$$|V_{tb}| >> |V_{td}|, |V_{ts}|$$

$$|f_{\mathrm{LV}} V_{tb}| = \sqrt{\frac{\sigma^{\mathrm{meas.}}_{t-\mathrm{ch}}}{\sigma^{\mathrm{theory}}_{t-\mathrm{ch}}}} = 1.00 \pm 0.05(\mathrm{exp}) \pm 0.02(\mathrm{theo})$$

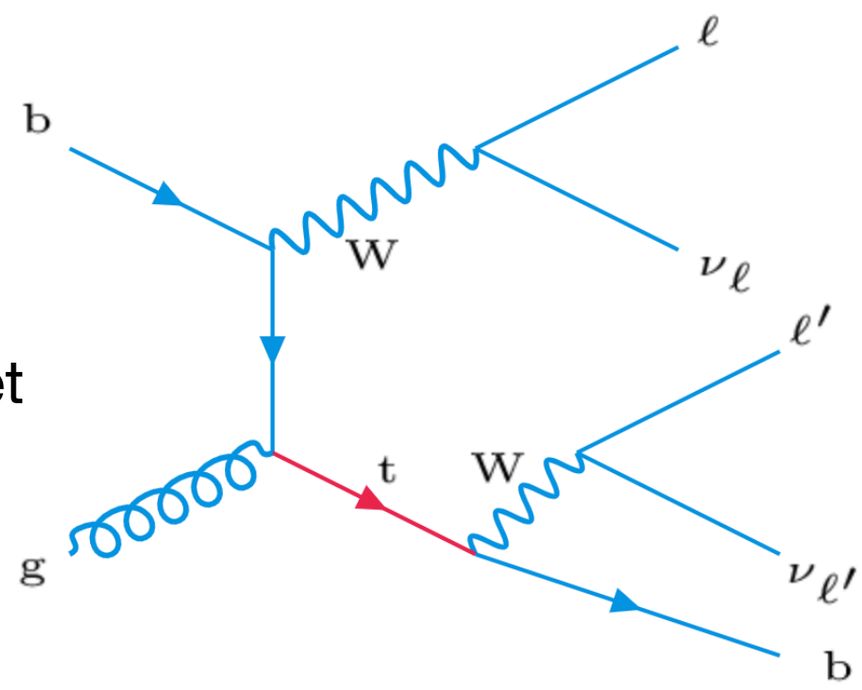
$$\mathrm{SM} : f_{\mathrm{LV}} = 1$$



tW

Topology

- 2 opposite charged isolated leptons
- 1 high-p_T central b-jet
- Missing p_T

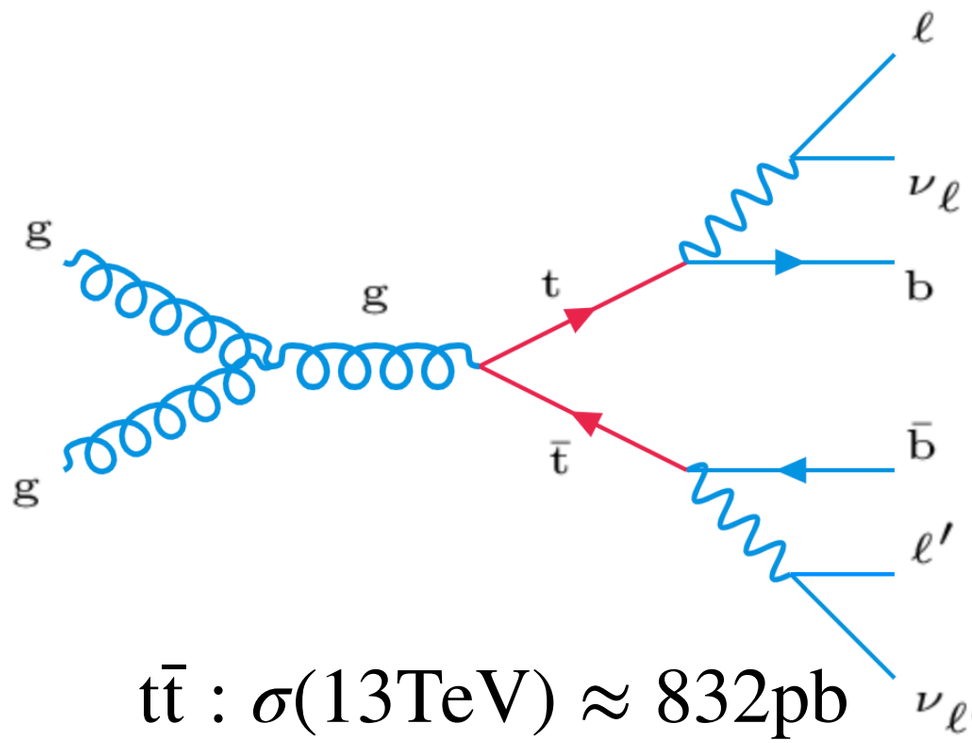


$$tW : \sigma(13\text{TeV}) = 71.7 \pm 3.8\text{pb}$$

Modeling

- Interference with $t\bar{t}$ @NLO
- DR: Remove $t\bar{t}$ diagrams
  - ➔ keep / drop interference terms
- DS: Add a local subtraction term to cancel resonant $t\bar{t}$ contribution
  - ➔ keep interference terms

Dominant Background



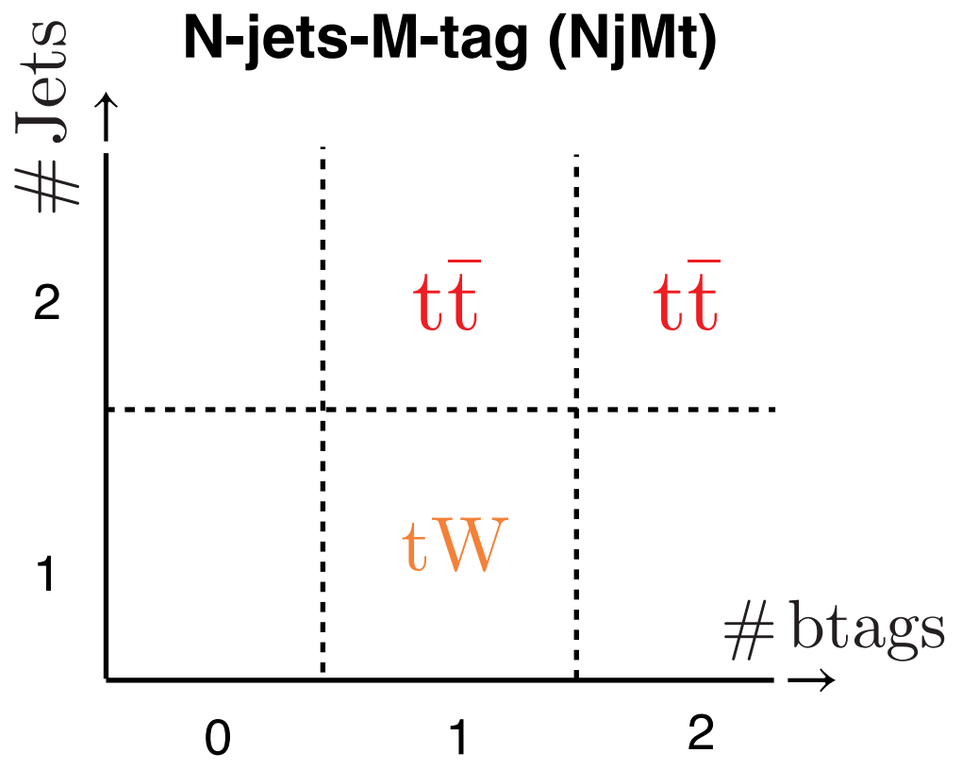
$$t\bar{t} : \sigma(13\text{TeV}) \approx 832\text{pb}$$

tW @13 TeV - Inclusive (JHEP 10 (2018) 117)

- Analysis in *eμ* final state with 35.9 fb^{-1} data collected in 2016

- Event Selection
  - ➤ **single and di-lepton triggers** for maximum eff. (≈ 98%)
  - ➤ **≥ 2 isolated OS leptons** with **p_T > 20 GeV, |η| < 2.4**
  - ➤ **≥ 1 jet** with **p_T > 30 GeV and |η| < 2.4**
  - ➤ **b-tagging "medium" WP** (light quark mistag prob. = 1%)

