Perspectives for top at the LHC at 13-14 TeV

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On behalf of the ATLAS and CMS collaborations

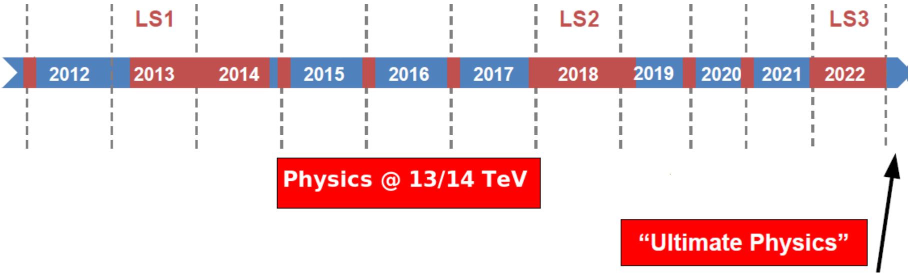
Top 2013 Workshop

14-19 September 2013, Durbach, Germany

Plan of talk

1. Schedule for 13/14 TeV run
2. Pile-up and how to fight it
3. Cross sections and 14/8 TeV ratios
4. Prospects for searches and measurements
5. Conclusion

Introduction: LHC schedule

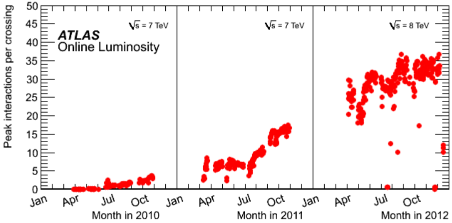


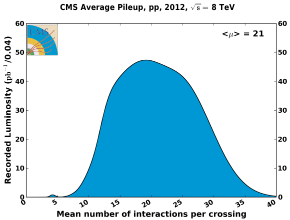
Period	Lumi $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	pile-up	$\mathcal{L}_{\mathrm{Int}}$ (fb^{-1})
2012	$7 \cdot 10^{33}$	21	25
2015-2017	$1 \cdot 10^{34}$	25	90
2019-2021	$2 \cdot 10^{34}$	50-80	300
2022-	$5 \cdot 10^{34}$	~ 140	3000

Pile-up corresponds to the average number of interactions per bunch crossing ($\langle\mu\rangle$).

Aiming to collect $90\mathrm{fb}^{-1}$ at 13-14 TeV by LS2!

Effects of pile-up



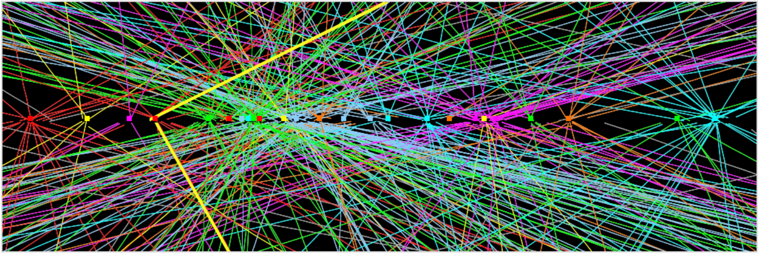


Top physics uses all types of objects in the events, which requires high performance of the reconstruction and identification algorithms.

Need to understand how high pile-up affects performance at high luminosity and how to deal with potential degradation.

1. trigger: needed to retain $\sim$ current trigger thresholds with higher rates.
2. lepton isolation affected.
3. additional jets from pile-up interactions present in events.
4. b-tagging: primary vertex mis-id, pile-up tracks, fake tracks.
5. Jet performance: need to subtract pile-up energy ($\sim$1 GeV per vertex for $R = 0.6$ jets); noise term larger $\implies$ degradation in jet resolution.

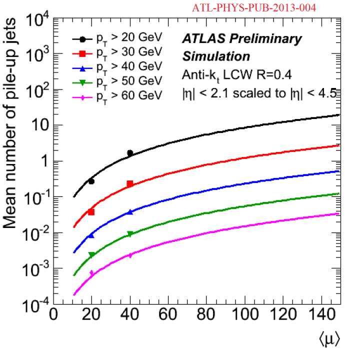
High pile-up environment

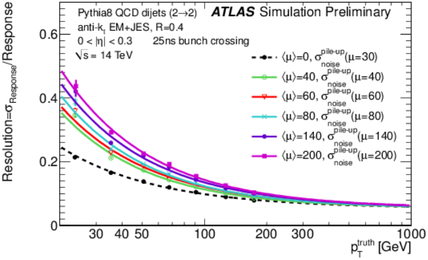


$Z\mu\mu$ event seen by ATLAS in 2012 data, with 25 vertices.

