Single top tW

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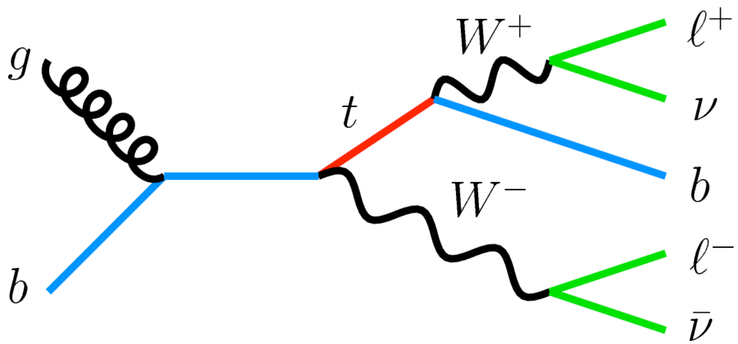
Why tW?

- From the three main single top production modes (t-channel, tW, s-channel), the tW associated production is the one that **could not be explored before the LHC**

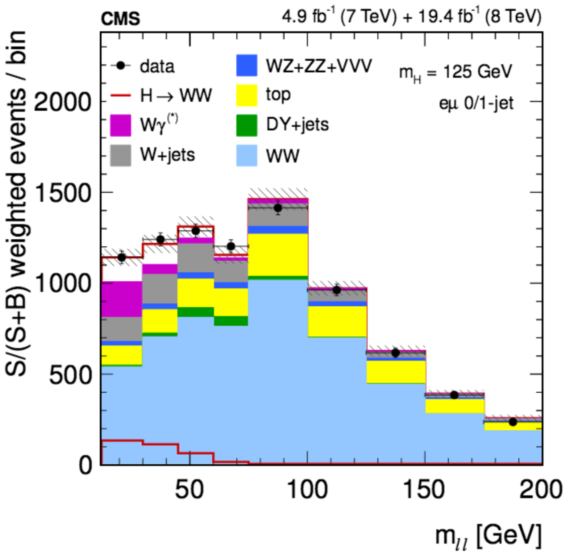
σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	**0.22**	1.046

- Like the other single top modes, it is sensitive to new physics, and provides an additional handle to study top properties

- Dilepton signature:
  - 2 opposite sign leptons (e,μ)
  - Substantial MET (2 neutrinos)
  - 1 b-jet
- Main backgrounds:
  - ttbar, DY (same flavor), VV…



tW as background



H→WW→2l2nu

arXiv:1312.1129, JHEP 01 (2014) 096

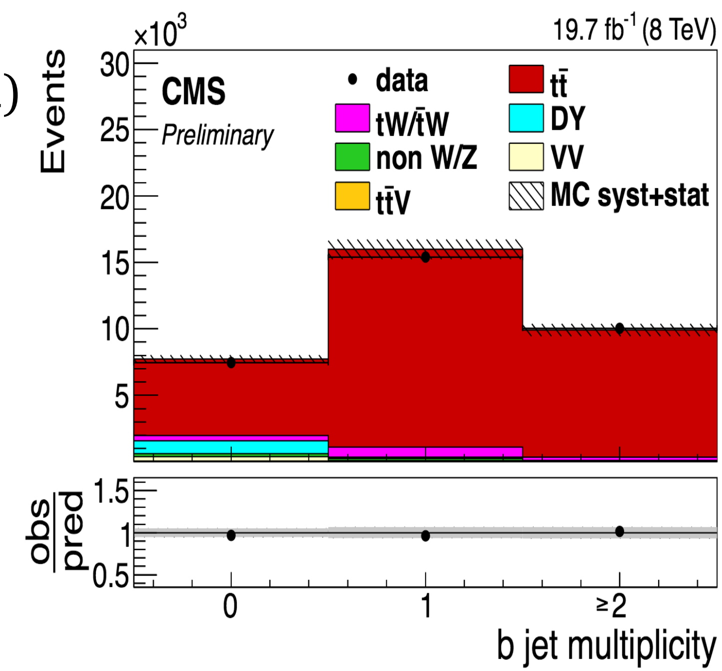
Top background is a mixture of tt and tW

0-jet bin: 45% of top is tW

1-jet bin: 25%

tt dilepton (TOP-13-004)