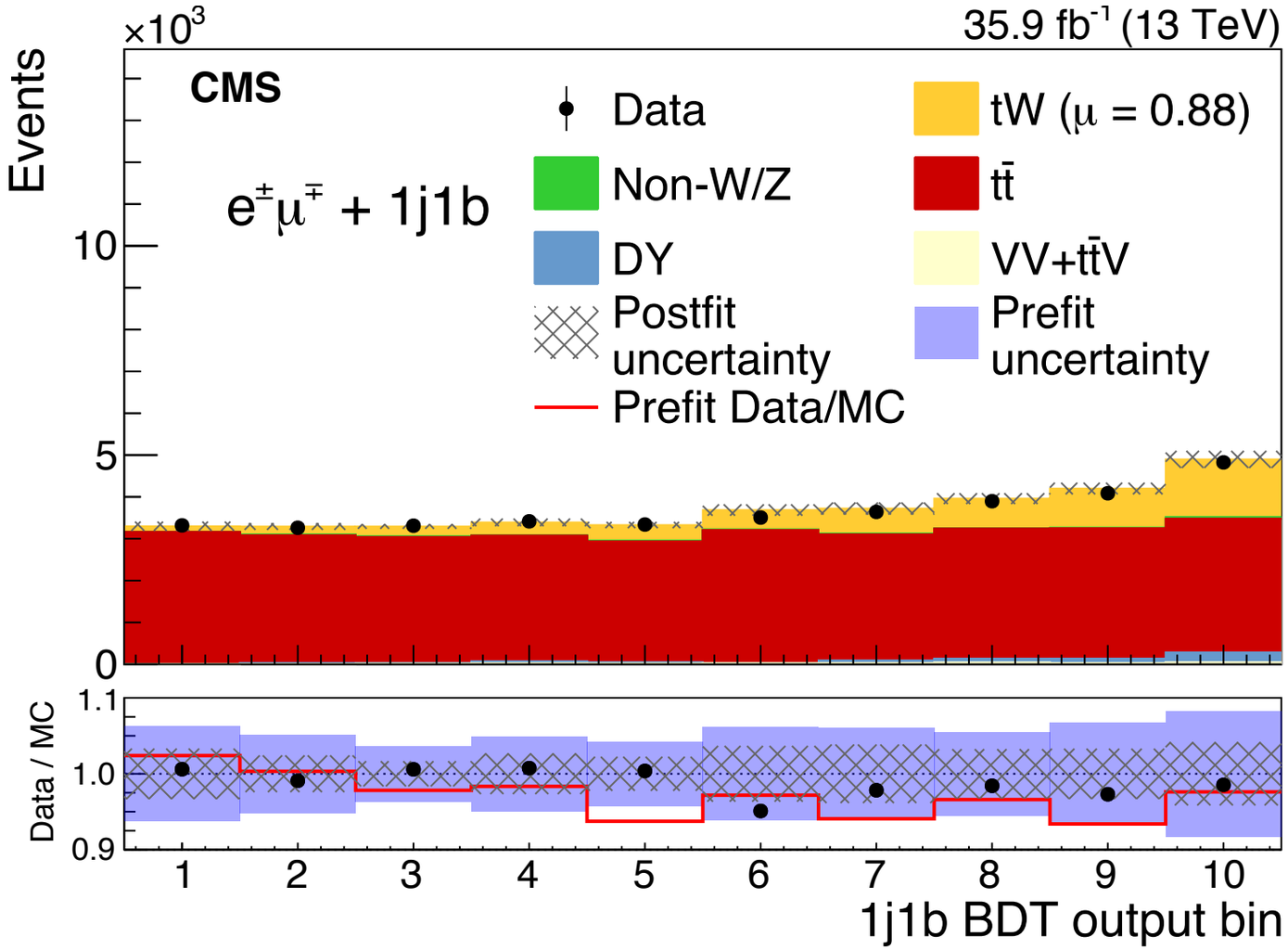
- **BDTs trained** in **1j1t** & **2j1t** for S-B separation



- Signal extraction:
  - ➤ **Simultaneous ML fit** to **BDTs in 1j1t & 2j1t** along with **p_T(j2) in 2j2t**

	Prefit		Postfit	
	tW	tt̄	tW	tt̄
1j1t	6147 ± 442	30622 ± 1862	5440 ± 604	30592 ± 582
2j1t	3125 ± 294	48484 ± 1984	2888 ± 321	47436 ± 612
2j2t	725 ± 85	25052 ± 2411	719 ± 88	25114 ± 281

tW @13 TeV - Inclusive (JHEP 10 (2018) 117)



$$\sigma(tW) = 63.1 \pm 1.8(\text{stat}) \pm 6.4(\text{syst}) \pm 2.1(\text{lumi})\text{pb}$$

$$\sigma_{\text{SM}} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\text{pb}$$

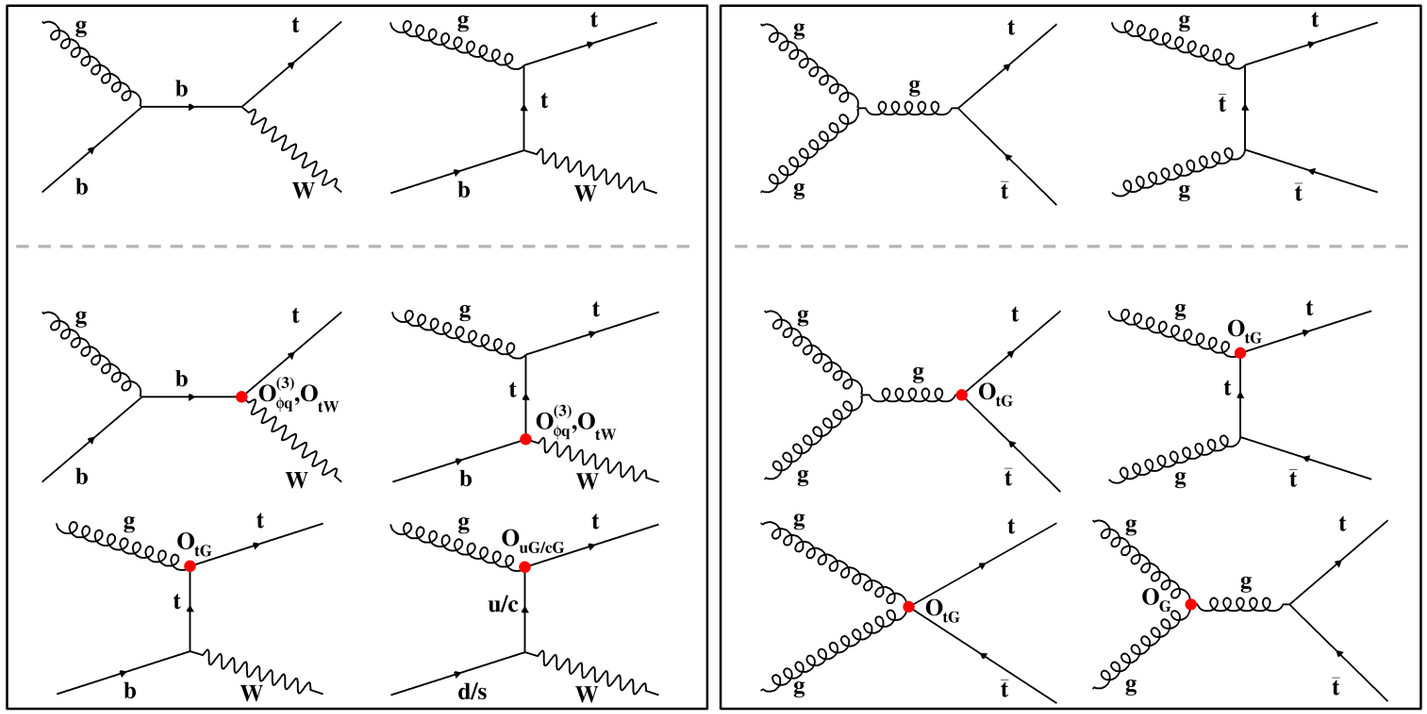
Source	Uncertainty (%)
Experimental	
Trigger efficiencies	2.7
Electron efficiencies	3.2
Muon efficiencies	3.1
JES	3.2
Jet energy resolution	1.8
b tagging efficiency	1.4
Mistag rate	0.2
Pileup	3.3
Modeling	
$t\bar{t}$ μ_R and μ_F scales	2.5
tW μ_R and μ_F scales	0.9
Underlying event	0.4
Matrix element/PS matching	1.8
Initial-state radiation	0.8
Final-state radiation	0.8
Color reconnection	2.0
B fragmentation	1.9
Semileptonic B decay	1.5
PDFs	1.5
DR-DS	1.3
Background normalization	
$t\bar{t}$	2.8
VV	0.4
Drell–Yan	1.1
Non-W/Z leptons	1.6
$t\bar{t}V$	0.1
MC finite sample size	1.6
Full phase space extrapolation	2.9
Total systematic (excluding integrated luminosity)	10.1
Integrated luminosity	3.3
Statistical	2.8
Total	11.1

New Physics search in *tW* (CMS-PAS-TOP-17-020)

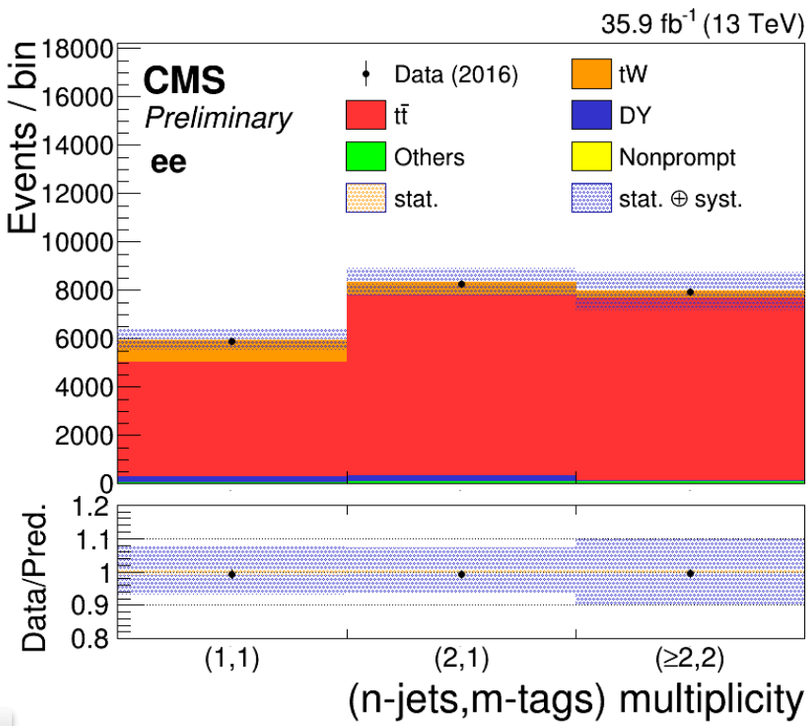
- New physics scale (Λ) too high to appear directly in the available energy
  ➛ integrate it out to form $\mathscr{L}_{\text{eff}}$ which includes new couplings (c_i / Λ^2)