The ATLAS and CMS detectors implementing a number of hardware upgrades to cope with high pile-up - Phase 0 upgrades in LS1 (now), Phase I in LS2 (2018); Phase II in 2022.

Jets at high pile-up

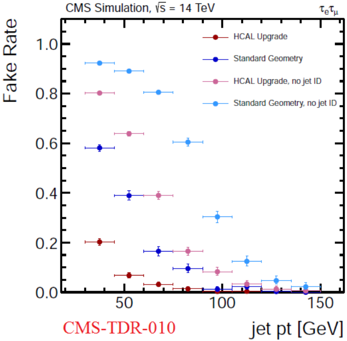


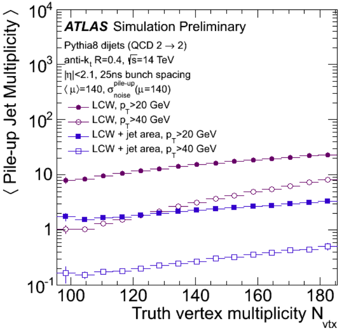


At very high luminosity, jet p_T thresholds may need to be increased to suppress pile-up jet contamination. Worsening in jet resolution due to local fluctuation of pileup activity.

Importance of new algorithms

Many new techniques under investigation in ATLAS and CMS.

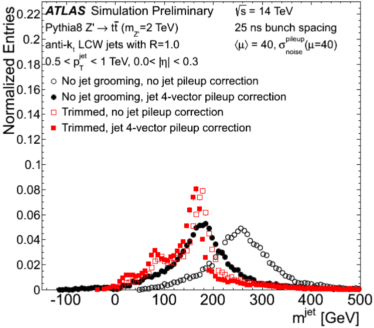


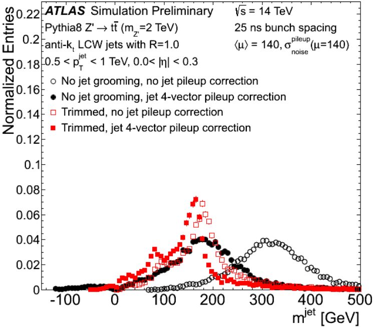


CMS will use multivariate discriminator (jet shape, multiplicity of neutral and charged components etc)+ HCAL upgrade. Pile-up subtraction reduces mean number of pile-up jets per event.

Boosted jet techniques for pile-up suppression

Particularly relevant to boosted top jets - many new ideas and techniques.





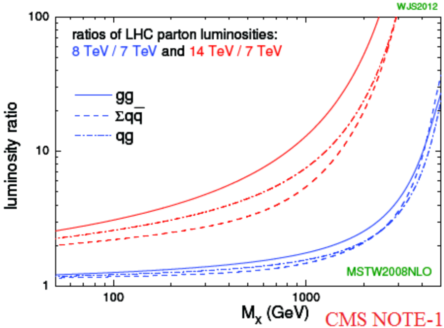
For both CMS and ATLAS, planned upgrades and algorithm improvements compensate for the worsening in perfomance due to more challenging conditions (pile-up, luminosity).

Reasonable to extrapolate current results to high luminosities (300-3000 fb^{-1}).

Parton luminosities and $t\bar{t}$ production

The dominant part of the $pp \to X$ production cross section tends to come from luminosity term,

$$\mathcal{L}(M, s) = \frac{1}{s} \int_{\tau}^{1} \frac{dx}{x} \sum_{i,j} f_i(x, M) f_j(\tau/x, M)$$



CMS NOTE-13-002

Cross sections of processes dominated by $gg \to X$ grow faster than those of $q\bar{q} \to X$.

The biggest gains are for high final state mass processes: factor of $\mathcal{O}(100)$ gains for multi-TeV masses!