Source	Number of $e^{\pm}\mu^{\mp}$ events	
	7 TeV	8 TeV
DY	$22.1 \pm 3.1 \pm 3.3$	$173.3 \pm 25.1 \pm 26.0$
Non-W/Z	$51.0 \pm 0.7 \pm 15.3$	$145.9 \pm 14.8 \pm 43.8$
Single top quark (tW)	$204.0 \pm 3.1 \pm 61.2$	$1033.6 \pm 2.9 \pm 313.8$
VV	$6.9 \pm 0.6 \pm 2.1$	$35.4 \pm 1.9 \pm 11.1$
Rare ($t\bar{t}V$)	−−	$83.6 \pm 1.3 \pm 25.5$
Total background	$284.0 \pm 16.0 \pm 63.2$	$1471.7 \pm 46.7 \pm 319.1$
$t\bar{t}$ dilepton signal	$5008.2 \pm 15.4 \pm 188.0$	$24439.6 \pm 43.6 \pm 956.4$
Data	4970	25441



tW → main background of the analysis

CMS teams involved in Run-1

Brunel UNIVERSITY LONDON

KU

UNIVERSITY OF Nebraska Lincoln

Vrije Universiteit Brussel

l+jets

中国科学院 CHINESE ACADEMY OF SCIENCES

+ perpetual single top contributor

Run-I 7 TeV

- At 7TeV we explored single top tW associated production using the full luminosity ($4.9 fb^{-1}$)

σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7TeV	177.31	63.89	**15.74**	4.29

- First PAS, then paper

September 2011
CMS PAS-TOP-11-022

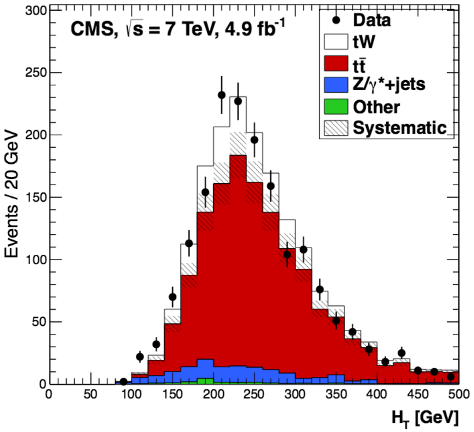
September 2012
Phys. Rev. Lett. 110 (2013) 022003
arXiv:1209.3489

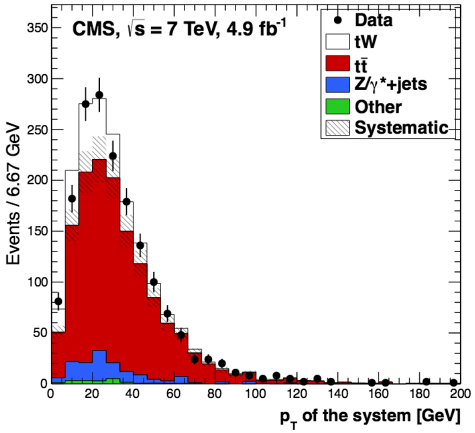
- The analysis used three regions
  - 1j1tag → signal region
  - 2j1tag → ttbar control region
  - 2j2tag → ttbar control region

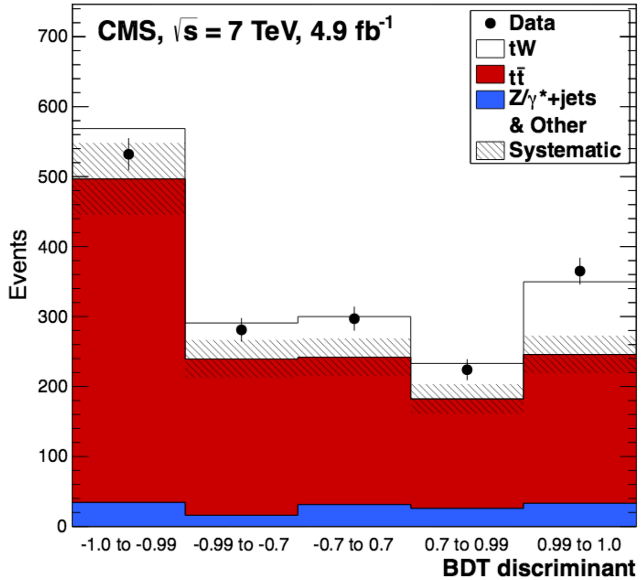
	1j1t	2j1t	2j2t
tW	336±5±16	180±3±16	45±1±6
$t\bar{t}$	1263±19±138	2775±28±205	1488±21±222
$Z/\gamma^\star$ +jets	128±12±28	113±10±22	8.5±1.8±1.8
Other	19±3	8.8±0.7±0.2	4±3
Total estimated	1746±23±141	3077±30±207	1546±21±222
Total data	1699	2878	1507

Analysis strategy

- BDT and cut-based analysis as cross-check
- 4 main kinematic variables for separating tW from tt:
  - p_T of the system
  - H_T
  - p_T of the leading jet
  - $\Delta\Phi_{\text{MET-closest lepton}}$



