Observation of ttZ and measurement of ttW at CMS

TOP LHC WG meeting
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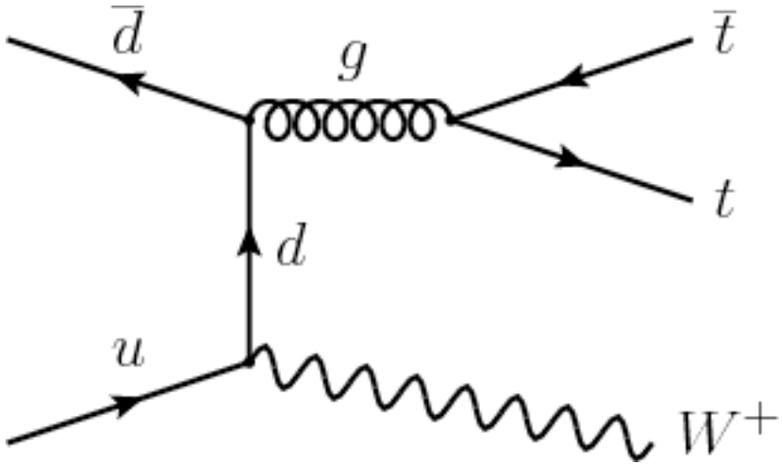
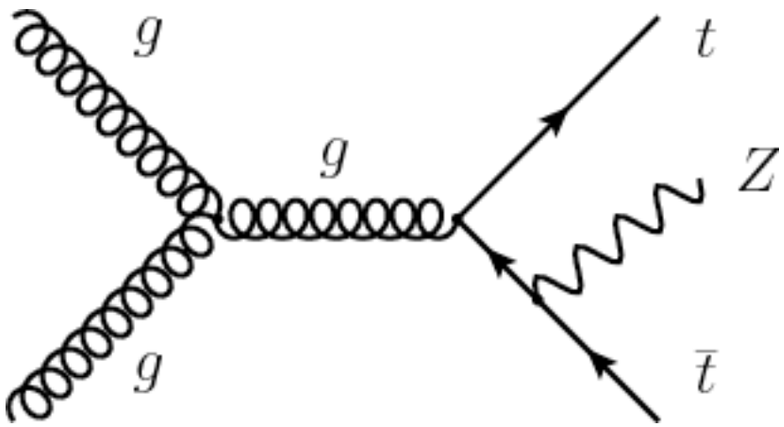
ttW and ttZ

- Rare, heavy SM processes
  - σ(ttW) = 203 fb, σ(ttZ) = 206 fb at 8 TeV
- ttZ provides best direct measurement of the top-Z coupling
- Some new physics models enhance the ttW and ttZ cross sections without affecting Higgs or top production
- ttW and ttZ are backgrounds to ttH and to many new physics processes





Tree-level ttW and ttZ production at the LHC

Previous ttW and ttZ results

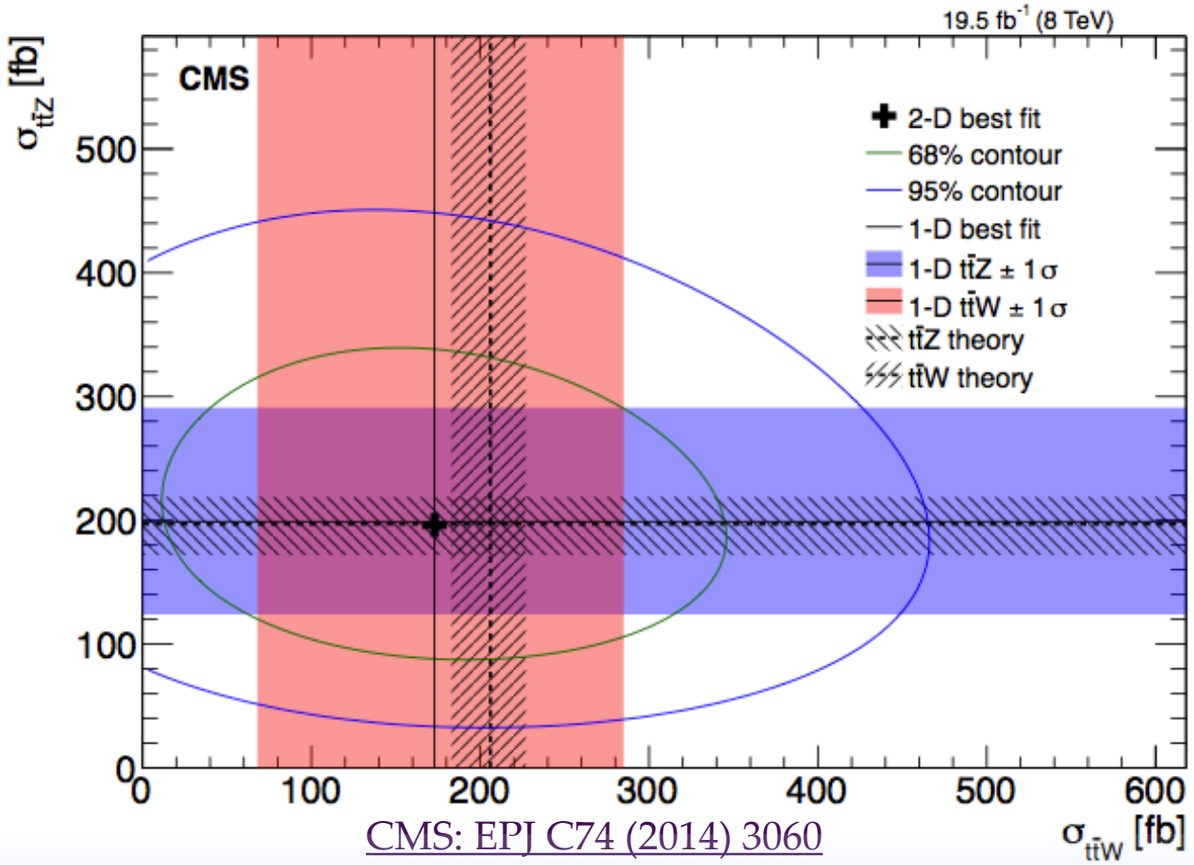
- Previous analyses by CMS and ATLAS at 7 and 8 TeV used a cut-based approach in the most sensitive channels, observed ttZ at ~3σ significance and achieved ~2σ sensitivity to ttW

CMS 8 TeV

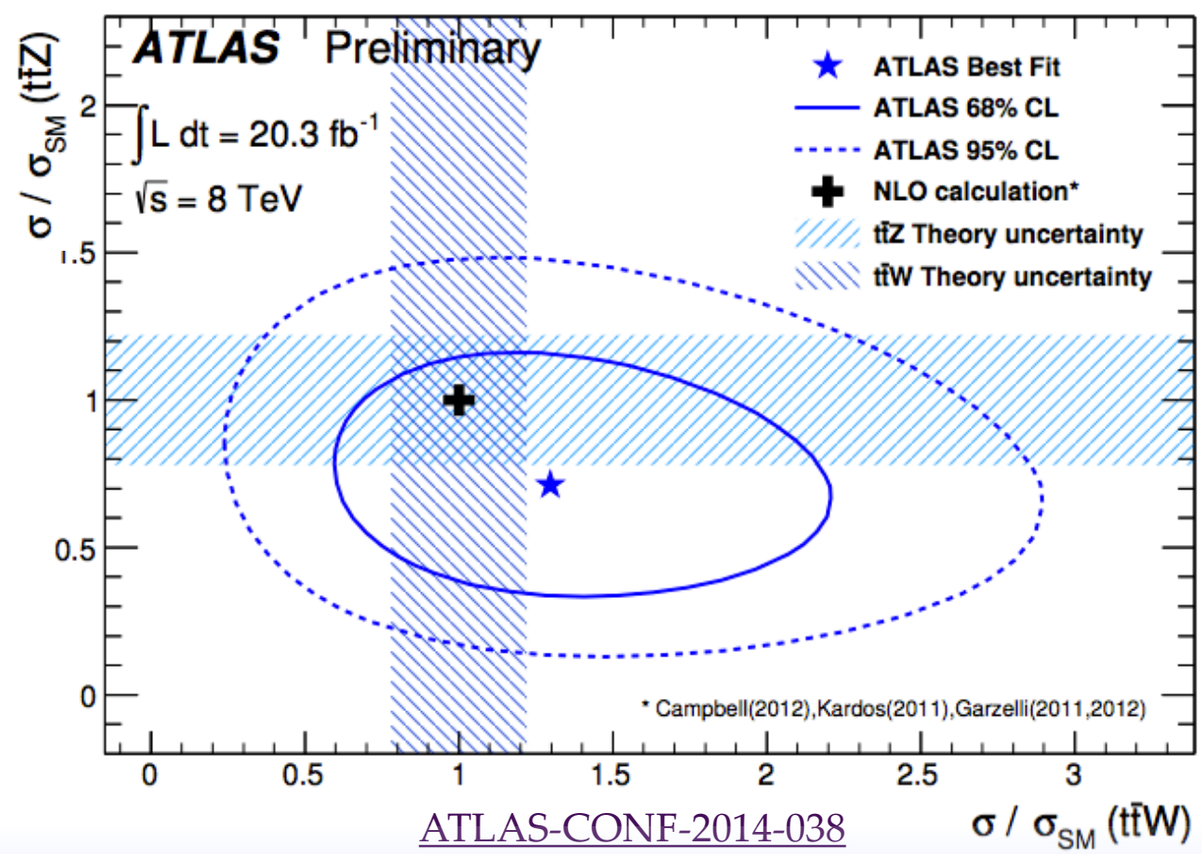
Channels used	Process	Cross section	Significance
$3\ell+4\ell$	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6

ATLAS 8 TeV

Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) $\pm$ 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