Cross section ratios: 14 TeV to 8 TeV

Cross Section	$R^{\mathrm{th,nnpdf}}$	δ_{PDF}(%)	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	2.12	$\pm$ 1.3	-0.8 – 0.8	-0.4 – 1.1
$t\bar{t}$	3.90	$\pm$ 1.1	-0.5 – 0.7	-0.4 – 1.1
Z	1.84	$\pm$ 0.7	-0.1 – 0.3	-0.3 – 0.2
W^+	1.75	$\pm$ 0.7	-0.0 – 0.3	-0.3 – 0.2
W^-	1.86	$\pm$ 0.6	-0.1 – 0.3	-0.3 – 0.1
W^+/W^-	0.94	$\pm$ 0.3	-0.0 – 0.0	-0.0 – 0.0
W/Z	0.98	$\pm$ 0.1	-0.1 – 0.0	-0.0 – 0.0
ggH	2.56	$\pm$ 0.6	-0.1 – 0.1	-0.9 – 1.0
$t\bar{t}(M_{tt} \geq 1\ \mathrm{TeV})$	8.18	$\pm$ 2.5	-1.3 – 1.1	-1.6 – 2.1
$t\bar{t}(M_{\mathrm{tt}} \geq 2\ \mathrm{TeV})$	24.9	$\pm$ 6.3	-0.0 – 0.3	-3.0 – 1.1
$\sigma_{\mathrm{jet}}(p_T \geq 1\ \mathrm{TeV})$	15.1	$\pm$ 2.1	-0.4 – 0.0	-1.9 – 2.4
$\sigma_{\mathrm{jet}}(p_T \geq 2\ \mathrm{TeV})$	182	$\pm$ 7.7	-0.3 – 0.2	-5.7 – 4.0

(from Mangano, Rojo, JHEP 1208 (2012))

Cross sections in tails increase by a lot - careful with extrapolations using overall cross section scaling!

Cross sections at 14 TeV

Process	σ (14 TeV) [in pb]	Reference
$t\bar{t}$	953.6 $\pm$ 38	Czakon et al, Phys.Rev.Lett. 110 (2013) 252004
s-channel single t	11.9 $\pm$ 0.4	Kidonakis, Phys.Rev. D81 (2010) 054028
t-channel single t	243 $\pm$ 6	Kidonakis, Phys.Rev. D83 (2011) 091503
Wt-channel single t	82.4	Kidonakis, Phys.Rev. D82 (2010) 054018

Top pair and single top production cross sections at 14 TeV.

With 300 fb^{-1} at 14 TeV, produce roughly 250 million $t\bar{t}$ and 100 million single top events.

Prospects of new and existing measurements for 14 TeV

Roughly 6 million $t\bar{t}$ events produced during $\sqrt{s} = 8$ TeV run $\implies$ most measurements already limited (/will soon be limited) by systematics - cross section (top and single top), mass measurements, spin correlation...

Systematics usually of tricky kind: generator, PDF, shower modelling, ISR/FSR. Constraining them will take time, even with much more data.

However, all searches and some measurements directly benefit from increased energy and luminosity:

1. searches for FCNC decays
2. searches for resonances decaying to $t\bar{t}$ pairs
3. searches for stops
4. mass measurements
5. measurement of $t\bar{t}V, V = W, Z, \gamma$

Prospects for FCNC searches

Different possibilities: $t \to Zq, t \to q\gamma, t \to qg, t \to hq$.

The best current limits just starting to probe the $< 10^{-3}$ range:

- $BR(t \to qZ) < 0.07\%$ at 95% CL (CMS, TOP-12-037, 19.5fb^{-1} at $\sqrt{s} = 8$ TeV)
- $BR(t \to cg) < 1.6 \cdot 10^{-4}$ (ATLAS-CONF-2013-063, $\sqrt{s} = 8$ TeV)
- $BR(t \to cH) < 3.1 \cdot 10^{-3}$ (SUS-13-002; also ATLAS-CONF-2013-063, both $\sqrt{s} = 8$ TeV)

The interesting range is however below this - Randall-Sundrum, 2DHM, (RPV) SUSY and other BSM model values typically expected to be $10^{-5} - 10^{-4}$, or less.

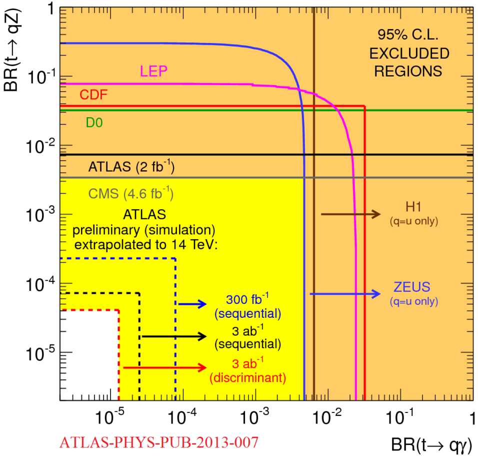
Performing searches in all the possible channels is important, since different models predict different FCNC branching ratios.