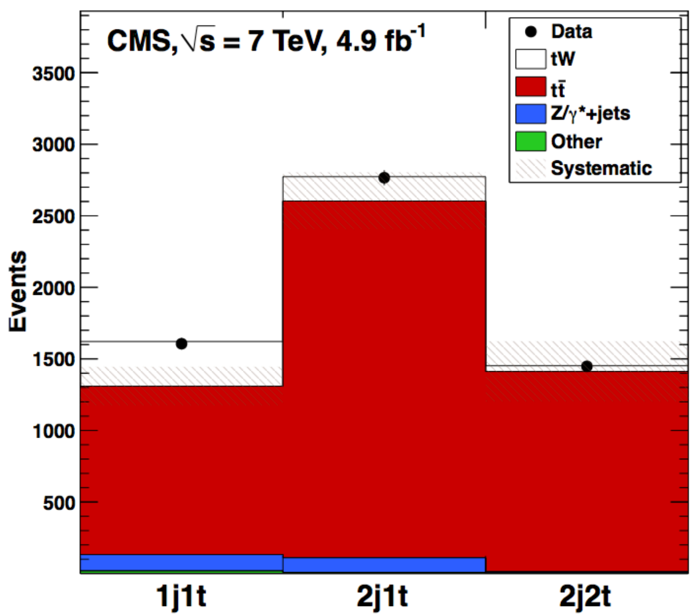




Drell-Yan background estimated from the Z mass peak (events vetoed in the analysis)
→ reweight of the MET distribution

Results

- Observed significance **4.0σ** (3.6 expected)
- Measured cross section: 16+5-4 pb
- Main uncertainty: **Statistical**, with a 20% effect
  - followed by theory uncertainties on ttbar (10%) and JES (up to 7%)



Evidence > 3σ
Analysis statistically dominated

Run-I 8 TeV

- Analysis repeated and improved
- BDT → different discriminant, more variables
- Additional cross-check → shape of the p_T of the system
- Not statistically dominated anymore → not full lumi used $12.2 fb^{-1}$
- PAS → then paper

July 2013
CMS PAS-TOP-12-040

January 2014
Phys. Rev. Lett. 112 (2014) 231802
arXiv:1401.2942

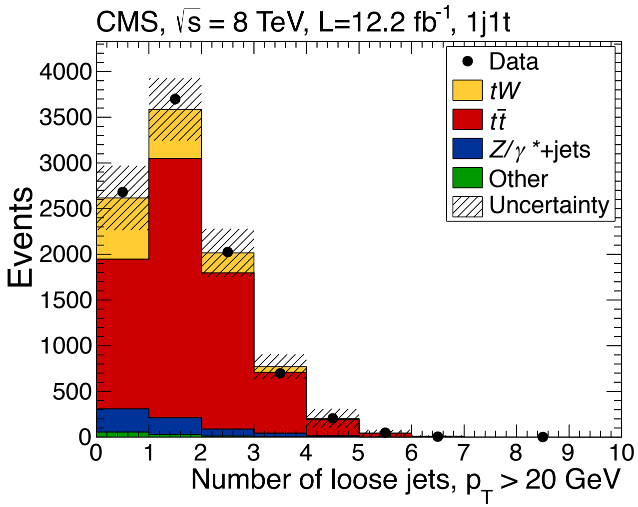
σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7TeV	177.31	63.89	15.74	4.29
LHC @ 8TeV	252.89	84.69	**22.2**	5.24