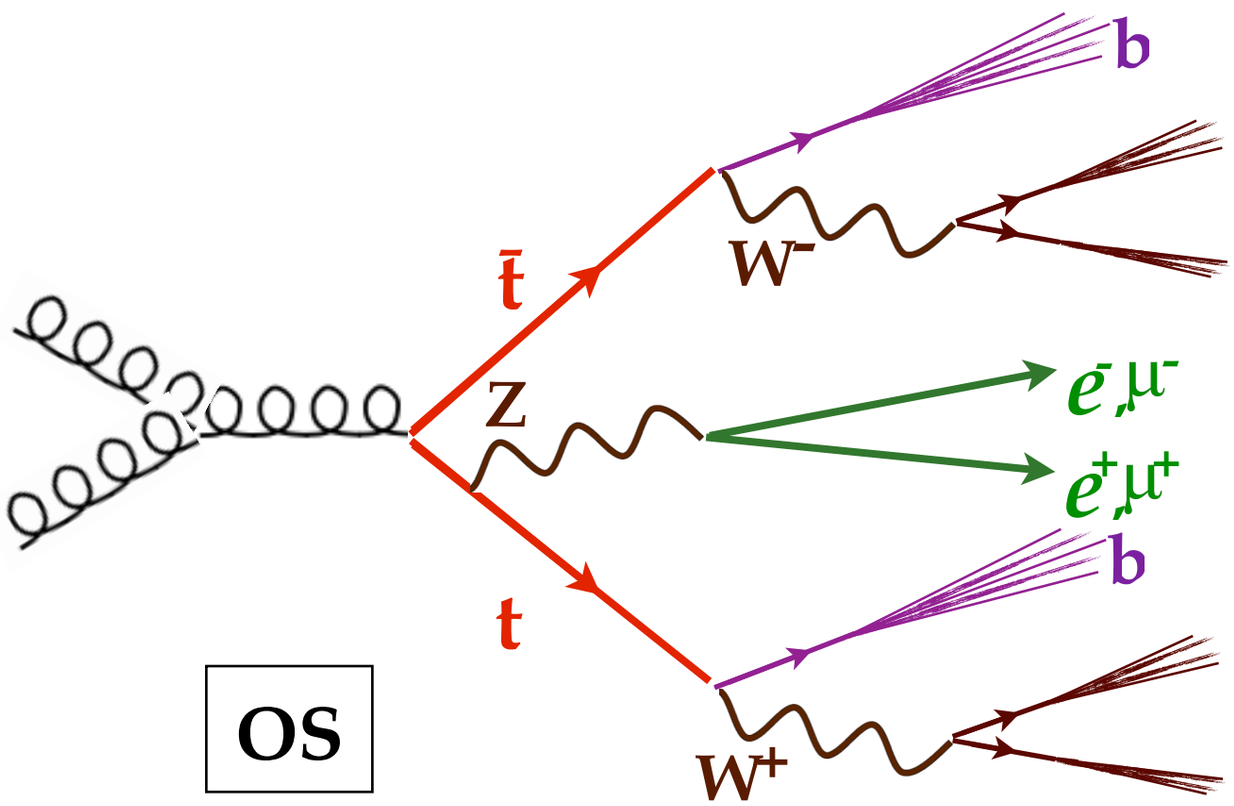
CMS: EPJ C74 (2014) 3060

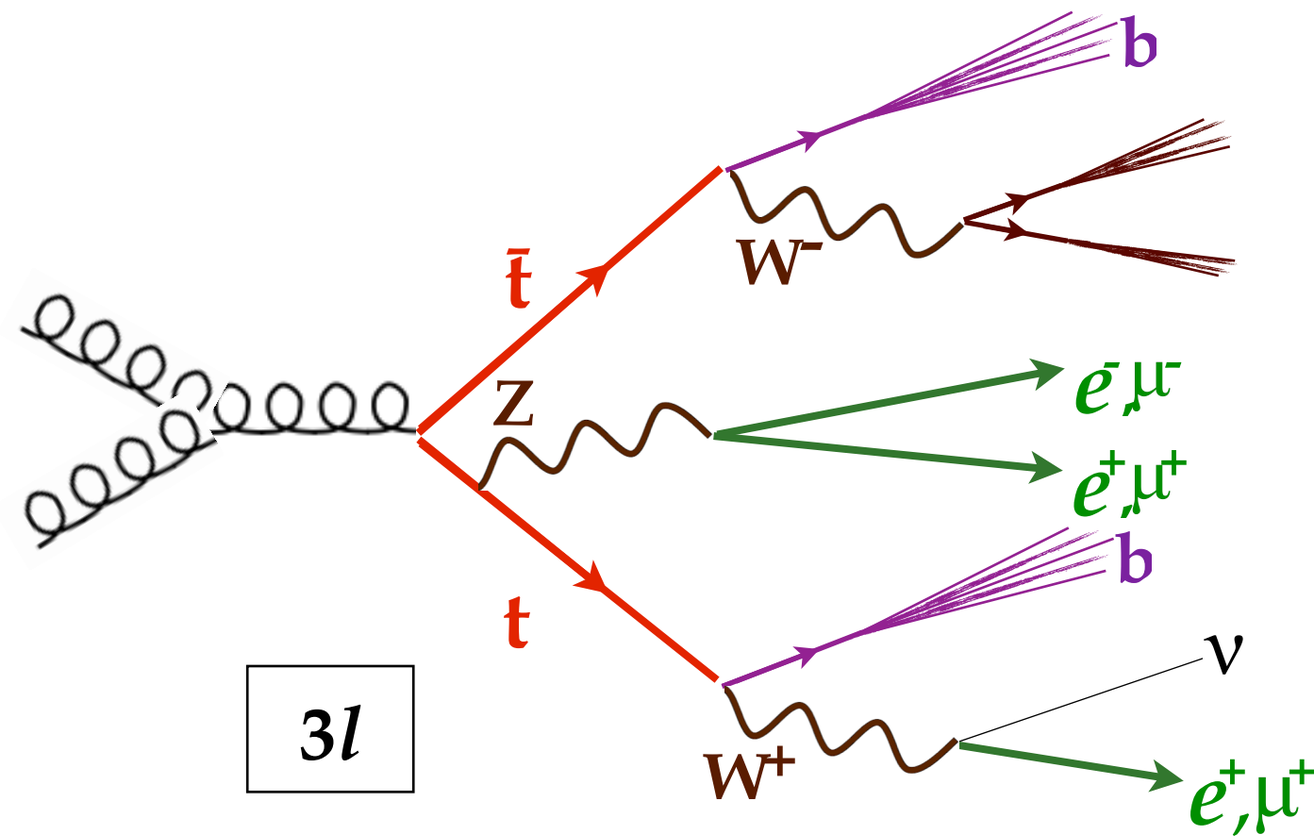


ATLAS-CONF-2014-038

ttZ signatures

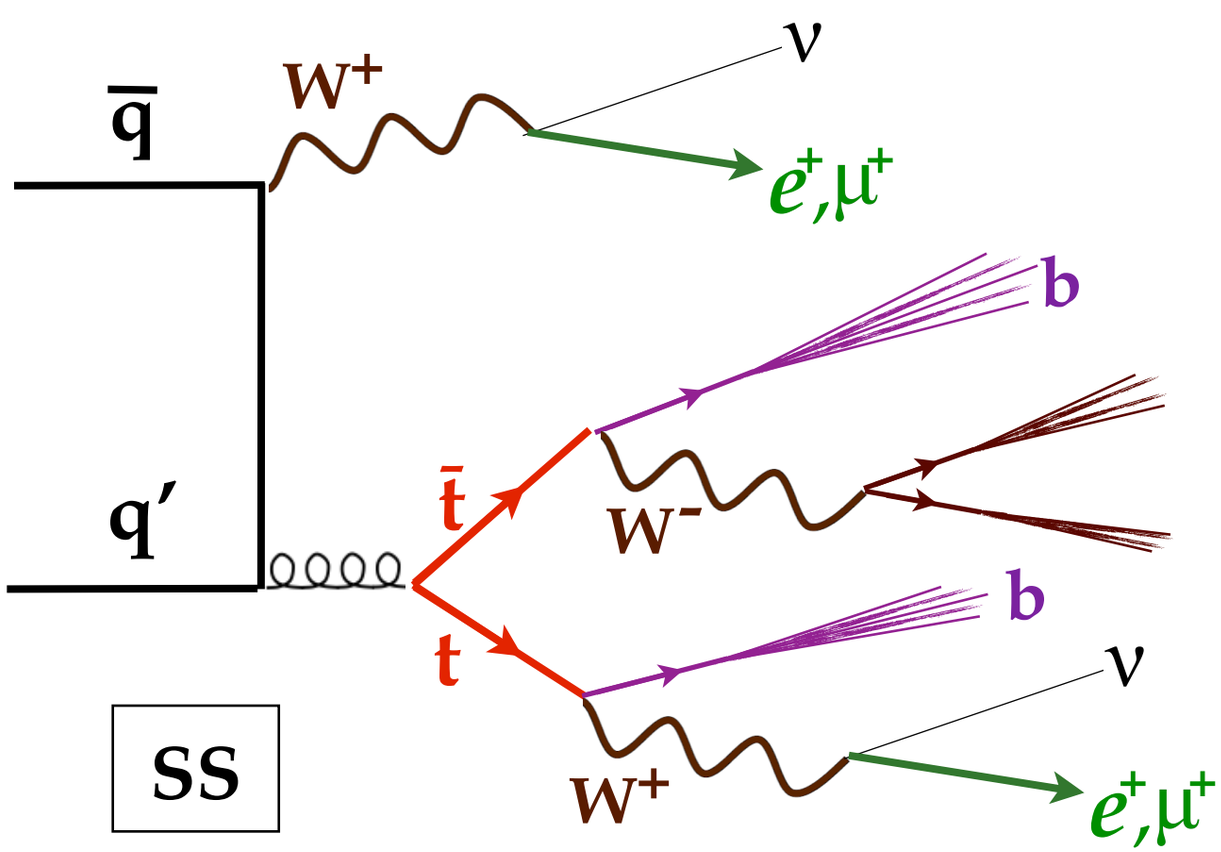
- Best S/B in opposite-sign 2*l* (OS), 3*l* and 4*l* final states
- Expect a Z-mass lepton pair and b-jets, plus one or two leptons, missing energy, and/or light flavor jets

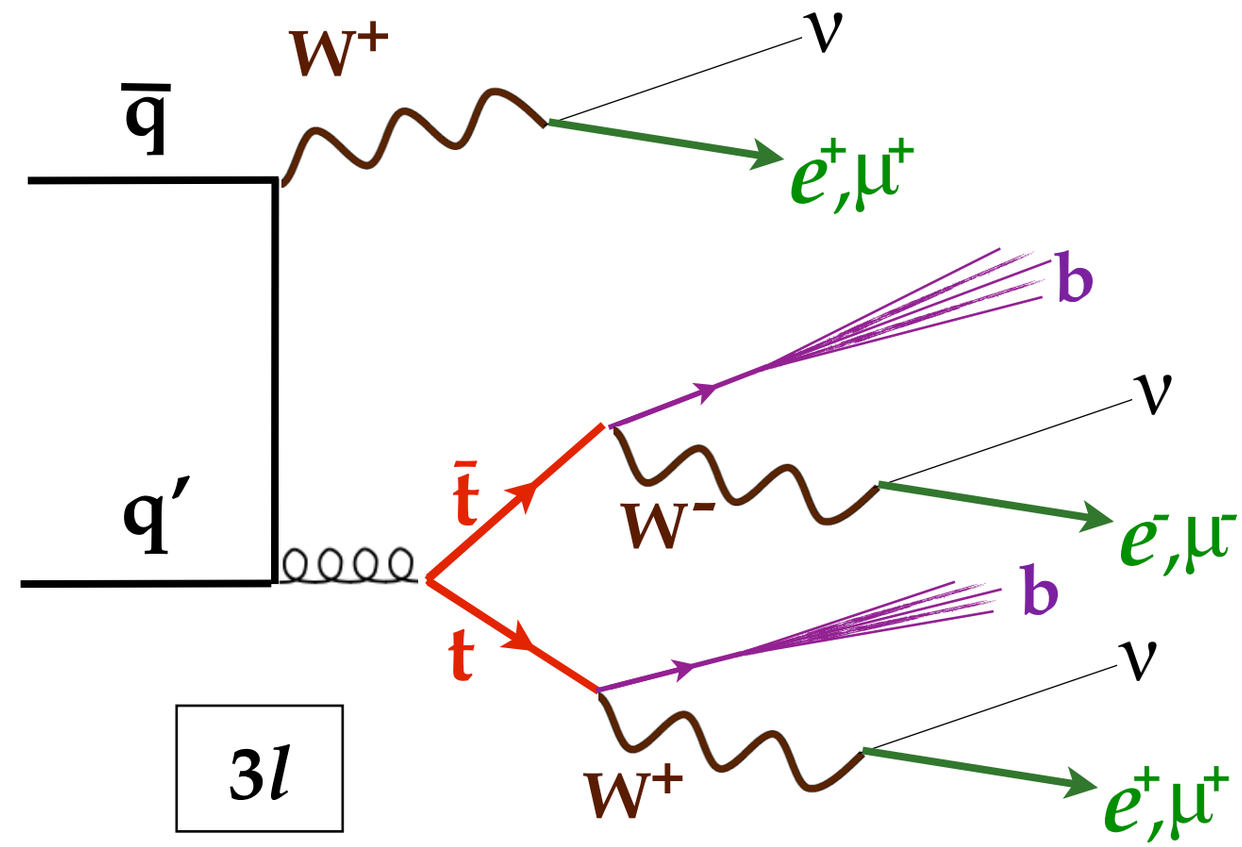




ttW signatures

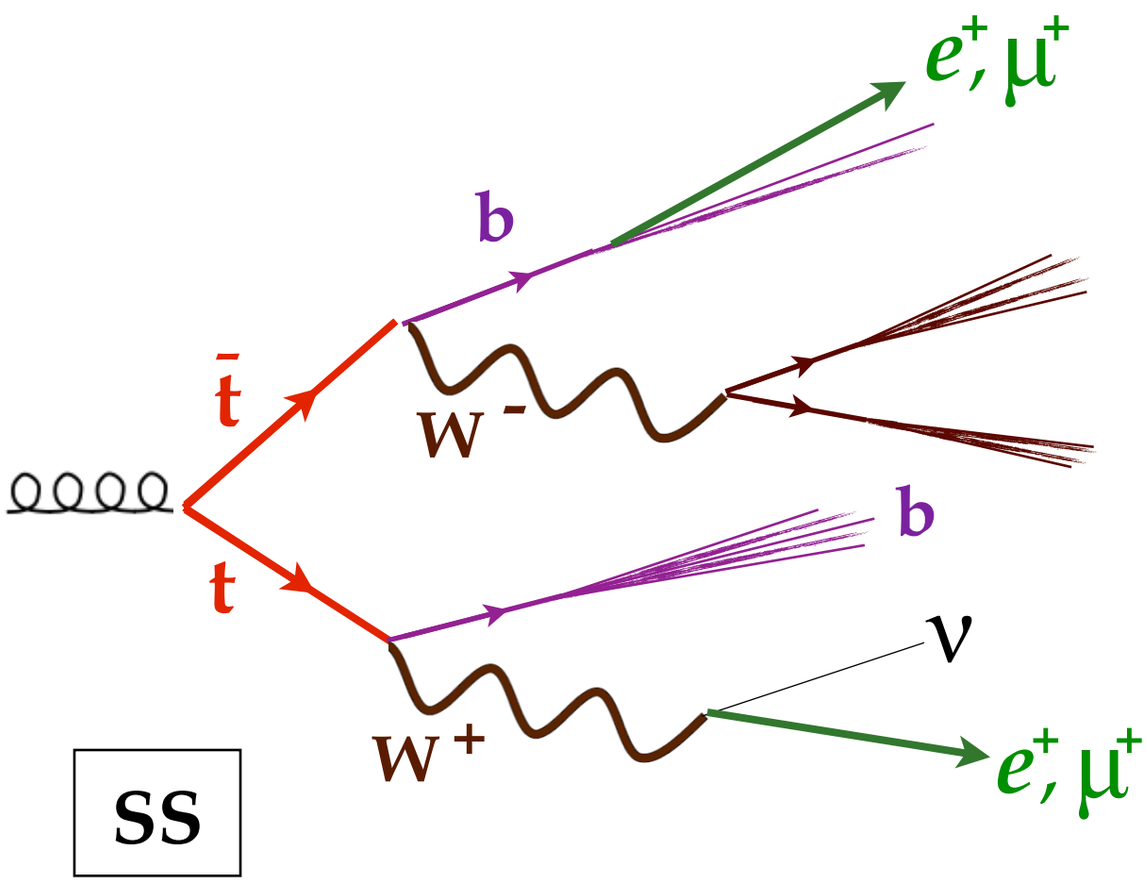
- Best S/B in same-sign 2*l* (SS) and 3*l* final states
- Expect leptons, b-jets, and missing energy, plus an extra lepton or extra light flavor jets

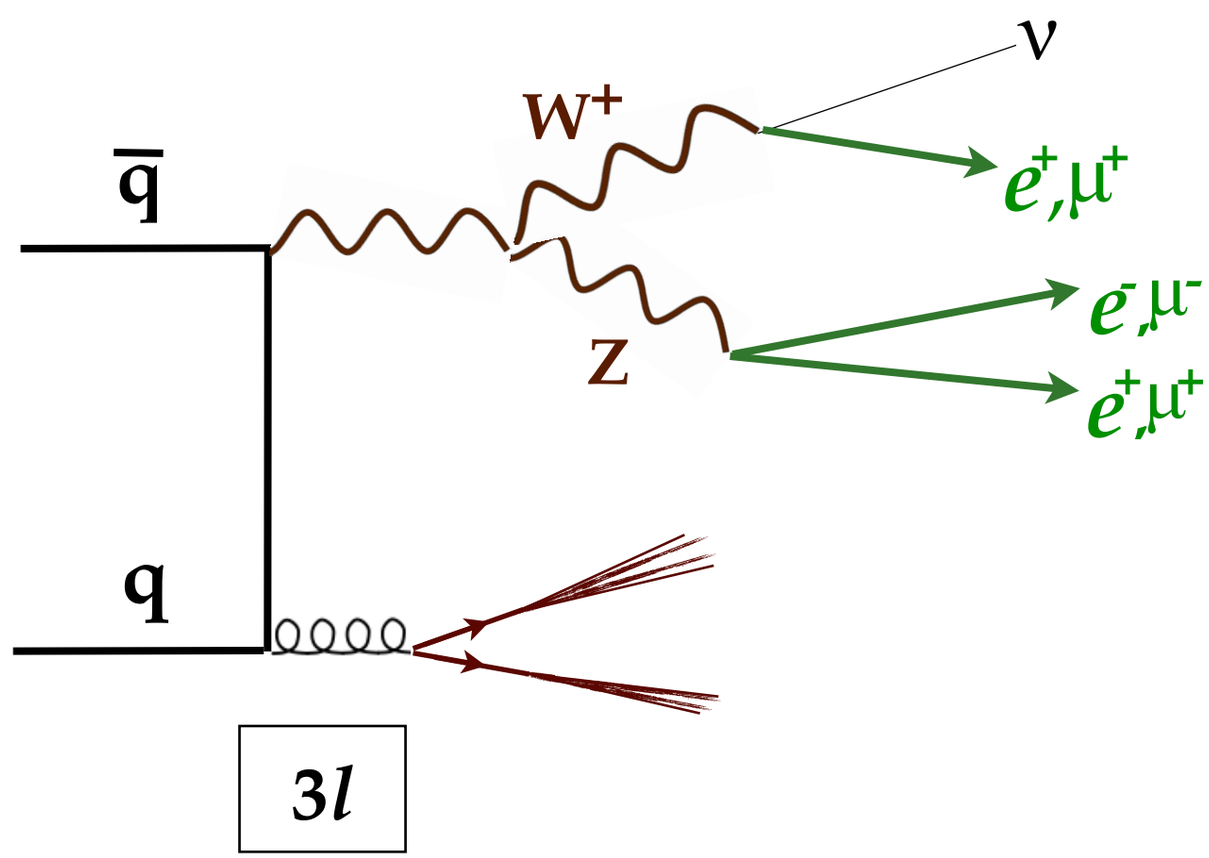




Backgrounds

- Primarily ttbar, Z, WZ, and ZZ plus extra jets
- Prompt leptons from W/Z and non-prompt from b decay





Reconstructed objects

Leptons	1st lepton $p_T > 20$ GeV, others $p_T > 10$ GeV
	Muon $\lvert\eta\rvert < 2.4$, electron $\lvert\eta\rvert < 2.5$
	Tight and loose cuts vs. **non-prompt** leptons*
Jets	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$, anti-k_t ($R = 0.5$)
	Medium and loose **b-tag** (CSV)
Missing E_T	From all objects (MET) and selected objects (MHT)

* Prompt leptons are usually isolated from other objects in the event, and their tracks originate close to the collision vertex. Non-prompt leptons have nearby hadrons, and are displaced from the vertex.

Selection

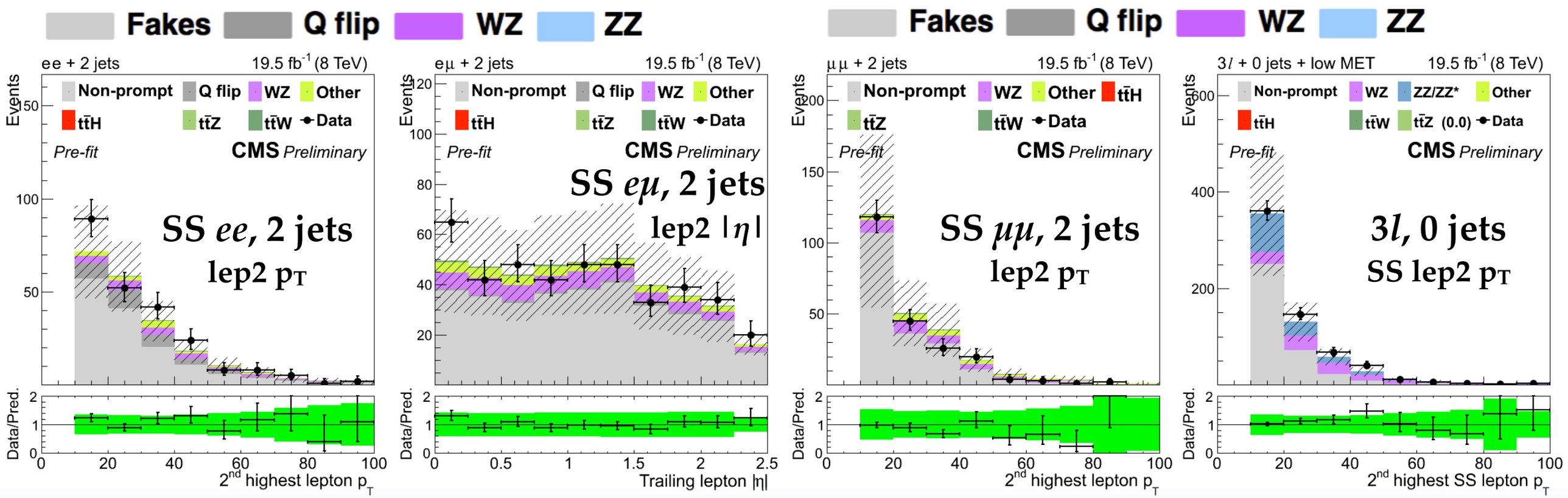
	OS ttZ		SS ttW			3*l* ttW		3*l* ttZ		4*l* ttZ	
Leptons	***ee*/*μμ***	***eμ***	***ee***	***eμ***	***μμ***	**3*l***		**3*l***		**4*l***	
	Both loose		Both tight			2 SS tight		2 SS tight		All loose	
	$\lvert m_{ll} - 91 \rvert < 10$		$\lvert m_{ee} - 91 \rvert > 10$			$\lvert m_{ll} - 91 \rvert > 10$		$\lvert m_{ll} - 91 \rvert < 10$		$\lvert m_{ll} - 91 \rvert < 10$	
Jets	**5**	**≥ 6**	**3**	**≥ 4**		**1**	**≥ 2**	**3**	**≥ 4**	**≥ 1**	
B-tags	≥ 1 medium		≥ 2 loose || ≥ 1 medium			≥ 2 loose || ≥ 1 medium		≥ 2 loose || ≥ 1 medium		≥ 1 loose	
Channels	**2**		**6**			**2**		**2**		MHT > 30	
										1 $Z \to ll$	2 $Z \to ll$
										2	

Event modeling

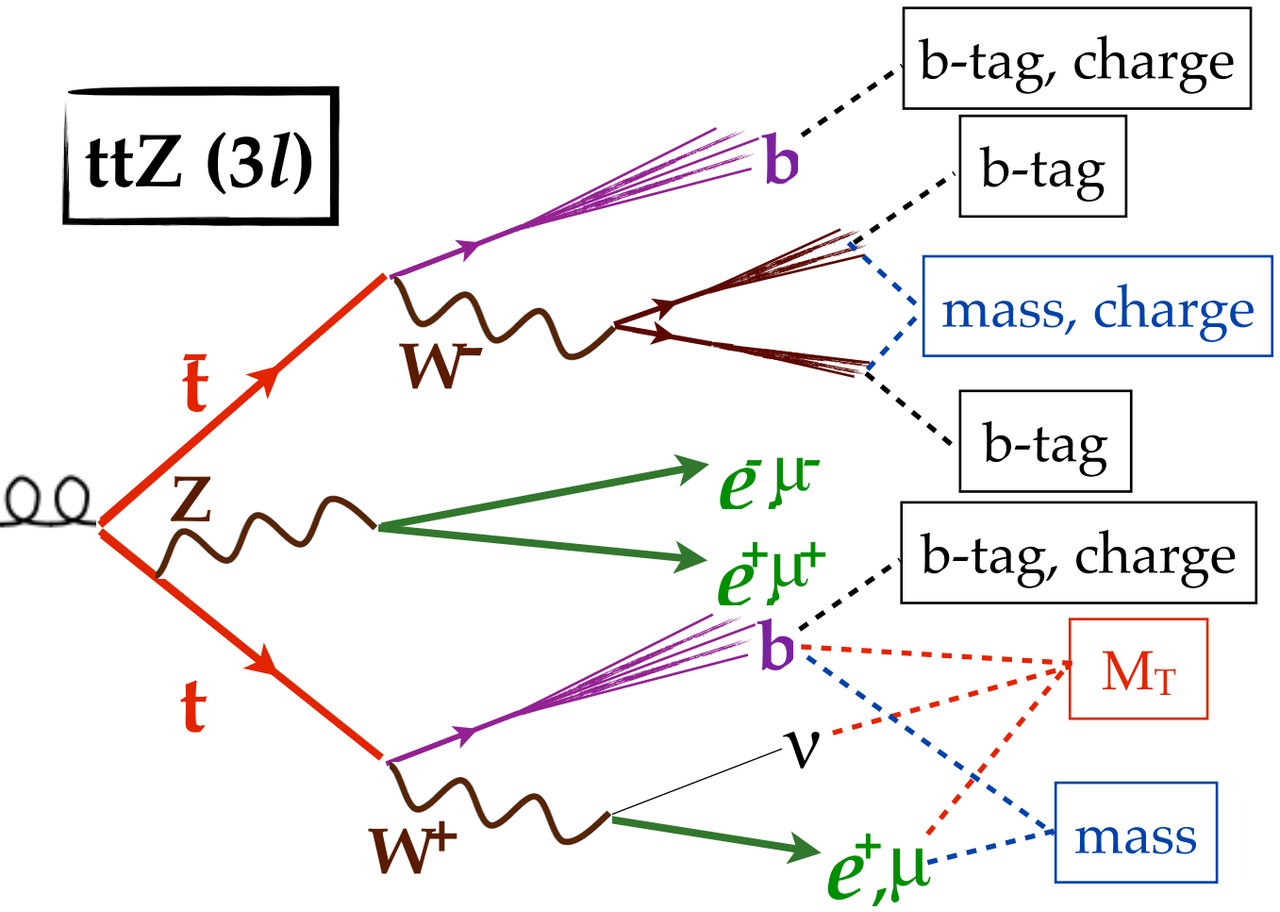
- Prompt: leptons from W or Z decays
  - ttbar and Z in OS events; WZ in SS; WZ and ZZ in 3*l*; ZZ in 4*l*
  - Estimated using MC; large uncertainty on extra jets and b-/c-jets
- Non-prompt (NP): leptons from quarks (semi-leptonic decay or jet fakes)
  - ttbar in SS events; ttbar and Z in 3*l*; ttbar, Z, and WZ in 4*l*
  - SS/3l estimated using data-driven fake rate from sideband; 4*l* using MC
- Charge flip (QF): leptons with mis-reconstructed charge
  - Opposite-sign ttbar and Z events can appear as SS events
  - Data-driven estimate from OS events

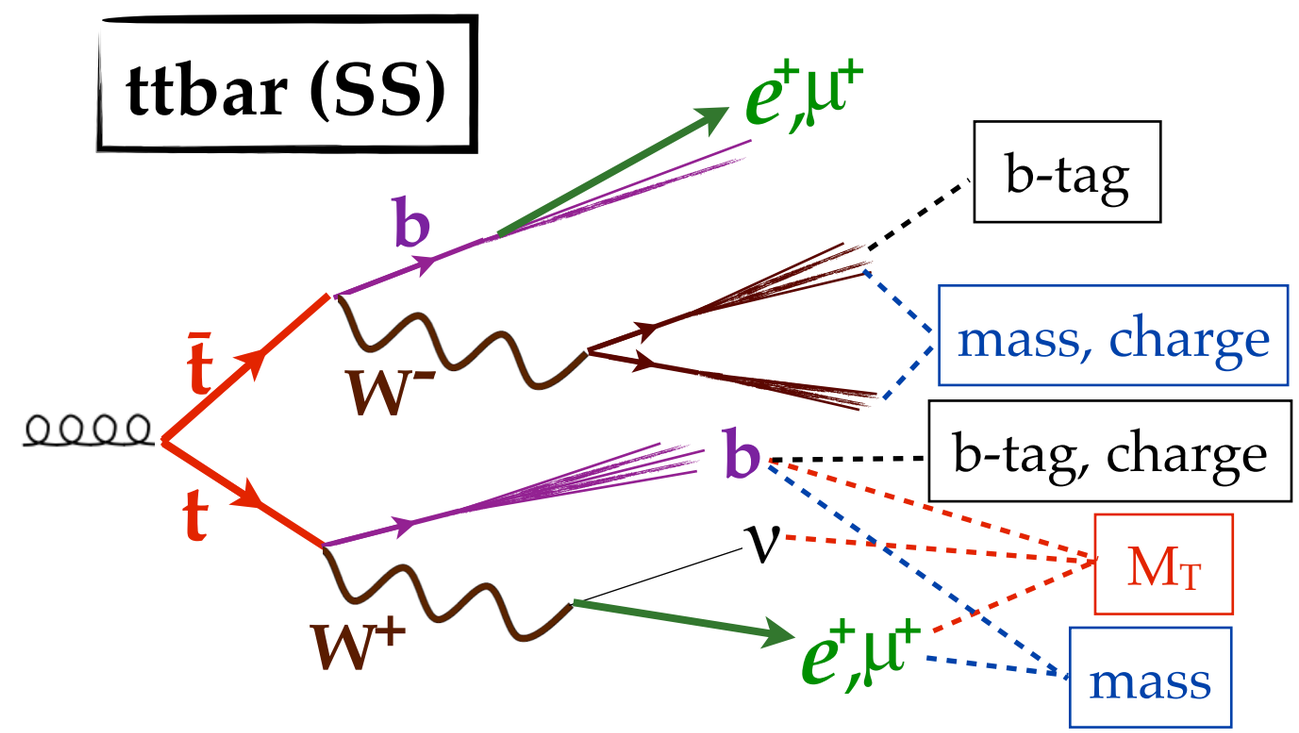
Non-prompt background

- To reject non-prompt leptons, apply cuts selecting well isolated leptons with tracks close to the collision vertex
- Derive fake rate from same-sign ttbar and 3*l* Z+fake events
  - Use events with leptons that fail cuts to model non-prompt background

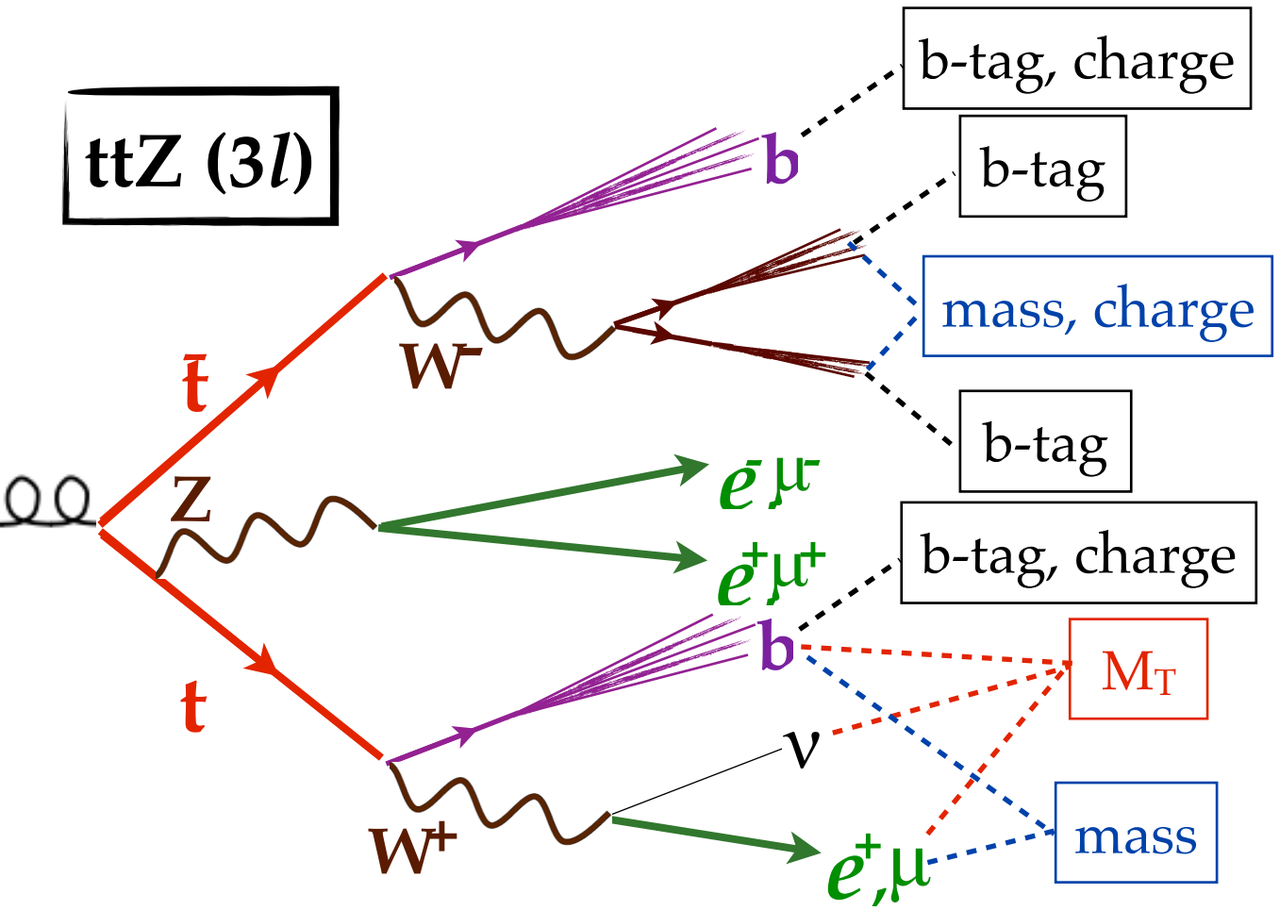


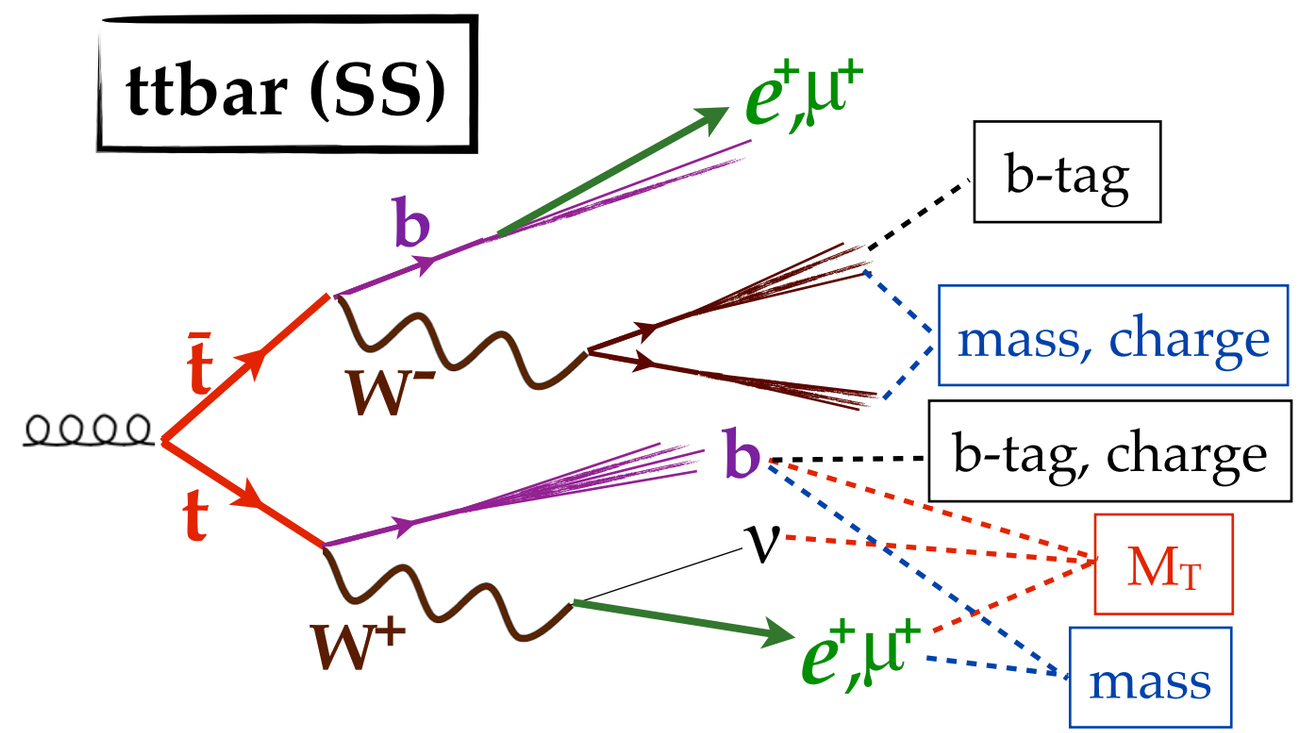
Event reconstruction





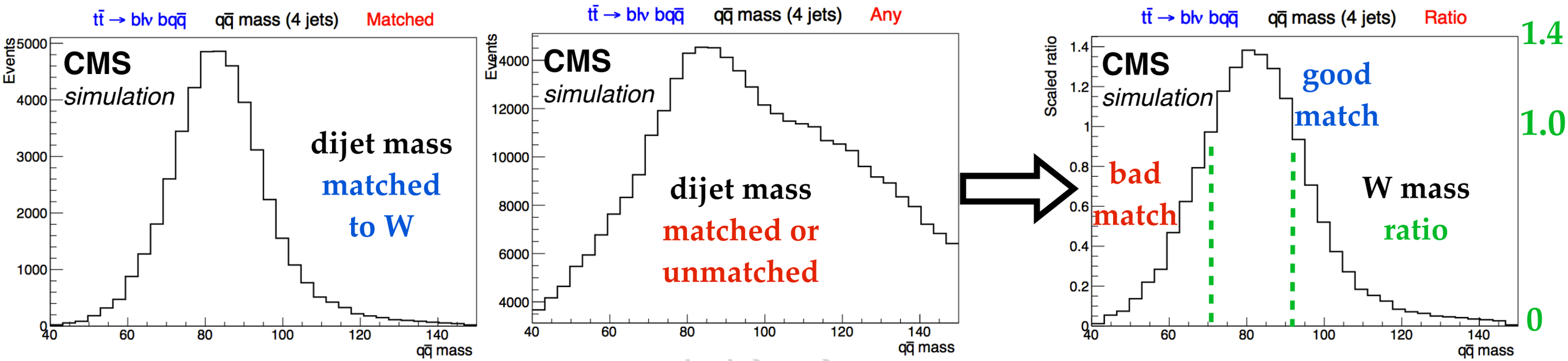
Event reconstruction





- Matching linear discriminant (MatchLD)
  - For each variable, get ratio of value for the correct jet(s) to value for any jet(s)

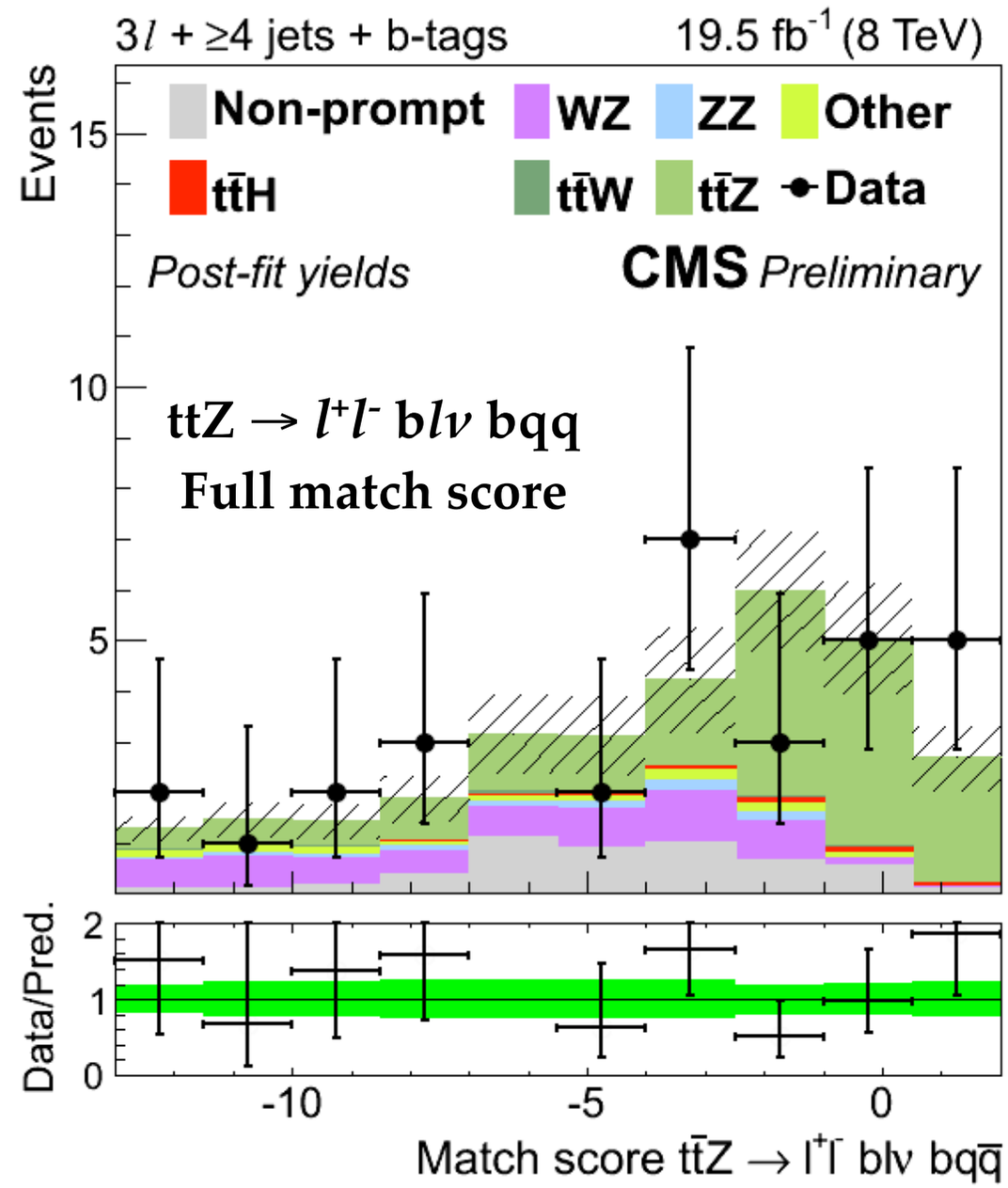
MatchLD: 3*l* ttZ



- Renormalize ratio histogram to have average value of 1.0 for events where the jets are correctly assigned
- Attempt every permutation of jets matched to the decay products of the ttbar system. Choose permutation with highest score = $\log(\Pi_i \text{ ratio}_i)$

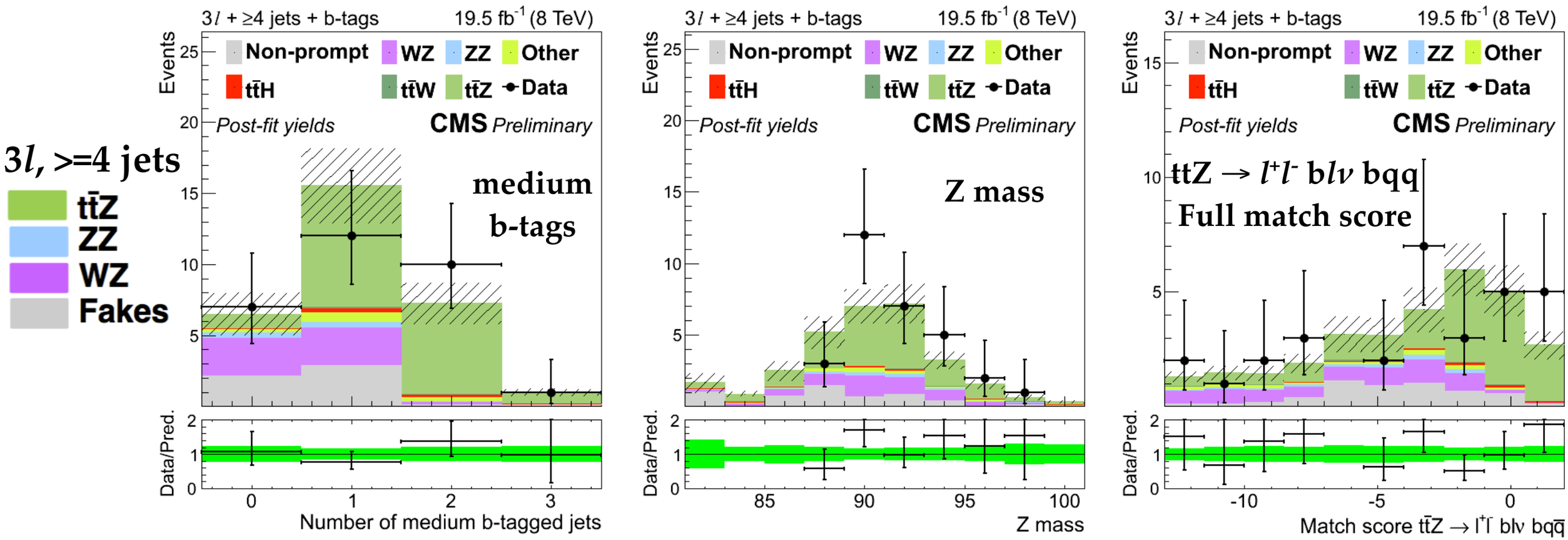
MatchLD: 3*l* ttZ

- For events where both b's from the top and both q's from the W are reconstructed as jets, 75% of 4 jet and 40% of >=5 jet events have every jet correctly matched to its parent particle
- For correct matches, the average ratio is 1 (so the match score centers near 0)
- Partial matches (all but one jet matched) allow us to identify signal events where one of the quarks forms a jet outside our acceptance



3*l* ttZ BDT

- Train boosted decision tree with ttZ vs. WZ and ttbar MC

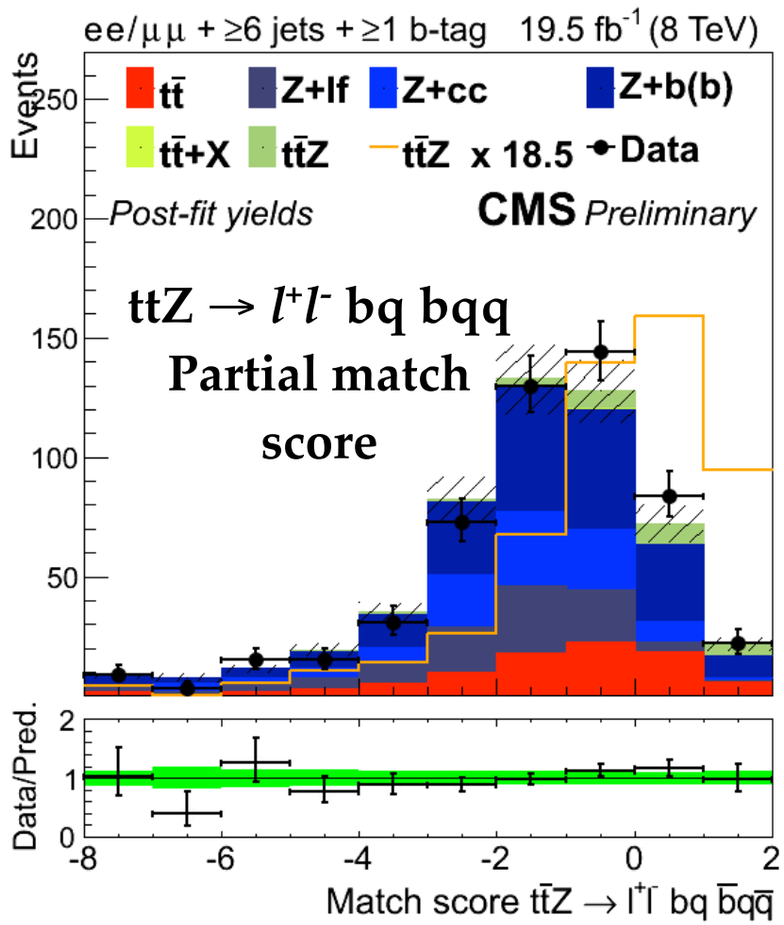


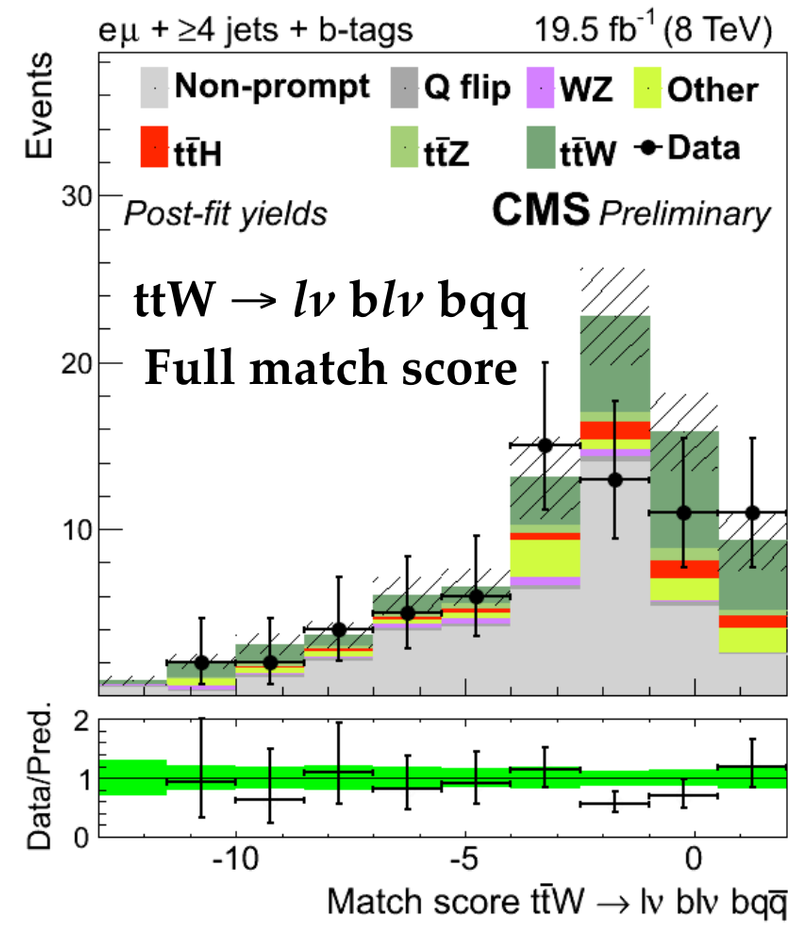
- Also include M_T of system, partial matches to ttZ system (ttZ → l^+l^- $bl\nu$ bq, ttZ → l^+l^- $l\nu$ bqq, ttZ → l^+l^- $bl\nu$ qq)

Matching other systems

ttZ

OS $ee/\mu\mu$
>=6 jets





ttW

SS $e\mu$
>=4 jets

Full and partial match scores used in BDTs	OS ttZ	SS ttW	3*l* ttW	3*l* ttZ
	ttZ → l^+l^- bqq bqq	ttW → $l\nu$ $bl\nu$ bqq	ttW → $l\nu$ $bl^+\nu$ $bl^-\nu$	ttZ → l^+l^- $bl\nu$ bqq
	tt → $bl^+\nu$ $bl^-\nu$	tt → l_b qq $bl\nu$	tt → l_b $l\nu$ $bl\nu$	

- Also use input variables, e.g. M_T of t → $bl\nu$ from best matched tt → l_b qq $bl\nu$

ttW BDT inputs

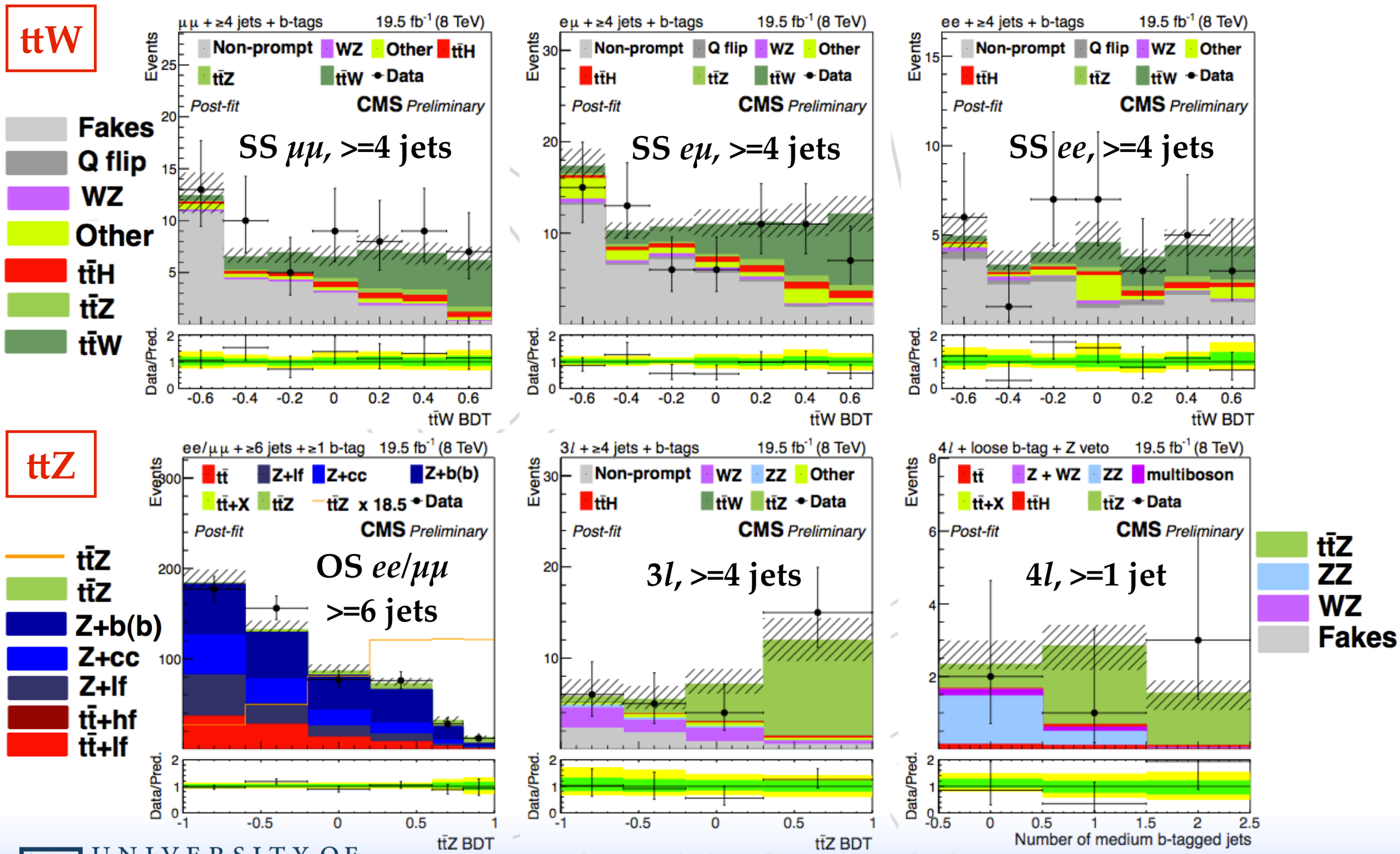
- Train boosted decision trees with ttW vs. ttbar MC
- Use a mix of kinematic and matching variables
  - Kinematic variables from p_T of objects and jet b-tag (CSV)
  - Event matching variables for ttW and ttbar systems

BDT inputs: same-sign $t\bar{t}W$ vs. $t\bar{t}$	3 jet	$\geq$4 jets
M_T of E_T^{miss}, leptons, and jets	1	1
E_T^{miss}	4	2
2nd highest lepton p_T	6	3
Match score for $t\bar{t} \to \ell_b jj\, b\ell\nu$	2	4
Highest lepton p_T	5	5
2nd highest CSV value of a jet	8	6
$t\bar{t}$ matched top M_T from $b\ell\nu$	7	7
Match score for $t\bar{t}W \to b\ell\nu\, bq$	9	8
Match score for $t\bar{t}W \to b\ell\nu\, bqq$	-	9
$t\bar{t}$ matched top mass from $\ell_b qq$	3	-

Variables ranked by signal-background separation

- Reconstructing events with a linear discriminant first allows for more input variables and better separation than a BDT alone, since BDTs are more limited by the statistics of training events

Final discriminants



PRELIMINARY

twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP14021

Results

	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
OS	206^{+142}_{-118}	257^{+158}_{-129}	$1.0^{+0.72}_{-0.57}$	$1.25^{+0.76(+1.76)}_{-0.62(-1.16)}$	1.84	2.12
3ℓ	206^{+79}_{-63}	257^{+85}_{-67}	$1.0^{+0.42}_{-0.32}$	$1.25^{+0.45(+1.02)}_{-0.36(-0.62)}$	4.55	5.11
4ℓ	206^{+153}_{-109}	228^{+150}_{-107}	$1.0^{+0.77}_{-0.53}$	$1.11^{+0.76(+1.79)}_{-0.52(-0.86)}$	2.65	3.39
$\boxed{\text{OS} + 3\ell + 4\ell}$	206^{+62}_{-52}	$\boxed{242^{+65}_{-55}}$	$1.0^{+0.34}_{-0.27}$	$1.18^{+0.35(+0.79)}_{-0.29(-0.51)}$	5.73	$\boxed{6.44}$

Cross section with 68% (95%) CL ranges and sensitivity for $t\bar{t}Z$.

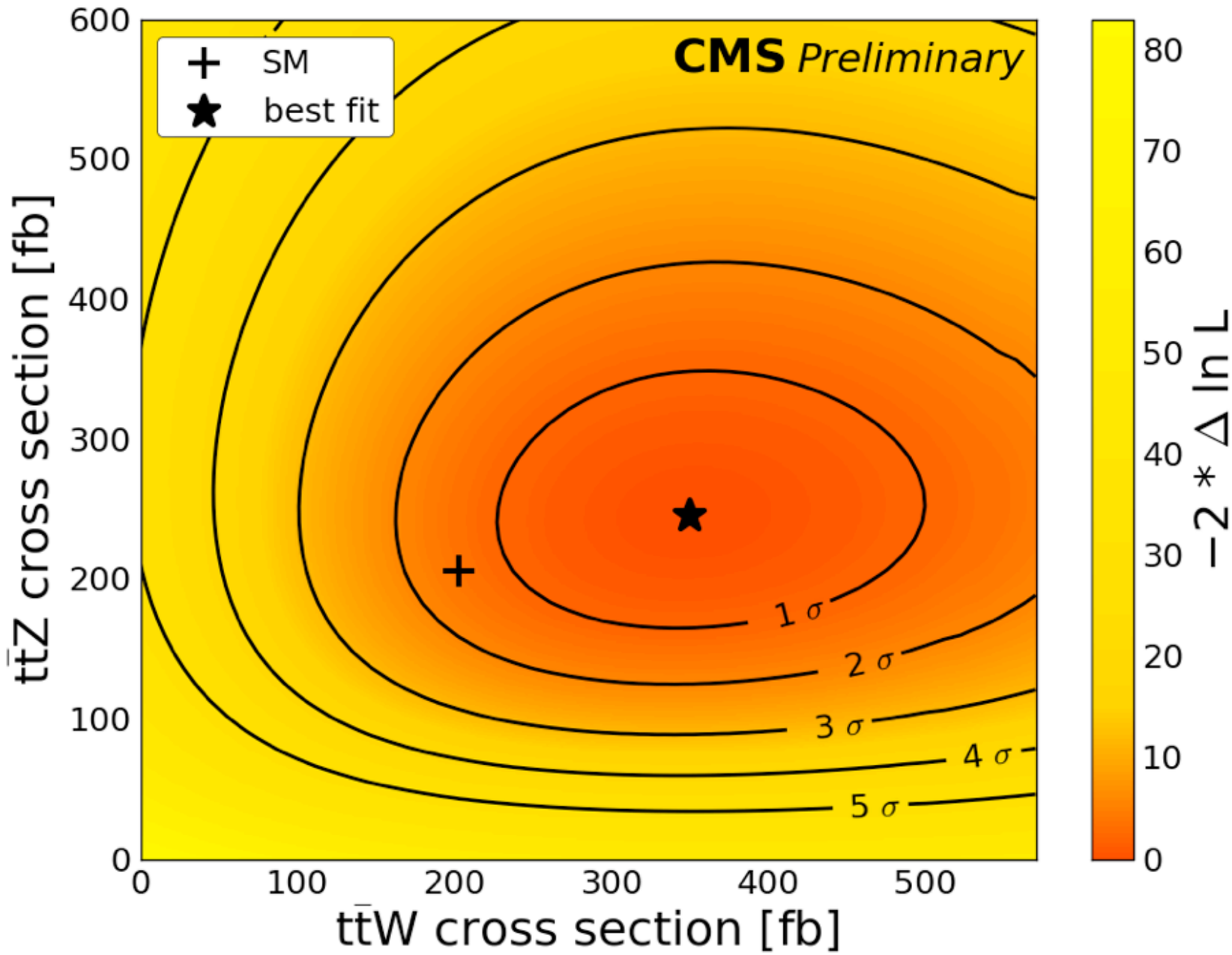
	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
SS	203^{+88}_{-73}	414^{+135}_{-112}	$1.0^{+0.45}_{-0.36}$	$2.04^{+0.74(+1.52)}_{-0.61(-1.05)}$	3.44	4.89
3ℓ	203^{+215}_{-94}	210^{+225}_{-203}	$1.0^{+1.09}_{-0.96}$	$1.03^{+1.07(+2.39)}_{-0.99(-1.92)}$	1.03	1.03
$\boxed{\text{SS} + 3\ell}$	203^{+84}_{-71}	$\boxed{382^{+117}_{-102}}$	$1.0^{+0.43}_{-0.35}$	$1.88^{+0.66(+1.35)}_{-0.56(-0.95)}$	3.54	$\boxed{4.81}$

Cross section with 68% (95%) CL ranges and sensitivity for $t\bar{t}W$.

PRELIMINARY

twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP14021

Results



- ttZ vs. ttW simultaneous cross-section measurement

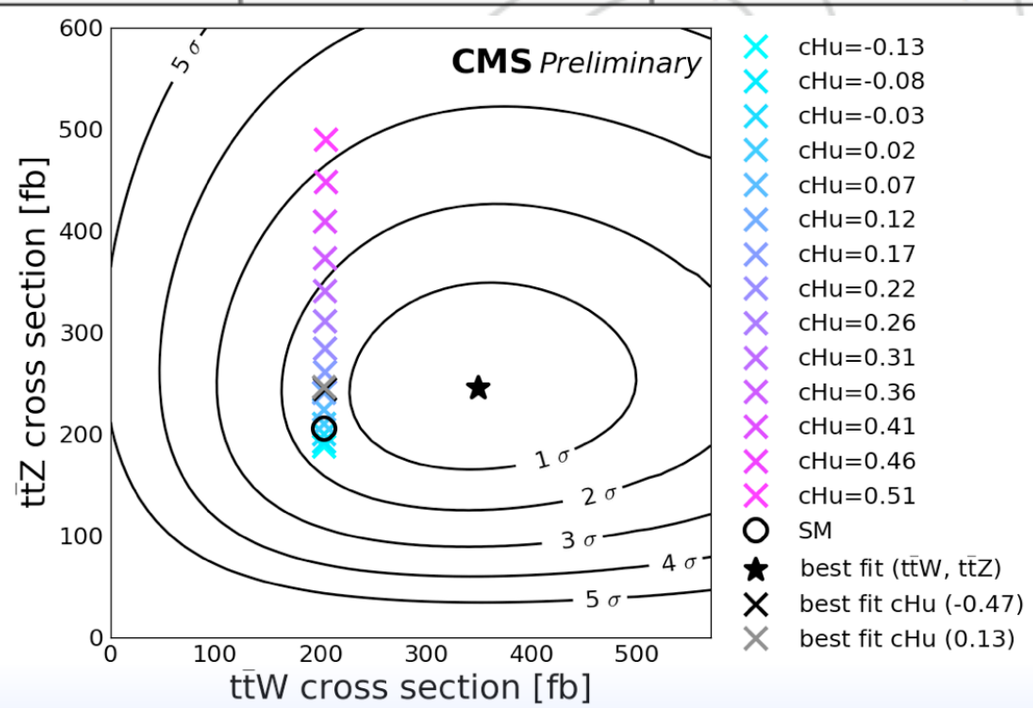
Constraints on new physics

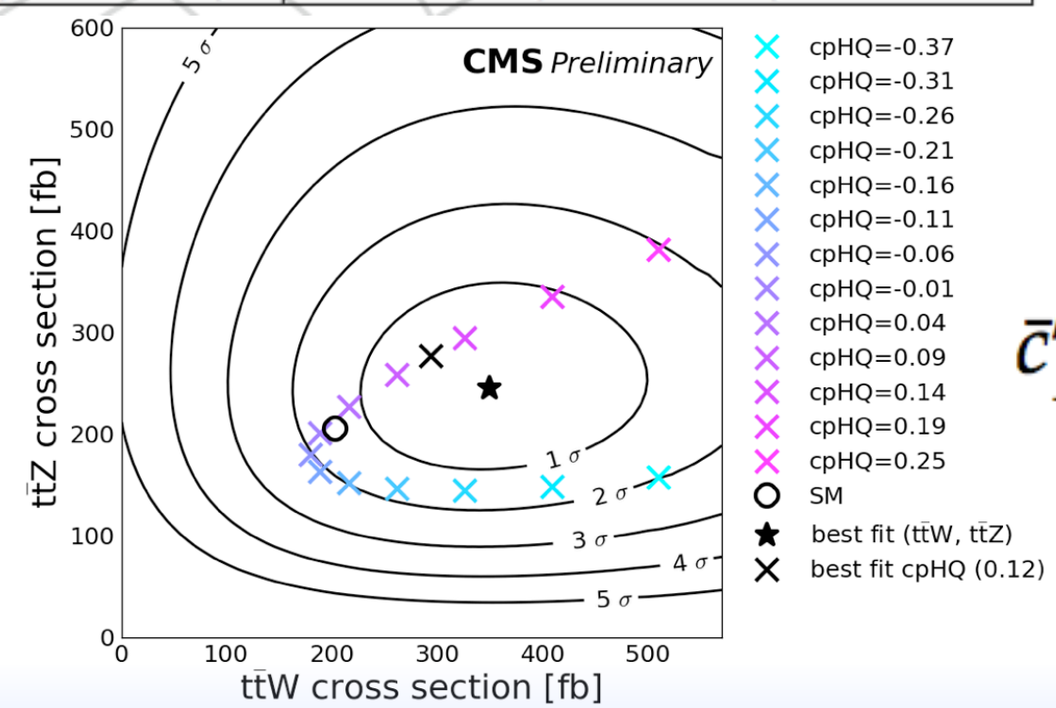
- These ttW and ttZ cross section measurements place the best direct constraints certain dimension six operators to date

PRELIMINARY

operator	best fit point(s)	1σ CL	2σ CL
$\bar{c}_{uB}$	-0.07 and 0.07	{-0.11, 0.11}	{-0.14, 0.14}
$\bar{c}'_{HQ}$	0.12	{-0.07, 0.18}	{-0.33, -0.24} and {-0.02, 0.23}
$\bar{c}_{HQ}$	-0.09 and 0.41	{-0.22, 0.08} and {0.24, 0.54}	{-0.31, 0.63}
$\bar{c}_{Hu}$	-0.47 and 0.13	{-0.60, -0.23} and {-0.11, 0.26}	{-0.71, 0.37}
$\bar{c}_{3W}$	-0.28 and 0.28	{-0.36, -0.18} and {0.18, 0.36}	{-0.43, 0.43}

$\bar{c}_{Hu}$





$\bar{c}'_{HQ}$

Constraints on new physics

- Some dimension six operators would specifically affect the vector and axial components of top-Z coupling

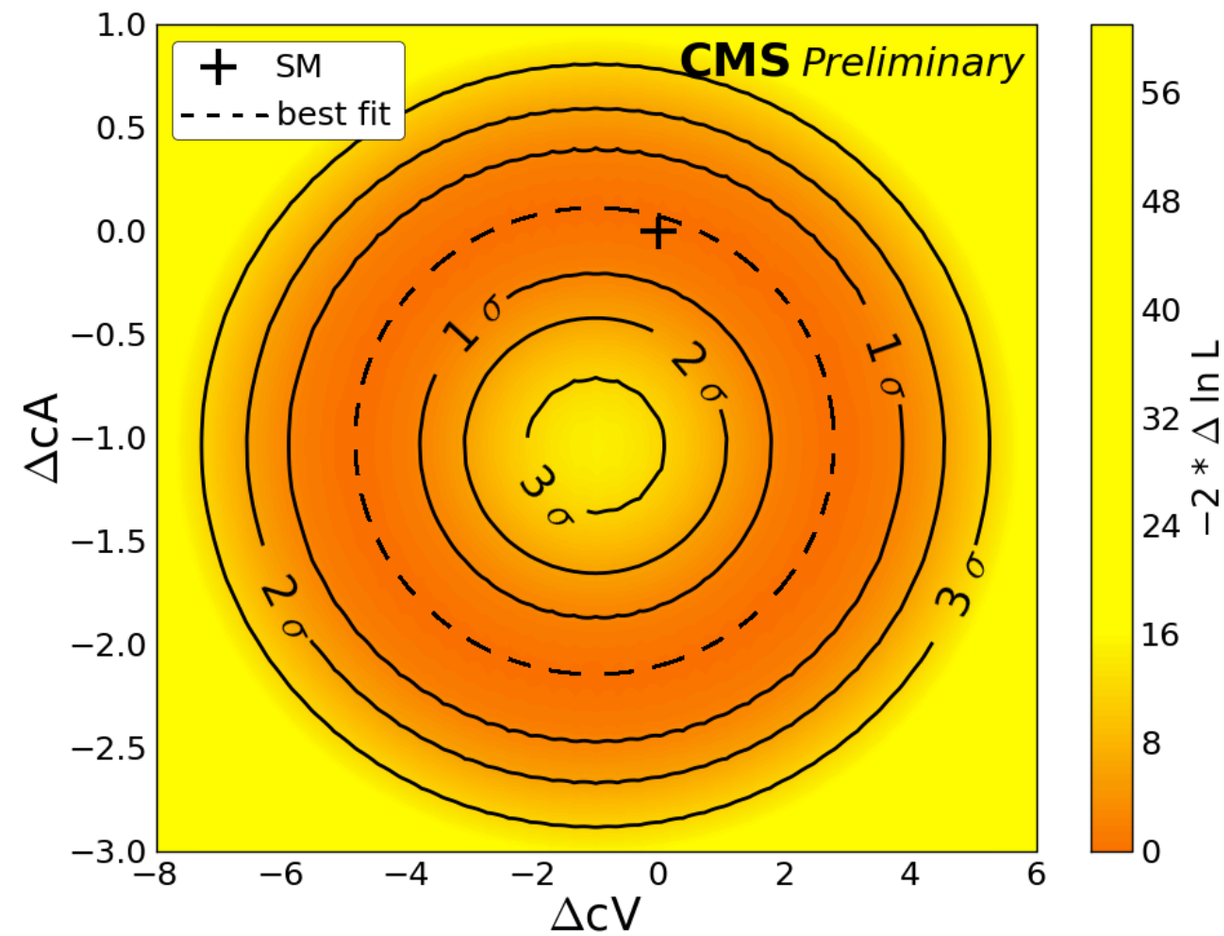
- Interpret ttZ cross section measurement in terms of best fit to, and limits on $C_{1,V}$ and $C_{1,A}$

PRELIMINARY

$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right]$$

$$C_{1,\mathrm{A}} = C_{1,\mathrm{A}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right) \mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33}\right]$$

*From http://arxiv.org/abs/1404.1005



Difference between SM C_V and $C_{1,V}$

Summary

ttW and ttZ measurements		ttW				ttZ			
		Cross section		Significance		Cross section		Significance	
Data	**Analysis**	**Theory***	**Obs.**	**Exp.**	**Obs.**	**Theory***	**Obs.**	**Exp.**	**Obs.**
7 TeV (5 fb^{-1})	CMS[1]	147^{+14}_{-16}	-	-	-	137^{+12}_{-16}	280^{+150}_{-110}	?	3.3
	ATLAS[2]		-	-	-		< 710	-	-
8 TeV (20 fb^{-1})	CMS[3]	203^{+20}_{-22}	170^{+110}_{-100}	2.0	1.6	206^{+19}_{-24}	200^{+90}_{-80}	3.1	3.1
	ATLAS[4]		300^{+140}_{-110}	2.3	3.1		150^{+58}_{-54}	3.4	3.1
	CMS ***Preliminary***		**382^{+117}_{-102}**	**3.5**	**4.8**		**242^{+65}_{-55}**	**5.7**	**6.4**

Preliminary documentation: twiki.cern.ch/twiki/bin/view/CMSPublic/**PhysicsResultsTOP14021**

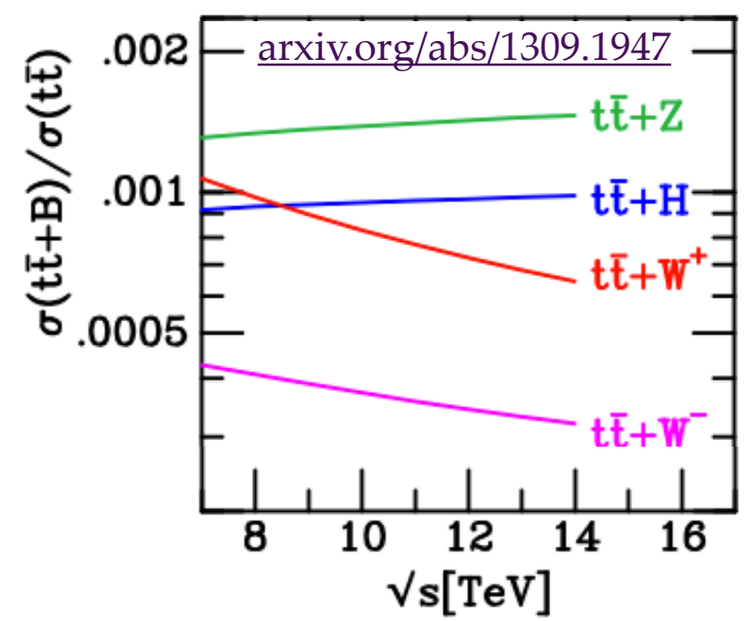
[1] CMS: *Phys. Rev. Lett.* 110 (2013) 172002
[2] ATLAS-CONF-12-126
[3] CMS: EPJ C74 (2014) 3060
[4] ATLAS-CONF-2014-038

* NLO cross sections with scale uncertainties from Garzelli et. al., JHEP 11 (2012) 056

BACKUP

Prospects for LHC Run II

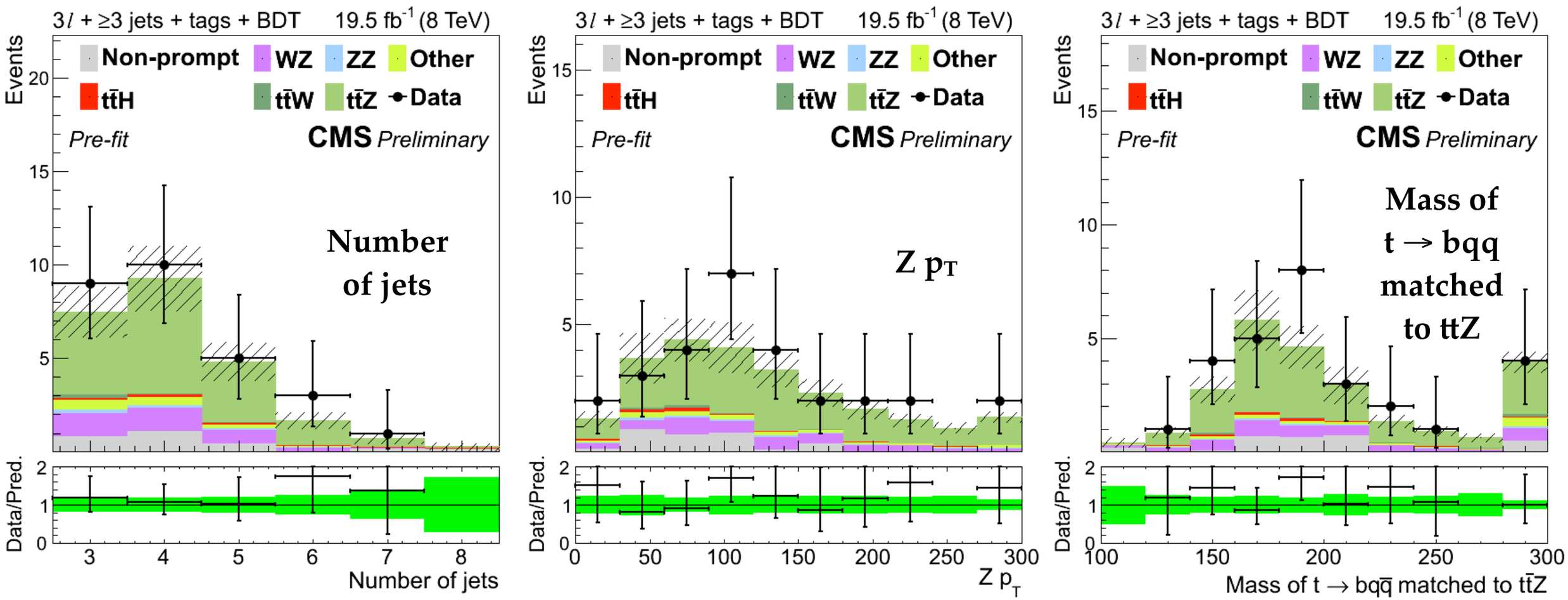
- Running at 13 TeV - all tt+X cross sections rise, some dramatically
- Plan to deliver 100 fb^{-1} in Run II
  - Expect ~900 tt+tt events per detector by 2018!
  - Expect ~55k ttW and ~76k ttZ events per detector
    - **~550 ttW and ~760 ttZ in 2015 alone, if we're lucky**
  - For comparison, Tevatron Run I produced ~670 tt pairs per detector, and Run II produced ~72k tt pairs per detector
- **Entering the era of precision studies of tt+X**



Expected SM cross sections		
	8 TeV	13 TeV
tt	248 pb	816 pb
ttW	203 fb	566 fb
ttZ	206 fb	760 fb
tt+tt	0.9 fb	9.2 fb

twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO
dx.doi.org/10.1007/JHEP07(2014)079

3*l* ttZ kinematics



- Pre-fit distributions with systematic uncertainties for signal-like events in the 3*l* ttZ channel (3 jets with BDT > 0.3 and ≥4 jets with BDT > -0.2)