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY	TC2
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\sim 10^{-4}$

Prospects for FCNC searches

Extrapolation of existing CMS results indicates that sensitivity with 300 fb^{-1} will go down to $\mathcal{O}(10^{-5})$.

ATLAS sensitivity for $t \to Zq$ and $t \to q\gamma$ expected to be $10^{-5} - 10^{-4}$ $(10^{-4} - 10^{-3})$ for 3000fb^{-1} (300fb^{-1}).



ATLAS-PHYS-PUB-2013-007

Ditop resonances

Prospects for the 14 TeV LHC for resonances decaying to $t\bar{t}$ have been studied by ATLAS (ATLAS-PHYS-PUB-2013-003, arXiv:1307.7292).

Considered broad (KK gluon, g_{KK}) and narrow (topcolor Z') resonances; detector parametrisations used for very high pile-up expected at the HL-LHC.

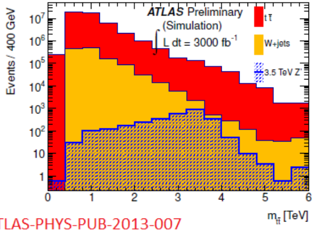
anti-k_t jets with $R = 0.4$ and $R = 1.0$, with p_T cuts of 25 GeV and 250 GeV, respectively. Leptons (e or μ) with $p_T > 25$ GeV.

Single lepton selection:

- exactly one lepton which fires the trigger
- at least one b-tagged $R = 0.4$ jet, and one $R = 1.0$ jet with $m_{\rm jet} > 120$ GeV
- $\not{E}_T > 50$ GeV

Dilepton selection:

- exactly two opposite sign leptons (m_{ll} outside the (81 GeV, 101 GeV) window, if same flavour)
- at least two b-tagged $R = 0.4$ jets
- $\not{E}_T > 60$ GeV



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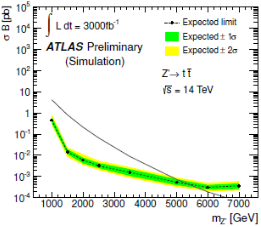


Topcolor Z' in the l+jets channel with 3000 fb^{-1} at 14 TeV.

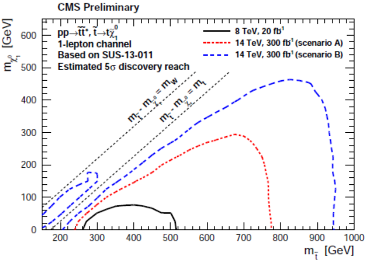
model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

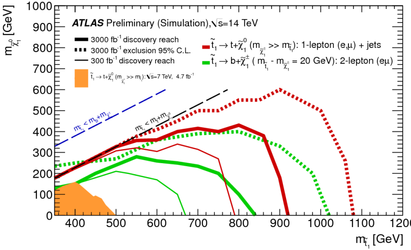
Expected limits in absence of signal, in TeV for the 14 TeV LHC, for the l+jets (dilepton) channels. Current limits 2-2.5 TeV.

Prospects for stop searches

Natural SUSY motivates light left and right handed stops, left handed sbottoms and, to a lesser extent, gluinos.

CMS considered the prospects of the $1l$ analysis (scenario A: scale background uncertainty from 20fb^{-1}, scenario B: assume it reduces by $1/\sqrt{L_1/L_0}$); ATLAS studied $1l$ and $2l$ analyses.



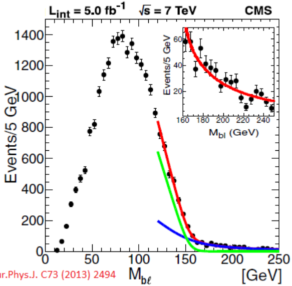


Discovery reach up to 800-1000 GeV in $m_{\tilde{t}}$. Shape and angular correlation techniques as well as use of boosted objects expected to improve reach considerably.

Mass measurements

New techniques whose systematics often different from more “conventional” methods. Some already done: measurement of m_t via transverse decay length (L_{xy}) of B-hadrons in $t\bar{t}$ events, or via endpoint in m_{bl} distribution.

Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{\text{stat}} \pm 1.6_{\text{syst}} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{\text{stat}} \pm 1.7_{\text{syst}} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{\text{stat}} \pm 1.4_{\text{syst}} \pm 2.4_{p_T(t)}$

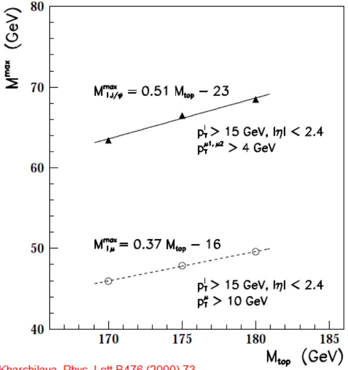


Eur.Phys.J. C73 (2013) 2494

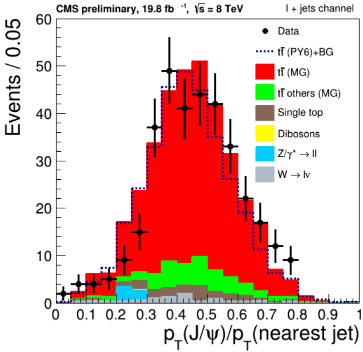
Eliminate dependence on jet physics (and uncertainties) as much as possible: lepton p_T spectrum, or $t \to b \to J/\psi \to \mu^+\mu^-$ decays (CMS, CERN/LHCCC92-3; Kharchilava, Phys. Lett **B476** (2000),73).

Top mass from $t \to b \to J/\Psi \to \mu^+\mu^-$ decays

Branching ratio for the required final state topology is low, $\sim 10^{-5}$.



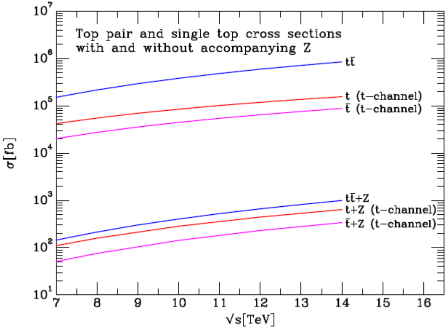
Kharchilava, Phys. Lett B476 (2000),73



Good correlation/linearity between m_t and $m_{lJ/\psi}$ (~ 2). Slope for $m_{l\mu}$ similar.
Dominant systematic from modelling of b fragmentation - expect < 1 GeV ultimate precision, complementary to existing measurements using jets.

Other methods: m_t via *differential* x-sec measurements - need theoretically well understood shapes (see talk by J. Fuster).

$t\bar{t}V\,(V = W, Z)$ and $tZ + \bar{t}Z$ processes



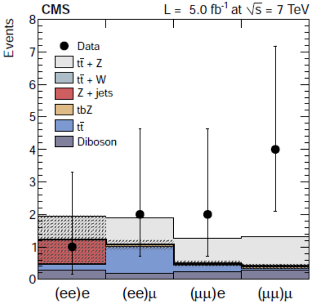
Campbell et al, Phys.Rev. **D87** (2013) 114006

Large final state mass $\Longrightarrow$ large gain in cross section when $\sqrt{s}$ increased. $tZ + \bar{t}Z$ cross section larger by a factor of 4 at 14 TeV compared to 8 TeV. ≈ 1 pb cross section; cross section of $t\bar{t}Z$ comparable to $tZ + \bar{t}Z$.

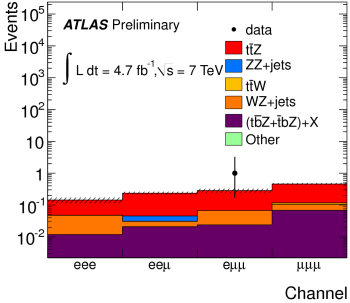
Backgrounds are rare SM processes, e.g. $WZb\bar{b}$+jets; in addition, $tZ + \bar{t}Z$ is a background to $t\bar{t}V\,(V = W, Z)$. Relatively little is known about these processes.

$t\bar{t}V, tZ$ are important backgrounds in a number of BSM searches, especially for naturalness motivated models involving multiple leptons, b-tagged jets and $\not{E}_T$.