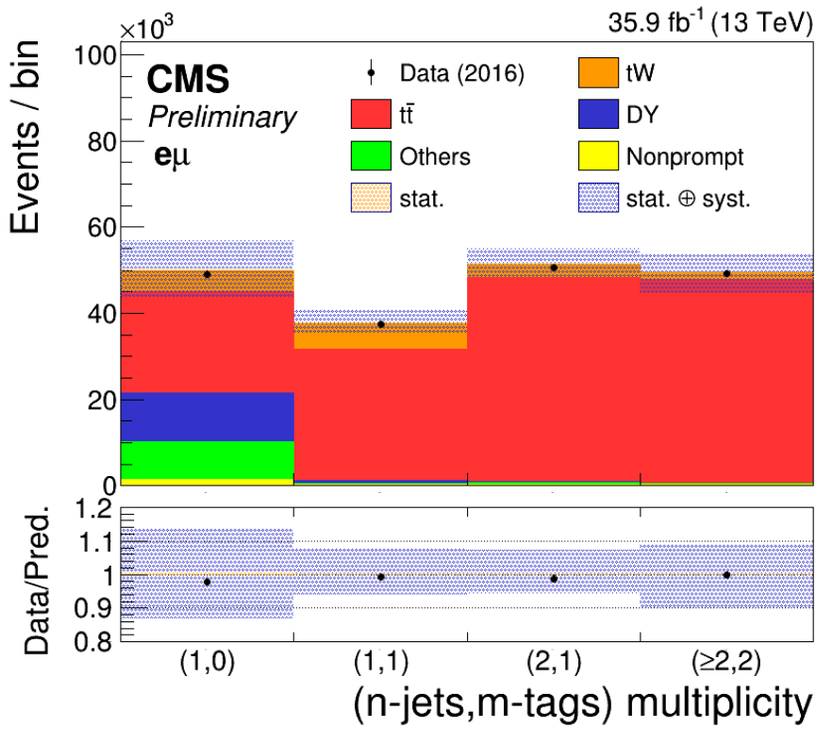
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \dots$$

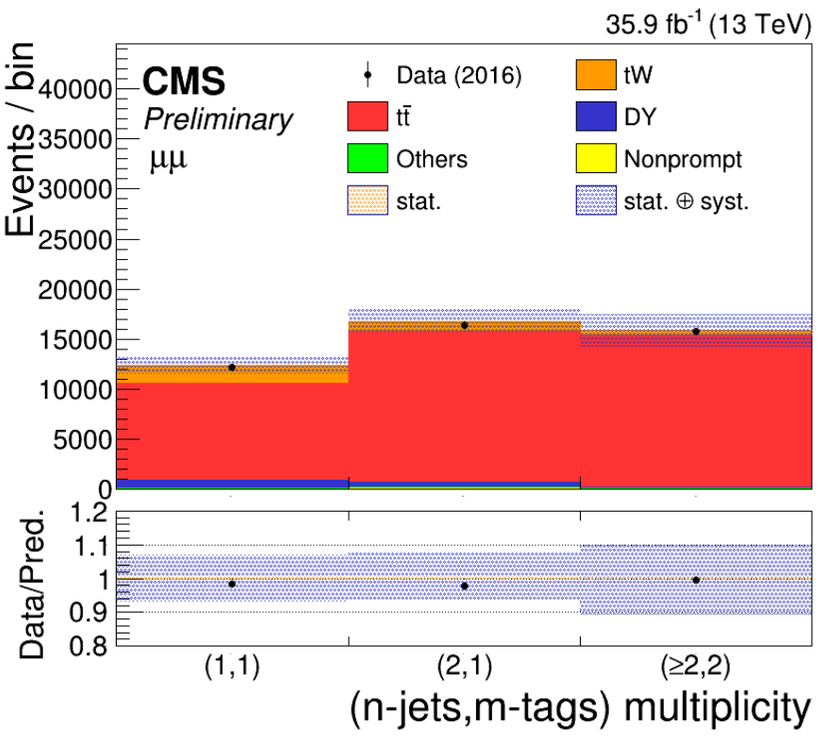
- Analysis with 35.9 fb^{-1} data collected in 2016
- Event selection:
  di-lepton (***ee, eμ, μμ***) + jets events
  ➛ Separated by lepton flavor
  ➛ $t\bar{t}$: >=2 jets (2 b jets)
  ➛ tW : 1-2 jets (0-1 b jet)



- Signal extraction is performed using NN ➛ training dependent on analysis channel







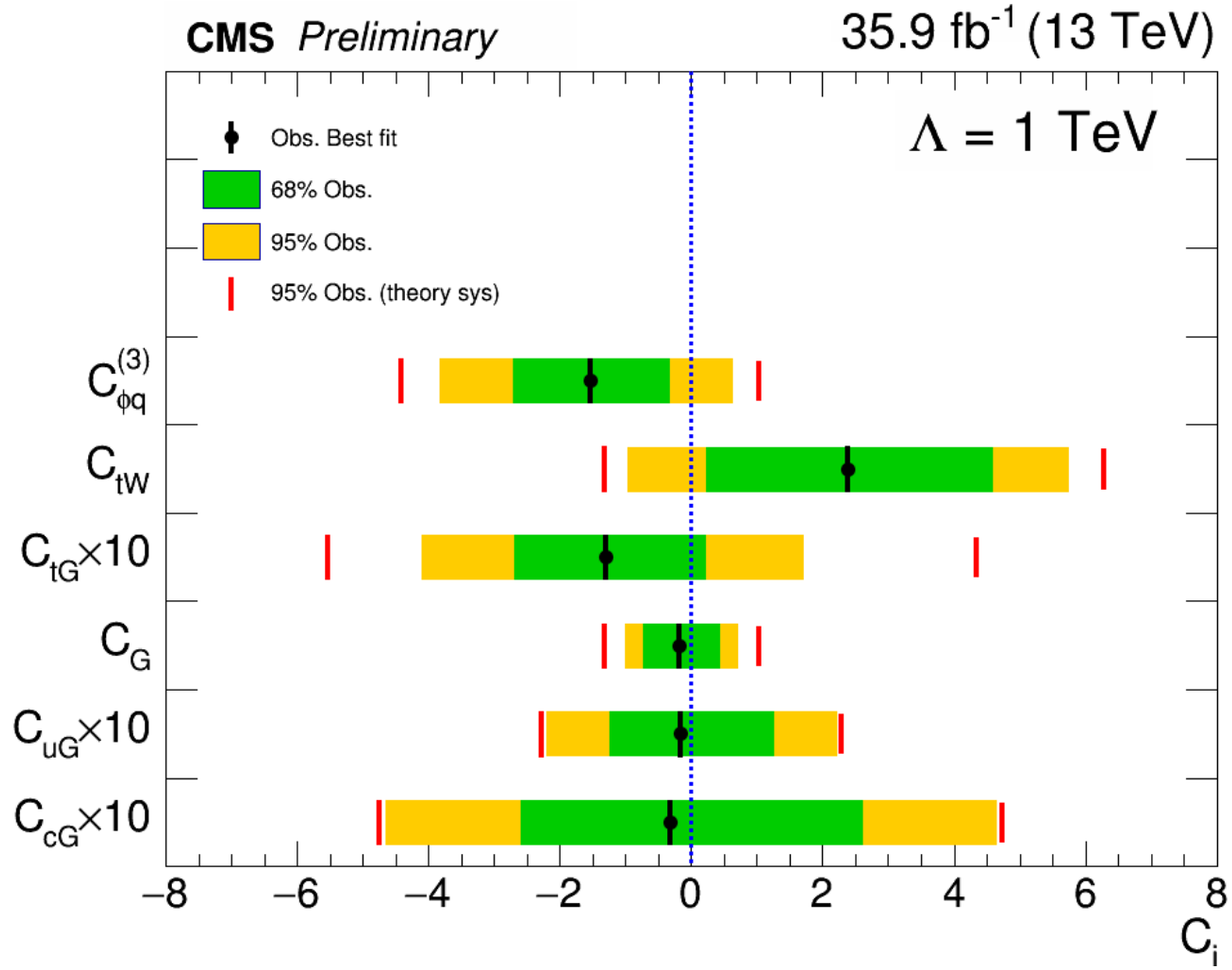
New Physics search in *tW* (CMS-PAS-TOP-17-020)