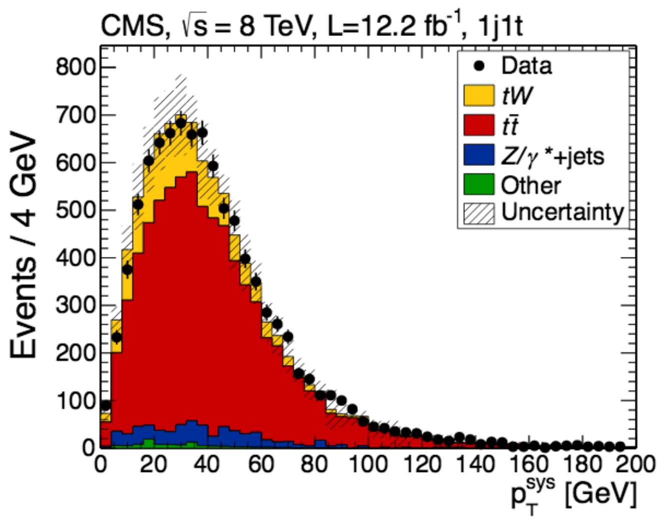
Analysis strategy

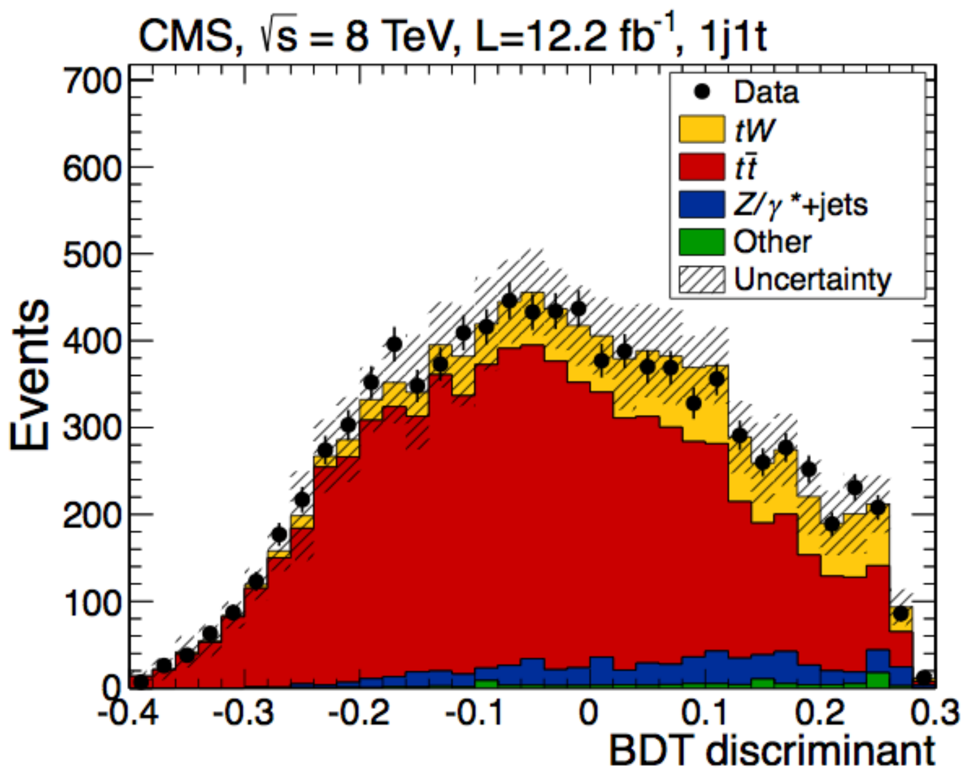
- The main challenge (as at 7TeV), is the **ttbar background**
  - ttbar with 1 jet outside acceptance or miss-reconstructed → signal
- We **maintained the 2 ttbar control regions** and improved the BDT
- 13 variables
  - Key upgrade: adding variables related to 'loose jets' → jets not fulfilling the main requirements for jets in the analysis but close to

Variable	Description
Nloosejets	Number of loose jets, $p_T > 20$ GeV, $\lvert\eta\rvert < 4.9$
NloosejetsCentral	Number of loose jets, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$
NbtaggedLoosejets	Number of loose jets, $p_T > 20$ GeV, CSVM btagged
$p_{T,sys}$	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
Jet p_T	p_T of the leading, tight, b-tagged jet
Loose jet p_T	p_T of leading loose jet, defined as 0 for events with no loose jet present
$p_{T,sys}/H_T$	Ratio of $p_{T,sys}$ to H_T for the event
Msys	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
centralityJLL	Centrality of jet and leptons
$H_{T,leptons}/H_T$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T-jll	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

Distributions







As for 7 TeV, he analysis performs a binned likelihood fit on the shape of the BDT

Results

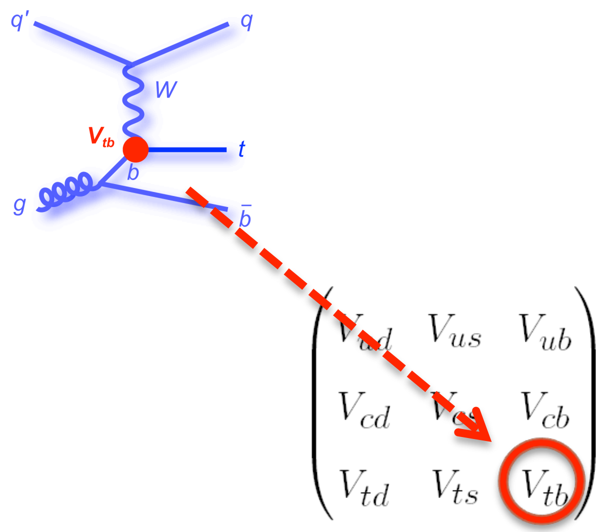
- Excess of events above the expected background with a significance of 6.1**σ** (5.4 expected)