$t\bar{t}Z$ searches/cross section



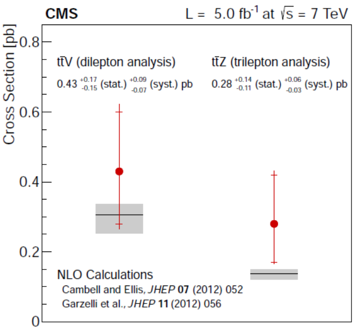
CMS-TOP-12-014

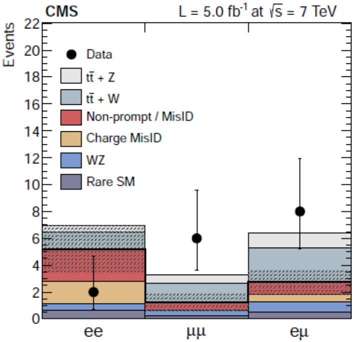


ATLAS-CONF-2012-126

Both analyses in trilepton channel. Handful of events expected in both cases (1-4). Will benefit a lot from increase in cross section and luminosity! With 100fb^{-1} at 14 TeV, expect hundreds of events.

$t\bar{t}V$ cross section

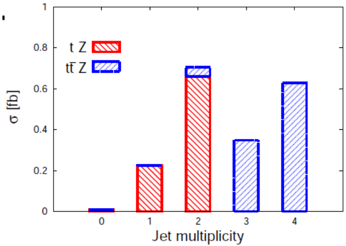




CMS measures the $t\bar{t}V$ cross section in the dilepton channel - both $t\bar{t}W \to (bl\nu)(\bar{b}jj)(l'\nu')$ and $t\bar{t}Z \to (bl\nu)(\bar{b}jj)(l'^{+}l'^{-})$ contribute here. With more statistics, the two processes can be separately measured. Good understanding of backgrounds crucial (data driven).

tZ at NLO

A good uncertanding of rare processes very important; at LO, $t + Z$ events have up to two jets, and are clearly separated from $t\bar{t}Z$ in jet multiplicity:



Campbell et al, Phys.Rev. D87 (2013) 114006

However, at NLO, almost 50% of the cross section is in the 3-jet bin (Cambpell et al)!

Jet multiplicity	0	1	2	3	-
$\sigma(tZ + \bar{t}Z)$	LO	0.014	0.331	1.05	-
$\sigma(tZ + \bar{t}Z)$	NLO	0.011	0.237	0.585	0.693

This is t-channel; no results for Wt-channel single $t + Z$.

Constraining top couplings with $t\bar{t}Z$

Can study the structure of ttV couplings (Baur et al (hep-ph/0412021)):

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

Deviations from SM values of the couplings can be observed in the $p_T(\gamma, Z)$ distributions.

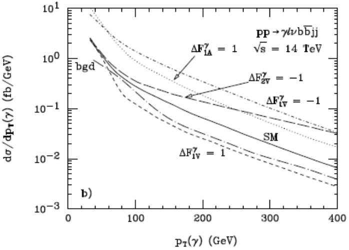
For $t\bar{t}Z$, obtain pure sample ($S/B \gtrsim 10$) with

- $m_Z - 10 \text{ GeV} < m(\ell\ell) < m_Z + 10 \text{ GeV}$
- $m_T(b_{1,2}\ell; \not{p}_T) < m_t + 20 \text{ GeV}, m_t - 20 \text{ GeV} < m(b_{2,1}jj) < m_t + 20 \text{ GeV}$

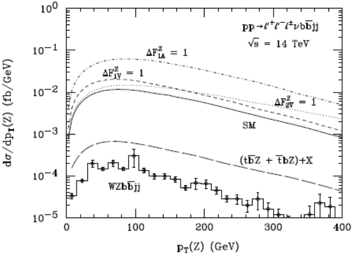
After these cuts, signal cross section is 2.25 fb before detector effects/object efficiencies. ATLAS/CMS studies indicate similar cross sections for their respective selections, while maintaining reasonable S/B ratios.

Determination of EW couplings of the top

A similar strategy can be used for the top couplings to the photon.



Baur et al, Phys.Rev. D71 (2005) 054013

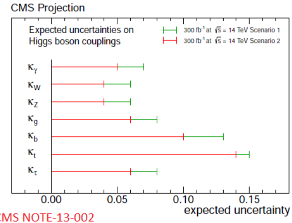


One can hope to determine the couplings of the top to γ with better than $\sim 35\%$ accuracy already with 30 fb^{-1} at 14 TeV; couplings to the Z are more difficult but can expect 20-50% precision with 300 fb^{-1}.

