Experimental results on $t\bar{t}$+W/Z/γ and SM top couplings

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on behalf of the ATLAS, CDF, CMS and DØ Collaborations

TOP2014, Cannes — 28th September - 3rd October

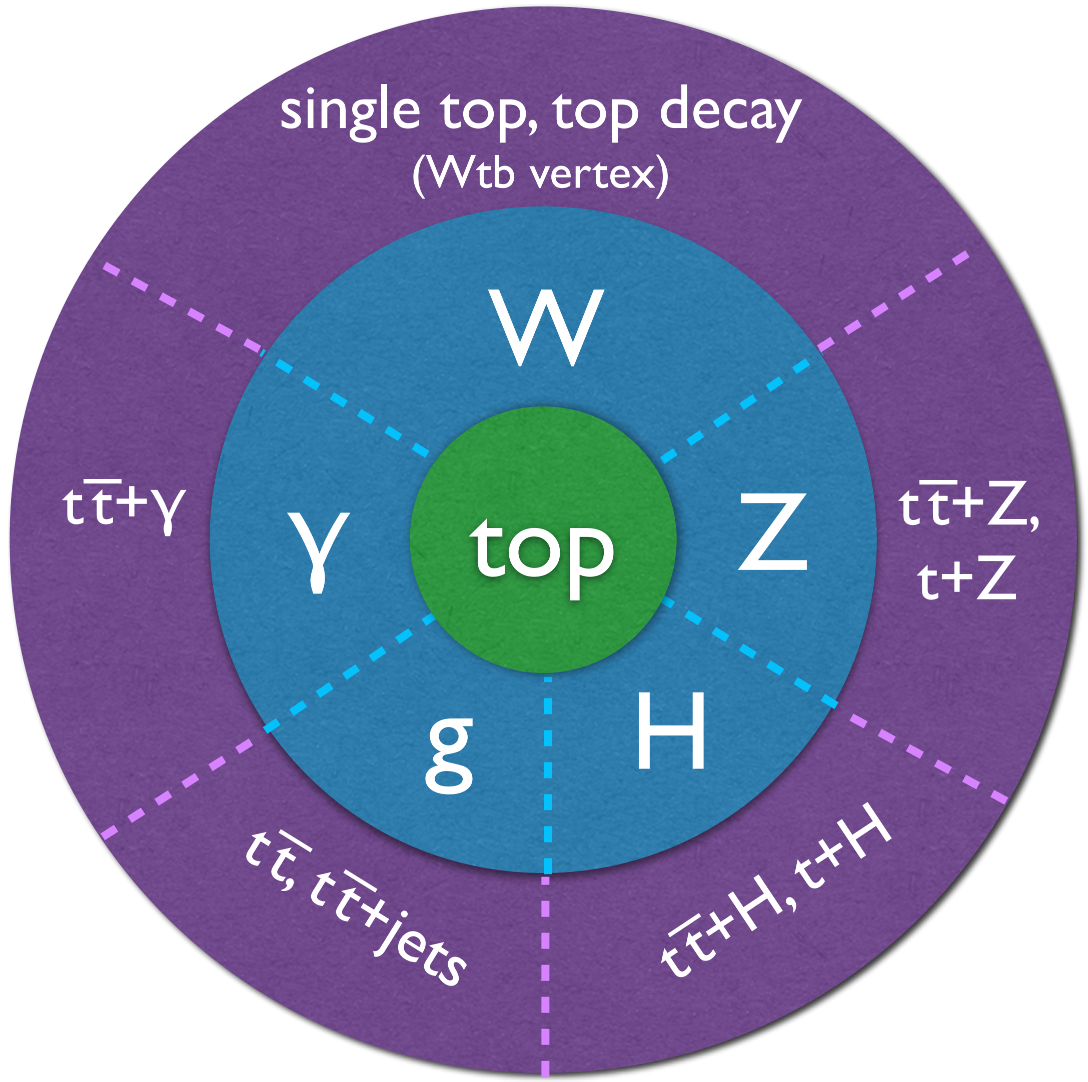
prepared with the help of Thorsten Chwalek

Outline

- Motivation
- $t \rightarrow Wb$ coupling:
  - Top decay: W-helicity
  - Top decay: ratio $B(t \rightarrow Wb)/B(t \rightarrow Wq)$
- $t\bar{t} + \gamma$
- $t\bar{t} + Z/W$
- Conclusions

Motivation

- The top quark couples to other SM fields through its **gauge** and **Yukawa interactions**
- t→Wb coupling measured already at the Tevatron
- High statistics top physics at the LHC: $t\bar{t}$ + bosons (γ, Z and H) becomes accessible!
- First evidence on the coupling of the top quark to these particles from **production rate**
- Important Standard Model test: **new physics** modifies the structure of the EW couplings



Top + X coupling, how to measure it?

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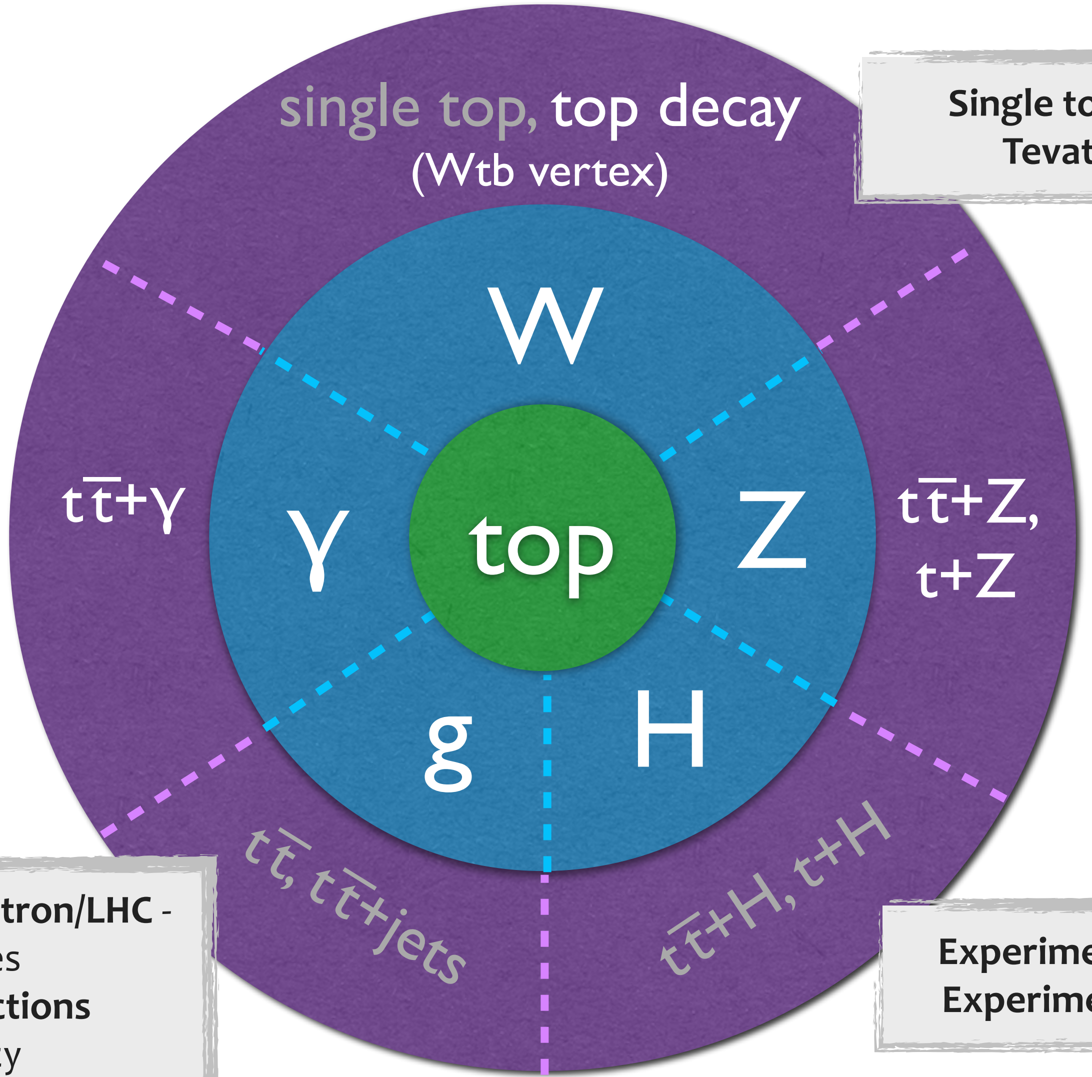


Single top measurements at the LHC/ Tevatron - A. Jafari, M. Ronzani

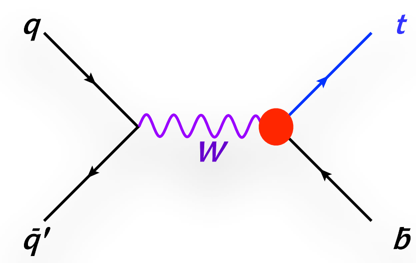
Inclusive top pair cross section at the Tevatron/LHC - E. Shabalina, J. Brochero Cifuentes
Latest results on differential cross sections (gap fraction, vs njets, ...) - J. Katzy

Experimental searches for $t\bar{t}H$ - M. Owen
Experimental searches for tHq - C. Böser

Top + X coupling, how to measure it?

Constraints on the top-W coupling from:

Single Top production



Direct measurement of V_{tb} with no assumption about number of generations ($\sigma \sim |V_{tb}|^2$)

$$V_{tb} = 0.999146^{+0.000021}_{-0.000046}$$ **(PDG)**

Top Decay

- Fraction of top decays that yield a b-quark

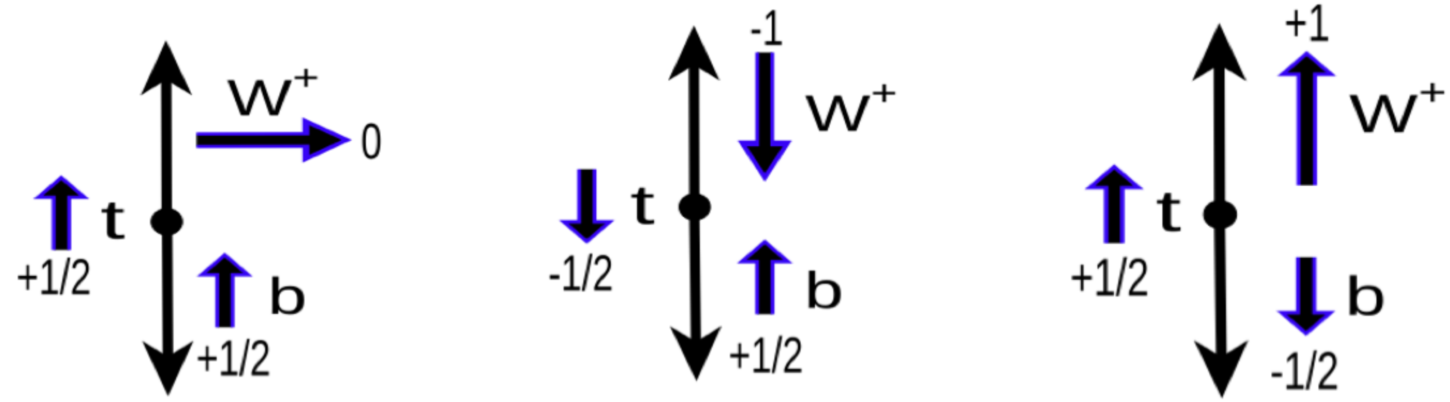
$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Test unitarity of CKM matrix

- **W-helicity** : probes the structure of the Wtb vertex

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\,F_0 + \frac{3}{8}(1-\cos\theta^*)^2\,F_L + \frac{3}{8}(1+\cos\theta^*)^2\,F_R$$

θ^* = Angle between the momenta of d-type decay product of W (lepton, d-, s-quark) and top quark in W rest frame

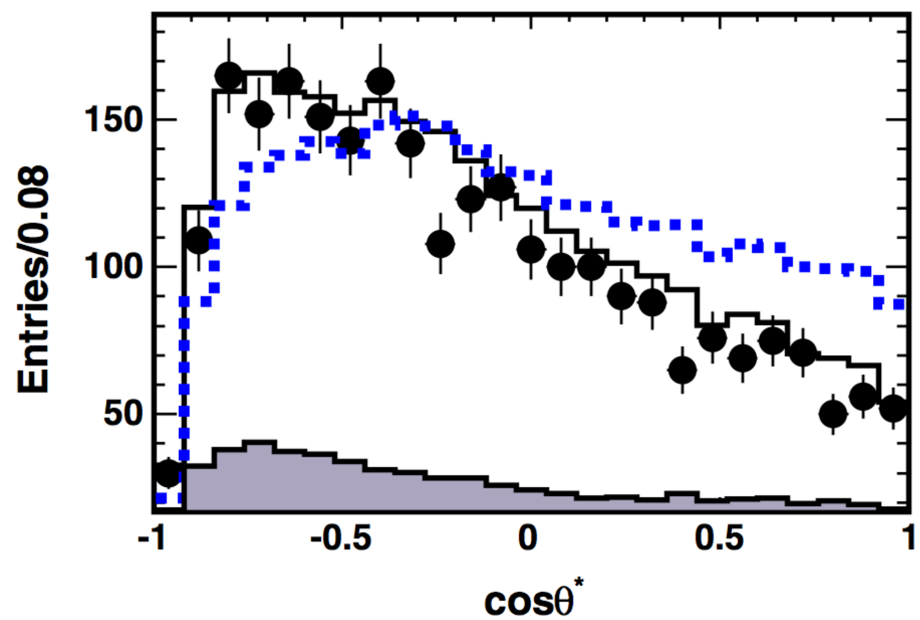


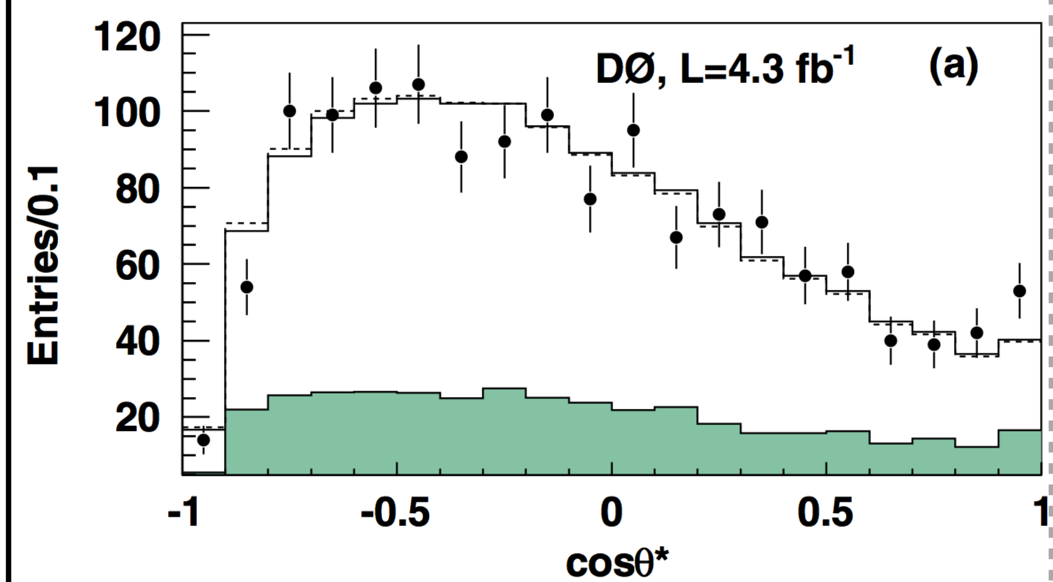
Sensitive to anomalous Wtb couplings

Helicity fractions @ NNLO
(for m_t = 172.8 ± 1.3 GeV)
Phys. Rev. D 81 (2010) 111503

F_0=0.678 F_L=0.311 F_R=0.0017

latest W-helicity measurements

<table>
<tr><th></th><th>CDF</th><th>DØ</th></tr>
<tr><td></td><td>Phys. Rev. D 87, 031104(R)</td><td>Phys. Rev. D 83, 032009</td></tr>
<tr><td>√s, lumi</td><td>1.96 TeV, (full dataset) 8.7 fb-1</td><td>1.96 TeV, 5.4 fb-1</td></tr>
<tr><td>Channels</td><td>l+jets</td><td>l+jets, dilepton</td></tr>
<tr><td>Results</td><td>matrix element method
variable cosθ*


leptonically decaying W-boson
$f_0 = 0.726 \pm 0.066(\text{stat}) \pm 0.067(\text{syst}),$
$f_+ = -0.045 \pm 0.044(\text{stat}) \pm 0.058(\text{syst}),$</td><td>template method
variable cosθ*


leptonically decaying W-boson
$f_0 = 0.669 \pm 0.102[\pm 0.078(\text{stat.}) \pm 0.065(\text{syst.})],$
$f_+ = 0.023 \pm 0.053[\pm 0.041(\text{stat.}) \pm 0.034(\text{syst.})].$</td></tr>
</table>

consistent with the SM expectations

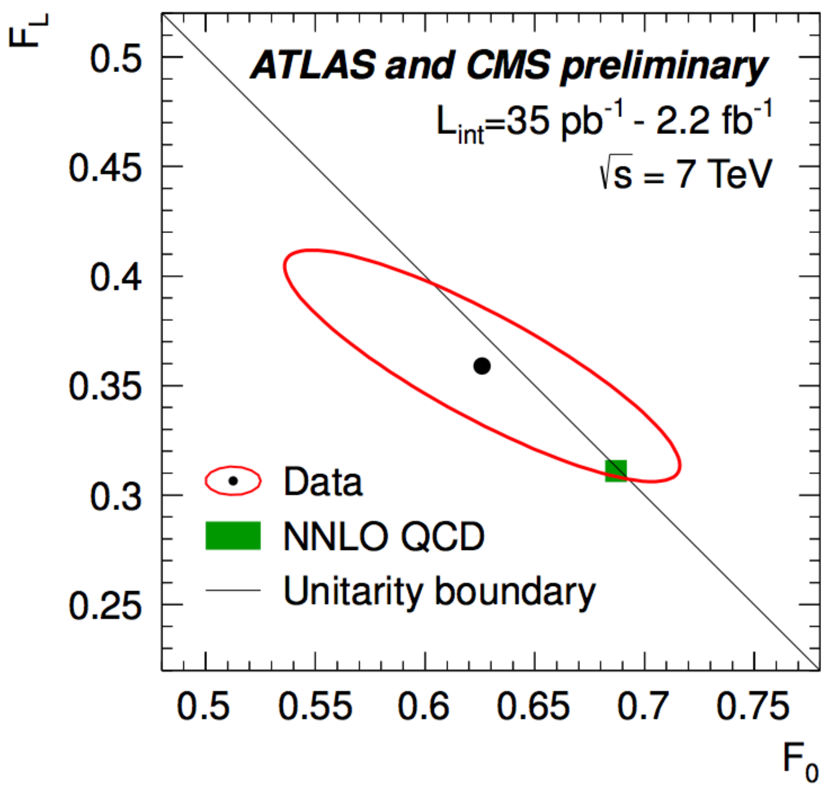
latest W-helicity measurements

Combination ATLAS&CMS @ 7 TeV

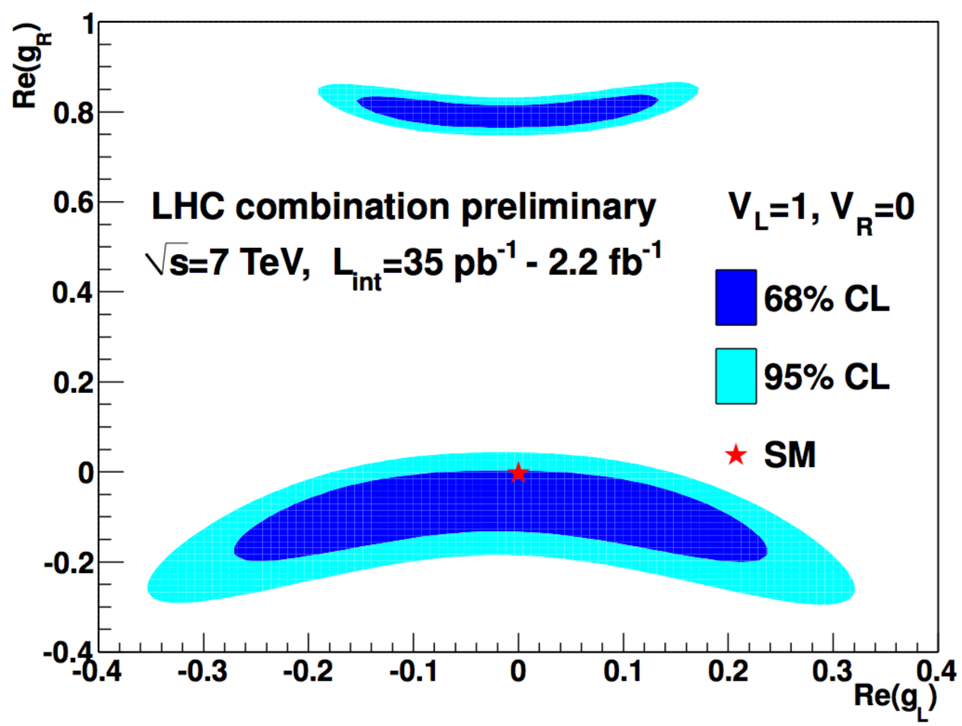
ATLAS-CONF-2013-033
CMS PAS TOP-12-025

new physics parameterized as effective Lagrangian

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-} + \text{h.c.}$$



SM: V_L=1,
V_R=g_L=g_R=0
at tree level



$$F_0 = 0.626 \pm 0.034\,(\text{stat.}) \pm 0.048\,(\text{syst.})$$
$$F_L = 0.359 \pm 0.021\,(\text{stat.}) \pm 0.028\,(\text{syst.})$$
$$F_R = 0.015 \pm 0.034$$

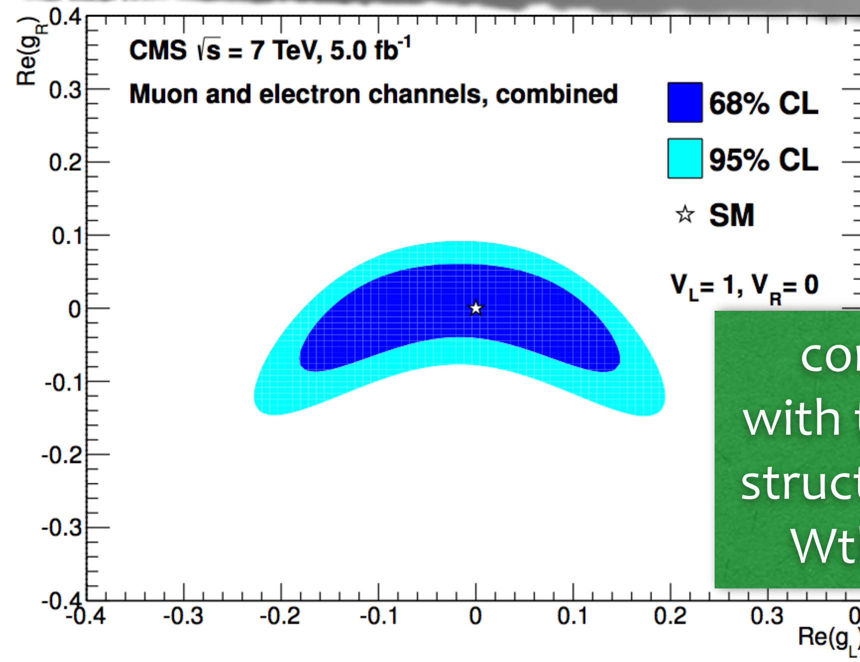
consistent with the SM expectations

consistent with the (V – A) structure of the Wtb vertex

latest W-helicity measurements

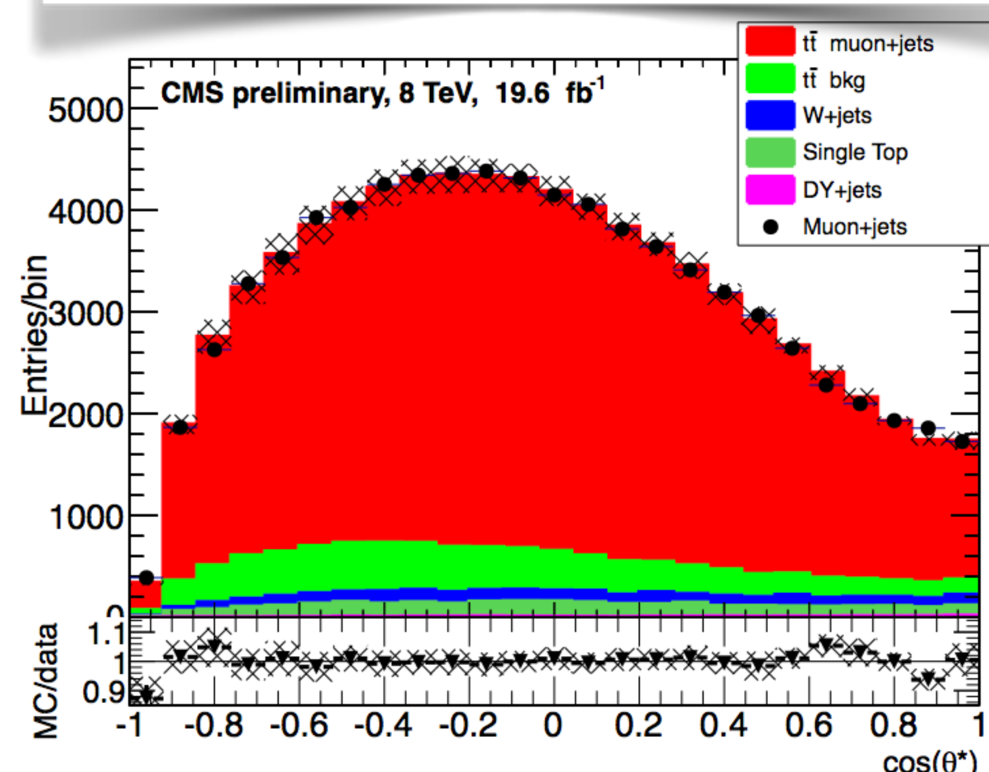
	CMS
	JHEP 10 (2013) 167
√s, lumi	**7 TeV**, (full dataset) 5.0 fb-1
Channels	l+jets
Results (2D, **3D** fit)	$F_0 = 0.682 \pm 0.030(stat.) \pm 0.033(syst.)$ $F_L = 0.310 \pm 0.022(stat.) \pm 0.022(syst.)$ $F_R = 0.008 \pm 0.012(stat.) \pm 0.014(syst.)$

	CMS
	CMS PAS TOP-13-008
√s, lumi	**8 TeV**, (full dataset) 19.6 fb-1
Channels	μ+jets
Results (3D fit)	$F_0 = 0.659 \pm 0.015(stat.) \pm 0.023(syst.)$ $F_L = 0.350 \pm 0.010(stat.) \pm 0.024(syst.)$ $F_R = -0.009 \pm 0.006(stat.) \pm 0.020(syst.)$



consistent with the (V – A) structure of the Wtb vertex

- Reweighting method
- Variable cosθ*
- 3D fit (Signal normalisation $F_{t\bar{t}}$, F_0, F_L):



consistent with the SM expectations

Summary R and V_{tb} measurements

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

(*) assuming unitarity of the three generation CKM matrix
(**) assuming $|V_{tb}| \leq 1$

CDF	Phys. Rev. Lett. 112, 221801	1.96 TeV, (full dataset) 8.7 fb-1 dilepton	R = 0.87 ± 0.07 $\lvert V_{tb}\rvert$ = 0.93 ± 0.04 (*) $\lvert V_{tb}\rvert$ > 0.85(0.87) at 95%(90%) CL
CDF	Phys. Rev. D 87, 111101(R)	1.96 TeV, (full dataset) 8.7 fb-1 l+jets	R=0.94 ± 0.09 $\lvert V_{tb}\rvert$ = 0.97 ± 0.05 (*) $\lvert V_{tb}\rvert$ > 0.89 at 95% CL
DØ	Phys. Rev. Lett. 107, 121802	1.96 TeV, 5.4 fb-1 l+jets and dilepton	R = 0.90±0.04 $\lvert V_{tb}\rvert$ = 0.95 ± 0.02 (*) $\lvert V_{tb}\rvert$ > 0.96 at 95% CL
CMS	PLB 736 (2014) 33	8 TeV, (full dataset) 19.6 fb-1 dilepton	**R = 1.014 ± 0.003 (stat) ± 0.032 (syst)** **$\lvert V_{tb}\rvert$ = 1.007 ± 0.016 (*)** **$\lvert V_{tb}\rvert$ > 0.975 at 95% CL (**)**

most precise to date!

Inclusive top pair cross section at the Tevatron/LHC -
E. Shabalina, J. Brochero Cifuentes

Summary R and V_{tb} measurements

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

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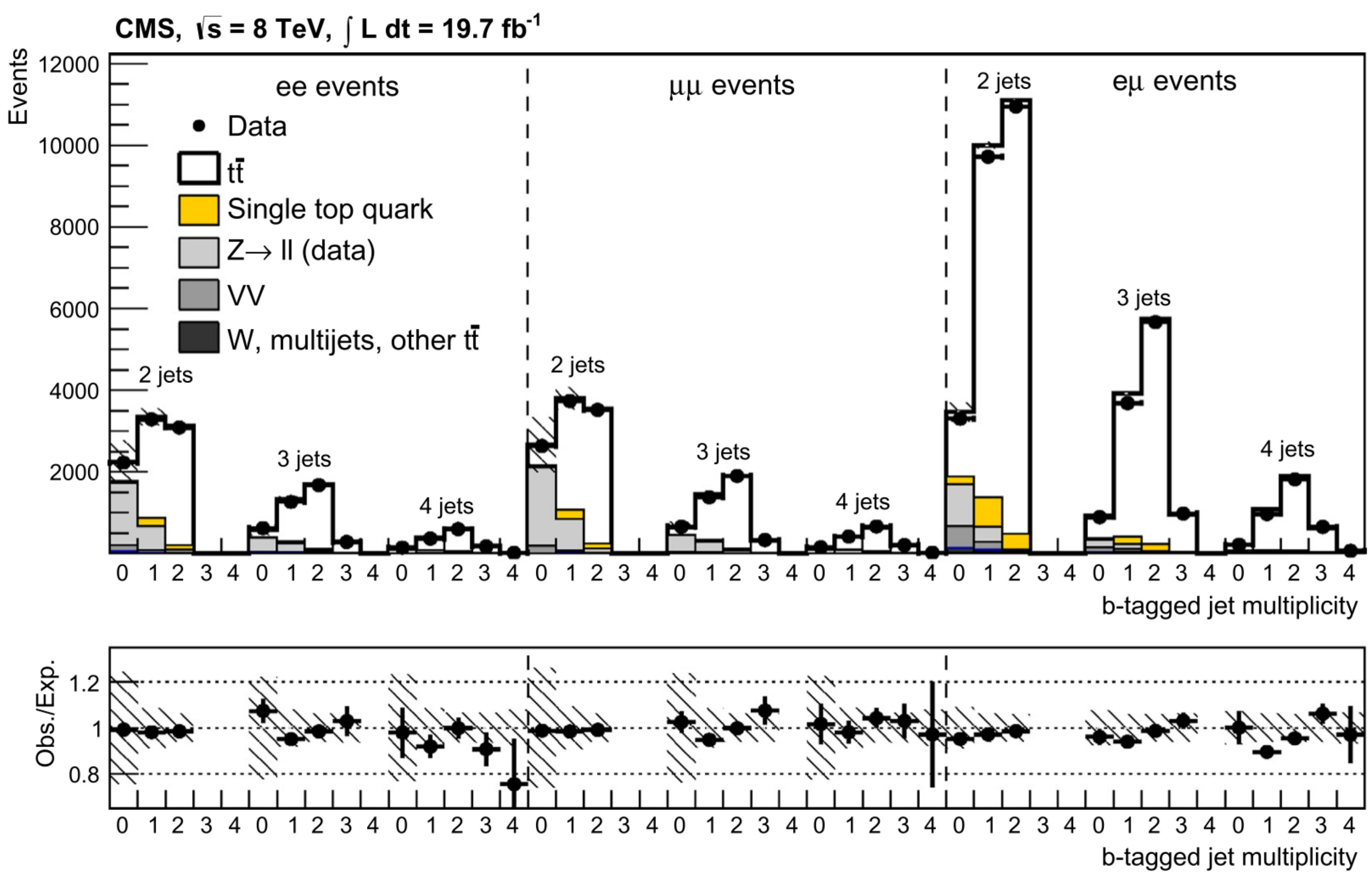
CMS	PLB 736 (2014) 33	8 TeV, (full dataset) 19.6 fb-1 dilepton	**R = 1.014 ± 0.003 (stat) ± 0.032 (syst)** **$|V_{tb}|$ = 1.007 ± 0.016 (*)** **1.6 %** **$|V_{tb}|$ > 0.975 at 95% CL (**)**



most precise to date!

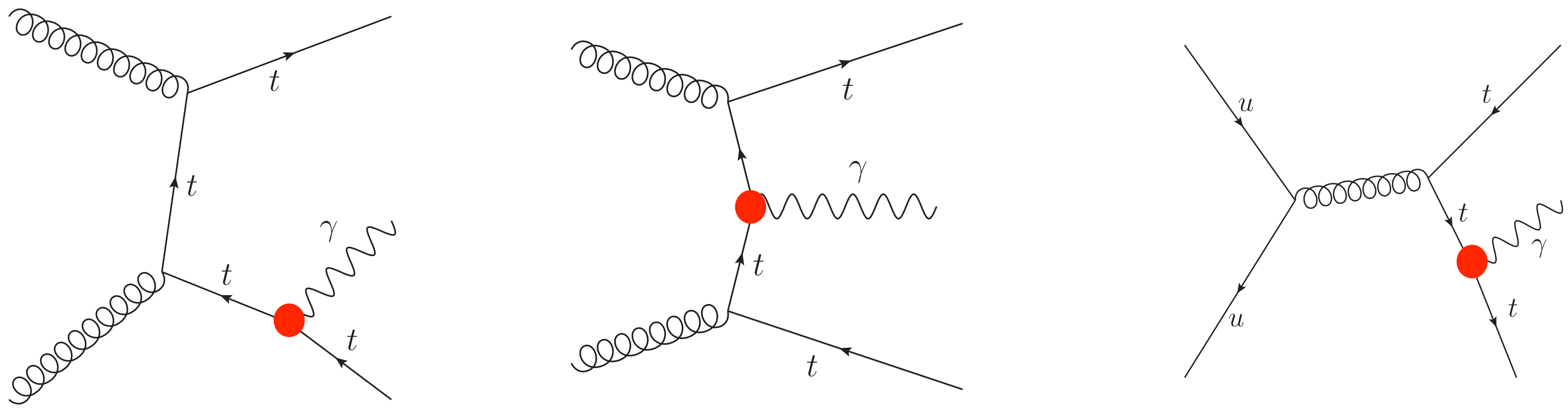
- profile likelihood fit (36 categories)

$$\mathcal{L}(\mathcal{R}, f_{t\bar{t}}, k_{st}, f_{\text{correct}}, \varepsilon_b, \varepsilon_q, \varepsilon_{q*}, \theta_i)$$

$$= \prod_{\ell\ell} \prod_{N_{\text{jets}}=2\ldots4} \prod_{k=0}^{N_{\text{jets}}} \mathcal{P}[N_{\text{ev}}^{\ell\ell, N_{\text{jets}}}(k), \hat{N}_{\text{ev}}^{\ell\ell, N_{\text{jets}}}(k)] \prod_i \mathcal{G}(\theta_i^0, \theta_i, 1)$$

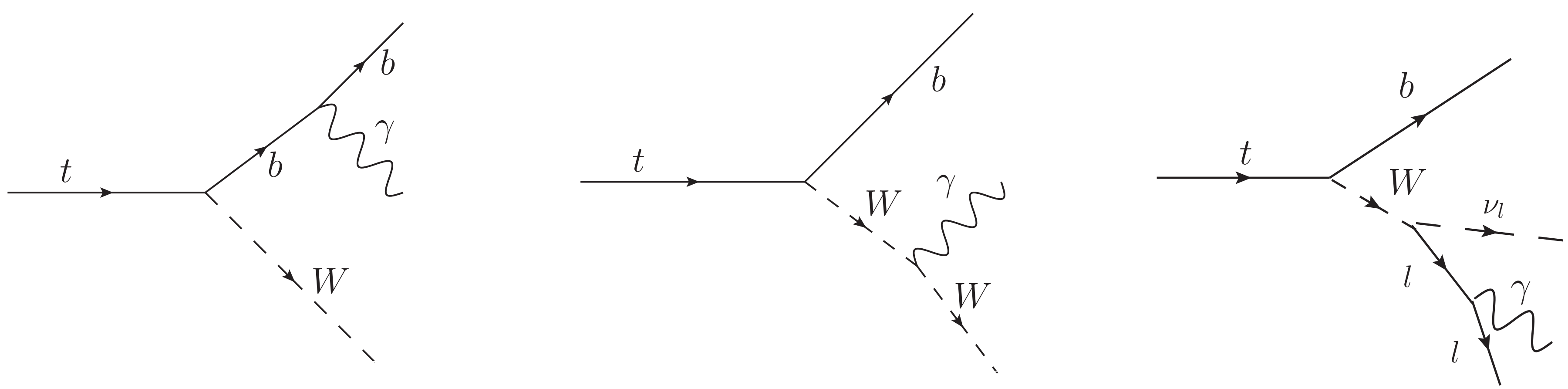
- dominant systematic uncertainty: b-tagging efficiency measurement (ε_b)

- $t\bar{t}\gamma$ cross section measurement:
  - direct probe of V-A and A coupling of the $t\bar{t}\gamma$ vertex
  - direct probe of EM coupling (top charge)
- γ can be radiated from:
  - **top** ($pp \rightarrow t\bar{t}\gamma$)



the only processes in pp/p$\bar{p}$ collisions with access to the $t\bar{t}\gamma$ vertex!

  - **top decay products** ($t \rightarrow Wb\gamma$ (on-shell decay) or W decay chain)



- Non-negligible interference effects taken into account!

$t\bar{t}\gamma$ previous measurements

	CDF	ATLAS
	Phys. Rev. D 84, 031104(R)	ATLAS-CONF-2011-153
√s, lumi	1.96 TeV, 6.0 fb-1	7 TeV, 1.04 fb-1
Results	**$\sigma(t\bar{t}\gamma)$ = 0.18±0.07 (stat) ±0.04 (sys) ±0.01 (lum) pb** (with $p_T(\gamma)$ > 10 GeV) **Observed significance 3σ** NLO prediction = 0.17 ± 0.03 pb	**$\sigma(t\bar{t}\gamma)$ * BR = 2.0 ± 0.5 (stat) ± 0.7 (syst) ± 0.08 (lumi) pb** (with $p_T(\gamma)$ > 8 GeV) **Observed significance 2.7σ (expected 3.0σ)** NLO prediction = 2.1 ± 0.4 pb

selection $t\bar{t}\gamma$: 1 high-p_T lepton,
a central photon with p_T>10 GeV,
Etmiss, large HT,
≥3 jets (1 b-tagged jet)

Analysis strategy: counting experiment

"standard l+jets" selection
+ additional selection $t\bar{t}\gamma$: ≥1 good photon with p_T>15 GeV,
|m(eγ) - m(Z)| > 5 GeV

Analysis strategy: template fit method
discriminating variable: track isolation **pTcone20** distributions
templates for prompt photons and hadron fakes from data

$t\bar{t}\gamma$ sample:
MadGraph+Pythia

Main background contribution: hadron fakes
Dominant systematic uncertainty: photon identification efficiency

$t\bar{t}\gamma$ sample:
WHIZARD+Herwig
$p_T(\gamma)$ > 8 GeV

$\sigma(t\bar{t}\gamma)$ measurement statistically limited!

$\sigma(t\bar{t}\gamma)$ measurement systematics-dominated!

$t\bar{t}\gamma$ previous measurements

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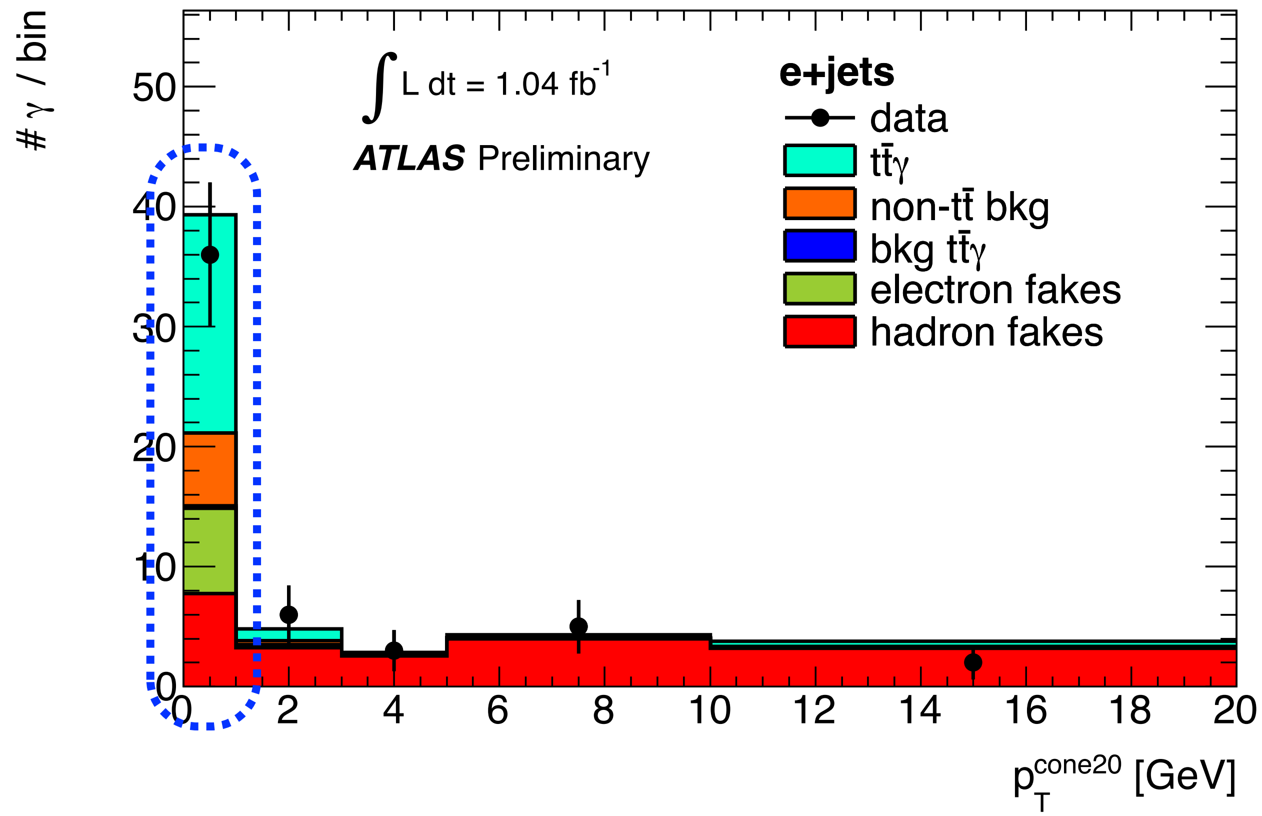
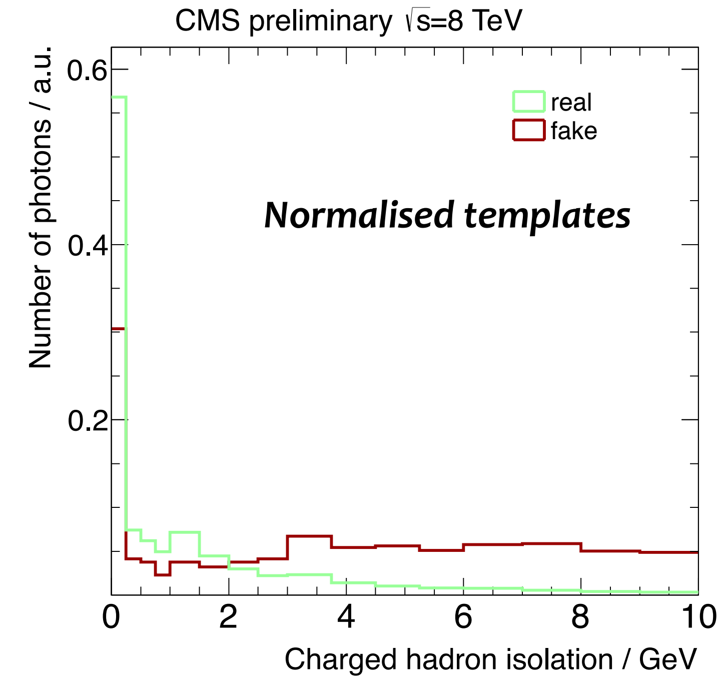
pTcone20 = scalar sum of all track pTs in a cone with ΔR<0.2 around the photon candidate

prompt photons (including signal photons) **are generally isolated!**



Measurement $t\bar{t}\gamma$ @ 8 TeV

	CMS
	CMS-PAS-TOP-13-011
√s, lumi	8 TeV, 19.7 fb-1
Channels	μ+jets

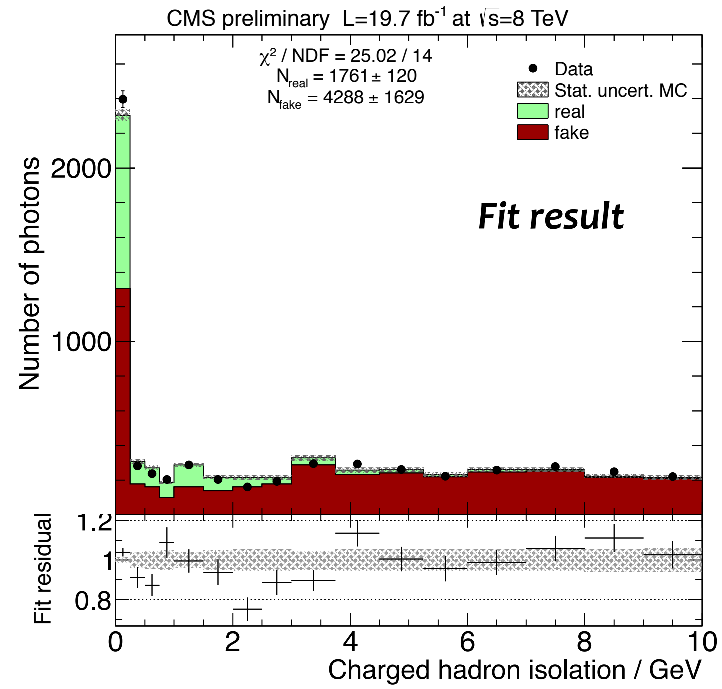


Additional selection $t\bar{t}\gamma$: ≥1 good central photon with ET>25 GeV
ΔR (photon, muon/jet) > 0.7

Analysis strategy: template fit method
discriminating variable: charged hadron isolation of photon candidate distribution
templates for signal photons from simulation, background from data

Dominant systematic uncertainty: background modelling (23%)

$$R = \sigma_{\bar{t}t+\gamma} / \sigma_{\bar{t}t} = (1.07 \ \pm 0.07\,(\text{stat.}) \ \pm 0.27\,(\text{syst.})) \times 10^{-2}$$



CDF (Phys. Rev. D 84, 031104(R)) @ 1.96 TeV
$\sigma(t\bar{t}\gamma) / \sigma(t\bar{t}) = 0.024 \pm 0.009$

$\sigma_{t\bar{t}}$ from CMS measurement
*[JINST **3** (2008) S08004]*

$t\bar{t}\gamma$ sample:
WHIZARD+Pythia
$E_T(\gamma) > 20$ GeV

$$\sigma^{\text{CMS}}_{\bar{t}t+\gamma} = 2.4 \ \pm 0.2\,(\text{stat.}) \ \pm 0.6\,(\text{syst.})\,\text{pb}$$

in agreement with NLO prediction: $\sigma^{SM}_{\text{t}\bar{\text{t}}+\gamma} = 1.8 \pm 0.5\,\text{pb}$

$t\bar{t}Z$ and $t\bar{t}W$

- **$t\bar{t}Z$ process:** FSR processes would allow us to measure the weak isospin of the top
  - but it can also arise from ISR processes
  - or Z radiated from the top quark decay products

    → **cross-section of $t\bar{t}Z$ production sensitive to anomalous couplings!**
- **$t\bar{t}W$ process:** ISR process

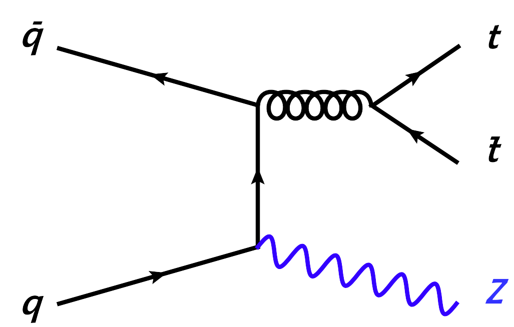
$$\gamma^{\mu}(C_V^{SM} - \gamma_5 C_A^{SM})$$

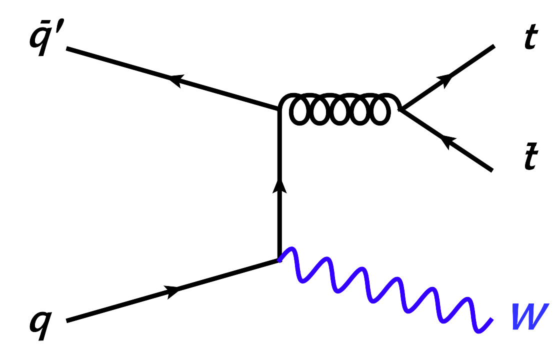
$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W) \qquad C_A^{SM} = T^3$$

- $t\bar{t}Z$ and $t\bar{t}W$ are dominant (and sometimes irreducible) backgrounds in many searches (e.g. $t\bar{t}H$ search in multilepton final states)

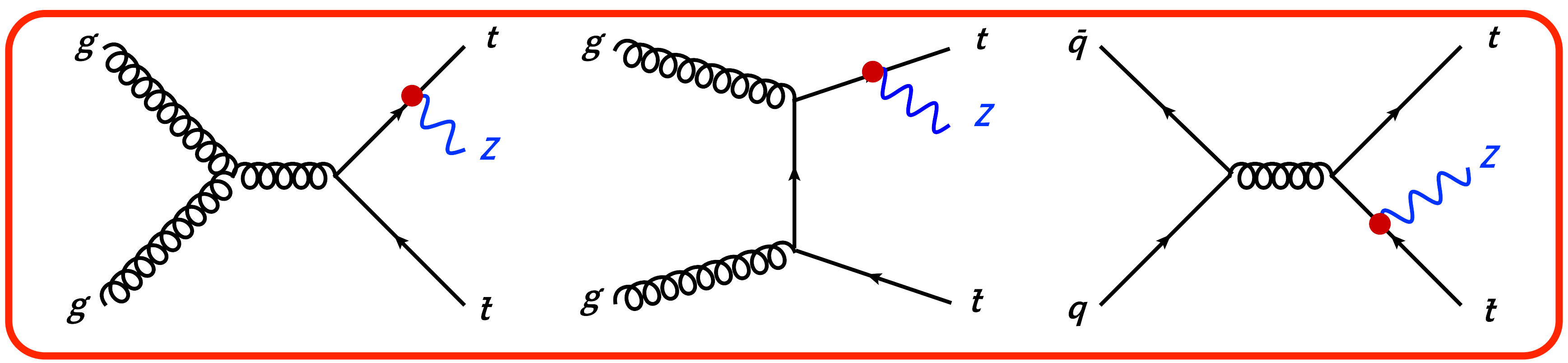
  → **both processes are important to be measured!**

ISR

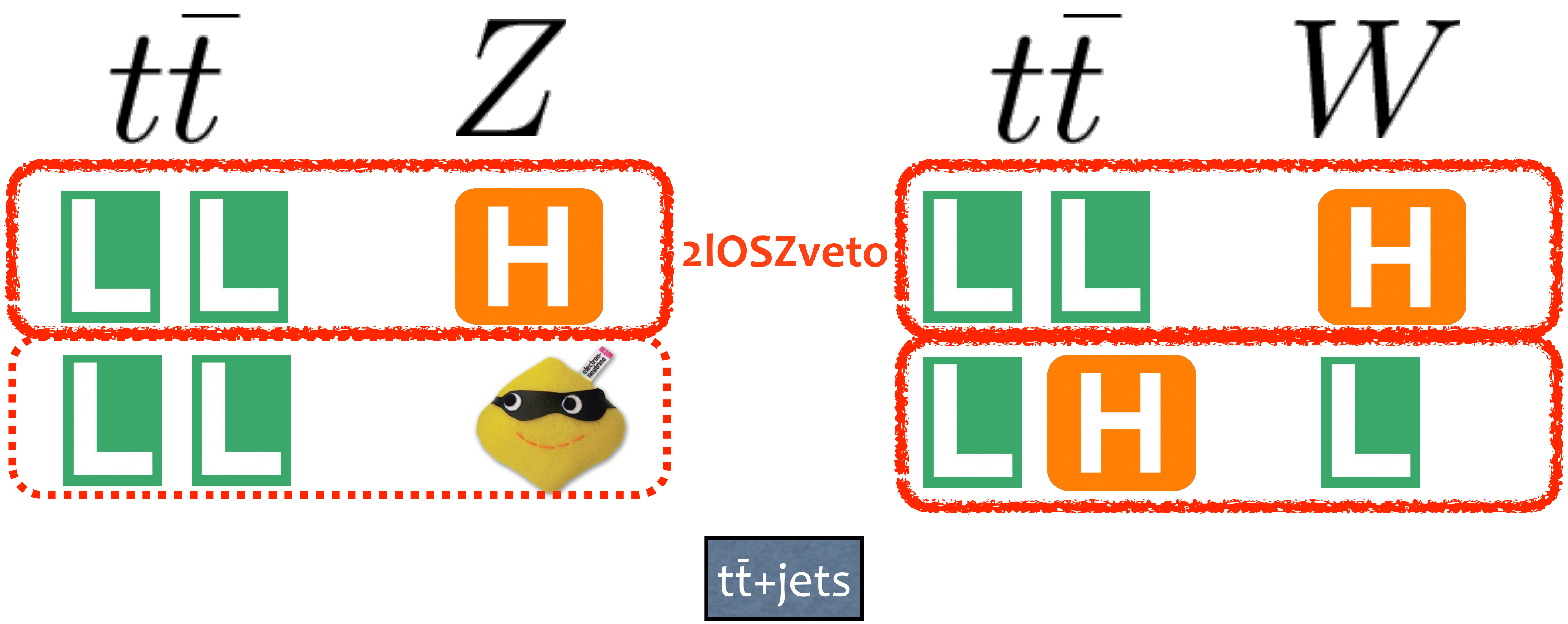




FSR

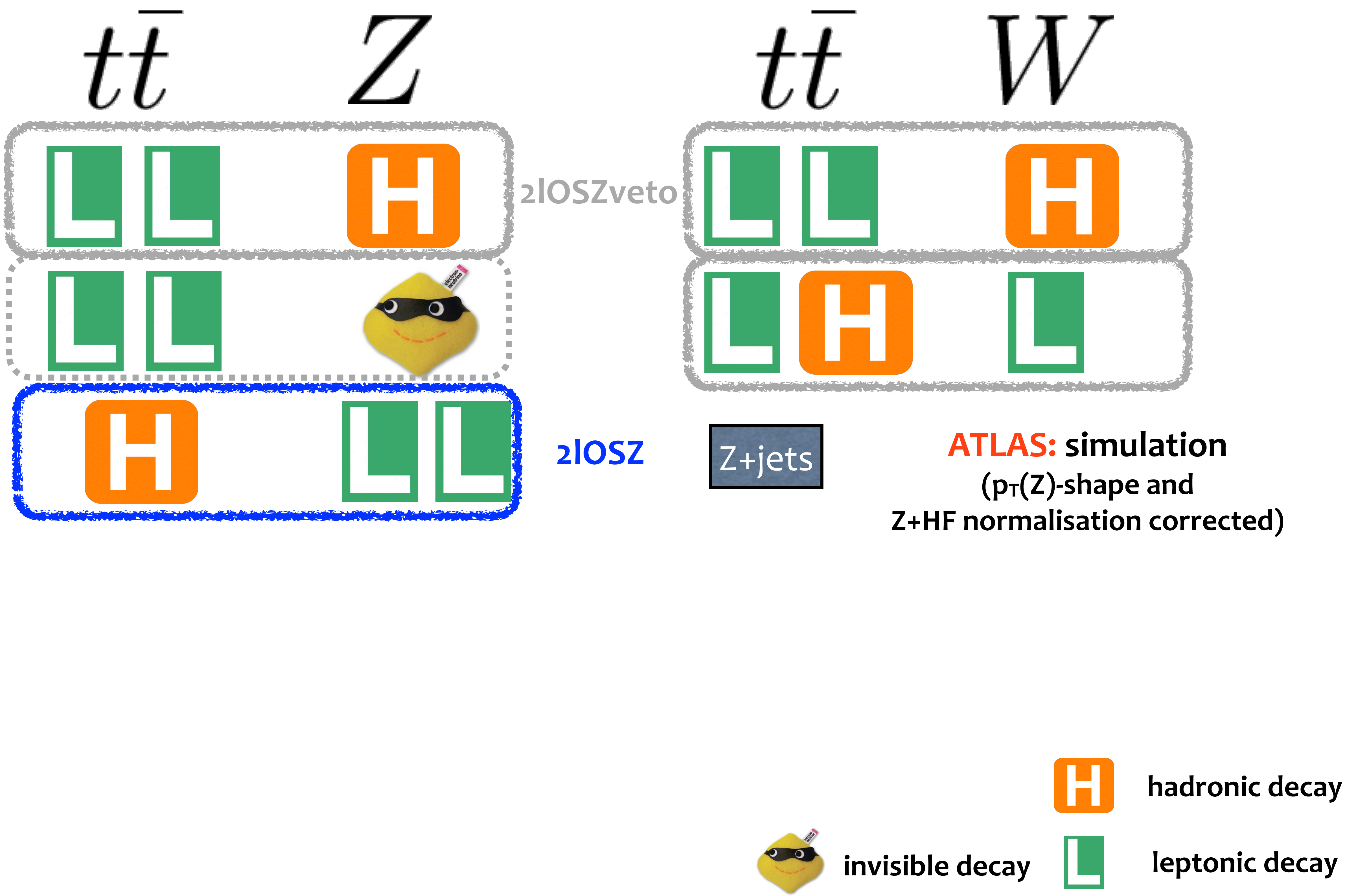


Truth $t\bar{t}V$ channels: 2l, 3l and 4l

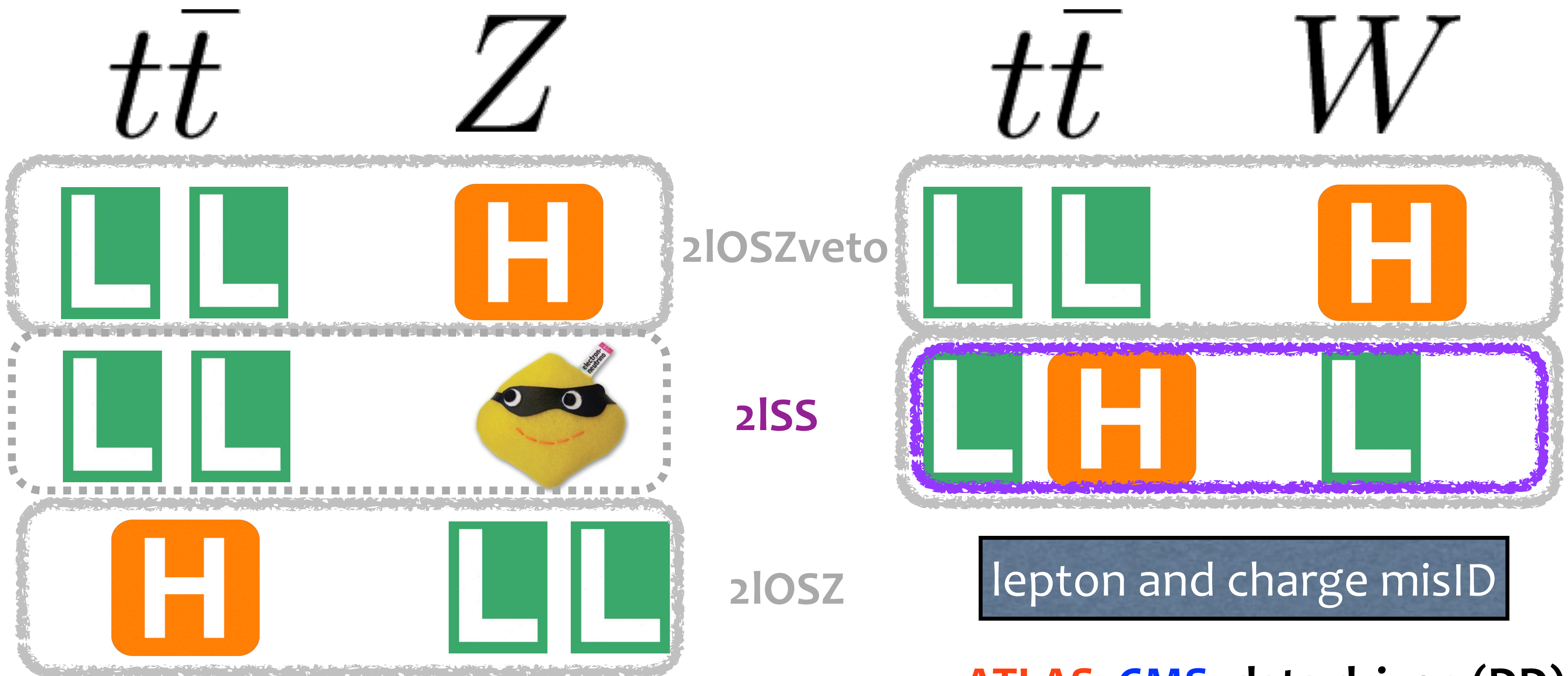


ATLAS: **simulation** (top and $t\bar{t}$ p_T corrected)

Truth $t\bar{t}V$ channels: 2l, 3l and 4l

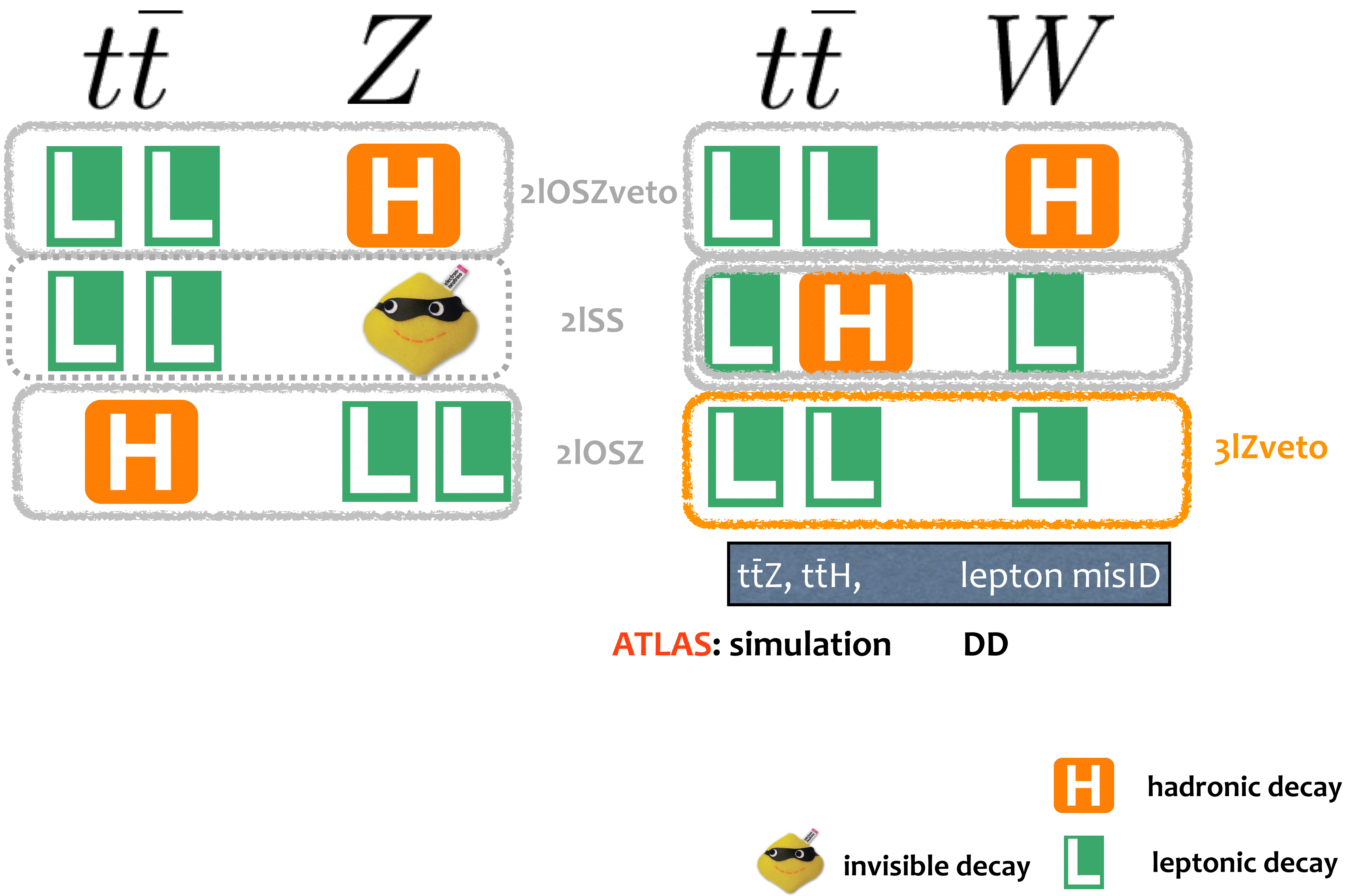


Truth $t\bar{t}V$ channels: 2l, 3l and 4l

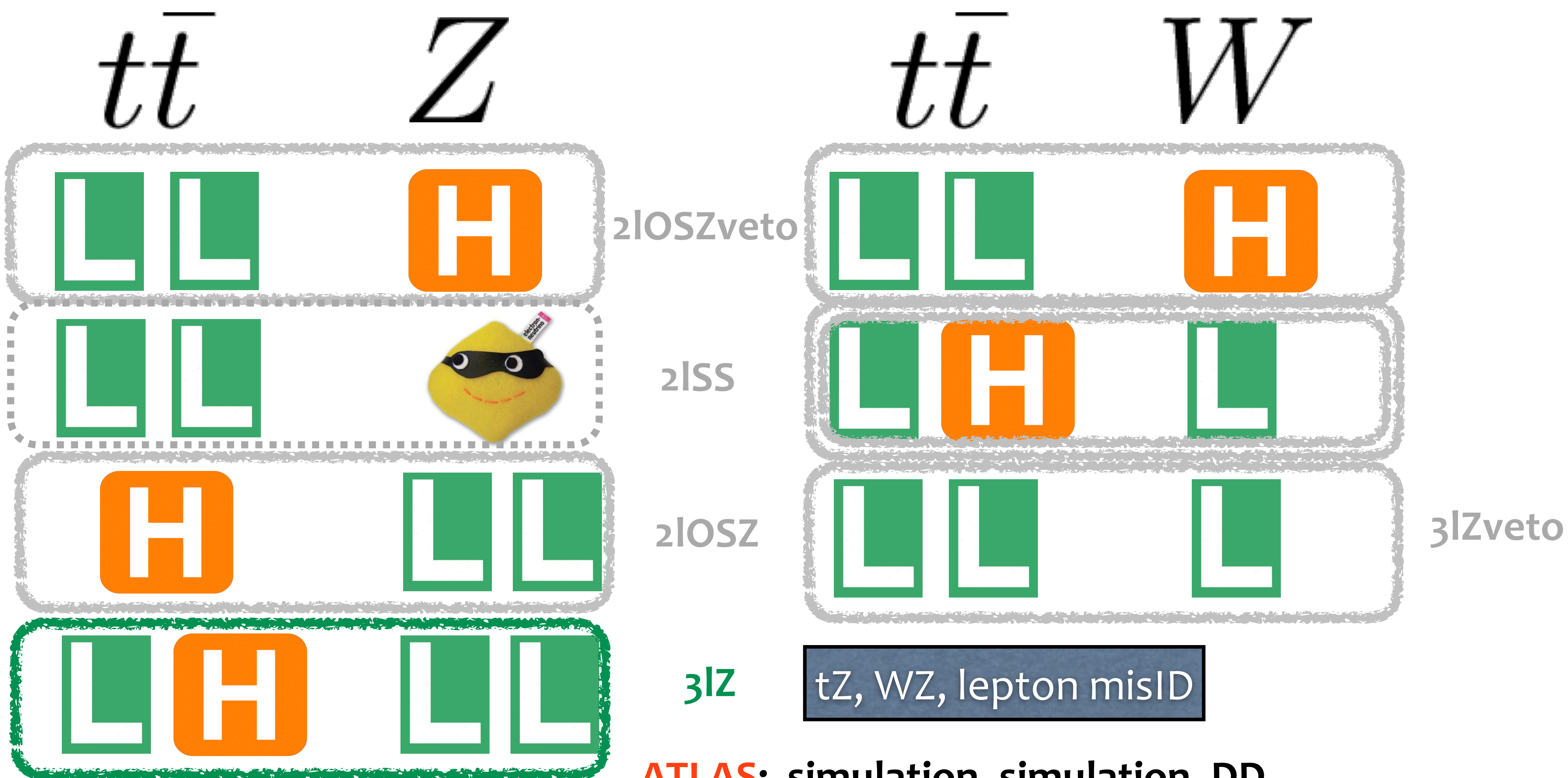


ATLAS, CMS: data driven (DD)

Truth $t\bar{t}V$ channels: 2l, 3l and 4l

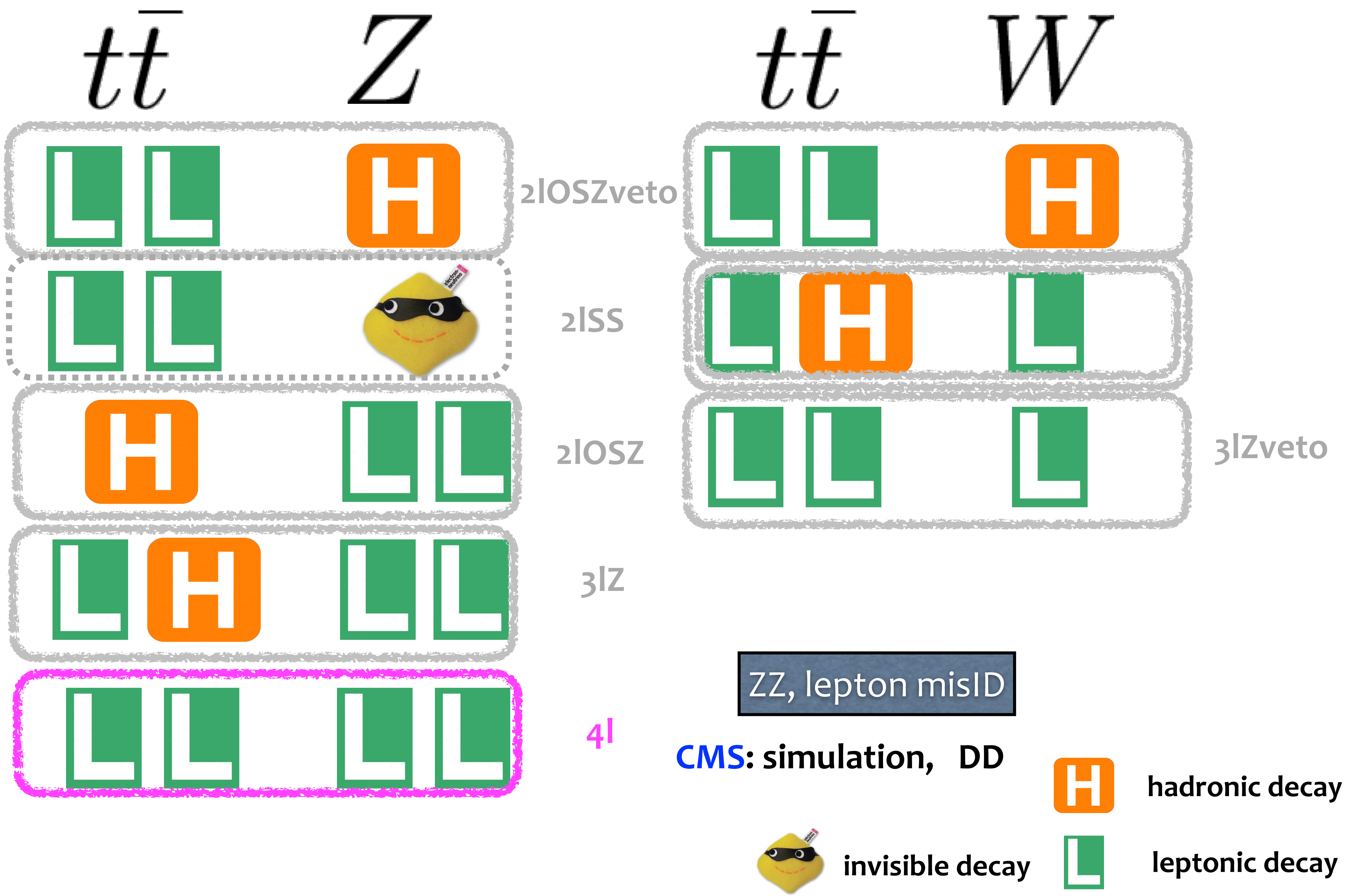


Truth $t\bar{t}V$ channels: 2l, 3l and 4l

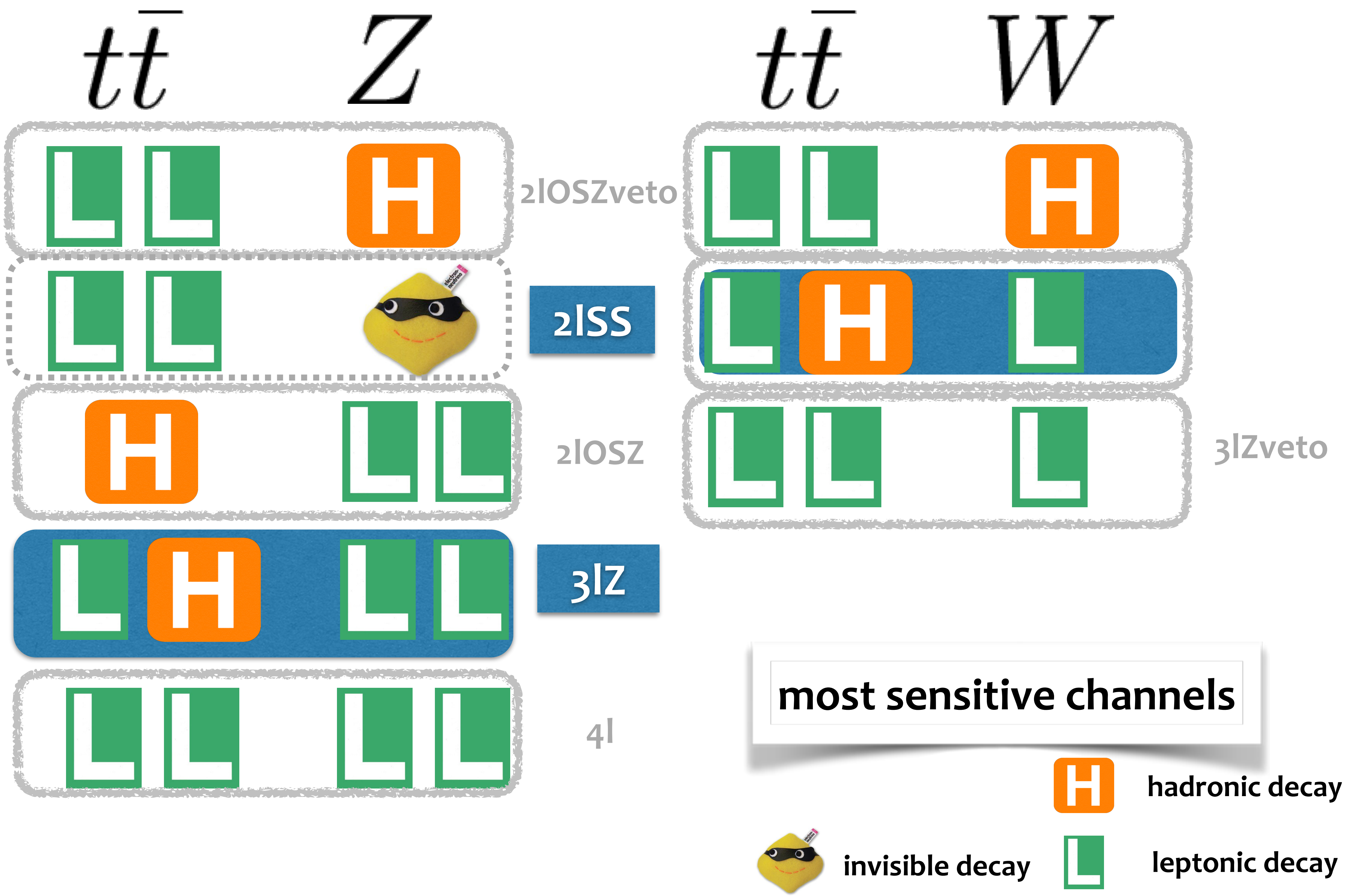


ATLAS: simulation, simulation, DD
CMS: simulation, DD, DD

Truth $t\bar{t}V$ channels: 2l, 3l and 4l

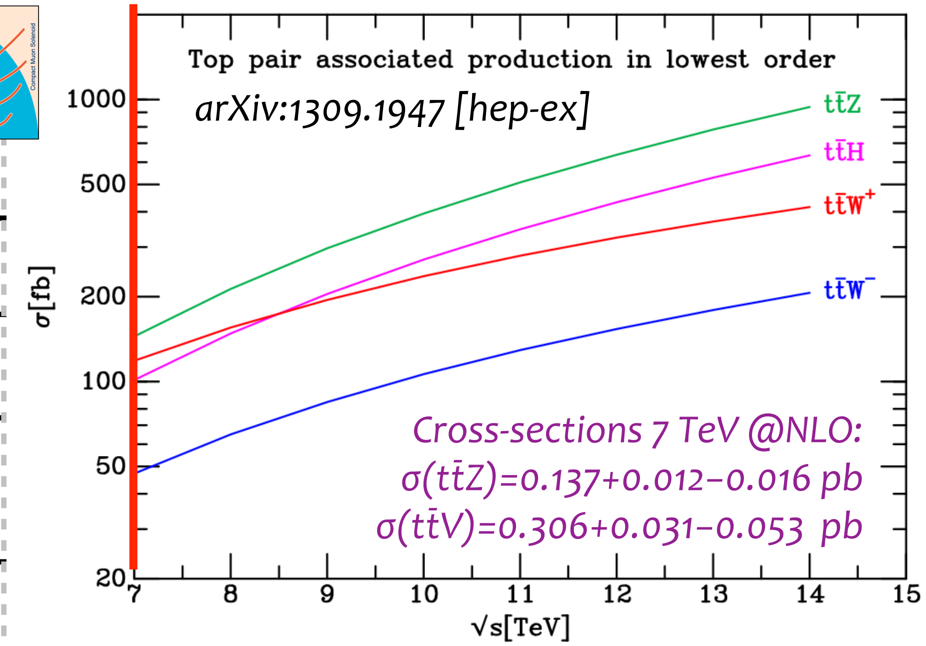


Truth $t\bar{t}V$ channels: 2l, 3l and 4l



Measurements/Searches at 7 TeV

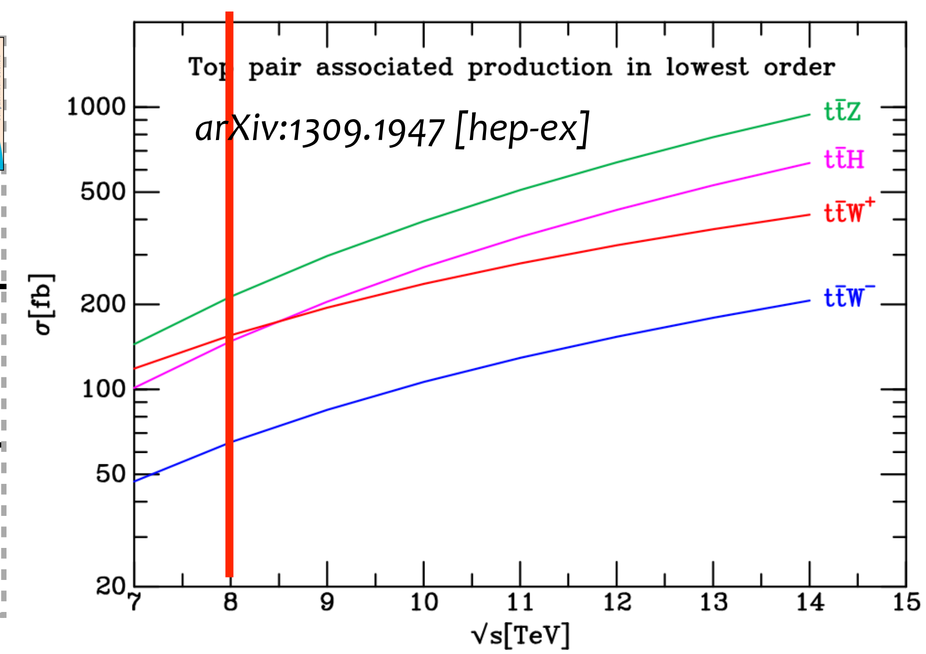
	ATLAS	CMS	
	ATLAS-CONF-2012-126	Phys. Rev. Lett. 110, 172002	
√s, lumi	7 TeV, 4.7 fb-1	7 TeV, 5.0 fb-1	
Channels	trilepton	trilepton + same-sign dilepton	
Results	σ(tt̄Z) < 0.71 pb @ 95% CL	3l	$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\,(\text{stat})^{+0.06}_{-0.03}\,(\text{syst})$ pb **significance = 3.3 σ**
		2lSS	$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})$ pb significance = 3.0 σ



J.M. Campbell and R.K. Ellis, JHEP 07 (2012) 052
M.V. Garzelli, A. Kardos, C.G. Papadopoulos, and Z. Trocsanyi, JHEP 11 (2012) 056

Measurements/Searches at 8 TeV

	ATLAS	CMS
	ATLAS-CONF-2014-038	Eur. Phys. J. C74 (2014) 3060
√s, lumi	8 TeV, 20.3 fb-1	8 TeV, 19.5 fb-1
Channels	trilepton + same-sign μμ + opposite-sign dilepton	trilepton + same-sign dilepton + four lepton



compare channels in detail!

Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Trilepton channel

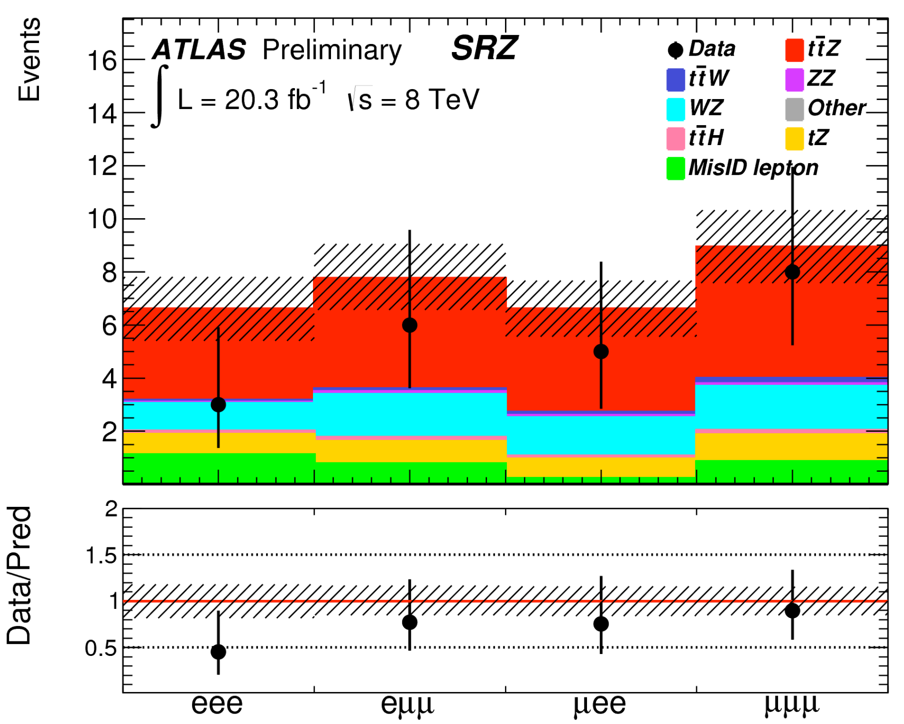
ATLAS — ATLAS-CONF-2014-038

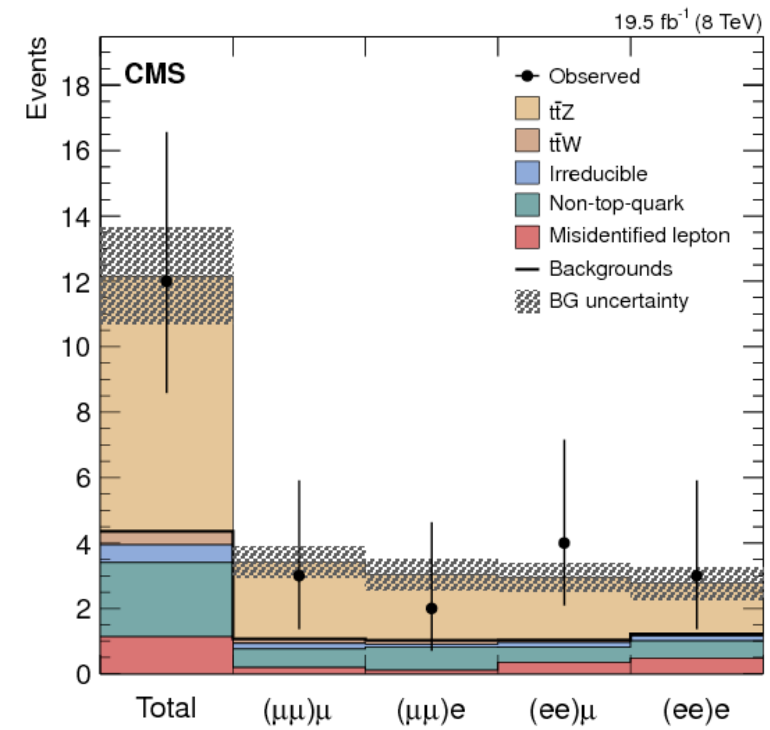
CMS — Eur. Phys. J. C74 (2014) 3060

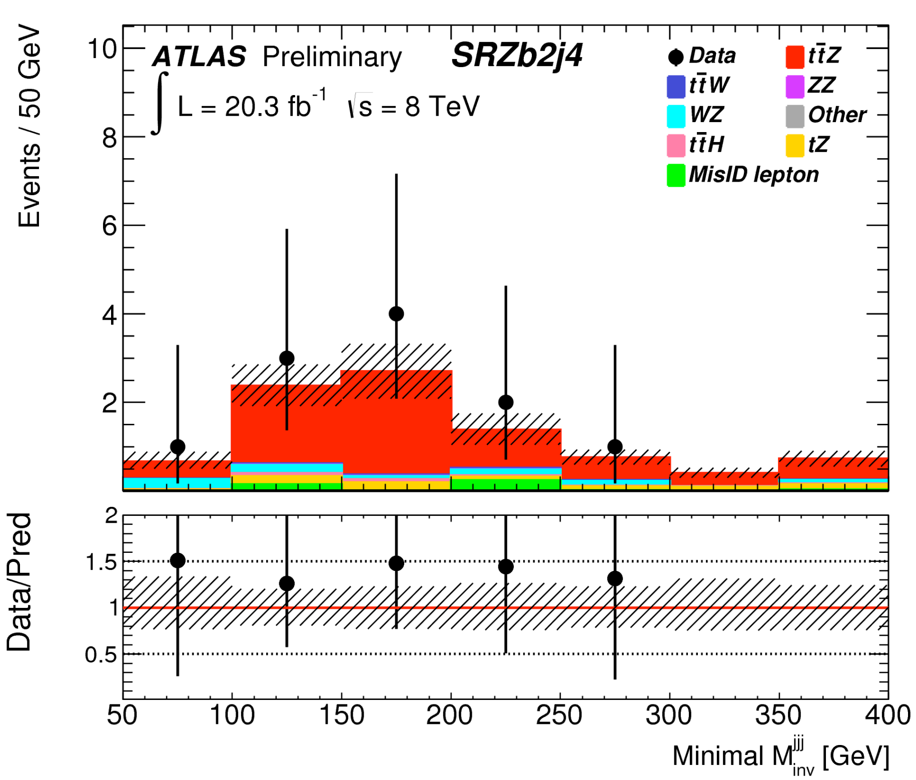
	ATLAS 3lZ	ATLAS 3lZveto	CMS 3lZ
Z-mass window cut (SF and OS)	< 10 GeV	> 10 GeV	< 10 GeV
Leptons	p_T > 15 GeV (except leading p_T > 25 GeV); 3rd leading electron p_T> 20 GeV	p_T > 15 GeV (except leading p_T > 25 GeV); 3rd leading electron p_T>25 GeV	p_T > 20 GeV relative iso < 0.09 (0.10) for electrons (muons)
Jets	p_T > 25 GeV	p_T > 25 GeV	≥ 3 jets with p_T > 30 GeV 4th jet p_T > 15 GeV
Btagging	70% WP	70% WP	≥ 1 *medium* btagged-jet (70% WP) and ≥ 1 *loose* btagged-jet (85% WP)
Signal	$t\bar{t}Z$ dominated	$t\bar{t}W$ dominated	$t\bar{t}Z$ dominated
Main background	tZ, WZ, fakes	$t\bar{t}Z$, $t\bar{t}H$, fakes	tZ, WZ, fakes
Fit channels (Signal Region)	4jin, 1bjex (SRB1J4) 3jex, 2bjin (SRB2J3) 4jin, 2bjin (SRB2J4)	2jex+3jex, 2bjin (SRW3l)	4jin, 2bjin

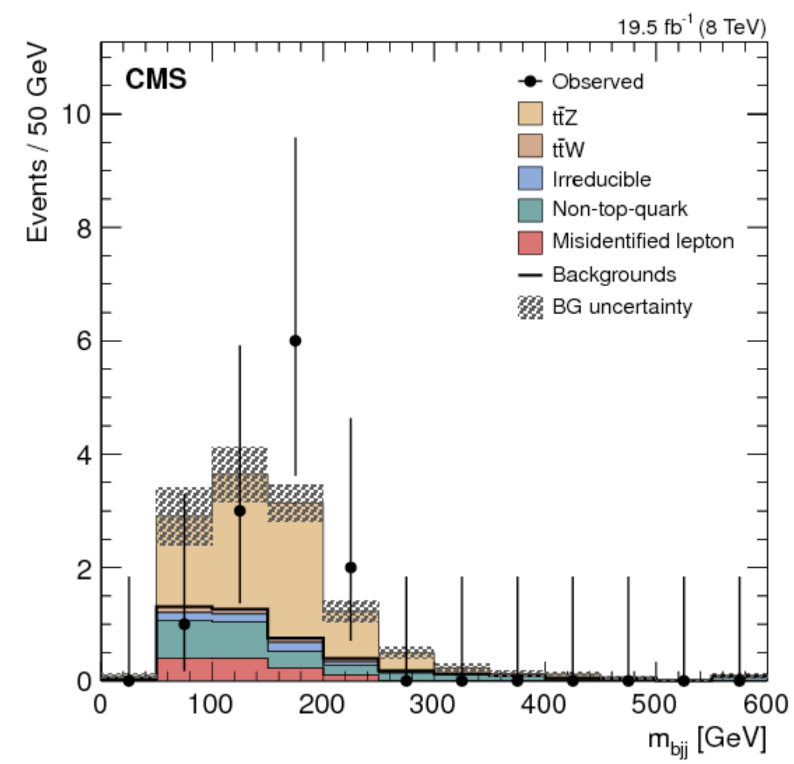
Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Trilepton channel









Same-sign dilepton channel

ATLAS — ATLAS-CONF-2014-038

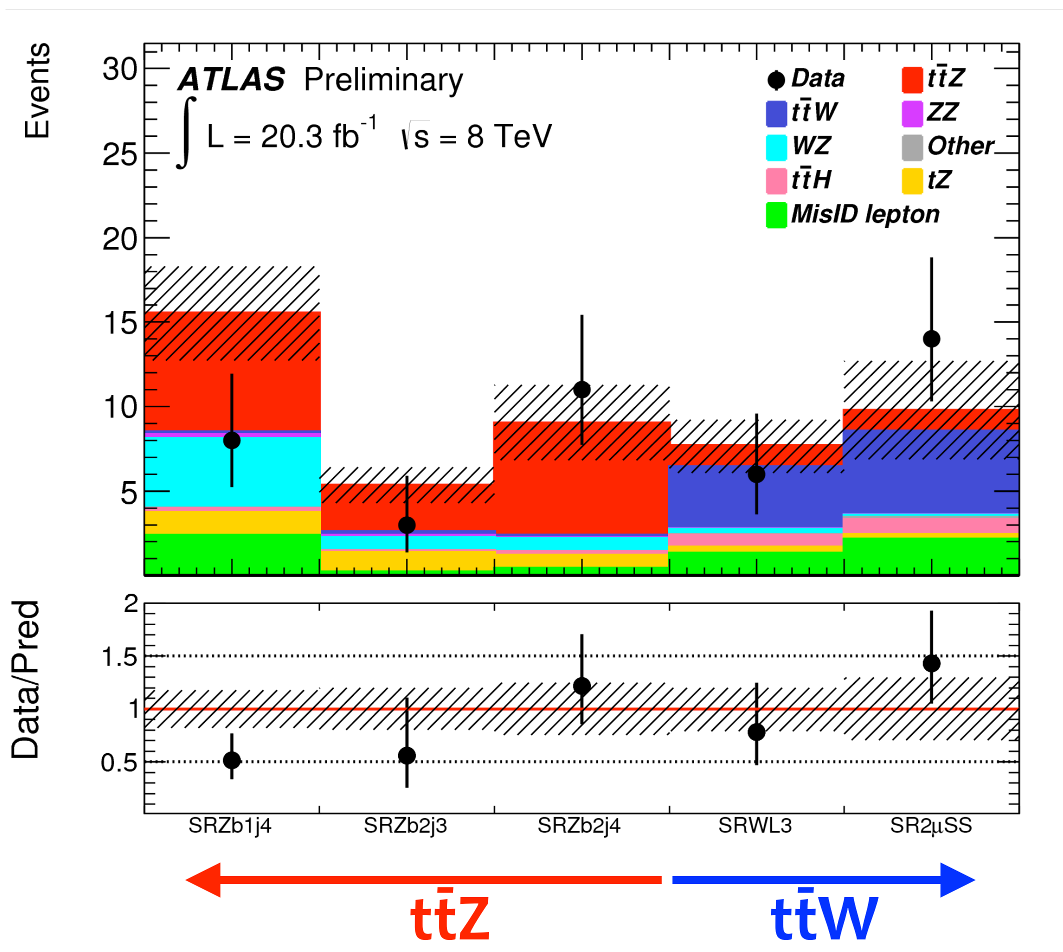
CMS — Eur. Phys. J. C74 (2014) 3060

	ATLAS 2μ	CMS 2l SS
Lepton channels (same charge)	μμ	ee, eμ, μμ split into charge (# $t\bar{t}W$+ > # $t\bar{t}W$-)
Additional cuts	H_T > 240 GeV ETmiss > 40 GeV	H_T > 155 GeV
Leptons	p_T > 25 GeV	p_T > 40 GeV **including events with 3 leptons passing the Z-boson veto (15 GeV)**
Jets	p_T > 25 GeV	p_T > 30 GeV
Btagging	70% WP	70% WP
Signal	$t\bar{t}W$ dominated	$t\bar{t}W$ dominated
Main background	lepton misidentification	lepton and charge misidentification
Fit channels (Signal Region)	**2bjin, 2jin (SR2μSS)**	**3jin, 1bjin (6 SR: charge and flavour leptons)**

Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

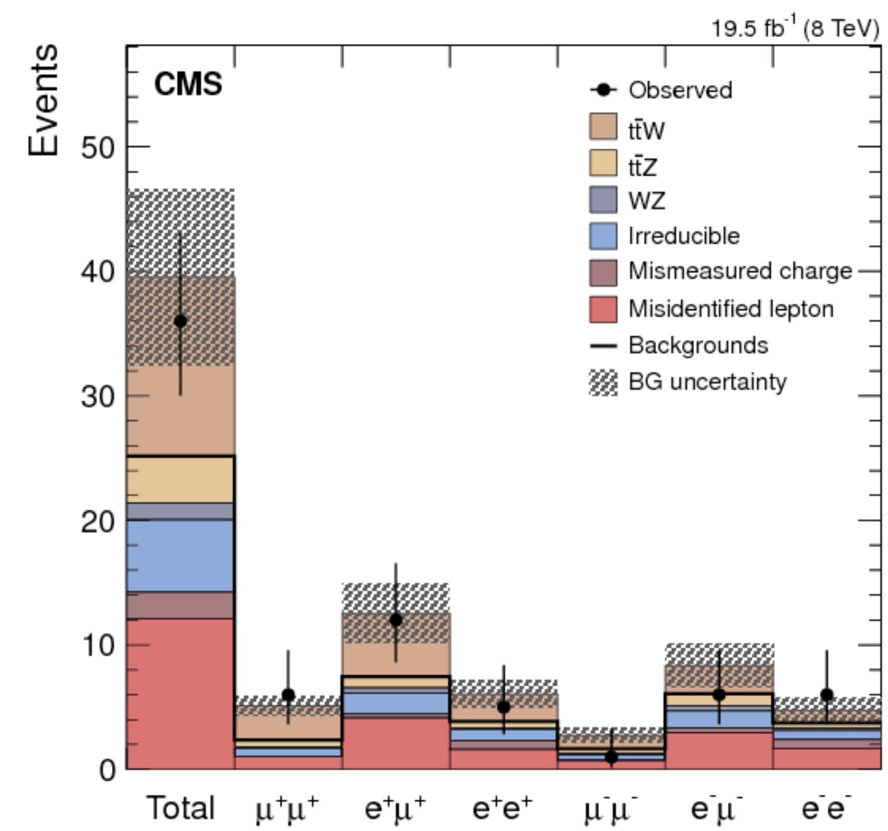
Same-sign dilepton channel

ATLAS



significance obs (exp) 3l+2μSS:
$t\bar{t}Z$: 2.8 (3.4)
$t\bar{t}W$: 3.0 (2.3)

CMS



significance obs (exp) 3l:
$t\bar{t}Z$: 2.3 (2.4)
significance obs (exp) 2lSS:
$t\bar{t}W$: 1.6 (2.0)

Additional channels

ATLAS

ATLAS-CONF-2014-038

Opposite-sign dilepton channel

	2lOSZveto	2lOSZ
Lepton channels (opposite charge)	ee, eμ, μμ	ee and μμ
Z-mass window	> 10 GeV	< 10 GeV
Additional cuts	HT > 130 GeV (eμ) ETmiss > 40 GeV (ee, μμ) ΔR(jj)ave > 0.75	ΔR(jj)ave > 0.75
Leptons	leading lepton pT > 25 GeV second leading pT > 15 GeV	
Jets	pT > 25 GeV	
Btagging	70% WP	
Signal	mix of $t\bar{t}Z$ and $t\bar{t}W$	$t\bar{t}Z$ dominated
Main background	$t\bar{t}$+jets	Z+jets
Fit channels (Signal Region, Control Region)	**3jex, 1+2bjex** **4jex, 1+2bjex** **5jin, 1+2bjex**	**3jex, 2bjex** **4jex, 2bjex** **5jin, 2bjex**

CMS

Eur. Phys. J. C74 (2014) 3060

Four lepton channel

	4l
Z-mass window	2 OS SF leptons: <15 GeV other 2 leptons **NOT** SF with Z-window <15 GeV
Leptons	leading lepton pT>20 GeV others pT> 10 GeV
Jets	pT > 30 GeV
Btagging	≥ 1 *medium* btagged-jet (70% WP) and ≥ 1 *loose* btagged-jet (85% WP)
Signal	$t\bar{t}Z$ dominated
Main background	ZZ, misidentified leptons
Fit channels (Signal Region)	**2bjex (1 tight + 1 loose)** **1bjex (1 tight + no loose)**

Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Opposite-sign dilepton channel — ATLAS

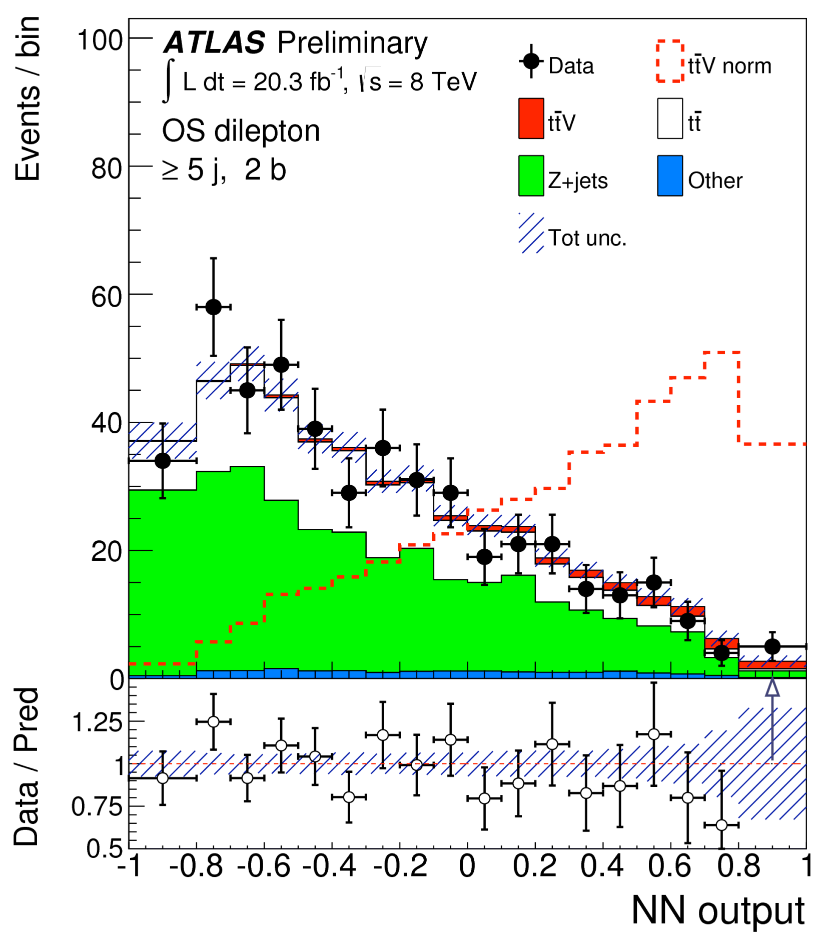
Four lepton channel — CMS

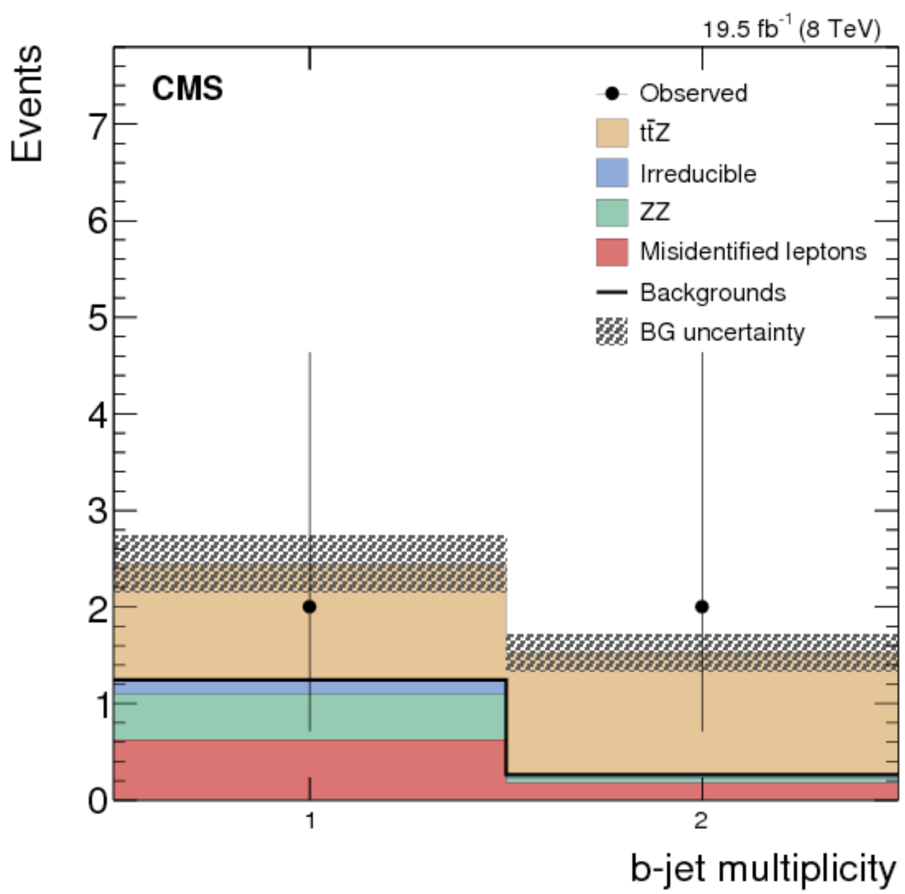
CONTROL REGION

SIGNAL REGION

	1+2bjex	2bjex
3jex	normalisation	HTj
4jex	NN	HTj
5jin	NN	NN

The only multivariate analysis!





significance obs (exp) 2lOS:
$t\bar{t}Z$: 1.4 (1.5)
$t\bar{t}W$: 0.3 (0.4)

significance obs (exp) 4l:
$t\bar{t}Z$: 2.2 (2.0)

Results 8 TeV

Combine 11 channels **ATLAS** ATLAS-CONF-2014-038

[binned profile likelihood fit]

Combine 9 channels **CMS** Eur. Phys. J. C74 (2014) 3060

1 POI

	observed μ	observed	expected
$t\bar{t}W$	1.25 + 0.57 - 0.48	3.1	2.4
$t\bar{t}Z$	0.73 + 0.29 - 0.26	3.2	3.8
$t\bar{t}V=t\bar{t}Z+t\bar{t}W$	0.89 + 0.23 - 0.22	4.9	4.9

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
$3\ell+4\ell$	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
$2\ell+3\ell+4\ell$	$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

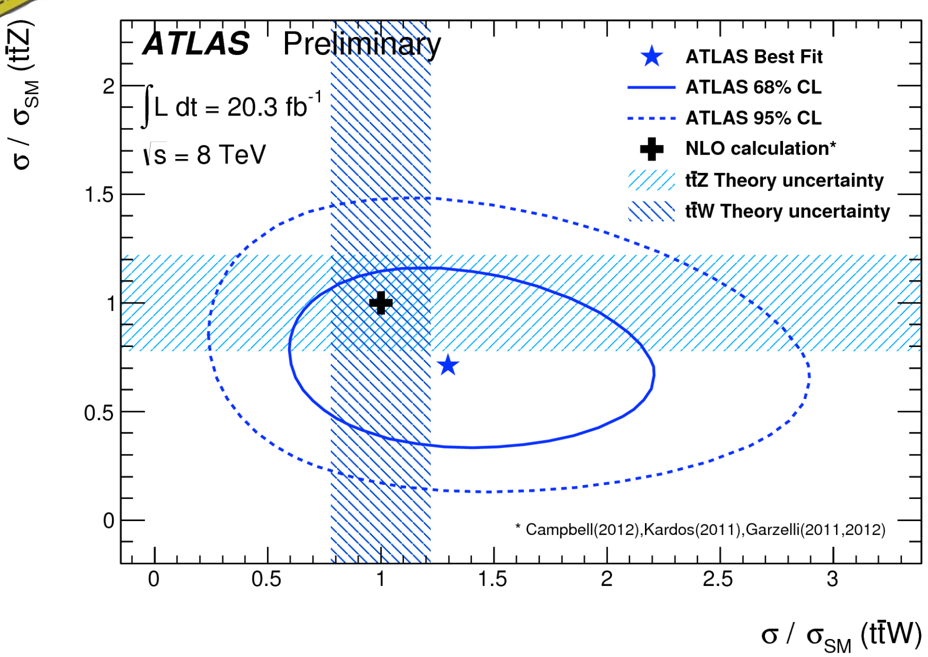
2 POI

Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) ± 21(syst.) fb	3.1	3.7
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1	2.3

Channels used	$t\bar{t}W$ cross section	$t\bar{t}Z$ cross section
$2\ell+3\ell+4\ell$	170^{+110}_{-100} (total) fb	200 $\pm$ 90 (total) fb

EVIDENCE

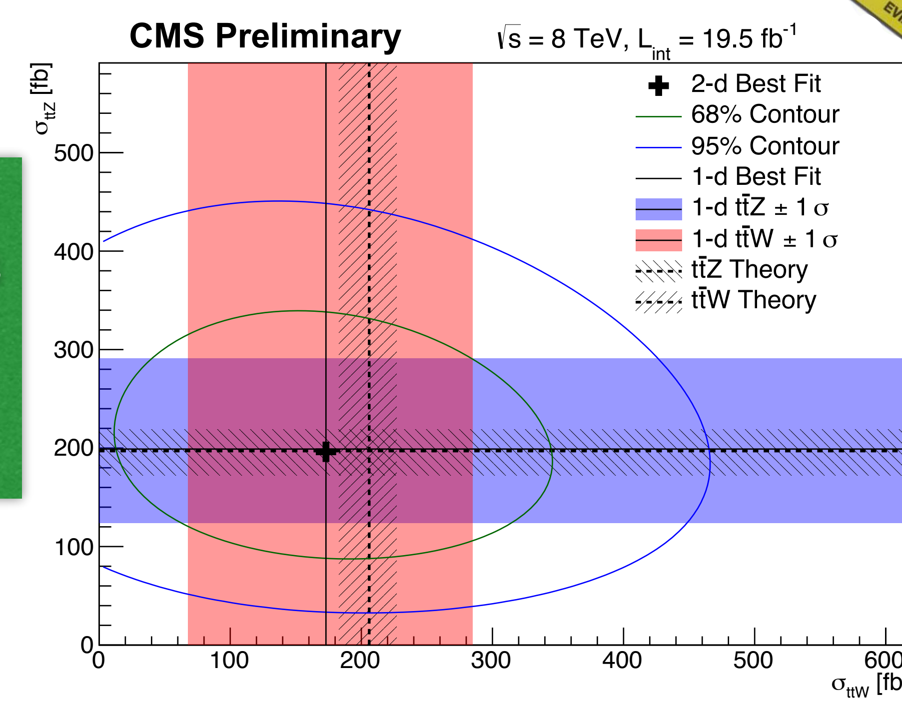
Evidence for $t\bar{t}Z$ and $t\bar{t}W$!



statistically limited measurements

very small correlation between $t\bar{t}Z$ and $t\bar{t}W$!

Evidence for $t\bar{t}Z$!



NLO QCD cross-sections: σ(ttZ) = 206 ± 45 fb [1] and σ($t\bar{t}W$) = 232 ± 51 fb [2]

[1] J. M. Campbell and R. K. Ellis, tt̄W production and decay at NLO, JHEP07(2012)052
[2] M. V. Garzelli, A. Kardos, C. G. Papadopoulos, and Z. Trocsanyi, JHEP11(2012)056.

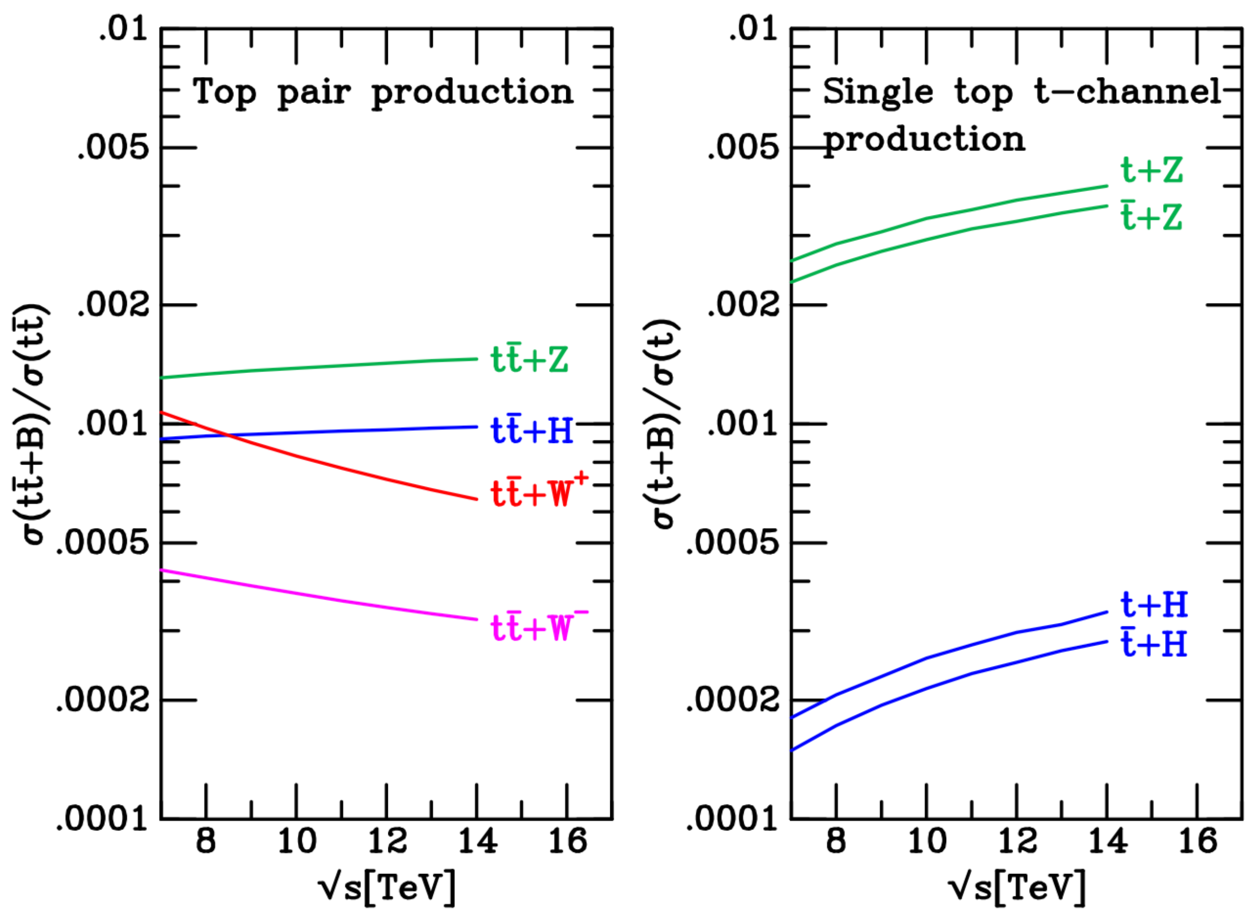
NLO QCD cross-section: σ($t\bar{t}Z$) = 197 +22 -25 fb and σ($t\bar{t}W$) = 206 +21 -23 fb calculated with MADGRAPH5_aMC@NLO

Conclusions

- ~20 years after discovery of the top, we start to have enough top pairs to explore the top+γ/Z/W couplings (via production rate / top decay Wtb vertex)

- Evidence for $t\bar{t}Z$ and $t\bar{t}W$ at $\sqrt{s}$=8 TeV !
- Wtb coupling via precision $t\bar{t}$/single top measurements

- No deviations from the SM predictions with current precision



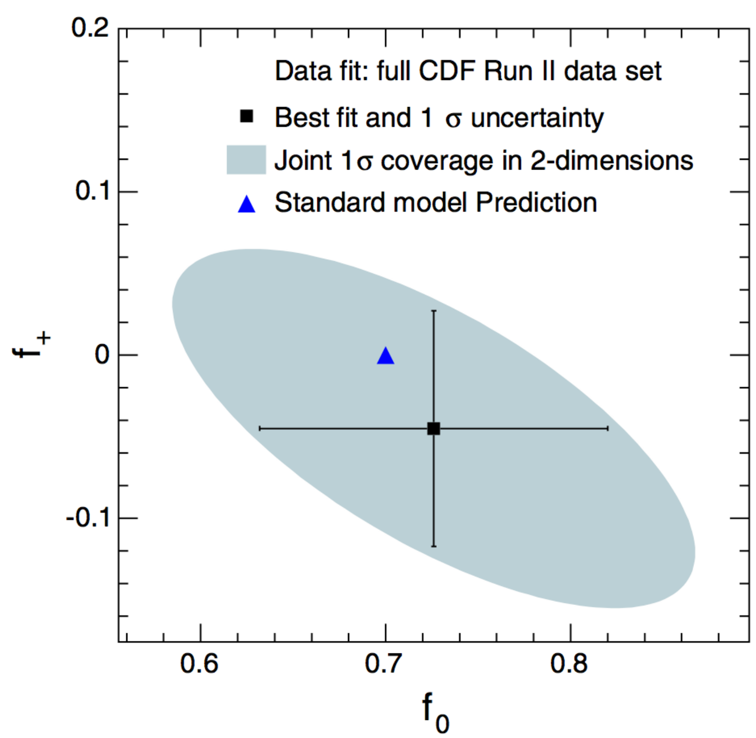
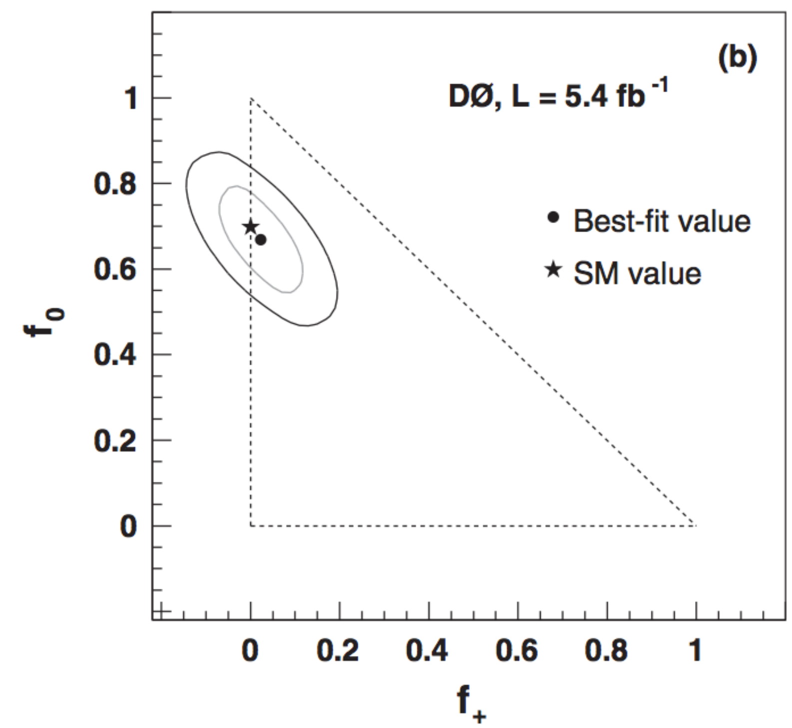
arXiv:1309.1947 [hep-ex]

- Top-EW coupling measurement is a long term project: high luminosity & high $\sqrt{s}$

JUST THE BEGINNING!

Backup

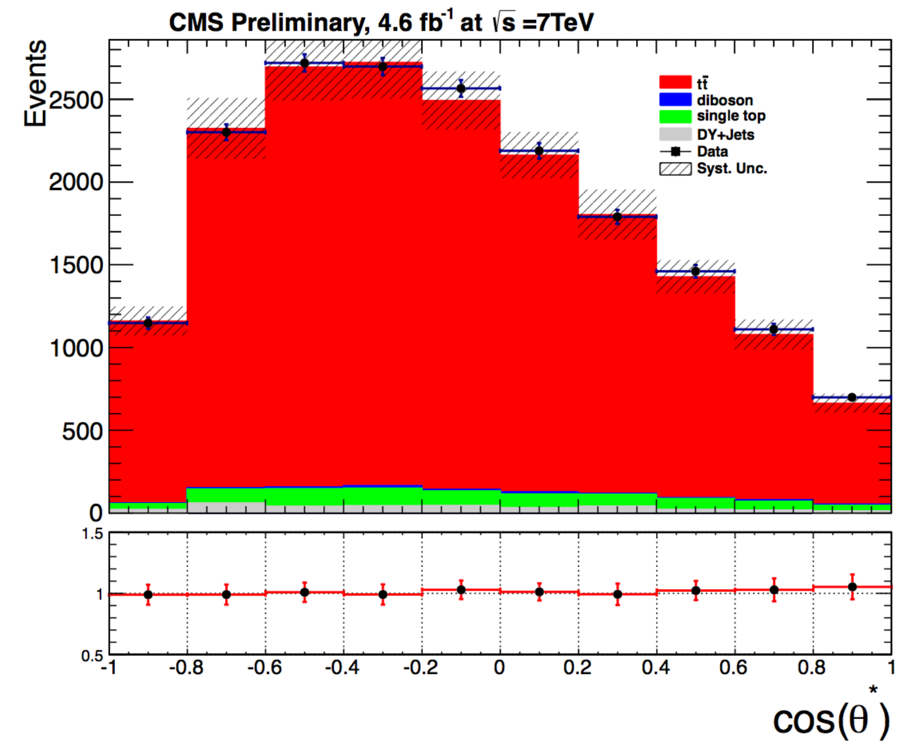
W-helicity

	CDF	Do
	Phys. Rev. D 87, 031104(R)	Phys. Rev. D 83, 032009
√s, lumi	1.96 TeV, (full dataset) 8.7 fb-1	1.96 TeV, 5.4 fb-1
Channels	l+jets	l+jets, dilepton
Results	(matrix element method)  $\rho(F0,FR) = -0.69$	(template method)  $\rho(F0,FR) = -0.83$

consistent with the SM expectations

W-helicity

	CMS
	JHEP 10 (2013) 167
√s, lumi	**7 TeV**, (full dataset) 5.0 fb-1
Channels	l+jets



- Reweighting method
- Variable cosθ*
- 3D fit (Signal normalisation $F_{t\bar{t}}$, F_0, F_L):

To account for these effects a reweighting technique is applied, with a weight function $W(\cos\theta^*_{rec};\vec{F})$ defined as:

$$W(\cos\theta^*_{gen};\vec{F}) = \frac{\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2} \quad (2)$$

where $F^{SM}_{L,R,0}$ are the SM helicity fractions and $F_{L,R,0}$ are the helicity fractions which are to be measured, and $\cos\theta^*_{gen}$ is the angular distribution at the generator level.

The $\cos\theta^*_{rec}$ distribution at the reconstructed level can be obtained :

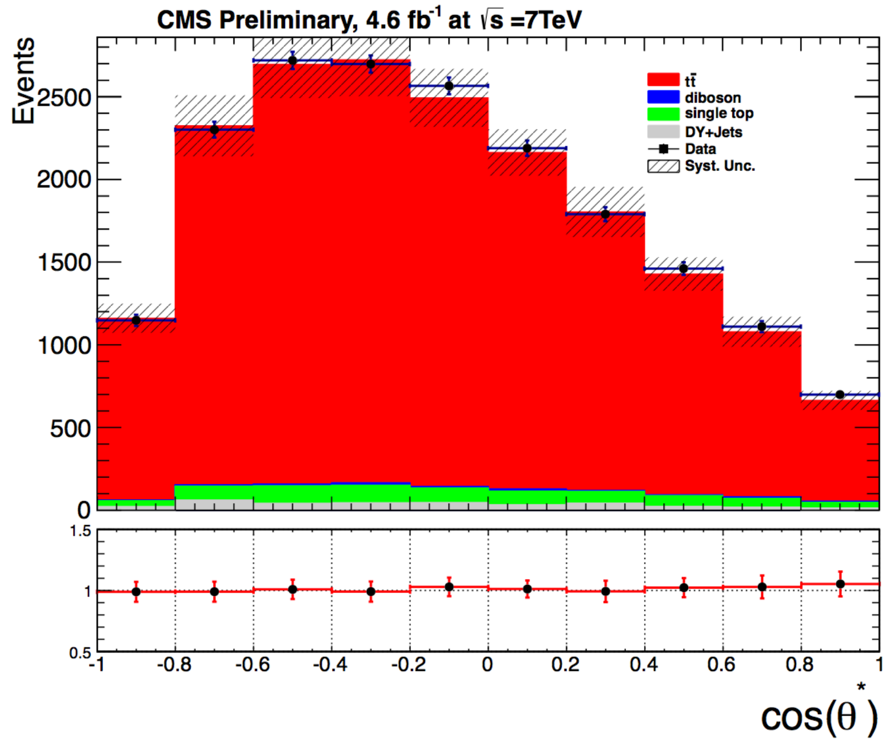
$$\rho(\cos\theta^*_{rec}) = \frac{1}{N}\frac{dN}{d\cos\theta^*_{rec}} = \int R(\cos\theta^*_{rec},\cos\theta^*_{gen})W(\cos\theta^*_{gen})\rho^{SM}(\cos\theta^*_{gen})d\cos\theta^*_{gen} \quad (3)$$

where $R(\cos\theta^*_{rec},\cos\theta^*_{gen})$ is the response matrix relating the generator level angular distribution $(\cos\theta^*_{gen})$ to the recosntructed level angular distribution $(\cos\theta^*_{rec})$. The response matrix

W-helicity

	CMS
	JHEP 10 (2013) 167
√s, lumi	**7 TeV**, (full dataset) 5.0 fb-1
Channels	l+jets

- Reweighting method
- Variable cosθ*
- 3D fit (Signal normalisation $F_{t\bar{t}}$, F_0, F_L):



$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!} exp(-N_{MC}(i;\vec{F}))$$

$$\begin{aligned}
N_{MC}(i;\vec{F}) &= N_{t\bar{t}}(i;\vec{F}) + N_{BKG}(i) \\
N_{t\bar{t}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}}[\sum_{t\bar{t}\ events,bin\ i} W(\cos\theta^*_{gen};\vec{F})] \\
N_{BKG}(i) &= N_{DY}(i) + N_{W+jets}(i) + N_{di-bosons}(i) + N_{single\ top}(i).
\end{aligned}$$

Systematic Source	$\pm\Delta F_L$	$\pm\Delta F_0$
Top QScale	0.027	0.051
Top Mass	0.016	0.003
WZ QScale	0.013	0.026
DY normalization	0.009	0.014
W normalization	0.000	0.002
SingleTopTW normalization	0.002	0.008
JES	0.010	0.006
Pile-up	0.014	0.017
PDF	0.004	0.005
Total	0.040	0.063

Table 2: Summary of the systematic uncertainties for combined channels.

W-helicity

	CMS
	CMS PAS TOP-13-008
√s, lumi	**8 TeV**, (full dataset) 19.6 fb-1
Channels	μ+jets

- Reweighting method
- Variable cosθ*
- 3D fit (Signal normalisation $F_{t\bar{t}}$, F_0, F_L):

Systematics	$\pm\,\Delta F_0$	$\pm\,\Delta F_L$
JES	0.002	$<$0.001
JER	0.004	0.003
Lepton eff.	0.001	$<$0.001
b-tag eff.	0.001	$<$0.001
Pileup	$<$0.001	0.001
Single-t bkg.	0.002	$<$0.001
DY+jets bkg.	0.001	$<$0.001
W+jets bkg.	0.009	$<$0.001
MC statistics	0.003	0.002
Top-quark mass	0.012	0.008
$t\bar{t}$ scales	0.012	0.012
$t\bar{t}$ match. scale	0.012	0.008
$t\bar{t}$ p_T reweig.	0.001	$<$0.001
E_T^{miss} shape	0.004	0.018
Total syst.	0.023	0.024

From Nadjieh's talk

	Theory PRD 83 (2011)	ATLAS 4.6 fb^{-1} 1406.7844v1	CMS 1.14 fb^{-1} JHEP12(2012) 035
σ (t-chan)	64.6 ± 3.4 pb	68 ± 8 pb	67.2 ± 6.1 pb

7 TeV

ATLAS: $|V_{tb}| = 1.02 \pm 0.07$

$|V_{tb}| < 1$ ➡ $0.88 < |V_{tb}| <= 1$ @ 95% C.L.

CMS: $|V_{tb}| = 1.020 \pm 0.049$

$|V_{tb}| < 1$ ➡ $0.92 < |V_{tb}| <= 1$ @ 95% C.L.

$m_t = 172.5$ GeV

7

t-channel

(full dataset) 8 TeV

ATLAS-CONF-2014-007

$|V_{tb}| = 0.97^{+0.09}_{-0.1}$

Assuming $m_t = 172.5$ GeV

8TeV (19.7 fb^{-1}) NEW

JHEP06(2014)090

With $|V_{tb}| \gg |V_{ts}|, |V_{td}|$

$|f_V^L V_{tb}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{th.})$

4.1 %

7 ⊕ 8

PDG: **0.89 ± 0.07**

$|V_{tb}| \gg |V_{td}|, |V_{ts}|$

$\mathcal{B}(t \to b + W) = 1$

$|f_{\mathrm{Lv}} V_{\mathrm{tb}}| = \sqrt{\sigma_{t\text{-ch.}} / \sigma^{\text{theo.}}_{t\text{-ch.}}}$

Single Top Vtb (2)

From Nadjieh's talk

$|V_{tb}|$: 1.03 ± 0.12(exp.) ± 0.04(th.) $(|V_{tb}| \gg |V_{ts}|, |V_{td}|)$

Constrained $|V_{tb}| < 1$: $|V_{tb}| > 0.78$ @95% C.L.

Phys. Rev. Lett. 112

8 TeV, 12.2 fb^{-1}

ATLAS-CONF-2013-100

8 TeV, 20.3 fb^{-1}

With $|V_{tb}| \gg |V_{ts}|, |V_{td}|$:
$|f_V^L V_{tb}|$: 1.10 ± 0.12(exp.) ± 0.03(th.)

Constrained $|f_V^L| = 1$: $|V_{tb}| > 0.72$ @95% C.L.

Wt-channel

- **$|f_V^L V_{tb}|$:** 1.06 ± 0.11
- **Constrained $|f_V^L| = 1$ & $|V_{tb}| \leq 1$:** $|V_{tb}| > 0.79$ @95% C.L.

10.4 %

LHC combined (Sep. 2014)
ATLAS-CONF-2014-052,
CMS-PAS-TOP-14-009

COMBINATION
8 TeV

Single Top Vtb (3)

From Manfredi's talk

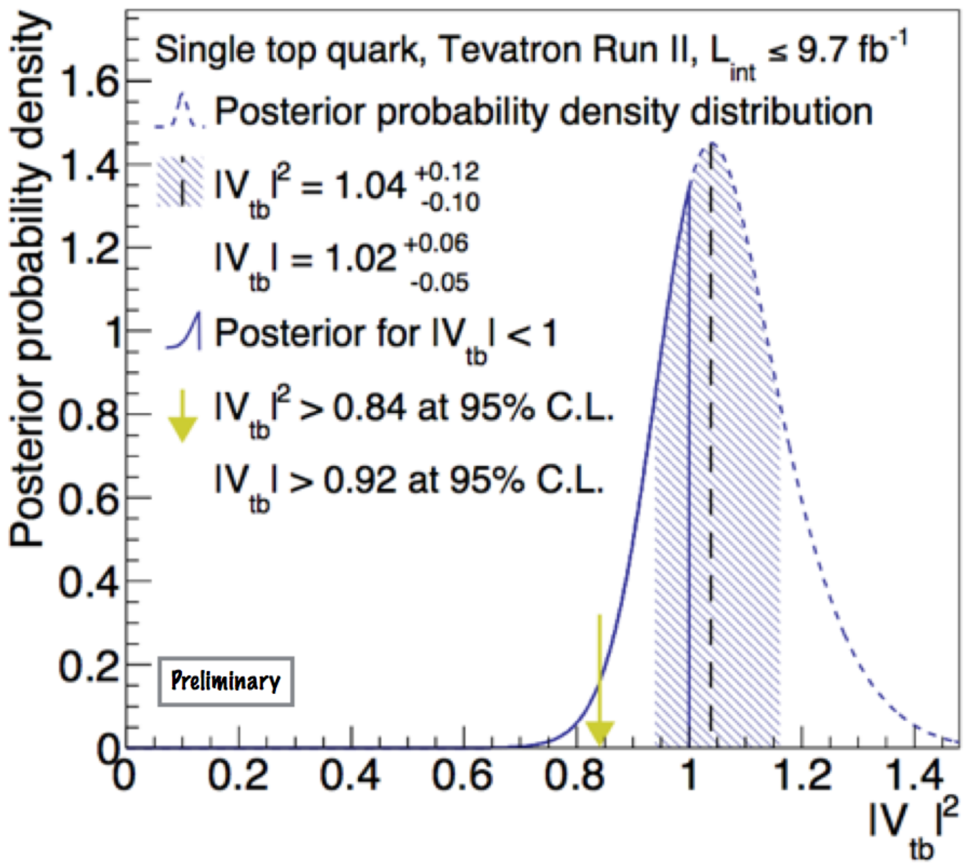
$|V_{tb}| > 0.84$ at 95% C.L.

$|V_{tb}| > 0.92$ at 95% CL

CDF note 110

DØ PLB 726, 656 (2013)

t+s channel combination



Tevatron combination

$|V_{tb}| > 0.92$ at 95% C.L.

$|V_{tb}| = 1.02^{+0.06}_{-0.05}$ 5.3 %

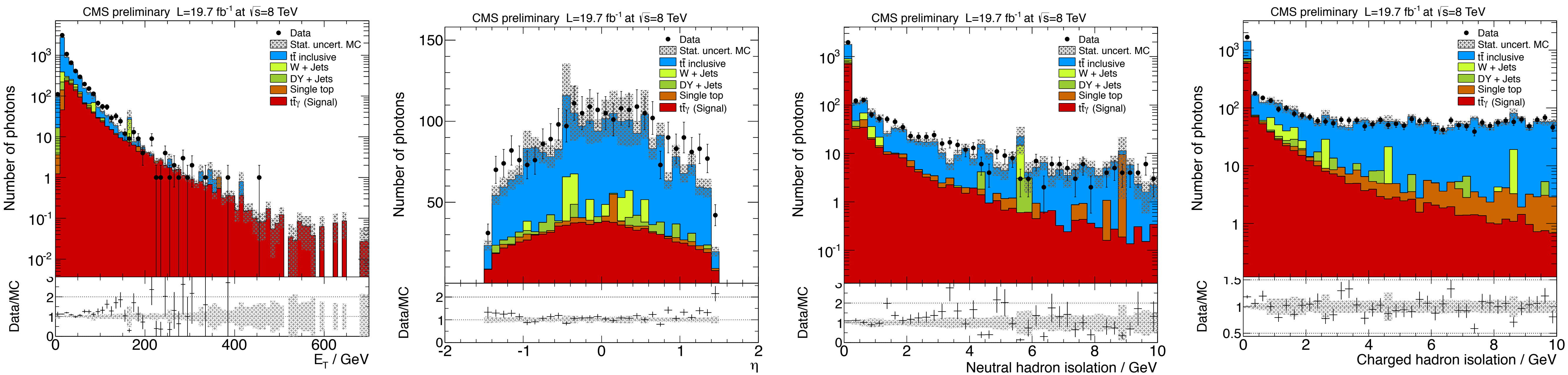
Fermilab-CONF-14-370-E

Measurements $t\bar{t}\gamma$ @ 8 TeV

	CMS
	CMS-PAS-TOP-13-011
√s, lumi	8 TeV, 19.7 fb-1
Channels	μ+jets

Selection

preselection: 1 isolated central muon with pT > 26 GeV
≥4 jets with pT > 55, 45, 35, 20 GeV (≥1 b-tagged jet)
veto on extra leptons
Additional selection $t\bar{t}\gamma$: ≥1 good central photon with ET>25 GeV
ΔR (photon, muon/jet) > 0.7



Some observables used in the photon selection

	CMS
	CMS-PAS-TOP-13-011
√s, lumi	8 TeV, 19.7 fb-1
Channels	μ+jets

Selection

preselection: 1 isolated central muon with pT > 26 GeV
≥4 jets with pT > 55, 45, 35, 20 GeV (≥1 b-tagged jet)
veto on extra leptons
Additional selection tt̄γ: ≥1 good central photon with ET>25 GeV
ΔR (photon, muon/jet) > 0.7

$$R \equiv \frac{\sigma_{t\bar{t}+\gamma}}{1} \cdot \frac{1}{\sigma_{t\bar{t}}} \equiv \frac{R^{\mathrm{vis}}}{\epsilon_\gamma^{\mathrm{vis}}} = \frac{N^{\mathrm{sig}}_{t\bar{t}+\gamma}}{\epsilon_\gamma^{\mathrm{vis}}\ \epsilon_\gamma} \cdot \frac{1}{N^{\mathrm{presel}}\ \pi_{t\bar{t}}},$$

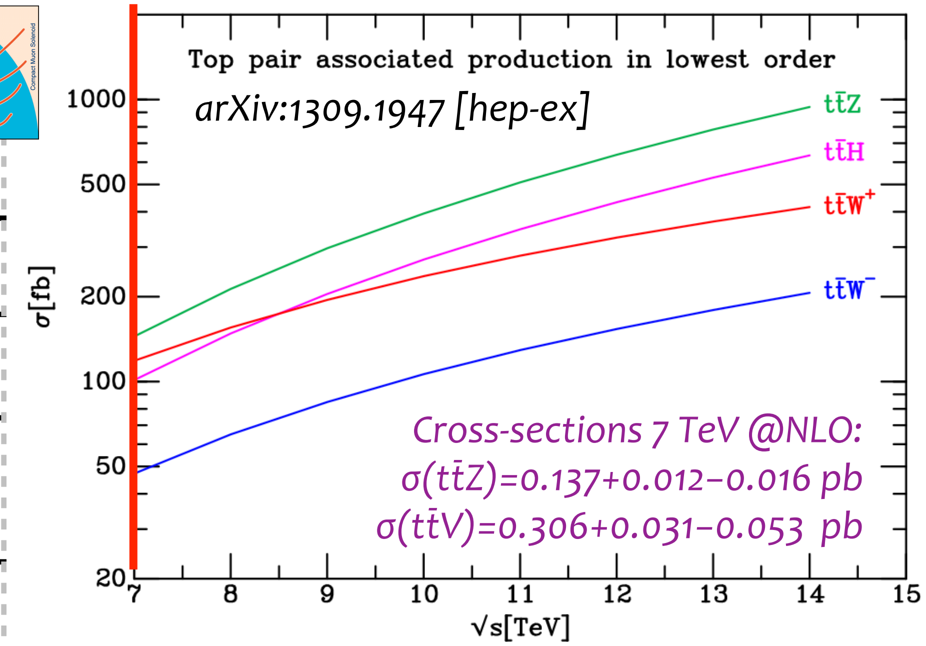
$$\pi_{t\bar{t}} = N^{presel}_{t\bar{t}} / N^{presel} = 84.3\,\%,$$

$$\epsilon_\gamma^{\mathrm{vis}} = N^{vis}_{t\bar{t}+\gamma} / N^{presel}_{t\bar{t}+\gamma} = 80.6\,\%,$$

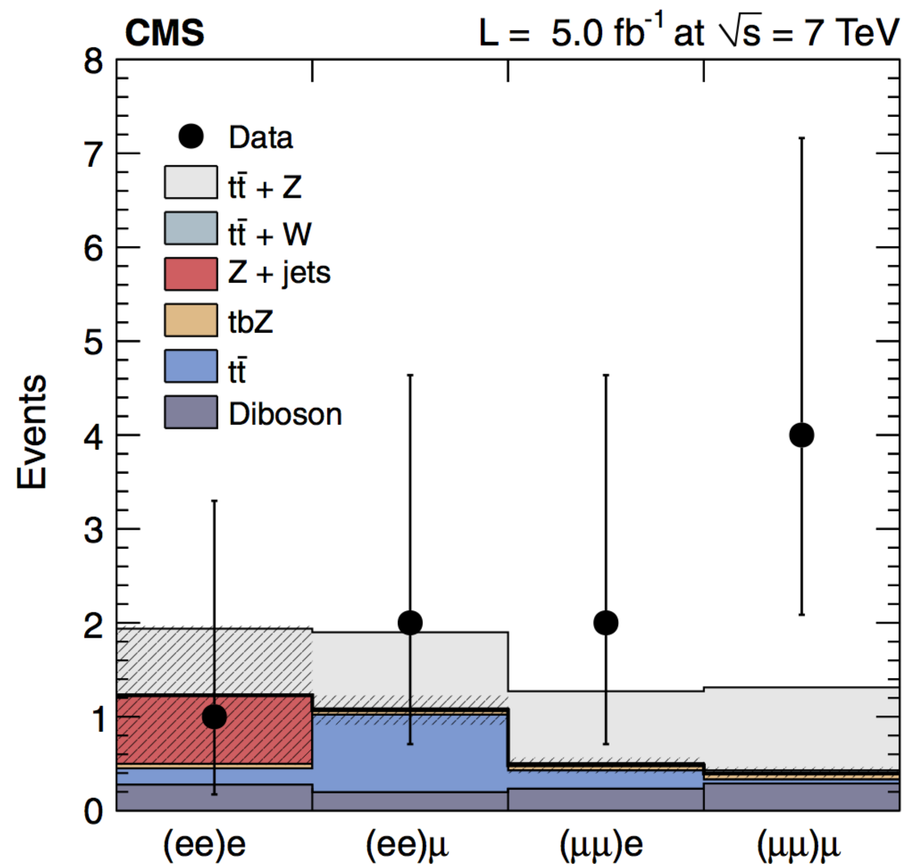
$$\epsilon_\gamma = N^{sel}_{t\bar{t}+\gamma} / N^{vis}_{t\bar{t}+\gamma} = 62.9\,\%.$$

Measurements/Searches at 7 TeV

	ATLAS	CMS	
	ATLAS-CONF-2012-126	Phys. Rev. Lett. 110, 172002	
√s, lumi	7 TeV, 4.7 fb-1	7 TeV, 5.0 fb-1	
Channels	trilepton	trilepton + same-sign dilepton	
Results	σ(tt̄Z) < 0.71 pb @ 95% CL	3l	$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\,(\text{stat})^{+0.06}_{-0.03}\,(\text{syst})$ pb **significance = 3.3 σ**
		2lSS	$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})$ pb significance = 3.0 σ



J.M. Campbell and R.K. Ellis, JHEP 07 (2012) 052
M.V. Garzelli, A. Kardos, C.G. Papadopoulos, and Z. Trocsanyi, JHEP 11 (2012) 056



Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Trilepton channel

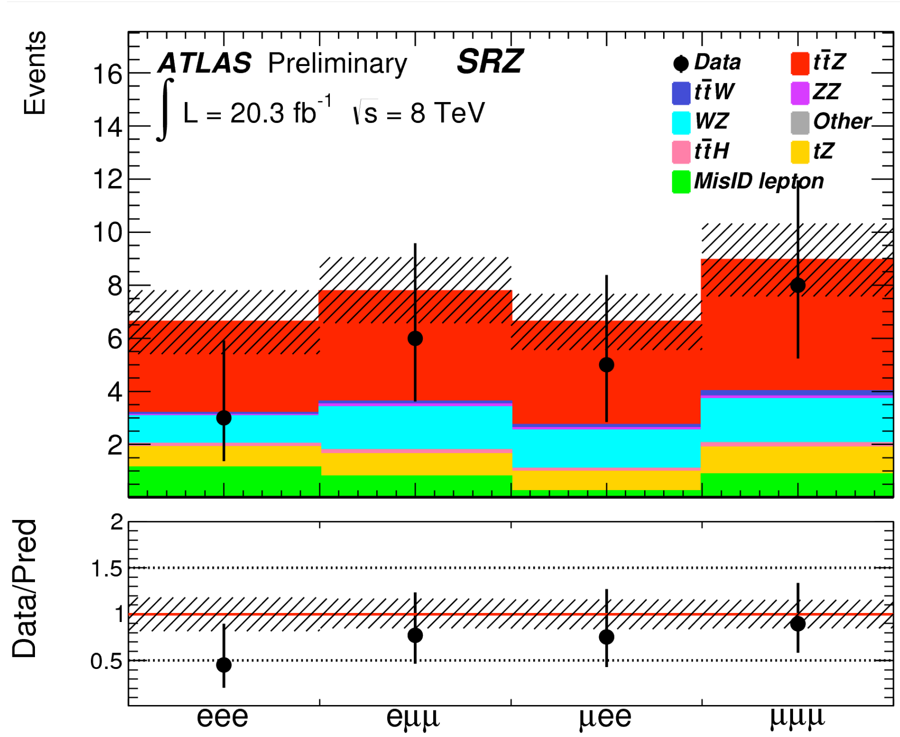
ATLAS

Simulation

- ***Irreducible component***: tqZ+tWZ (20% unc), $t\bar{t}H$ (12% unc)
- **WZ** (Sherpa with massive b,c quarks)
  - Validated in CRWZ: m_T (W) > 50 GeV
  - Uncertainty: 20% + 10% (3j→4j) + 40% (2b)

Data driven

- ***Misidentified-lepton component*** (30% uncertainty)
  - Control sample: relaxed lepton selection
  - Efficiencies for real and fake leptons: events with 2 leptons and 1 btagged jet



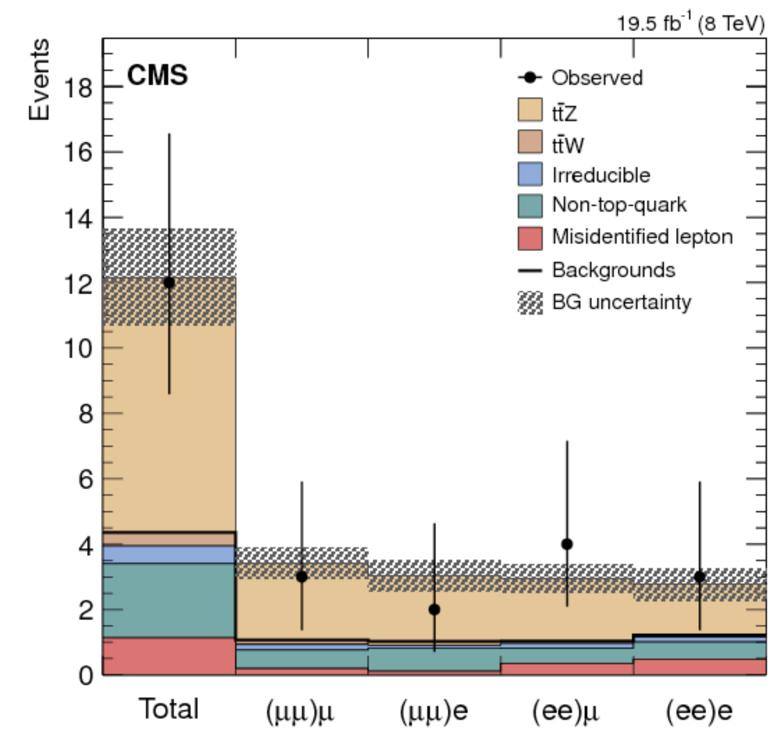
CMS

Simulation

- ***Irreducible component:*** tbZ, $t\bar{t}H$, $t\bar{t}W$ (50% unc)

Data driven

- ***Non-top quark component***: **WZ** dominated (50% unc)
  - Correction of 1.4 to WZ+HF from differences wrt Z+jets CR
- ***Misidentified-lepton component*** (main source: $t\bar{t}$) (50% unc)
  - Control sample: looser lepton requirements
  - Weight events by the "tight-to-loose" ratio (p_T and η dependent)



Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Same-sign dilepton channel

ATLAS

Simulation

- WZ, tZ, $t\bar{t}Z$
- *Irreducible component*: $t\bar{t}H$, like-sign WW

CMS

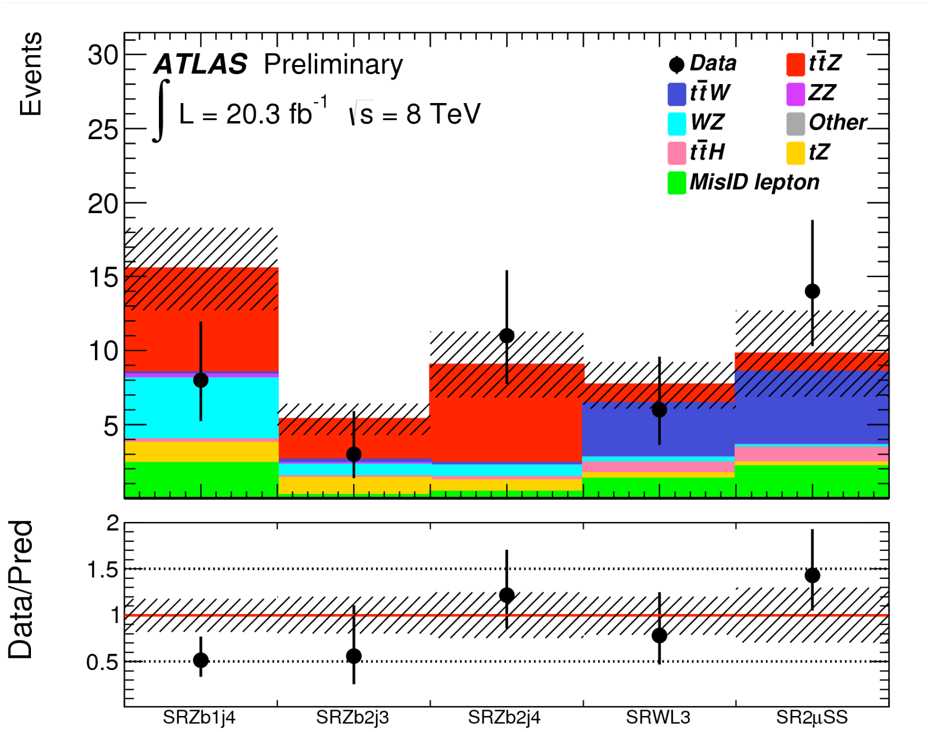
Data driven (ATLAS)

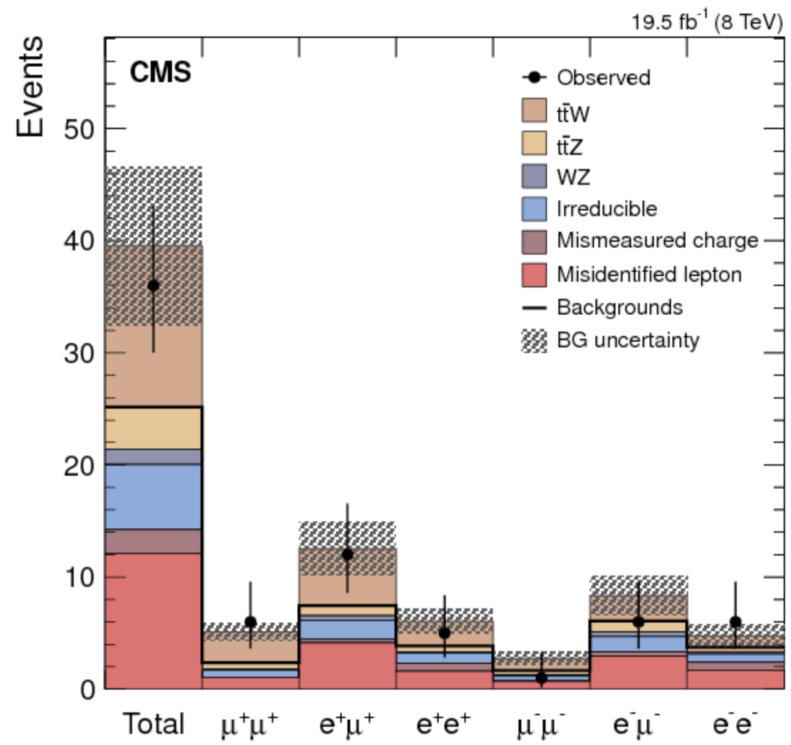
- ***Misidentified-lepton component***
  - similar to trilepton channel
- ***Mismeasured-charge component***
  - *Negligible*

significance obs (exp) 3l+2μSS:
$t\bar{t}Z$: 2.8 (3.4)
$t\bar{t}W$: 3.0 (2.3)

Data driven (CMS)

- ***Misidentified-lepton component*** (main source: $t\bar{t}$ and W+jets)
  - similar to trilepton channel
- ***Mismeasured-charge component*** - 30 (15) % unc. for ee (eμ)
  - fail same-sign requirement
  - weighting events by pT- and η-dependent probability for electron charge misassignment





significance obs (exp) 3l:
$t\bar{t}Z$: 2.3 (2.4)
significance obs (exp) 2lSS:
$t\bar{t}W$: 1.6 (2.0)

Measurements $t\bar{t}Z$ and $t\bar{t}W$ @ 8 TeV

Opposite-sign dilepton channel

ATLAS

- **$t\bar{t}$+jets** ($t\bar{t}$ and top pT correction)
- **Z+jets** (p_T(Z)-shape and Z+HF normalisation correction)

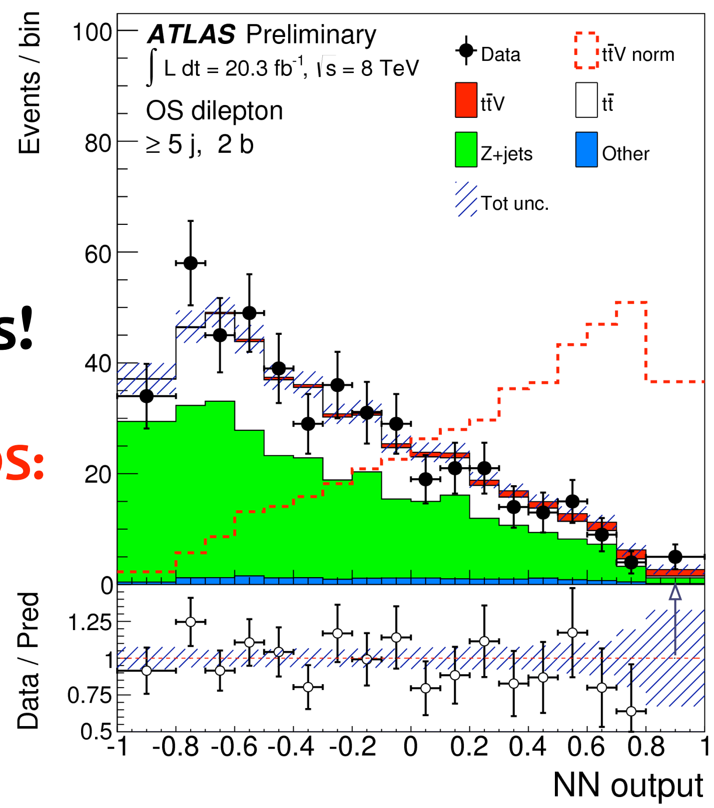
	1+2bjex	2bjex
3jex	**normalisation**	**HTj**
4jex	**NN**	**HTj**
5jin	**NN**	**NN**

CONTROL REGION

SIGNAL REGION

The only multivariate analysis!

significance obs (exp) 2lOS:
$t\bar{t}Z$: 1.4 (1.5)
$t\bar{t}W$: 0.3 (0.4)



Four lepton channel

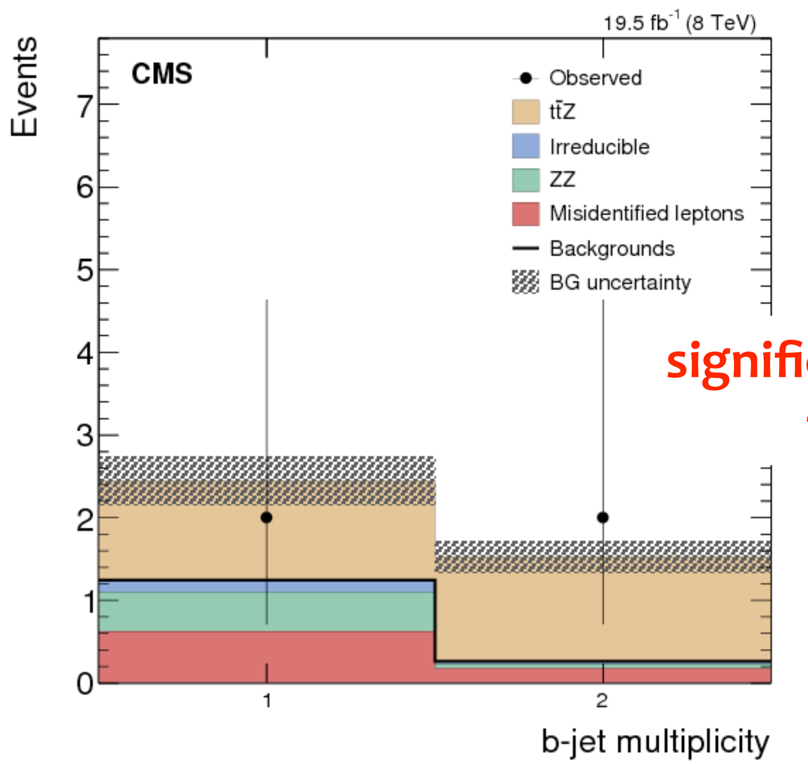
CMS

Simulation

- **ZZ** (validated in ZZ-dominated region in data)

Data driven

- ***Misidentified-lepton component***
  - *"track-to-lepton"* ratio from 2 CRs with different HF content
  - define 2 sideband regions with 3 leptons in the two btagging categorisations
  - # background events in signal region = sideband region * "track-to-lepton" ratio



significance obs (exp) 4l:
$t\bar{t}Z$: 2.2 (2.0)

Systematic uncertainties

ATLAS

	Combination	
Uncertainty	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Detector	0.07	0.13
Background from simulation	0.08	0.09
MisID lepton	0.03	0.09
Signal modelling	< 0.01	< 0.01
Total systematics	0.10	0.24
Statistics	+0.26−0.24	+0.49−0.43
Total	+0.29−0.26	+0.57−0.48

CMS

	Channels		
	2ℓ	3ℓ	4ℓ
Source of uncertainty	Uncertainty (%)		
Modelling of trigger eff.	3	1	1
Modelling of lepton sel. (ID/isolation)	4	6	8
Jet energy scale and resolution	4	5	4
Identification of b jets	2	3	3
Pileup modelling	1	1	1
Choice of parton distribution functions	1.5	1.5	1.5
Signal model	5	5	5
Total	8	10	11