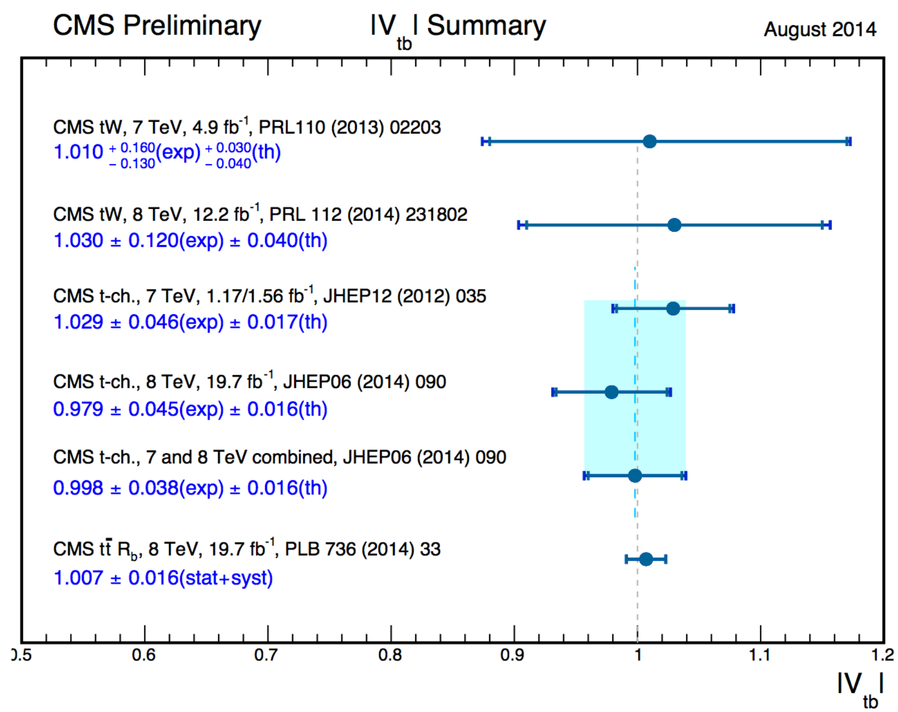
  → First observation of the process
- The measured cross section is 23.4±5.4 pb
- Main uncertainty:
  - choice of thresholds for the matrix element and parton showering (ME/PS) matching in simulation of ttbar and renormalization/factorization scales

Cross-section and $|V_{tb}|$

- From the inclusive production cross section of single top (**t-channel, tW**), a value of the **CKM matrix element, $|V_{tb}|$**, can be extracted
- Considering $|V_{td}|$, $|V_{ts}|$ << $|V_{tb}|$
- Cross section ~ $|V_{tb}|^2$

$$|V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{theory}}}$$





7 TeV	8TeV
$|V_{tb}|$ = 1.01	$|V_{tb}|$ = 1.03

ATLAS

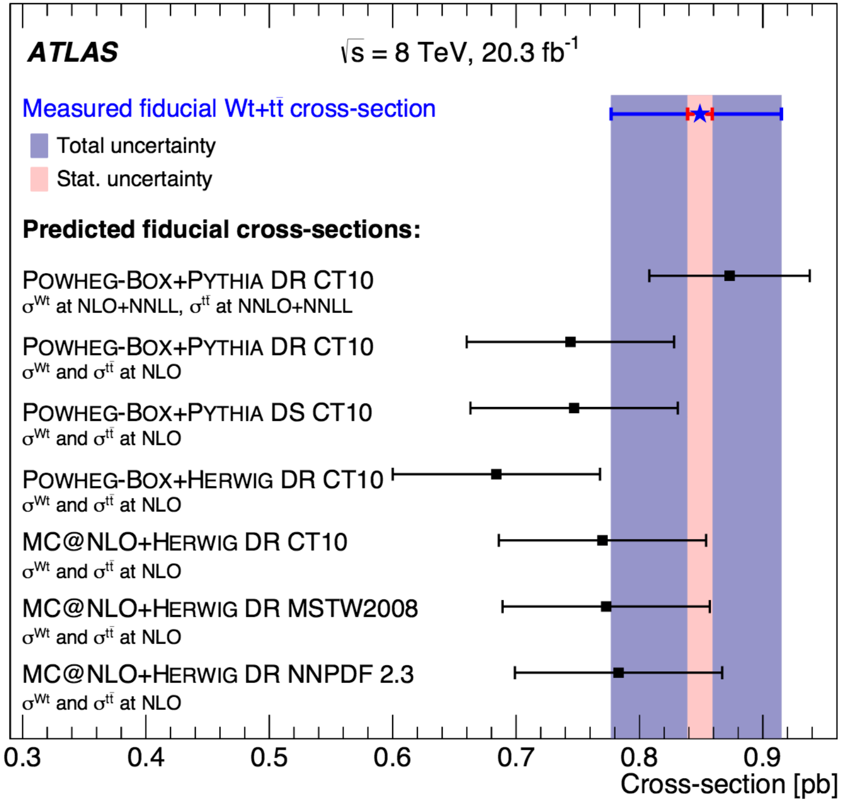
- Meanwhile ATLAS has been following a parallel route:
- In may 2012 they submitted the (first) evidence at 7TeV
  - http://arxiv.org/abs/1205.5764
- **Last week** they submitted the observation at 8TeV
  - http://arxiv.org/abs/1510.03752v2
- Together, we made a combination a while ago (with an ATLAS CONF note)

Energy	Predicted	CMS	ATLAS	LHC
7TeV	15.6±0.4±1.1	16+5-4	16.8±2.9±4.9	nope
8TeV	22.2±0.6±1.4	23.4±5.4	23.0±1.3+3.2−3.5±1.1	25.0±1.4±4.4±0.7

In the latest ATLAS paper

- Something new was reported:
  - Fiducial cross section
  - 1jet-1tag region → **tW + ttbar**

- Fiducial measurements are interesting on their own:
  - more robust comparison to the theoretical prediction reducing the sensitivity to theory modeling uncertainties
- But especially, the study of the tW-tt interplay is interesting

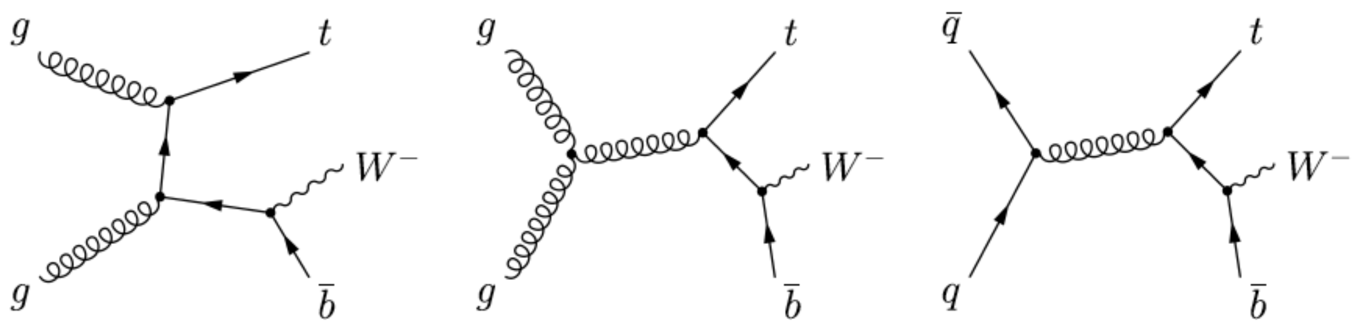


ttbar and tW

- tt production is the main background for the tW analysis
  - ~10X the cross-section (depending on the center of mass energy)
  - able to provide identical final states when one of the b-quarks is outside acceptance

- But there is something more:
  - At NLO tW mixes with ttbar, sharing initial/final states → this causes theoretical problems in the signal definition

NLO

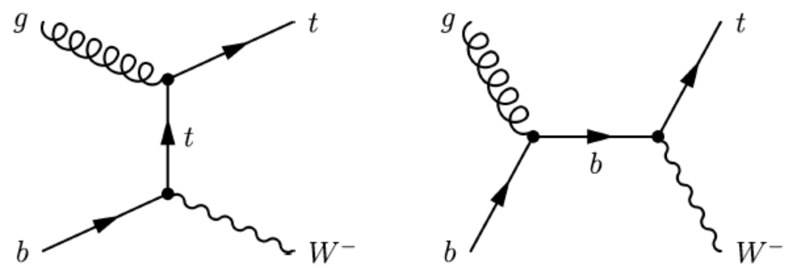


ttbar in tW

- Two alternative solutions → **none of them theoretically sound**
  - diagram removal (DR): the problematic diagrams are removed
  - diagram subtraction (DS): resonant diagrams cancelled with the introduction of a gauge-invariant term
  - http://arxiv.org/abs/0908.0631

- In practice this means:
  - tW is defined at LO → O(20%) accuracy

LO



  - Traditional workarounds suffer from conceptual issues → systematic theoretical uncertainty that **cannot be reduced**

tW+tt unified description

- Recently **(2013)**, several papers suggested an unified description at NLO, 4FS (massive b):
  - Frederix :
    - http://arxiv.org/abs/1311.4893
  - F. Cascioli, S. Kallweit, P. Maierhöfer, S. Pozzorini:
    - http://arxiv.org/abs/1312.0546
  - G. Heinrich, A. Maier, R. Nisius, J. Schlenk, J. Winter:
    - http://arxiv.org/abs/1312.6659
- Topic **discussed in the single top workshop**:
  - 2013 (Frederix): https://indico.cern.ch/event/275626/session/0/contribution/2/attachments/499458/689961/frederix.pdf
  - 2014 (Caola): https://indico.cern.ch/event/331154/session/1/contribution/20/attachments/644959/887235/singletop_napoli.pdf

Going into more details

- Frederix (for example) proposes the unified studied of the processes for a specific problem: top background to Higgs searches (1 jet bin)
  - This is relevant in the H→WW channel
  - It applies in the same way to the tt dilepton measurements
- The idea is to achieve a unified description that does not separate tt and tW, keeping all their interference effects
  - Requires NLO calculation to the pp → 2l2nubb+X in the 4FS

- **5FS**: the mass of the b is neglected, the process (pp → 2l2nubb+X) is not finite in fixed-order perturbation theory without requiring phase-space cuts on the final state b jets
  - → cannot be used for tW
- **4FS**: b massive with a finite value, includes:
  - double quark resonant production (tt)
  - single top-quark resonant contributions (tW)
  - non top-quark resonant contributions

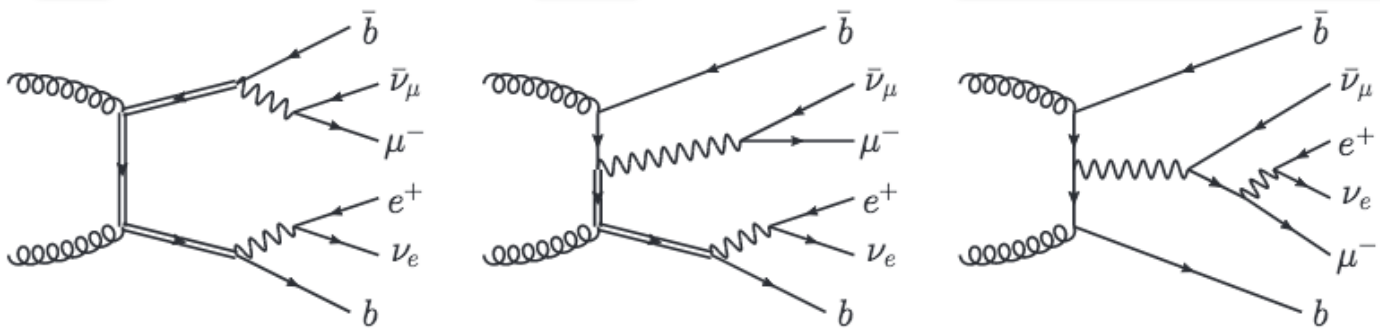
What does this mean?

- Means that we could describe a set of processes **accurately at NLO** including ttbar and tW:

tt

tW

b-quark associated llvv production



- The fixed order NLO the combined **pp → bb2l2nu+X** is possible and has been done already (in Madgraph5_AMC@NLO)
- For a more exclusive description of the final state, matching to the parton shower would be required
  - The parton shower is not yet available. It will take at least a couple of more months → **Maybe sometime early next year?**

Run-2

- In terms of cross section, is the single top process that will grow the most (similar increase as ttbar)

σ [pb]	ttbar	t-channel	tW	s-channel
LHC @ 8TeV	252.89	84.69	22.2	5.24
LHC @ 13TeV	831.76	216.99	71.2	10.32
From 8 to 13TeV	**3.3**	2.6	**3.2**	1.9

- The process has been already established
  - Still interesting to check it at 13TeV
- In Run-2 the **role of tW as background** will become particularly relevant
  - For H→WW (obvious)
  - And especially for tt dilepton precision measurements
- The study of ttbar and tW together will therefore be very important and should be done either like ATLAS → fiducial region(s), or directly with the appropriate full NLO simulation

Measuring tt+tW

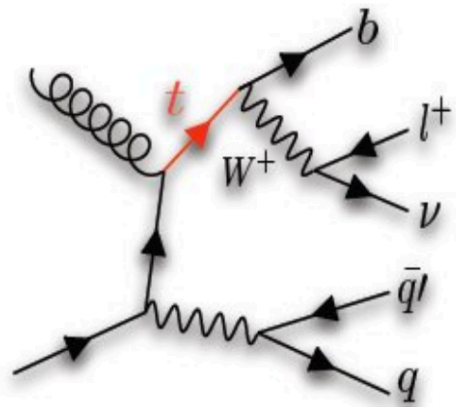
- Common measurement of tW and tt:
  - 1j1t (tW signal region)
  - 2j2t (ttbar and interference region)
  - Fiducial (like in ATLAS) or not

- Once the region to perform the analysis is defined:
  - If there is MC for the unified description → compare directly
  - If the MC is not available yet → make a simultaneous fit of tt and tW using separated samples (neglecting interference)

- This can be done either within the tW or ttbar analyses, or by teams from both working together (depending on amount of people)
  - Use the same objects/selections from the start of the tW and tt analyses

tW in the l+jets channel

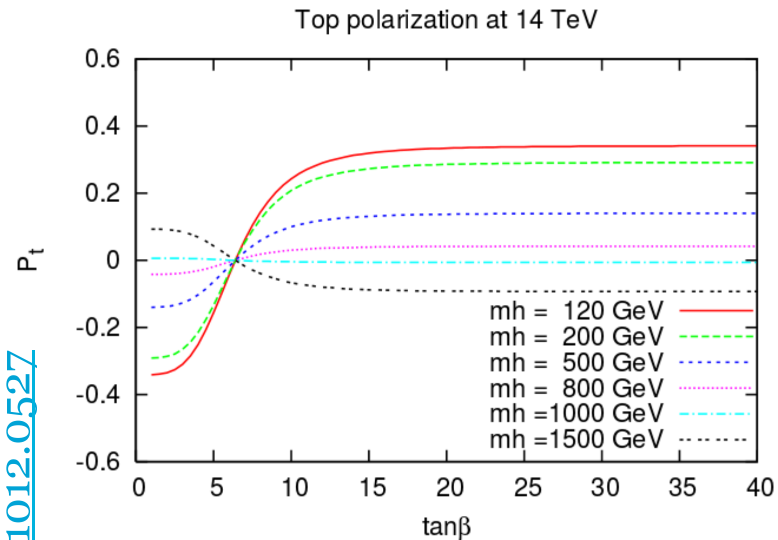
- There has been an effort with Run-1 data on exploring the l+jets signature that is ongoing
- Signature:
  - 1 lepton and MET from a W decay
  - 1 b quark from the top
  - 2 light quarks from a W decay
- Not only ttbar background, also W+jets
- Cons:
  - Smaller S/B,
  - separation between ttbar and tW even more difficult
- Pros:
  - Higher statistics, potential reconstruction of angular variables

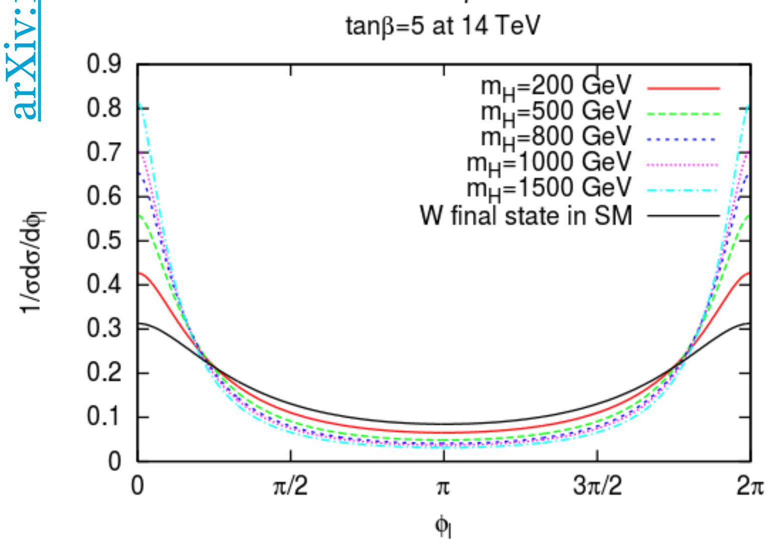


top polarization, angular distributions

- Top polarization can also be measured in the tW channel:
  - sensitive to anomalous couplings
  - sensitive to charged Higgs pp → tH^-
- More challenging than in the t-channel:
  - The polarization is 0.25 (0.9 in the t-channel)
  - signal over background ratio worse in tW
  - Requires top quark reconstruction:
    - Maybe a study for the l+jets decay
- Other options :
  - measure angular distributions in the lab frame :
    - $\Delta\Phi_{ll}$: (Is it worth it?)
    - Φ_l: lepton azimuthal angle. Need to determine the lepton from top.

arXiv:1012.0527





Summary

- Run-1 was good for singlet top tW associated production
  - We achieved first evidence at 7 TeV, then observation at 8TeV, and measured the cross section

- A key role for tW lays on its contribution to other analyses as background
  - Higgs is the classic case
  - Ttbar dilepton is also important

- The main issue when studying tW is the ttbar background
  - Large contribution, similar final states, mixing at NLO

- A common description of tt and tW at NLO could be used → both processes studied together, that could have an immediate use case in H→WW