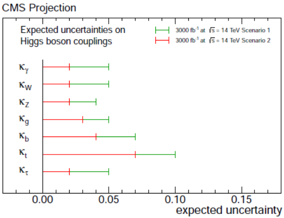
coupling	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
ΔF^{γ}_{1V}	$^{+0.23}_{-0.14}$	$^{+0.079}_{-0.045}$	$^{+0.037}_{-0.019}$
ΔF^{γ}_{1A}	$^{+0.17}_{-0.52}$	$^{+0.051}_{-0.077}$	$^{+0.018}_{-0.024}$
ΔF^{γ}_{2V}	$^{+0.34}_{-0.35}$	$^{+0.19}_{-0.20}$	$^{+0.12}_{-0.12}$
ΔF^{γ}_{2A}	$^{+0.35}_{-0.36}$	$^{+0.19}_{-0.21}$	$^{+0.11}_{-0.14}$

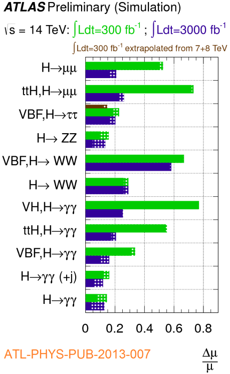
Yukawa coupling of the top

Important (due to role of top in EWSB) and difficult to determine due to low $\sigma \times BR$: $\sigma(t\bar{t}H) = 623$ fb at 14 TeV (129 fb at 8 TeV); e.g. $BR(H \to \gamma\gamma) \sim 2.3 \cdot 10^{-3}$. CMS considers two systematics scenarios. Scenario 1: systematics unchanged with respect to 8 TeV. Scenario 2: theory systematics scaled by 1/2, other systematics reduced by $1/\sqrt{L_1/L_0}$.



CMS NOTE-13-002





ATL-PHYS-PUB-2013-007

Conclusions

Lots of new and exciting top physics expected with the 13/14 TeV LHC.

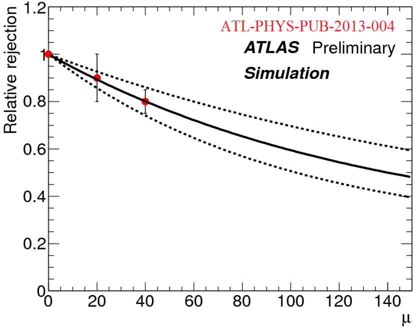
Lots of work already underway - both on the hardware/object reconstruction (detector upgrades, tackling difficult high luminosity/pile-up conditions, development of new and improved reconstruction algorithms) and analysis fronts.

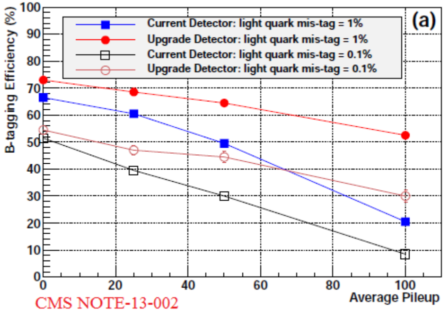
New measurements at 14 TeV: electroweak couplings of the top; the $t + Z$ process; new methods for top mass measurements, and many others.

Room for improvement in measurements dominated by systematics: MC tuning, data driven methods, etc.

Synergy between theory and experiment - e.g. constraints of gluon PDFs from top cross section. Commissioning latest-generation Monte Carlo tools (MEPS@NLO, aMC@NLO, etc.) will benefit many measurements.

Backup: b-tagging at high pile-up





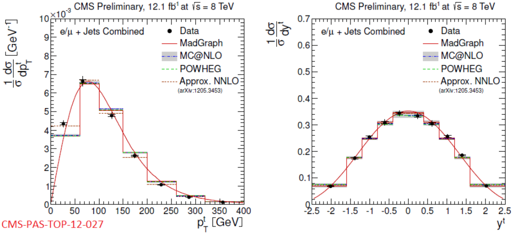
Significant degradation expected at very high μ - e.g. light jet rejection worsens by up to a factor of ~ 2 (NB assuming the current detector - Phase II upgrades should ameliorate this significantly!).

Backup: Differential cross sections

$t\bar{t}$ cross section has been measured as a function of $m_{t\bar{t}}, p_{t\bar{t}}, y_{t\bar{t}}$.