- Limits on 6 EFT operators that affect $t\bar{t}$ and tW are obtained for Λ = 1 TeV
- Limits on C_{uG} and C_{cG} translated to observed (expected) limits on FCNC BRs @95% CLs

$$\mathcal{B}(t \to ug) < 0.12(0.22)\,\%$$

$$\mathcal{B}(t \to cg) < 0.53(1.05)\,\%$$

- First experimental bound on C_G coupling

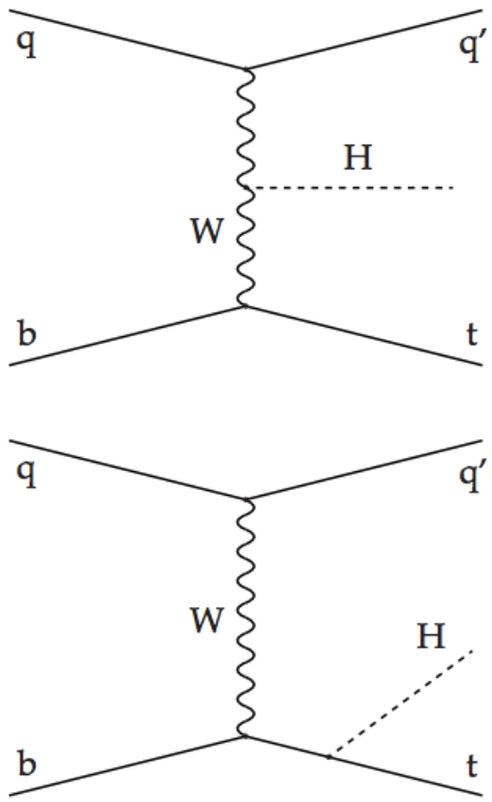


Single top + Higgs (*tH*)

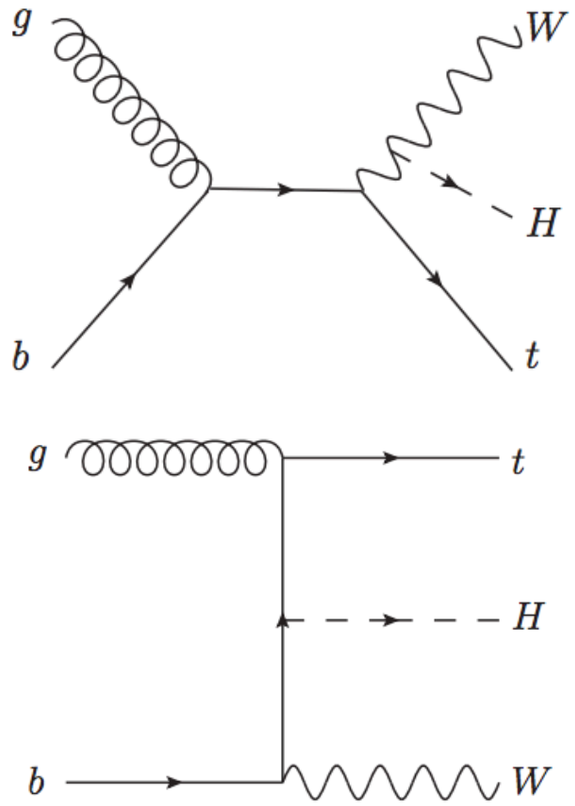
$$\kappa_V = \frac{g_{HVV}}{g_{HVV}^{SM}}$$

$$\kappa_t = \frac{y_t}{y_t^{SM}}$$

tHq : $\sigma_{SM}(13TeV) \approx 71fb$



tHW : $\sigma_{SM}(13TeV) \approx 15fb$

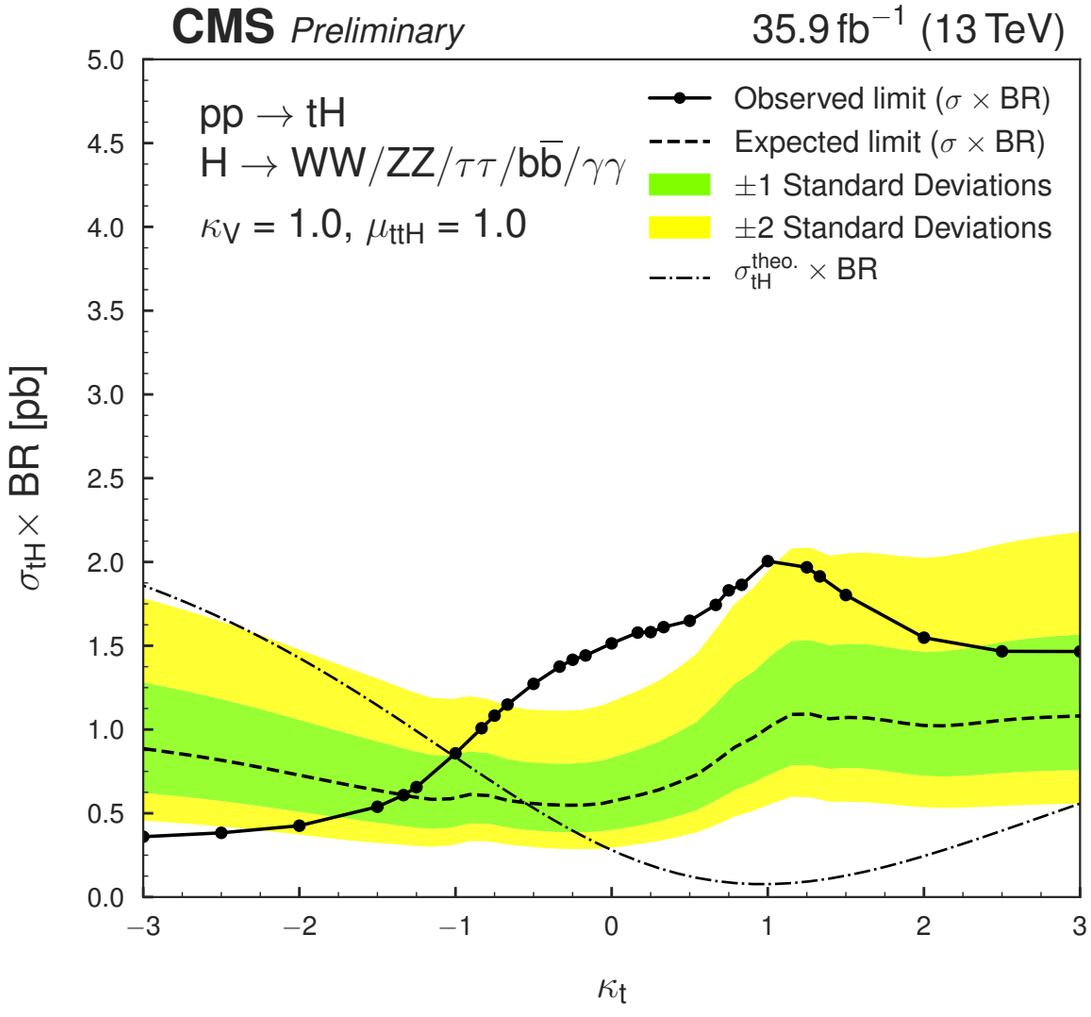


- In SM: **Destructive interference** leads to very small rates
- Inverted Top Coupling (ITC): **Constructive interference** ➛ $\kappa_t = -1,\ \kappa_V = 1$
- Combination of decay channels based on 2016 data (35.9 fb^{-1}) ➛ CMS-PAS-HIG-18-009
  - ➛ Leptonic top + b-jets (H ➛ $b\bar{b}$) CMS-PAS-HIG-17-016
  - ➛ Multilepton (H ➛ WW/ZZ/$\tau\tau$) CMS-PAS-HIG-17-005
  - ➛ Leptonic top + $\gamma\gamma$ (H ➛ $\gamma\gamma$) arXiv:1804.02716 (Submitted to JHEP)

tH Combination

- Simultaneous ML fit on discriminator outputs of multi-lepton & $b\bar{b}$ channels and $m_{\gamma\gamma}$ for $\gamma\gamma$
- Luminosity, b-tagging and theoretical uncertainties are considered to be fully correlated
- Profile likelihood scan as a function of $\kappa_t \Rightarrow \kappa_t \in$ [-0.9, -0.5] & [1.0, 2.1] for $\kappa_V = 1$
- <u>Limits on tH cross-section:</u>
  - ➤ Observed : $\sigma_{tH}^{Fid.} \times BR < 2.0pb$
  - ➤ Expected : $\sigma_{tH}^{Fid.} \times BR < 0.9pb$

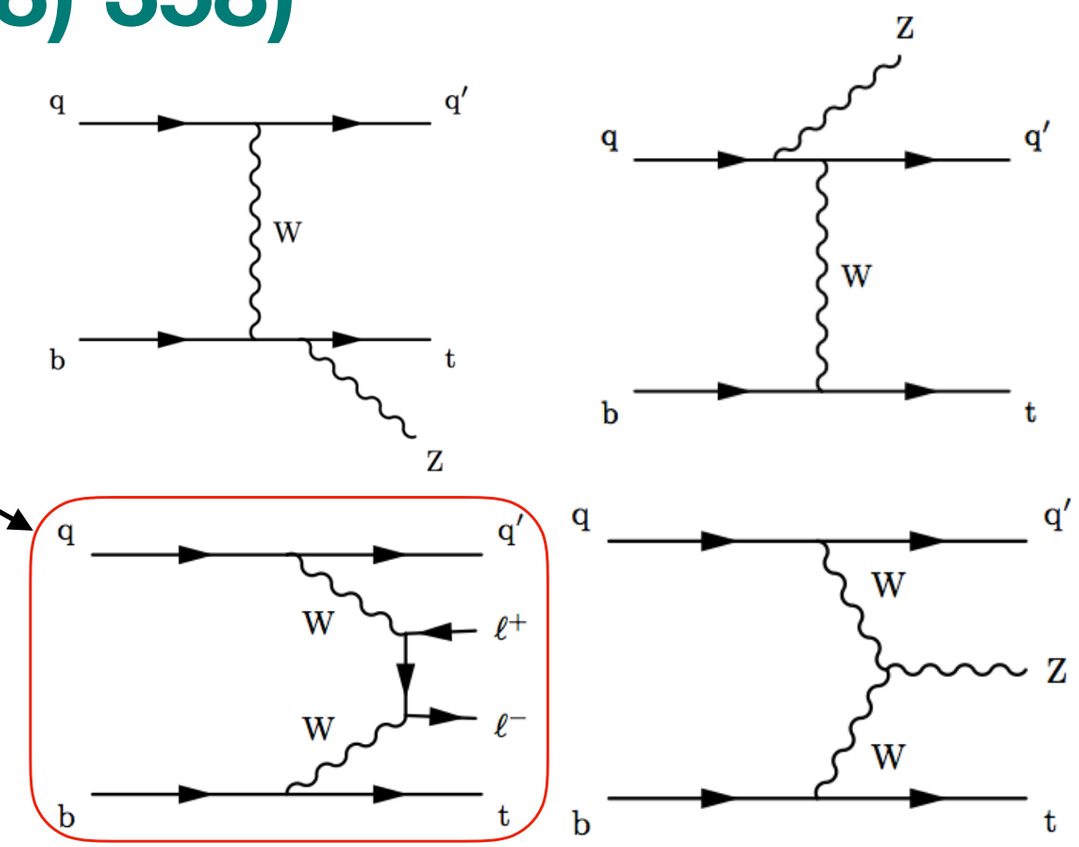
  } SM : $\kappa_t = \kappa_V = 1.0,\ \mu_{ttH} = 1.0$

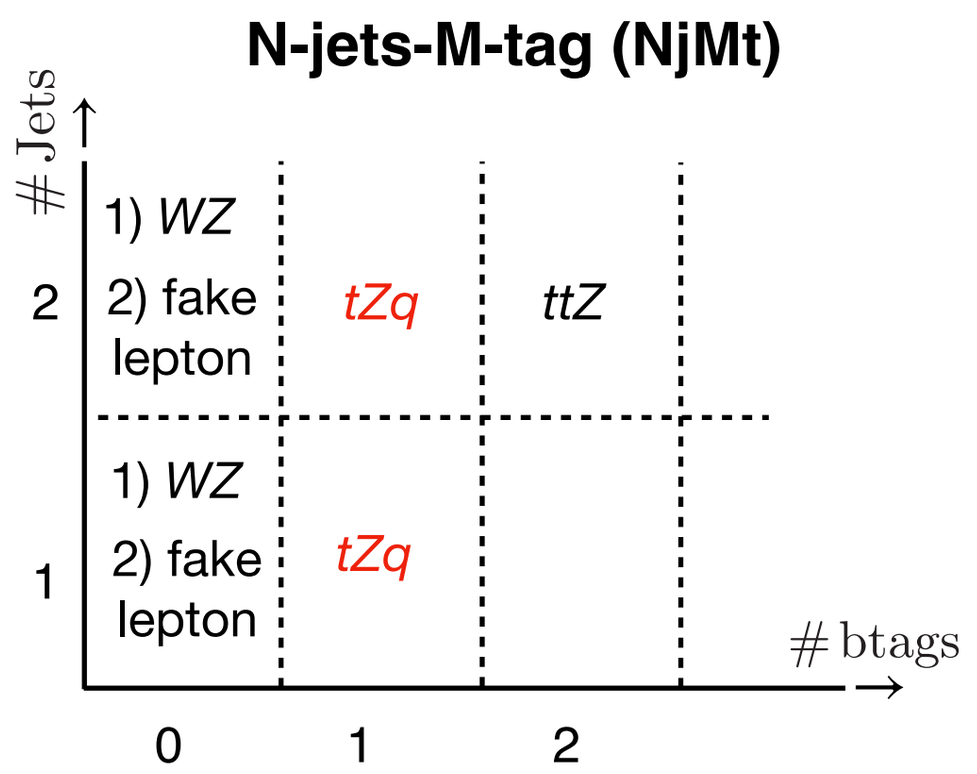


<u>CMS-PAS-HIG-18-009</u>

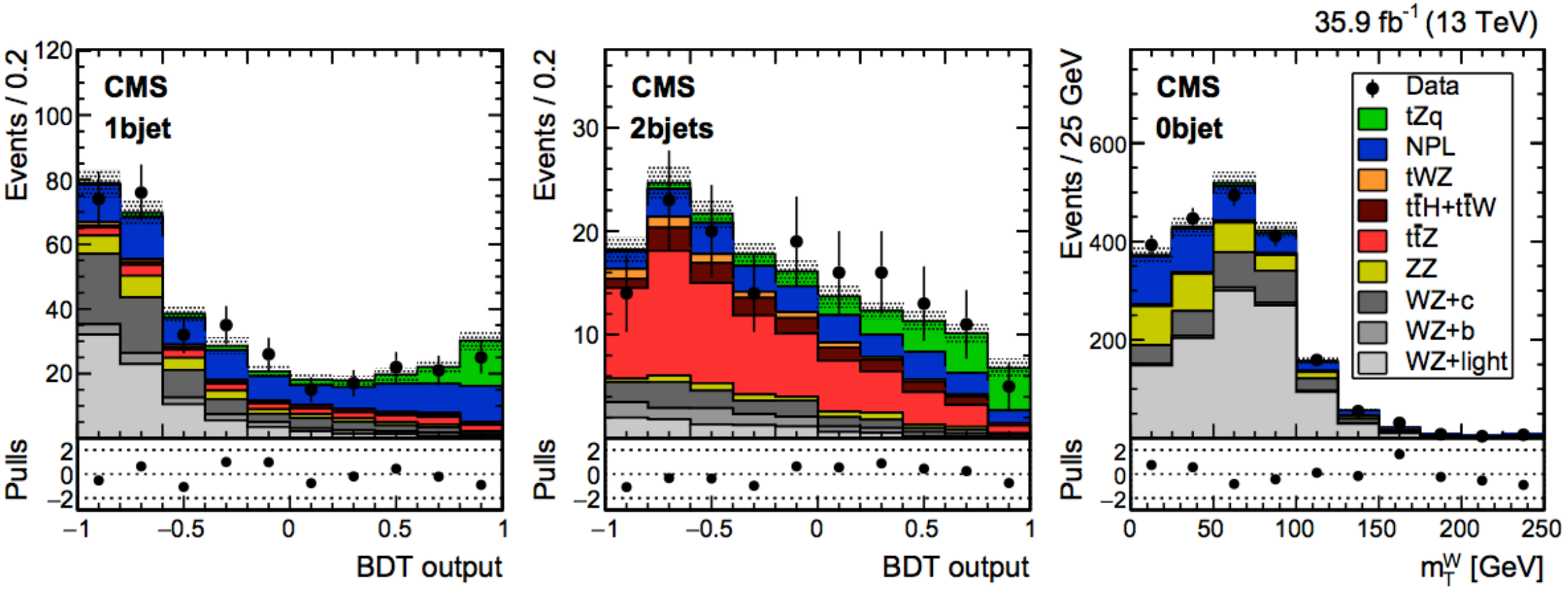
Evidence for *tZq* (PLB 779 (2018) 358)

- Analysis with 2016 data (35.9 fb^{-1})
- Inclusion of non-resonant $t\ell^+\ell^- q$ contribution
- Ref. cross-section @NLO
- Event Selection:
  - ➤ ***eee, eeμ, μμe, μμμ*** selected using **single, di- and tri-lepton triggers**
  - ➤ **3 isolated leptons** with $p_T > 25$ GeV, $|\eta| < 2.4$ (2.5)
  - ➤ **2 same-flavor OS** leptons with $|m_{\ell\ell} - 91| < 15$ GeV
  - ➤ **≥ 1 jet** with $p_T > 30$ GeV, $|\eta| < 4.5$
  - ➤ **"loose" WP** for **b-tags** (light quark mistag prob. ≈ 10%)
- Data-driven background:
  - ➤ Events with fake leptons (**3rd**) modeled using SB data ➛ inversion of lepton isolation
- Simultaneous ML fit to BDTs in SR and CR





Evidence for *tZq* (PLB 779 (2018) 358)



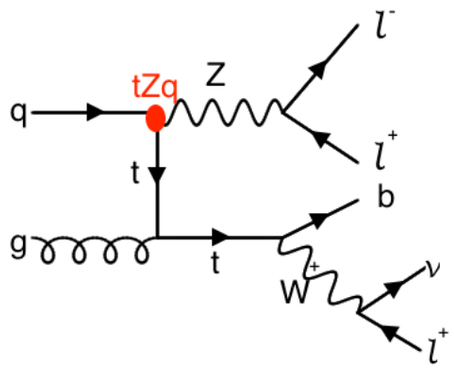
- **Observed (Expected) significance of 3.7 (3.1) all channels combined**

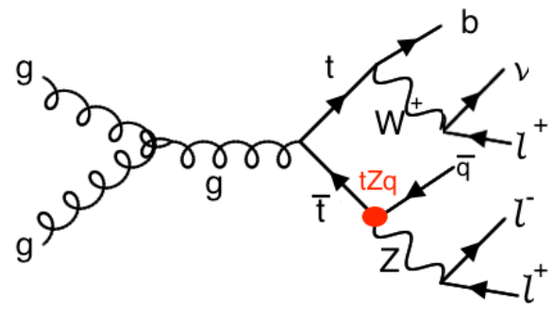
$$\left.\begin{aligned}\sigma(t\ell^+\ell^-q) &= 123^{+33}_{-31}(\text{stat})^{+29}_{-23}(\text{syst})\text{fb}\\ \sigma_{\text{SM}} &= 94.2^{+1.9}_{-1.8}(\text{scale}) \pm 2.5(\text{PDF})\text{fb}\end{aligned}\right\} m_{\ell^+\ell^-} > 30\text{GeV}$$

- Dominant uncertainties:
  - ➤ Statistics dominated
  - ➤ Estimation of non-prompt bkg.
  - ➤ PS scale
  - ➤ b-tagging
  - ➤ ttZ cross-section.

FCNC searches in *tZq* (CMS-PAS-TOP-17-017)

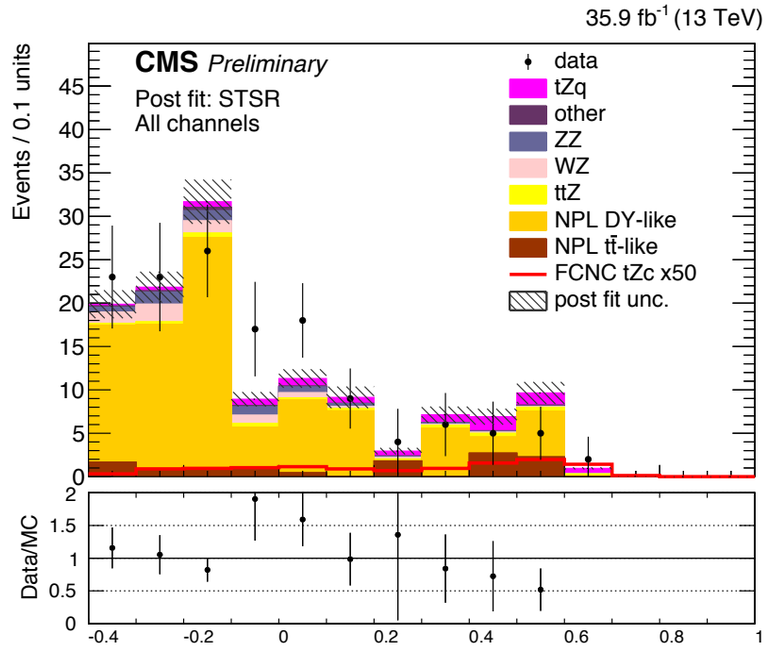
- SM:
  - ➤ FCNC is forbidden @ LO
  - ➤ Can appear at higher orders with very low BR
    $\mathscr{B}(\mathrm{t} \to \mathrm{cZ}) \approx 10^{-14}, \mathscr{B}(\mathrm{t} \to \mathrm{uZ}) \approx 10^{-17}$
- Several BSM models predict FCNC enhancement of 7-8 orders of magnitude





- **Same event selection as tZq analysis** ➤ 3ℓ final state
- 2 **simultaneous likelihood** fits: one for **single top FCNC** & one for **tt̄ FCNC**
- 4 lepton categories (***eee, eeμ, μμe, μμμ***) and 5 regions

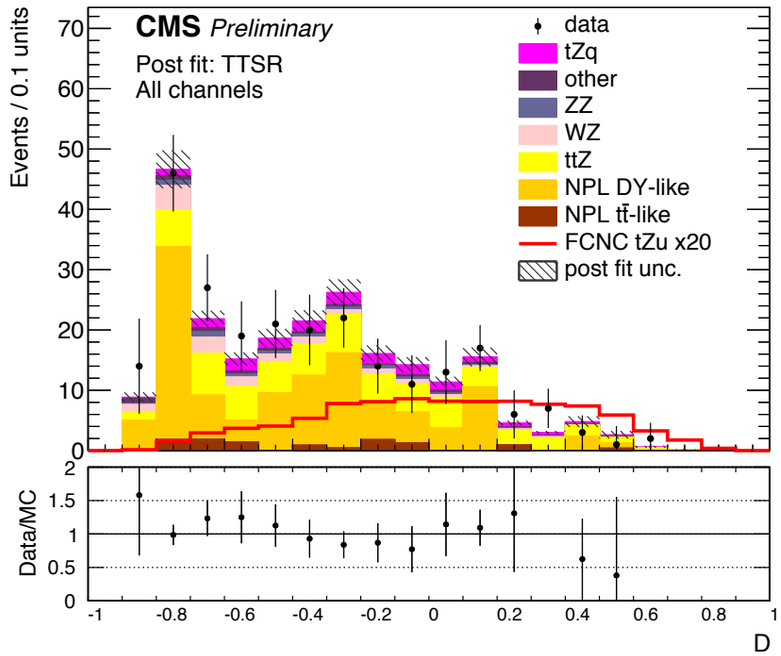
	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{\mathrm{reco}})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



- Observed (expected) upper limits @95% CL

$$\mathscr{B}(\mathrm{t} \to \mathrm{uZ}) < 0.024(0.015)\,\%$$

$$\mathscr{B}(\mathrm{t} \to \mathrm{cZ}) < 0.045(0.037)\,\%$$



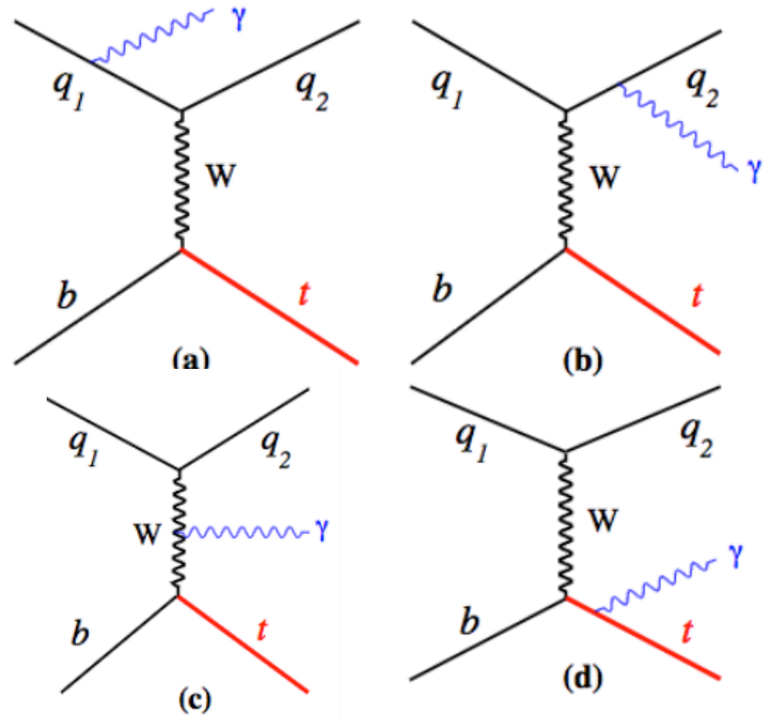
Evidence for $t\gamma q$ (arXiv:1808.02913, accepted by PRL)

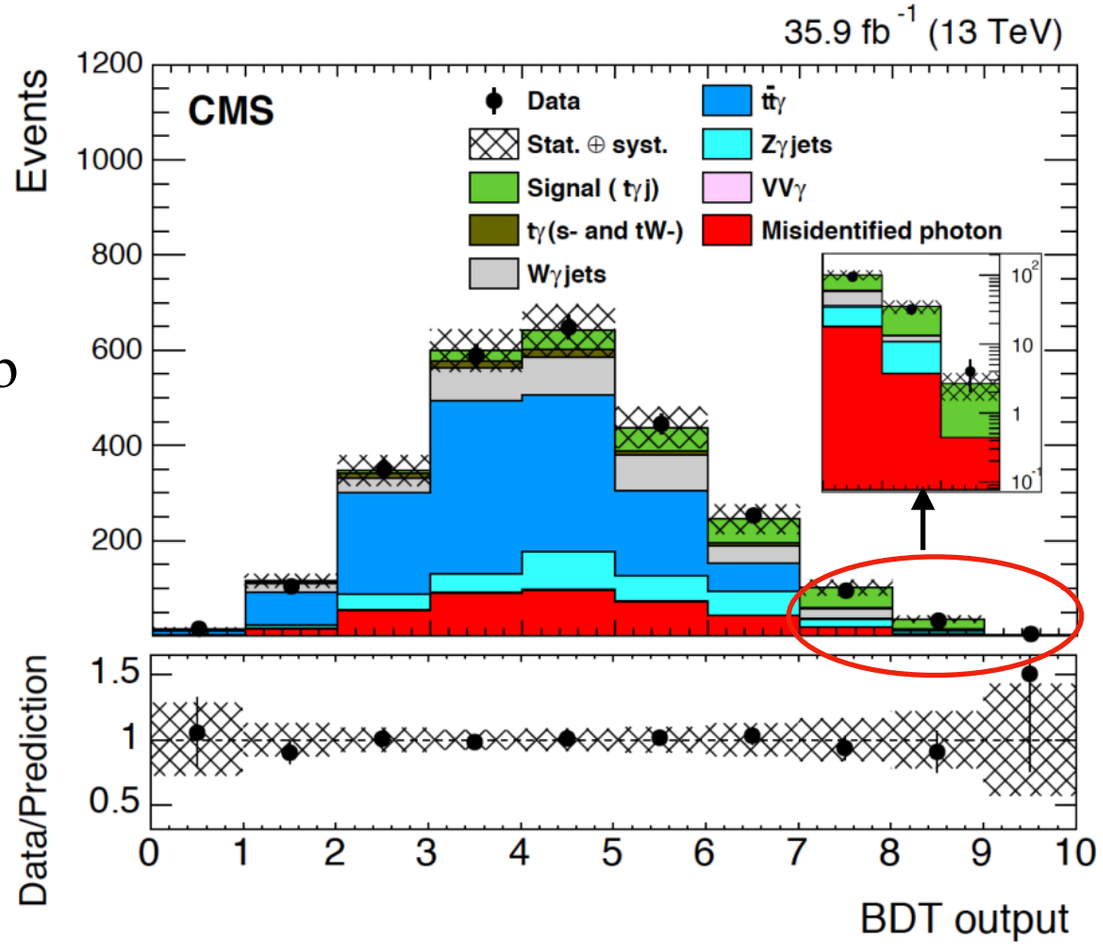
- Associated production of a single top quark (*t*-ch.) with a γ
- Event Selection:
  - ➤ **Standard 2j1t selection** for *t*-ch. single top in μ + jets final state
  - ➤ **Missing p_T > 30 GeV**
  - ➤ **1 isolated** γ with **p_T > 25 GeV, $|\eta|$ < 1.44**
  - ➤ **$\Delta R(X,\gamma)$ > 0.5, *X* = μ or jets**
  - ➛ Removes overlap b/w single top+"soft" γ (PS) & single top + "hard" γ (ME)
- **Bkg with real photons estimated from simulation**
- **Bkg with fake photons estimated from SB data**
  - ➛ loose ID and isolation/shower shape inversion
- ML fit to **BDT** discriminant to extract signal
- **Observed (Expected) significance of 4.4 (3.0)**

$$\sigma^{\text{Fid.}}(\text{pp} \to t\gamma j)\mathcal{B}(t \to \mu\nu\text{b}) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\text{fb}$$

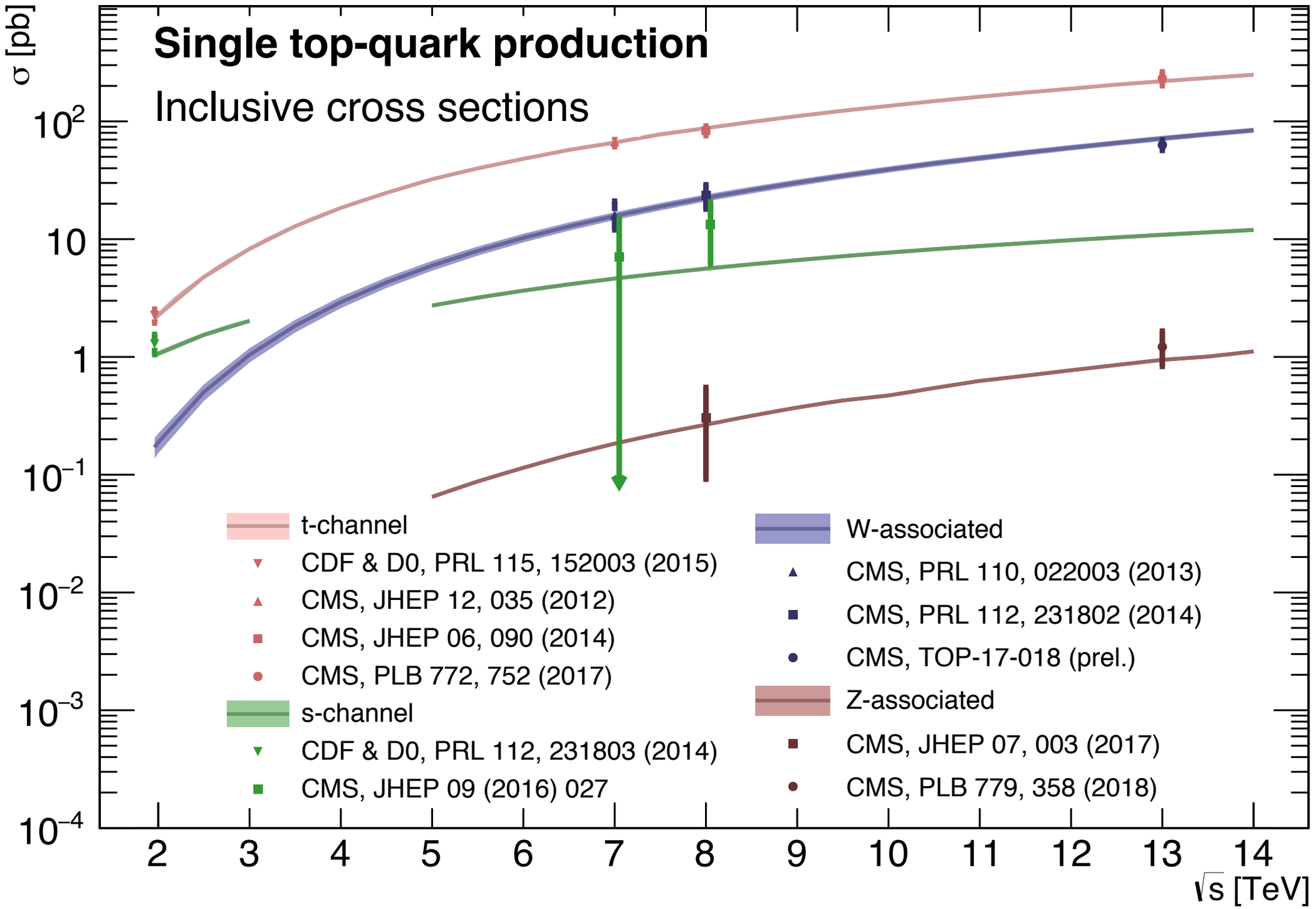
$$\sigma^{\text{Fid.}}_{\text{SM}} = 81 \pm 4\text{fb}$$

- Dominant Uncertainties:
  - ➤ JES ~ 12%
  - ➤ Signal modeling ~ 9%
  - ➤ Estimation of Zγ+jets Bkg. ~ 8%
  - ➤ b-tag/mistag ~ 7%





CMS Summary


Single top-quark production
Inclusive cross sections
σ [pb]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2
3
4
5
6
7
8
9
10
11
12
13
14
√s [TeV]
t-channel
CDF & D0, PRL 115, 152003 (2015)
CMS, JHEP 12, 035 (2012)
CMS, JHEP 06, 090 (2014)
CMS, PLB 772, 752 (2017)
s-channel
CDF & D0, PRL 112, 231803 (2014)
CMS, JHEP 09 (2016) 027
W-associated
CMS, PRL 110, 022003 (2013)
CMS, PRL 112, 231802 (2014)
CMS, TOP-17-018 (prel.)
Z-associated
CMS, JHEP 07, 003 (2017)
CMS, PLB 779, 358 (2018)

Concluding Remarks

- Precise measurements of the *t* -ch cross-sections and $R_{t\text{-ch}}$ at 13 TeV
  ➛ results in agreement with the SM within uncertainties

- $R_{t\text{-ch}}$ provides an extra handle to constrain different PDF predictions

- Current *t* -ch measurements are dominated by modeling uncertainties
  ➛ Need better understanding of MC generator

- *tW* cross-section has also been measured with good precision

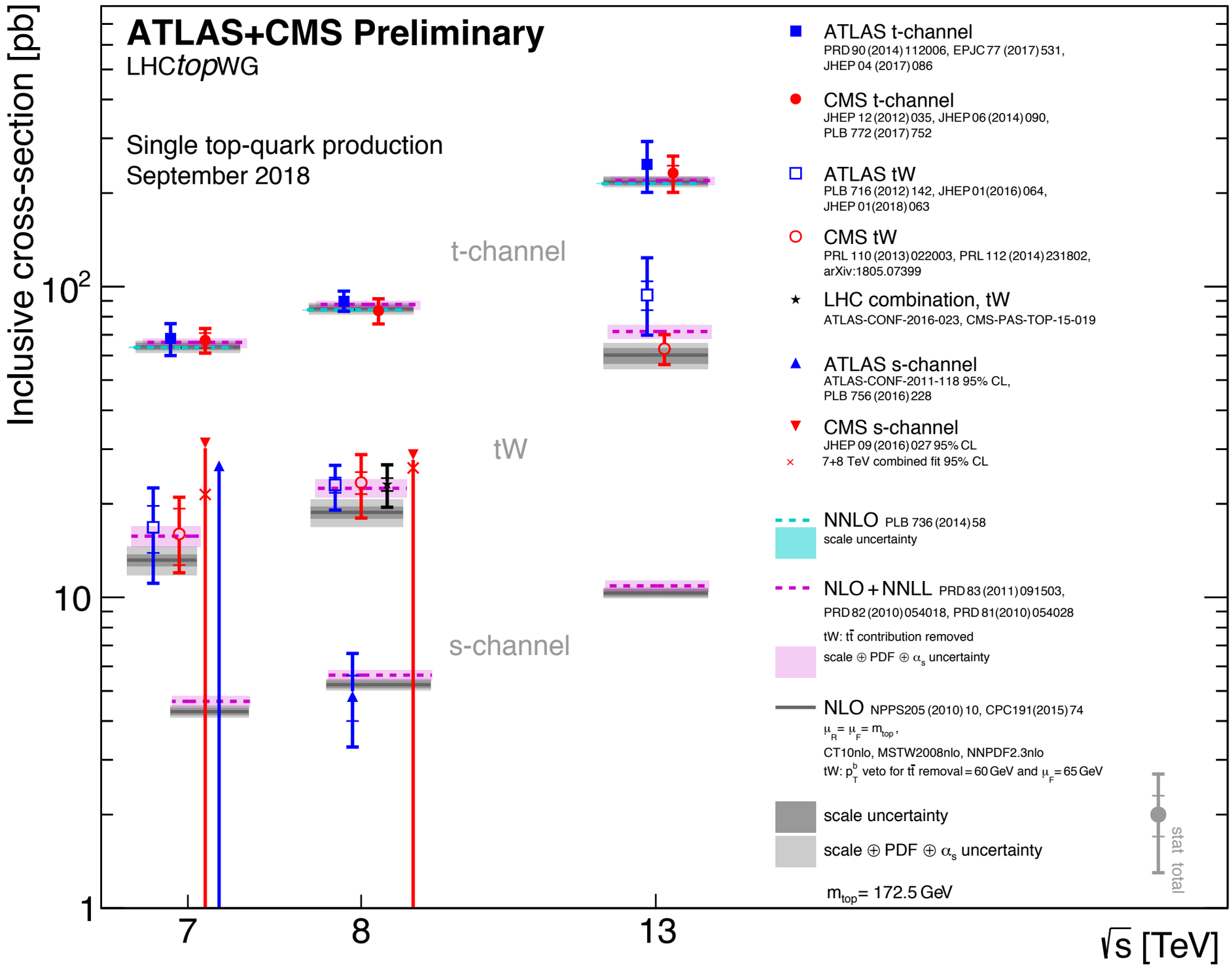
- Observation of *s* - ch ➛ a definite future target

- Detailed study of rare processes (*tZq*, *tHq*, *tγq*) will shed light on the nature of the couplings

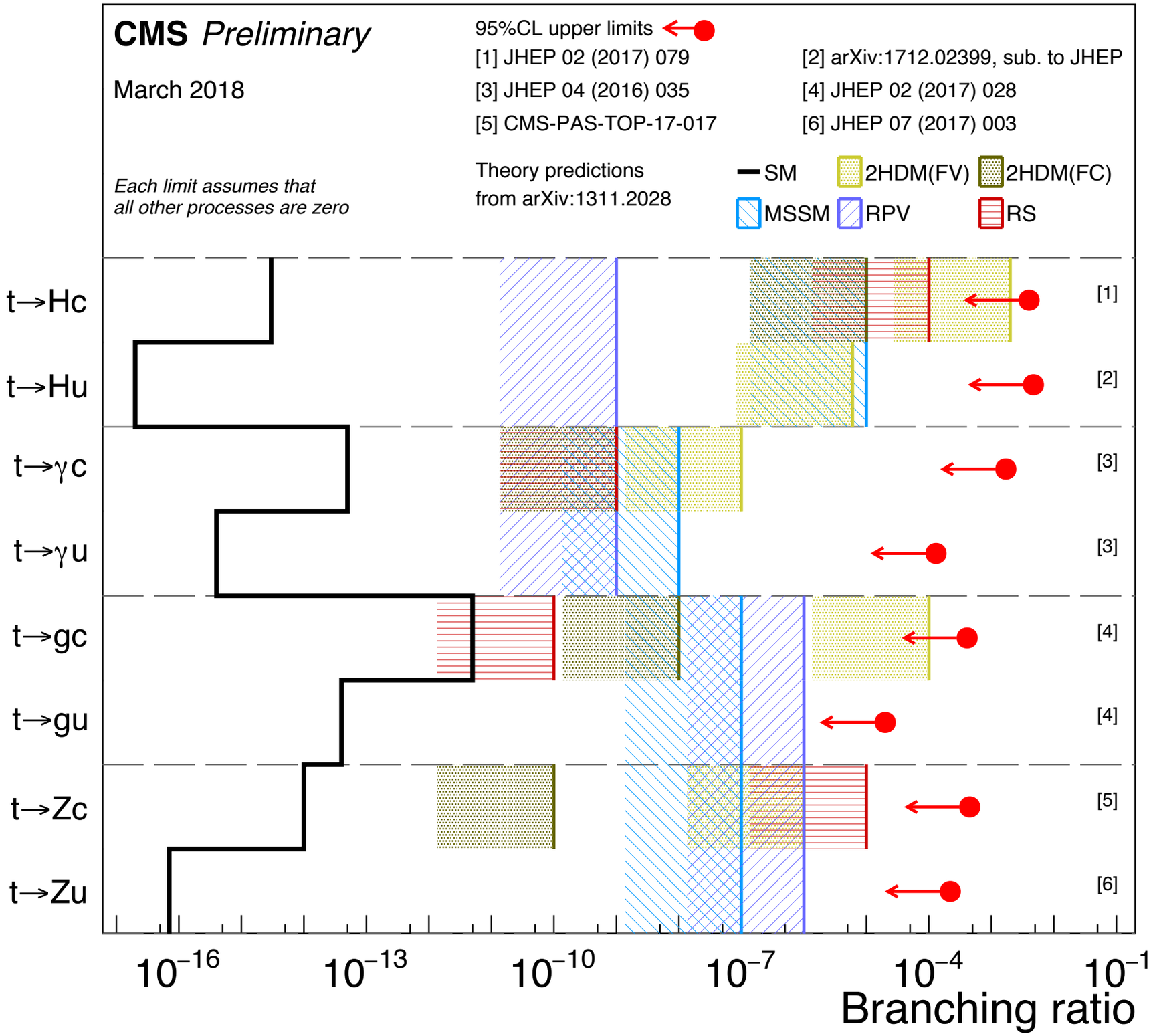
Thank You

Back Up

LHC Summary


ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
September 2018
Inclusive cross-section [pb]
10²
10
1
t-channel
tW
s-channel
7
8
13
√s [TeV]
ATLAS t-channel
PRD 90 (2014) 112006, EPJC 77 (2017) 531, JHEP 04 (2017) 086
CMS t-channel
JHEP 12 (2012) 035, JHEP 06 (2014) 090, PLB 772 (2017) 752
ATLAS tW
PLB 716 (2012) 142, JHEP 01(2016) 064, JHEP 01(2018) 063
CMS tW
PRL 110 (2013) 022003, PRL 112 (2014) 231802, arXiv:1805.07399
LHC combination, tW
ATLAS-CONF-2016-023, CMS-PAS-TOP-15-019
ATLAS s-channel
ATLAS-CONF-2011-118 95% CL, PLB 756 (2016) 228
CMS s-channel
JHEP 09 (2016) 027 95% CL
7+8 TeV combined fit 95% CL
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503, PRD 82 (2010) 054018, PRD 81(2010) 054028
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ αs uncertainty
NLO NPPS205 (2010) 10, CPC191(2015) 74
μR = μF = mtop,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: pTb veto for tt̄ removal = 60 GeV and μF = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ αs uncertainty
mtop = 172.5 GeV
stat
total

CMS Summary of FCNC searches



t-channel @13 TeV - Inclusive (CMS-PAS-TOP-17-011)

Variable	Description
Light-quark jet $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the light-quark jet
Dijet mass	Invariant mass of the light-quark jet and the b-tagged jet associated to the top quark decay
Top quark mass	Invariant mass of the top quark reconstructed from the lepton, the neutrino and the b-tagged jet associated to the top quark decay
ΔR (lepton, b jet)	ΔR between the momentum vectors of the lepton and the b-tagged jet associated to the top quark decay
$\cos(\theta^*)$	Cosine of the angle between the lepton and the light-quark jet in the rest frame of the top quark
Jet p_{T} sum	Scalar sum of the transverse momentum of the light-quark jet and the b-tagged jet associated to the top quark decay
$m_{\mathrm{T}}^{\mathrm{W}}$	Transverse mass of the W boson
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing momentum in the transverse plane of the event
ΔR (light jet, b jet)	ΔR between the momentum vectors of the light-quark jet and the b-tagged jet associated to the top quark decay
Lepton $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the selected lepton
W boson $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the reconstructed W boson
Light-quark jet mass	Invariant mass of the light-quark jet

New Physics search in *tW* - Operator Expressions

$$O_{\phi q}^{(3)} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q), \quad L_{eff} = \frac{C_{\phi q}^{(3)}}{\sqrt{2}\Lambda^2} g v^2 \bar{b}\gamma^\mu P_L t W_\mu^- + h.c.,$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I, \quad L_{eff} = -2\frac{C_{tW}}{\Lambda^2} v \bar{b}\sigma^{\mu\nu} P_R t \partial_\nu W_\mu^- + h.c.,$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, \quad L_{eff} = \frac{C_{tG}}{\sqrt{2}\Lambda^2} v \left(\bar{t}\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,$$

$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}, \quad L_{eff} = \frac{C_G}{\Lambda^2} f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu} + h.c.,$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, \quad L_{eff} = \frac{C_{u(c)G}}{\sqrt{2}\Lambda^2} v \left(\bar{u}\,(\bar{c})\,\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,$$

t-channel @13 TeV - Differential (CMS-PAS-TOP-16-004)

- Analysis with 2015 data (2.3 fb^{-1}) in μ + jets final state
- Standard 2J1T event selection
- BDT trained with variables uncorrelated to top p_T and lyl
- BDT > 0.6 to obtain signal enriched sample
- Bkg. subtracted data unfolded to compare with prediction
- Dominant uncertainties:
  - Data statistics
  - μ_R / μ_F scale
  - top quark mass
  - JEC
- Harder p_T spectrum in data compared to prediction in signal enriched region