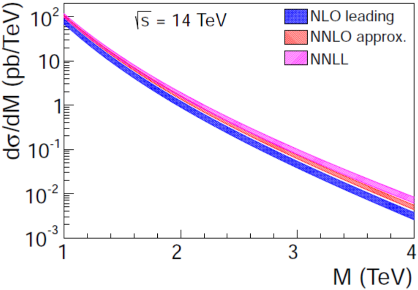
The uncertainties tend to be systematics dominated, even for large values of $m_{t\bar{t}}, p_{t\bar{t}}$ (due to choice of binning/unfolding procedure).

Very important to understand higher order effects on the theory side.



(Approximate) NNLO seems gives best description of p_T distribution. At the moment, approximate NNLO calculations available for $p_T, y_{t\bar{t}}$ (Kidonakis, arXiv:1205.3453) and $m_{t\bar{t}}$ distributions (Ferroglia et al, arXiv:1306.1537).

$m_{t\bar{t}}$ spectrum at approximate NNLO



(from Ferroglia et al, arXiv:1306.1537)

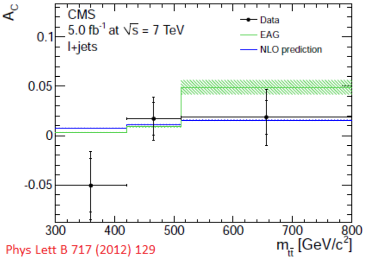
Relevant to resonance searches as well as differential cross section measurement.

Can we improve systematics in regions of interest (e.g. high $m_{t\bar{t}}$)? Ratios can be important here (Mangano, Rojo 2013): considering the ratio of measured cross sections at two different values of $\sqrt{s}$ can (i) cancel theoretical systematics and (ii) enhance sensitivity to BSM physics, **if** cross section of BSM process scales differently from $t\bar{t}$ - true e.g. if production dominated by $q\bar{q}$ initial state.

Backup: Other topics

Many other measurements interesting to look at from the 14 TeV LHC point of view.

- $gt\bar{t}$ vertex: $(g_s/2)G^a_{\mu\nu}\bar{t}(T^a\sigma^{\mu\nu}(\mu + i\gamma^5 d))t$. Spin correlation measurements will constrain μ, d to $< 1\%$ (Bernreuther, Si 2013; Baumgart, Tweedie, JHEP 1303 (2013) 117).
- Charge asymmetry - can benefit from more statistics in differential measurements:



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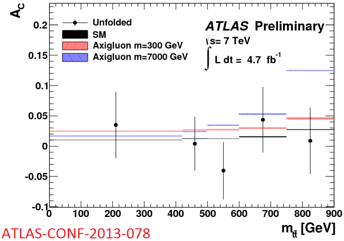

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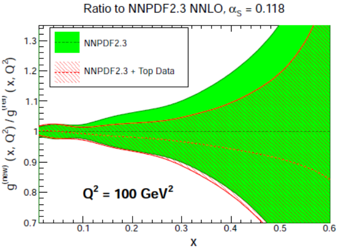
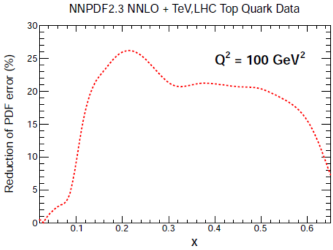
However, the asymmetry decreases at 14 TeV since $gg \to t\bar{t}$ more important. Explore new observables which can enhance the asymmetry (Berge, Westhoff arXiv:1307.6225, Aguilar-Saavedra et al, Phys.Lett. **B707** (2012)).

Synergies between theory and experiment: reduction of PDF uncertainties

A nice example is constraining on the gluon PDF from the top pair cross section measurement (Czakon et al, arXiv:1303.7215). $gg \to t\bar{t}$ is 85-90% of $t\bar{t}$ production at LHC, depending on $\sqrt{s}$.

Works because other theory uncertainties (e.g. from renormalisation/factorisation scales) very small (NNLO+NNLL!).





Can reduce high x gluon PDF uncertainties by $\sim 20\%$ with present measurements.

Gluon PDF uncertainties in BSM searches

Many BSM model production cross sections suffer from large PDF uncertainties (large mass $\equiv$ high x), e.g. uncertainty on gluino pair production cross section with $m_{\tilde{g}} = 2$ TeV is 32% at $\sqrt{s} = 13$ TeV. Finding ways of reducing these very important.

Effect of including top cross section constraints in PDF fits on KK gluon production: