HL-HE LHC: Top Studies

Paolo Nason

CERN and INFN, sez. di Milano Bicocca

for the Conveners of the Standard Model Working group (WG1):

Patrizia Azzi (CMS)
Dieter Zeppenfeld (Theory)
Paolo Nason (Theory)
Stephen Farry (LHCb)
Alessandro Tricoly (ATLAS)

Bad Neuenahr, September 21 2018

Top related activities

- Top Cross Sections
  - $t\bar{t}$ cross sections
  - Single Top
- Top Properties
  - Charge Asymmetries
  - Spin Asymmetries
- Top Mass
  - Theory issues
  - Mass with J/Ψ
  - Standard Measurements
- Top Couplings
  - $t\bar{t} + X$ and anomalous couplings
  - Single Top
- FCNC
  - tqg
  - $tq\gamma$
  - tHq
  - tZq

Top-quark studies at the HL/HE LHC

Marco Zaro

with material and input from

Matteo Cacciari, Fabrizio Caola, Alexander Mitov, Davide Pagani,
Andew Papanastasiou, Emanuele Re, Ioannis Tsinikos…

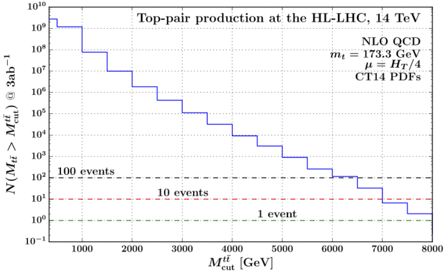
Disclaimer: Everything is preliminary!

Nikhef

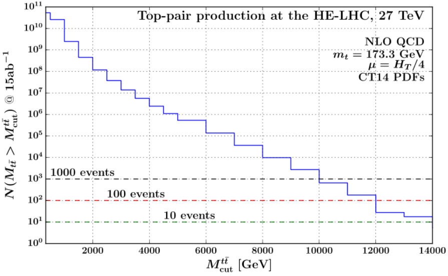
NWO
Netherlands Organisation
for Scientific Research

Cumulative in M_{tt}

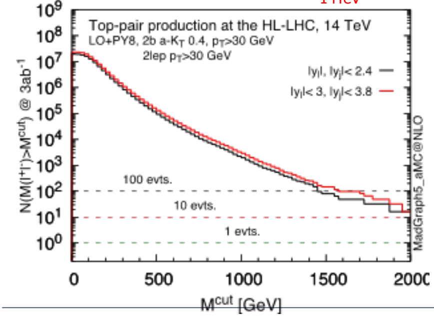
14TeV



27TeV



14TeV

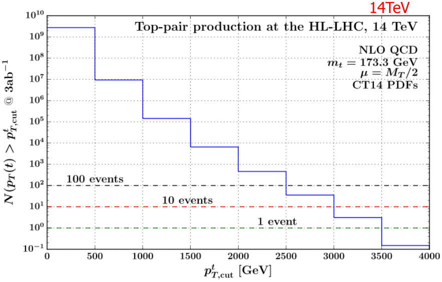


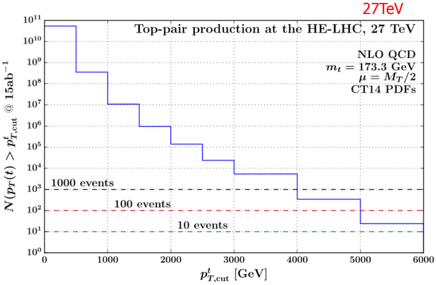
- ✓ All at NLO QCD.
- ✓ Shown is: cumulative times max luminosity

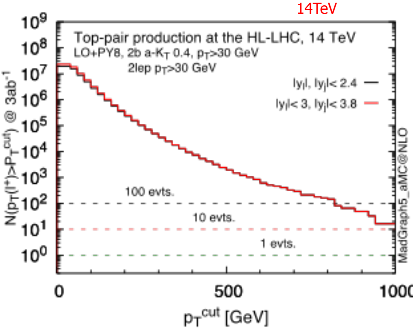
- ✓ For tops: to add EW (and possibly NNLO?)
- ✓ Decay: if feasible, may add some NNLO corrections
- ✓ Assess the advantage of calorimeter upgrade (extended lepton tracking/b-tagging)

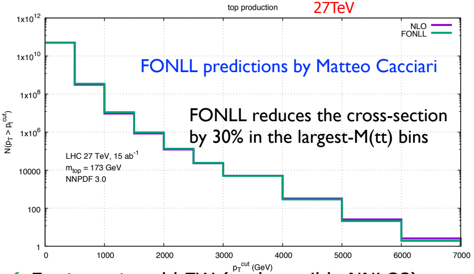
Slide by Alex Mitov

Cumulative in P_T









FONLL predictions by Matteo Cacciari

FONLL reduces the cross-section by 30% in the largest-M(tt) bins

- ✓ For tops: to add EW (and possibly NNLO?)
- ✓ Decay: if feasible, may add some NNLO corrections

Slide by Alex Mitov

Predictions for rates at 14 and 27 TeV

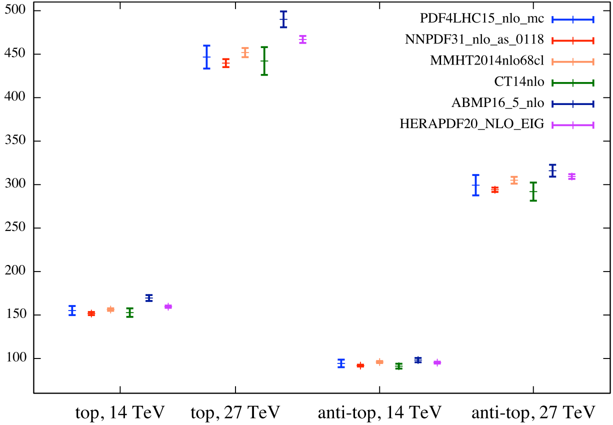
	14 TeV			27 TeV		
	σ [pb]	$\Delta_7^{\mu_r,\mu_f}$	$\Delta_{\rm PDF}$	σ [pb]	$\Delta_7^{\mu_r,\mu_f}$	$\Delta_{\rm PDF}$
$\sigma_{\rm NLO,\,t\text{-}ch,}\ t$	**156**	+3% -2.2%	2,3 %	**447**	+3% -2.6%	2 %
$\sigma_{\rm NLO,\,t\text{-}ch,}\ \bar{t}$	**94**	+3.1% - 2.1%	3,1 %	**299**	+3.1% -2.5%	2,6 %
$\sigma_{\rm NLO,\,Wt} = \sigma_{\rm NLO,\,W\bar{t}}$ $\mu_{r,f} = p_{\perp,b,\rm veto}$ = 50 GeV	**36**	+2.9% -4.4%	5 %	**137**	+3.8% -6.1%	4 %
$\sigma_{\rm NLO,\,s\text{-}ch,}\ t$	**6,8**	+2.7% -2.2%	1,7 %	**14,8**	+2.7% -3.2%	1,8 %
$\sigma_{\rm NLO,\,s\text{-}ch,}\ \bar{t}$	**4,3**	+2.7% -2.2%	1,8 %	**10,4**	+2.7% -3.3%	1,8 %

PDF4LHC15_nlo_mc, $\mu_0 = m_t = 173.2$ *GeV,* $V_{tb} = 1$*, 5FNS*

- t-channel, NNLO: very similar central value, error reduced by ~1/2 [*results for LHC14: Berger, Gao, Zu, arXiv:1708.09405*]
- For differential distributions: error above is in many cases underestimate
- Nevertheless, good NLO → NNLO convergence

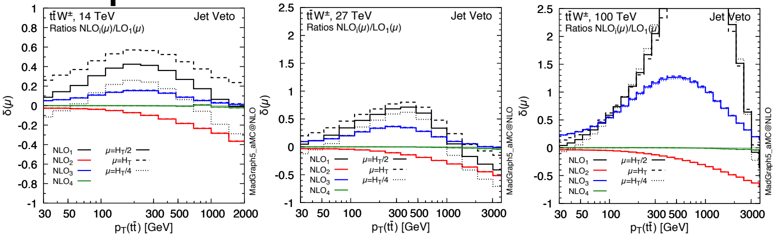
Slide by Fabrizio Caola

Total t-channel cross section

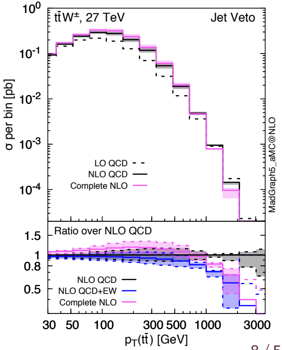


Slide by Fabrizio Caola

Complete-NLO corrections for $t\bar{t}W$



- QCD corrections to ttW are dominated by hard-jet and soft-W configurations (giant K-factors)
- A jet veto (p_T>100 GeV, $|y|<2.5$) disfavours these configurations, bringing more stable predictions
- NLO$_3$ ($\alpha_s\alpha^3$) includes t-W scattering, large and positive contribution which survives jet veto: 10/20/55% (vs NLO$_1$ 25/30/70%) w.r.t LO$_1$ at 14/27/100 TeV, while EW ($\alpha_s^2\alpha^2$) corrections are ~-5%
- Complete-NLO and NLO QCD+EW bands barely overlap in large part of the phase-space

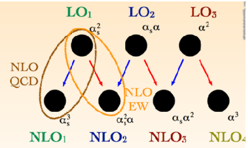


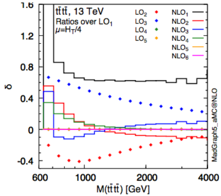
Complete NLO predictions 4 top cross sections at 14 TeV and 27 TeV

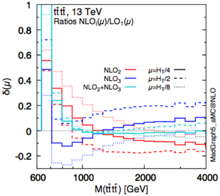
Frederix, Pagani, Zaro

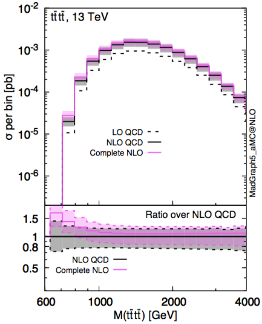
complete NLO computations including EW effects

- main contribution from NLO$_1$, NLO$_2$ and NLO$_3$
- cancelations among terms at LO (LO$_{2,3}$) and NLO (NLO$_{2,3}$)
- numerical relevant near the $t\bar{t}t\bar{t}$ threshold









Results for the 4 top cross sections at 14 TeV and 27 TeV

Frederix, Pagani, Zaro

14

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$9.04^{+69\%}_{-38\%}$	$14.72^{+19\%}_{-23\%}$	$10.04^{+63\%}_{-35\%}$	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)

27

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$45.34^{+59\%}_{-35\%}$	$71.31^{+16\%}_{-20\%}$	$48.57^{+54\%}_{-33\%}$	$73.94^{+15\%}_{-18\%}$	1.07(1.04)

100

σ[pb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$2.37^{+49\%}_{-31\%}$	$3.98^{+18\%}_{-19\%}$	$2.63^{+44\%}_{-28\%}$	$4.18^{+17\%}_{-17\%}$	1.11 (1.05)

x 5

Preliminary

x 56

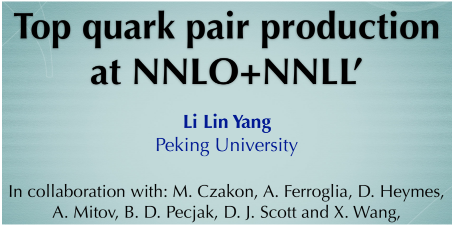
δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−25.8	−28.1	−30.4
$\mathrm{LO_3}$	32.5	38.9	45.8
$\mathrm{LO_4}$	0.2	0.3	0.4
$\mathrm{LO_5}$	0.0	0.0	0.1
$\mathrm{NLO_1}$	14.7	62.9	103.3
$\mathrm{NLO_2}$	8.1	−3.5	−15.1
$\mathrm{NLO_3}$	−10.0	1.8	15.8
$\mathrm{NLO_4}$	2.2	2.7	3.4
$\mathrm{NLO_5}$	0.1	0.2	0.2
$\mathrm{NLO_6}$	0.00	0.00	0.00
$\mathrm{NLO_2 + NLO_3}$	−1.9	−1.7	0.7

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−22.2	−24.4	−26.5
$\mathrm{LO_3}$	25.8	31.1	36.8
$\mathrm{LO_4}$	0.2	0.3	0.4
$\mathrm{LO_5}$	0.0	0.1	0.1
$\mathrm{NLO_1}$	14.3	57.3	93.8
$\mathrm{NLO_2}$	6.2	−2.4	−11.2
$\mathrm{NLO_3}$	−10.0	−2.7	6.3
$\mathrm{NLO_4}$	2.8	3.5	4.3
$\mathrm{NLO_5}$	0.2	0.3	0.3
$\mathrm{NLO_6}$	< 0.01	< 0.01	< 0.01
$\mathrm{NLO_2 + NLO_3}$	−2.8	−5.1	4.9

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−18.7	−20.7	−22.8
$\mathrm{LO_3}$	26.3	31.8	37.8
$\mathrm{LO_4}$	0.05	0.07	0.09
$\mathrm{LO_5}$	0.03	0.05	0.08
$\mathrm{NLO_1}$	33.9	68.2	98.0
$\mathrm{NLO_2}$	−0.3	−5.7	−11.6
$\mathrm{NLO_3}$	−3.9	1.7	8.9
$\mathrm{NLO_4}$	0.7	0.9	1.2
$\mathrm{NLO_5}$	0.12	0.14	0.16
$\mathrm{NLO_6}$	< 0.01	< 0.01	< 0.01
$\mathrm{NLO_2 + NLO_3}$	−4.2	−4.0	2.7

Accuracy and theoretical progress

- One aim of the workshop is to document cross sections, both for the High Luminosity upgrade (14 TeV, $3\,\mathrm{ab}^{-1}$), and for an eventual high energy phase (27 TeV, $15\,\mathrm{ab}^{-1}$). Emphases on reach in distributions.
- Constant progress in accuracy of predictions, driven by current needs of LHC top physics (see also this workshop:



Top quark pair production at NNLO+NNLL′

Li Lin Yang
Peking University

In collaboration with: M. Czakon, A. Ferroglia, D. Heymes, A. Mitov, B. D. Pecjak, D. J. Scott and X. Wang,

- Can assume fairly advanced theoretical frameworks by the beginning of the HL hera. Further goal of the workshop: Attempt to estimate future theretical uncertainties.

Differential $t\bar{t}$ cross sections in the ℓ+jets channels at CMS and the HL-LHC

O. Hindrichs[1] (CMS), Stephen Farray[2] (LHCb)

1. University of Rochester
2. University of Liverpool

18.06.2018

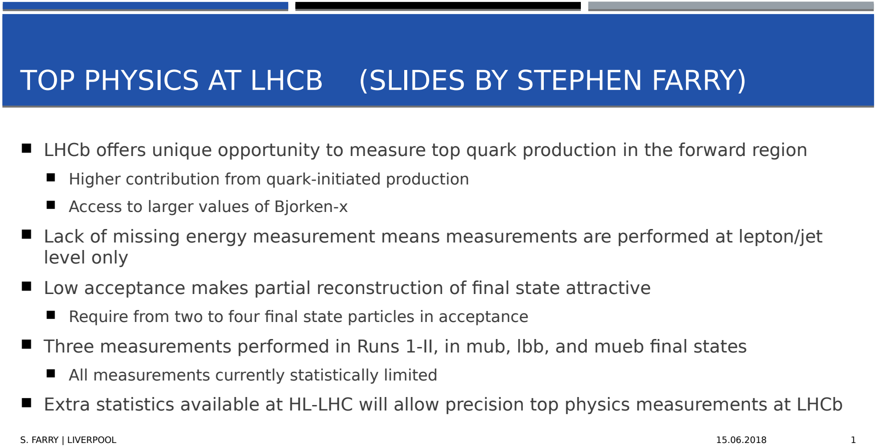
Status

Analysis based on CMS-TOP-17-002 (arXiv:1803.08856)

- Successfully ran the analysis on HL-LHC full simulation MC with pileup of 200 (3M events):
  - switched to PUPPI jets and $p_{\mathrm{T}}^{\mathrm{miss}}$. (Run2 charged hadron subtracted jets not working, about 100 jets per event)
  - reconstruction algorithm successfully working. However, resolution of reconstructed top quarks slightly worse than in Run2.
- Successfully ran the analysis on HL-LHC DELPHES simulation with pileup of 200 (50M events):
  - spent some time to convert DELPHES output into analysis framework format.
  - resolutions of top quarks kinematics in reasonable agreement between full simulation and DELPHES.
  - unfolding is working (tested with skewed spectra). Use CMS-TOP-17-002 binning with extended η/rapidity ranges.

MC production and conversion from DELPHES *were hopefully the biggest obstacles – CMS internal document in preparation.*

LHCb, PUB-2018-009



TOP PHYSICS AT LHCB (SLIDES BY STEPHEN FARRY)

- LHCb offers unique opportunity to measure top quark production in the forward region
  - Higher contribution from quark-initiated production
  - Access to larger values of Bjorken-x
- Lack of missing energy measurement means measurements are performed at lepton/jet level only
- Low acceptance makes partial reconstruction of final state attractive
  - Require from two to four final state particles in acceptance
- Three measurements performed in Runs 1-II, in mub, lbb, and mueb final states
  - All measurements currently statistically limited
- Extra statistics available at HL-LHC will allow precision top physics measurements at LHCb

S. FARRY | LIVERPOOL 15.06.2018 1

FINAL STATES AND SELECTION

- Four final states considered
  - lb – lepton and a b-jet (measured in Run 1)
  - lbb – lepton plus two b-jets (measured in Run 1)
  - mueb – muon, electron and b-jet (measured in Run II)
  - muebb – muon, electron and two b-jets
- Fiducial Region:
  - Leptons : pt > 20 GeV, 2.0 < eta < 4.5
  - B-jets : pt > 20 (60) GeV, 2.2 < eta < 4.2

LHCb upgrade for HL, 300 fb^{-1}

EVENT YIELD

final state	6 fb^{-1}	22 fb^{-1}	300 fb^{-1}	$< x >$
ℓb	16k	54k	830k	0.295
$\ell b\bar{b}$	2k	8k	130k	0.368
$\mu e b$	200	1k	12k	0.348
$\mu e b\bar{b}$	30	120	1.5k	0.415

- Expected yield extrapolated from existed measurements and NLO predictions
  - Improvements in selection and tagging efficiency assumed
- Sub-percent statistical precision in lepton+jets channel, percent level in di-lepton channels
  - Can make two-dimensional cross-section measurements to test predictions in new region and constrain gluon PDF at high-x

HL-LHC and HE-LHC top: Spin Correlations & Charge Asymmetry

Pieter David, Stephen Farry, Andrea Giammanco,
Jay Howarth, Alex Mitov, Liam Moore, Marcel Vos

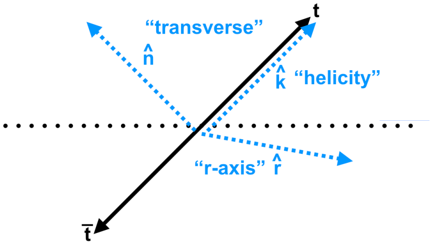
Spin Correlation

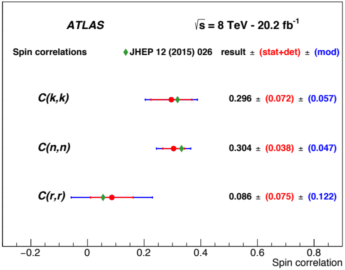
- Measured using angles between decay products of top and some spin axis:

Double diff. xsec **Polarisation (0 in SM)** **Spin Correlation**

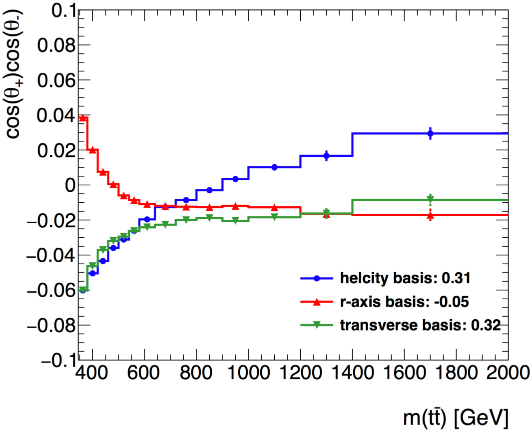
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}\left(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b\right)$$

- Measured ATLAS and CMS inclusively in Run1. HL-LHC should be differential.
- Principal limitations are stats (in differential) and signal modelling uncertainties.



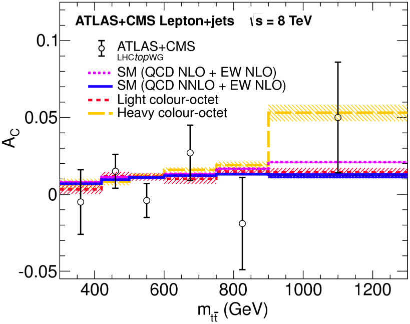


Spin Correlation



- Here is an example of the kind of plot we would like to produce.
- Spin correlation, in this case using cos(**θ**)cos(**θ**), as a function of $m(t\bar{t})$.

Charge Asymmetry



$$A(|\Delta y|) = \frac{N(|\Delta y| > 0) - N(|\Delta y| < 0)}{N(|\Delta y| > 0) + N(|\Delta y| < 0)}$$

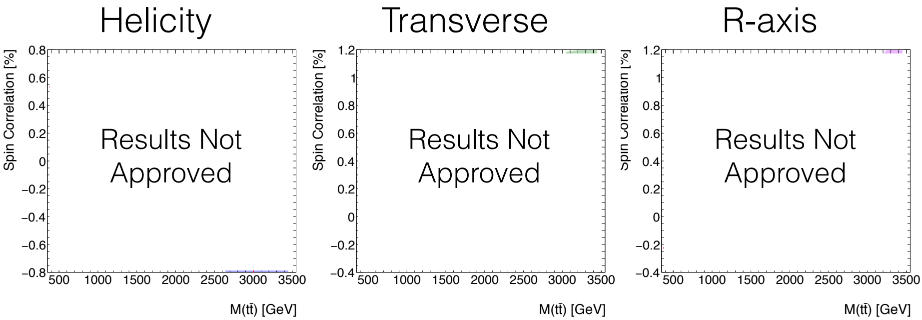
$$A(|\Delta \eta|) = \frac{N(|\Delta \eta| > 0) - N(|\Delta \eta| < 0)}{N(|\Delta \eta| > 0) + N(|\Delta \eta| < 0)}$$

- Can be measured in fully reconstructed or lab-frame only observables ($t\bar{t}$ or ll).
- Measured inclusively and differentially and combined by ATLAS + CMS.
- Principal limitations are stats and signal modelling.
- Severely statistics-hungry measurement.
  ➡ Only arises in higher orders of qqbar.
- Ideal candidate for HL-LHC studies!

Strategy

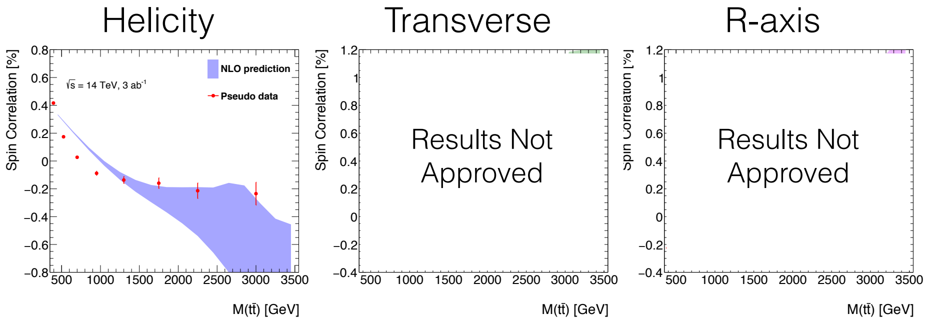
- ATLAS + CMS Unfolded measurements:
  - ➡ Both ATLAS and CMS publish detector-corrected cross-sections and properties already.
  - ➡ Often allows you to reduce the effect of modelling uncertainties (other option is profiling but really should use data for that).
  - ➡ Strategy here is to setup realistic unfolding analyses using pseudo-data derived from 14 TeV MC and determine expected statistical and systematic uncertainties for 3 ab^{-1}.
- Only covering dilepton today, l+jets still in progress (and no motivation for the analyses in all-hadronic.
- LHCb analysis is using single lepton and dilepton final states to measure charge asymmetry using leptonic η.

Spin



- Stat uncertainties and resolution are excellent for most values of $m(t\bar{t})$ and inclusively -> limitation will be systematics (most likely signal modelling).
- Relative stat. uncertainty <1%, compared to ~20% [ATLAS/CMS 8TeV]

Spin


Helicity

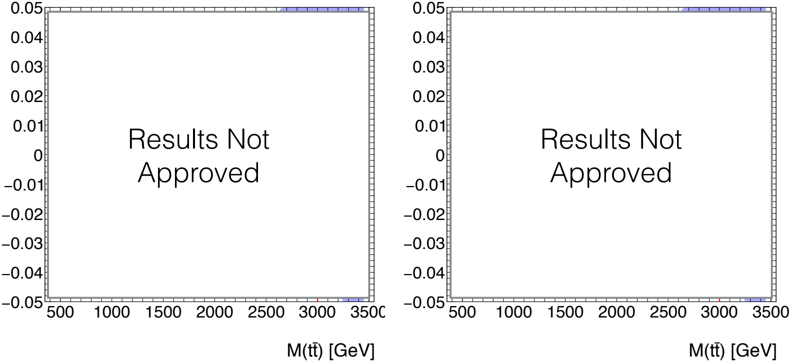
Transverse

R-axis

Non-official 'blinded' plot

- Stat uncertainties and resolution are excellent for most values of m($t\bar{t}$) and inclusively -> limitation will be systematics (most likely signal modelling).
- Relative stat. uncertainty <1%, compared to ~20% [ATLAS/CMS 8TeV]

Charge Asymmetry



- Inclusive values for NLO dilepton pseudo-data.
- Should be possible to have sensitivity for 3 sigma evidence for charge asymmetry in this channel.

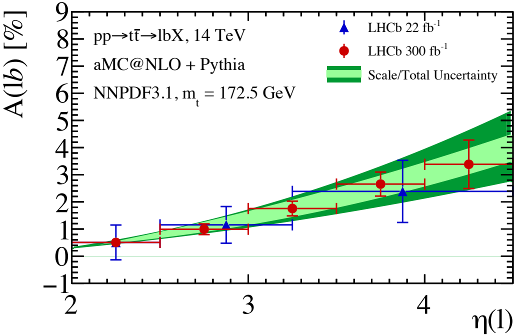
Charge Asymmetry (LHCb)

- LHCb defines charge asymmetry a little differently:

$$A(\ell b) = \frac{N(\ell^+ b) - N(\ell^- b)}{N(\ell^+ b) + N(\ell^- b)}$$

- Asymmetry parameterised differentially vs. eta of the lepton.
- Predictions from aMC@NLO.
- Uncertainties on the pseudo-data are statistics only.

An actually approved plot!



final state	$6\,\mathrm{fb}^{-1}$	$22\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$<x>$
ℓb	16k	54k	830k	0.295
$\ell b\bar{b}$	2k	8k	130k	0.368
$\mu e b$	200	1k	12k	0.348
$\mu e b\bar{b}$	30	120	1.5k	0.415

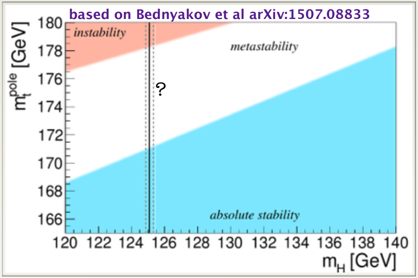
Top Mass
- experimental -

Jan Kieseler
CERN

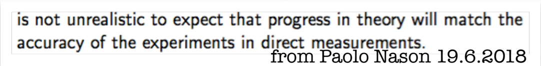
13.6.2018

The Top-Quark Mass

- Fundamental parameter in the Lagrangian
- Renormalisation scheme dependent
- Essential for EWK precision fits, EWK vacuum stability
  - Gain in precision from m_t measurements in contrast to direct m_W measurements



- Already have highly precise MC mass measurements
- Pole mass measurements with increasing precision
- Work ongoing to relate both


is not unrealistic to expect that progress in theory will match the accuracy of the experiments in direct measurements.

from Paolo Nason 19.6.2018

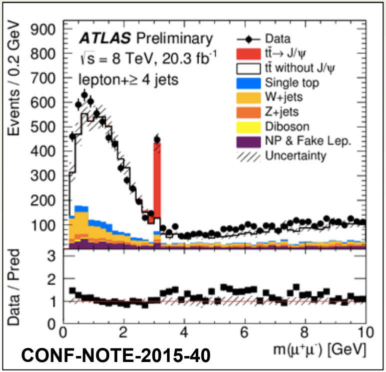
Worth to continue measuring the top-quark (MC) mass at the HL-LHC?

- Possibility for high-precision differential measurements of m_t
  - Gain insight into more tunes, the 'darkest' corners of phase space
- Almost unlimited possibilities for data-driven constraints
- Ultimate precision for one of the key legacy measurements from the LHC

Projections based on standard techniques

Starting Point

- J/Psi mostly limited by statistics
- Good starting point for HL-LHC studies



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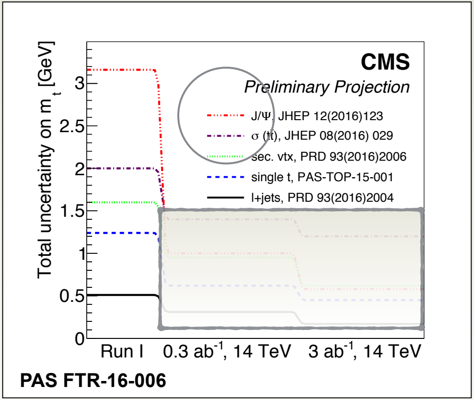

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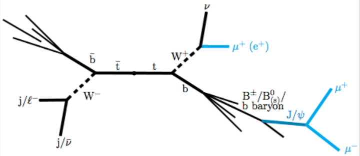
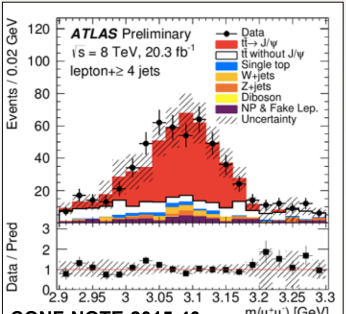


J/Psi from B decays in top events

- High statistics
- Excellent resolution, even at 200 PU
- Full analysis on HL-LHC simulation ongoing performed by the ATLAS team members
  - nothing public yet



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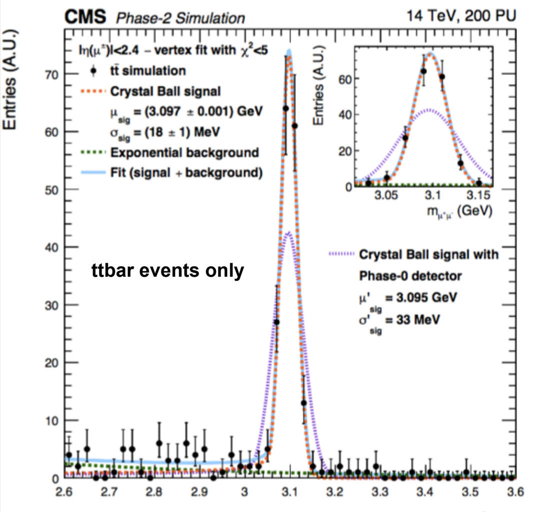


ttbar events only

TDR-17-001

Systematics Details

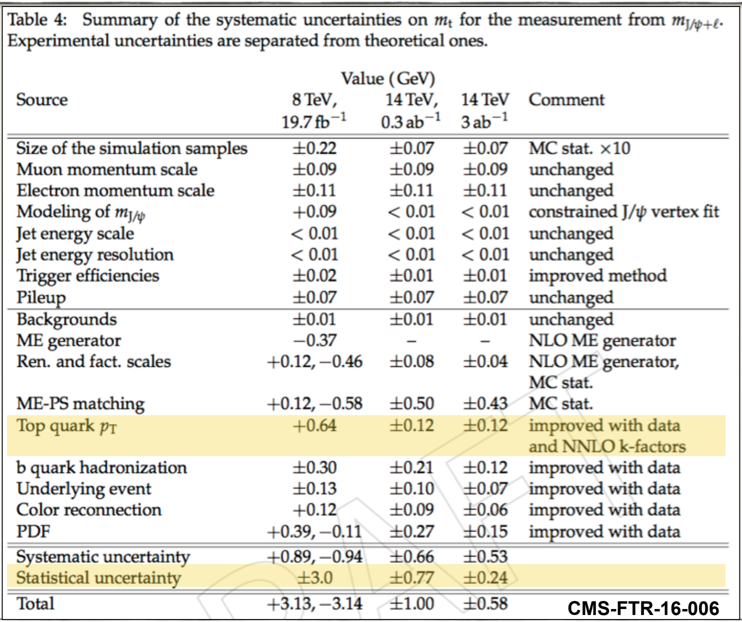


Table 4: Summary of the systematic uncertainties on m_t for the measurement from $m_{J/\psi+\ell}$. Experimental uncertainties are separated from theoretical ones.

Source	Value (GeV)			Comment
	8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	
Size of the simulation samples	±0.22	±0.07	±0.07	MC stat. ×10
Muon momentum scale	±0.09	±0.09	±0.09	unchanged
Electron momentum scale	±0.11	±0.11	±0.11	unchanged
Modeling of $m_{J/\psi}$	+0.09	< 0.01	< 0.01	constrained J/ψ vertex fit
Jet energy scale	< 0.01	< 0.01	< 0.01	unchanged
Jet energy resolution	< 0.01	< 0.01	< 0.01	unchanged
Trigger efficiencies	±0.02	±0.01	±0.01	improved method
Pileup	±0.07	±0.07	±0.07	unchanged
Backgrounds	±0.01	±0.01	±0.01	unchanged
ME generator	−0.37	–	–	NLO ME generator
Ren. and fact. scales	+0.12, −0.46	±0.08	±0.04	NLO ME generator, MC stat.
ME-PS matching	+0.12, −0.58	±0.50	±0.43	MC stat.
Top quark p_T	+0.64	±0.12	±0.12	improved with data and NNLO k-factors
b quark hadronization	±0.30	±0.21	±0.12	improved with data
Underlying event	±0.13	±0.10	±0.07	improved with data
Color reconnection	+0.12	±0.09	±0.06	improved with data
PDF	+0.39, −0.11	±0.27	±0.15	improved with data
Systematic uncertainty	+0.89, −0.94	±0.66	±0.53	
Statistical uncertainty	±3.0	±0.77	±0.24	
Total	+3.13, −3.14	±1.00	±0.58	

CMS-FTR-16-006

‘standard’ method (l+jets)

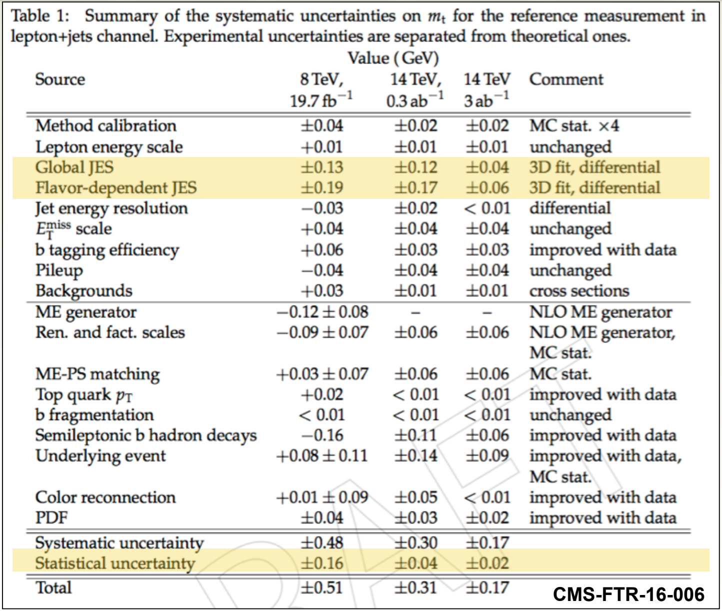


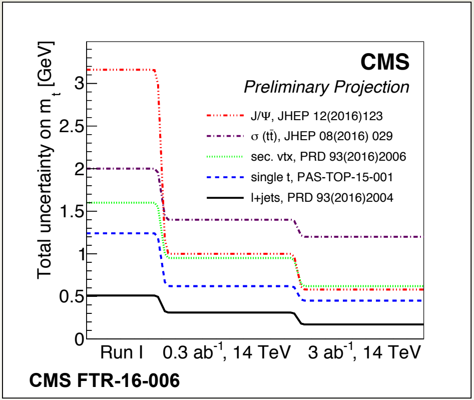
Table 1: Summary of the systematic uncertainties on m_t for the reference measurement in lepton+jets channel. Experimental uncertainties are separated from theoretical ones.

Source	Value (GeV) 8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	Comment
Method calibration	±0.04	±0.02	±0.02	MC stat. ×4
Lepton energy scale	+0.01	±0.01	±0.01	unchanged
Global JES	±0.13	±0.12	±0.04	3D fit, differential
Flavor-dependent JES	±0.19	±0.17	±0.06	3D fit, differential
Jet energy resolution	−0.03	±0.02	< 0.01	differential
E_T^{miss} scale	+0.04	±0.04	±0.04	unchanged
b tagging efficiency	+0.06	±0.03	±0.03	improved with data
Pileup	−0.04	±0.04	±0.04	unchanged
Backgrounds	+0.03	±0.01	±0.01	cross sections
ME generator	−0.12 ± 0.08	–	–	NLO ME generator
Ren. and fact. scales	−0.09 ± 0.07	±0.06	±0.06	NLO ME generator, MC stat.
ME-PS matching	+0.03 ± 0.07	±0.06	±0.06	MC stat.
Top quark p_T	+0.02	< 0.01	< 0.01	improved with data
b fragmentation	< 0.01	< 0.01	< 0.01	unchanged
Semileptonic b hadron decays	−0.16	±0.11	±0.06	improved with data
Underlying event	+0.08 ± 0.11	±0.14	±0.09	improved with data, MC stat.
Color reconnection	+0.01 ± 0.09	±0.05	< 0.01	improved with data
PDF	±0.04	±0.03	±0.02	improved with data
Systematic uncertainty	±0.48	±0.30	±0.17	
Statistical uncertainty	±0.16	±0.04	±0.02	
Total	±0.51	±0.31	±0.17	

CMS-FTR-16-006

Projections

- Clear benefit from statistics for J/Psi
- Moderate improvement for pole mass from cross sections
  - Ultimately limited by luminosity uncertainty and theory uncertainty (no N^{3}LO assumed)
- Single top:
  - Benefit from statistics and modelling improvements
- ‘standard’ l+jets
  - Benefit from differential studies constraining modelling



- All MC mass analysis will go well below 1 GeV uncertainty.
  - Differences in production/decay mechanism may be visible
- Likely even more analyses techniques become available not covered here
  - More in-situ constrains

The Top Quark Mass, Theory

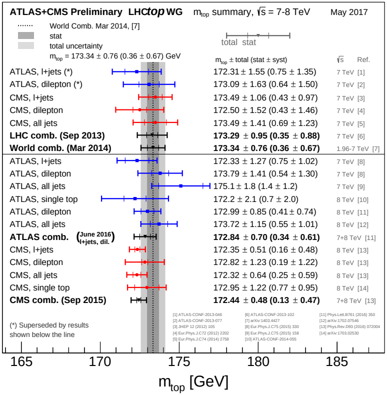
authors:

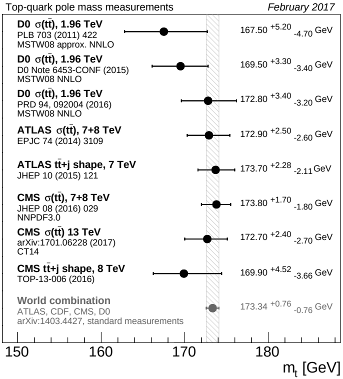
Gennaro Corcella, Andre Hoang, Hiroshi Yokoya, Paolo Nason

Goals of the Theory Top Mass Group

- To clarify as much as possible the present controversies on the top mass measurement, in the hope to perform a first step towards the formation of a consistent apprach in the experimental community.
- To attempt to quantify the theory uncertainties in top mass measurements, most likely to give "conservative" and an "aggressive" estimates.
- A projection of the theoretical error in direct measurements.
- Statements about "ultimate" precision limits in alternative techniques.
- A summary of research directions and key questions to be resolved that can lead to progress in this field.

Controversies: Pole mass versus "?"





- Some measurements are classified as "Pole Mass" measurements
- Direct measurements do not state what they measure, or are presented as "Monte Carlo mass measurements".
- EW fits, or vacuum stability studies, use the mass from direct measurements as "Pole mass", often enlarging the error.

Monte Carlo mass: view "A"

- According to this view, the mass extracted in direct measurement should be qualified as being made in a "Monte Carlo scheme", with no precise relation to the pole or MSbar mass.
- No precise statement is made on the size of the difference between such "Monte Carlo" mass and some well defined field theoretical mass.

Since no precise statement is made about this difference, and since the differences in mass due to the scheme choice are of order $\alpha_s(m_t)m_t$, this point of view does not exclude that the MC and pole mass difference could be of order $\alpha_s(m_t)m_t$.

Notice that this is the only possible justification for not including the direct measurements in the Pole Mass measurement table.

Monte Carlo mass: view "B"

A different concept of "Monte Carlo mass" has been put forward in Hoang,Stuart,2008, followed by several publications.

- It is argued that the generator mass is different from the pole mass, because the MC generators do not have renormalon ambiguities, while the pole mass has.
- The MC generator mass has a close relation to low-scale short distance masses such as the MSR mass, $m^{(\mathrm{MSR})}(Q_0)$, where Q_0 is the shower cutoff.
- Several studies performed in the context of mass measurements from boosted top (parton showers are based on quasi-collinear limit), with attempts to quantify numerically the relation of the generator mass of a specific Monte Carlo to the MSR mass and other mass schemes.
- The difference between the generator masses and m^{pole} is claimed to be of order $Q_0\alpha_s(Q_0)$.

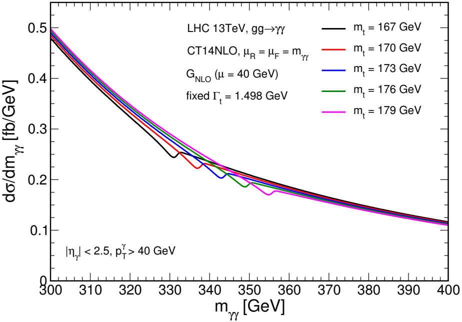
Monte Carlo mass: View “C”

Other authors (P.N., 2018), argue *against* the MC mass concept, for several reasons:

- The Monte Carlo accuracy depends upon the observables. Thus, for example, the $t\bar{t}$ cross section in a Monte Carlo is only LO accurate. The mass of the top decay products is accurate to all orders (with caveats, beware of renormalons ...) if the top mass parameter is interpreted as the pole mass.
- According to this view, when considering observables closely related to the mass of the top decay products, the Monte Carlo mass plays the role of the top pole mass, up to corrections of the order of a typical hadronic scale Λ.
- Pole mass renormalon problem not so important; other (renormalons associated with jets, etc.) non perturbative effects may be much more relevant.
- $\mathcal{O}(\Lambda)$ ambiguities can and should be studied and estimated by usual means (variations in shower and hadronization parameters, comparisons of different MC generators, etc.).

Goals of the workshop: alternative techniques

$\gamma\gamma$ spectrum at LHC
Kawabata,Yokoya, 2016
Aims to avoid theoretical problems present in direct measurements.
Needs further theoretical scrutiny (higher $t\bar{t}$ excitations, possibly coloured, may decay in $\gamma\gamma + X$).



- HL Projected error: 2-3 GeV for HL;
- HE Projected error: 0.3-0.6 GeV (depending upon signal/background ratio)

A systematics of 1 GeV from the EM calorimeter calibration should also be added. Theoretical error: to be investigated.

4-top Production Studies for the HL/HE-LHC Yellow Report

Frédéric Déliot
CEA-Saclay

with material and input from:
Ezequiel Alvarez, Mojtaba Najafabadi, Marco Zaro, Giovanni Zevi della Porta, Cen Zhang
WG1

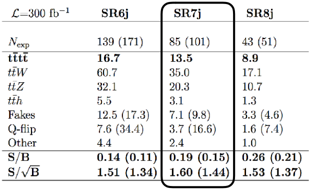
HL/HE-LHC workshop
CERN, 18 June 2018

Phenomenological extrapolation of the cross section sensitivity

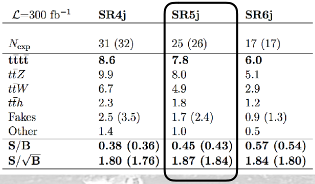
- phenomenological studies using 300 fb^{-1} (arXiv:1611.05032)
  - same-sign and trilepton channels
  - signal region (SR7j and SR5j)
    - combined: $S/\sqrt{B}<1.87$ at 95% CL
  - assumptions:
    - 12% and 13% uncertainties for ttZ/W
    - 50% for fakes and charge mis-ID background (at 13.2 fb^{-1})
    - Scale the uncertainties from fakes and charge mis-ID with sqrt(luminosity)

- theory extrapolation:
  - Rescale # of events by the signal cross section at 14/27 TeV (for both signal and background) yields
    - 14 TeV 3 ab^{-1}: $0.55<S/\sqrt{B}<1.45$
    - 27 TeV 15 ab^{-1}: $0.79<S/\sqrt{B}<1.21$
  - including theory uncertainties, precision:
    - 58% for 14 TeV 3 ab^{-1}
    - 40% for 27 TeV 15 ab^{-1}

E. Alvarez, D. Faroughy, J. Kamenik, R. Morales, A. Szynkman



$\mathcal{L}$=300 fb^{-1}	**SR6j**	**SR7j**	**SR8j**
N_{exp}	139 (171)	85 (101)	43 (51)
$t\bar{t}t\bar{t}$	**16.7**	**13.5**	**8.9**
$t\bar{t}W$	60.7	35.0	17.1
$t\bar{t}Z$	32.1	20.3	10.7
$t\bar{t}h$	5.5	3.1	1.3
Fakes	12.5 (17.3)	7.1 (9.8)	3.3 (4.6)
Q-flip	7.6 (34.4)	3.7 (16.6)	1.6 (7.4)
Other	4.4	2.4	1.0
S/B	**0.14 (0.11)**	**0.19 (0.15)**	**0.26 (0.21)**
$S/\sqrt{B}$	**1.51 (1.34)**	**1.60 (1.44)**	**1.53 (1.37)**



$\mathcal{L}$=300 fb^{-1}	**SR4j**	**SR5j**	**SR6j**
N_{exp}	31 (32)	25 (26)	17 (17)
$t\bar{t}t\bar{t}$	**8.6**	**7.8**	**6.0**
$t\bar{t}Z$	9.9	8.0	5.1
$t\bar{t}W$	6.7	4.9	2.9
$t\bar{t}h$	2.3	1.8	1.2
Fakes	2.5 (3.5)	1.7 (2.4)	0.9 (1.3)
Other	1.4	1.0	0.5
S/B	**0.38 (0.36)**	**0.45 (0.43)**	**0.57 (0.54)**
$S/\sqrt{B}$	**1.80 (1.76)**	**1.87 (1.84)**	**1.84 (1.80)**

Constraints from 4tops on the EFT 4-fermion operator at 14 TeV and 27 TeV

C. Zhang

- $t\bar{t}t\bar{t}$ operators
  - 5 relevant tttt operators in the Warsaw basis, 4 d.o.f's are relevant (1 LLLL, 1 RRRR, 2 LLRR with color singlet and octet)
  - Interesting for BSM states that mainly couple to 3rd generation
  - Cross section is a quadratic function of C

$$\mathcal{O}^{(+)}_{QQ} \equiv \frac{1}{2}\mathcal{O}^{(1)(3333)}_{qq} + \frac{1}{2}\mathcal{O}^{(3)(3333)}_{qq} ,$$

$$\mathcal{O}_{tt} \equiv \mathcal{O}^{(3333)}_{uu} ,$$

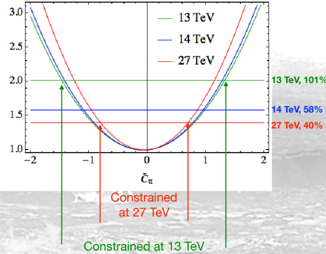
$$\mathcal{O}^{(1)}_{Qt} \equiv \mathcal{O}^{(1)(3333)}_{qu} ;$$

$$\mathcal{O}^{(8)}_{Qt} \equiv \mathcal{O}^{(8)(3333)}_{qu} ;$$

- $q\bar{q}t\bar{t}$ operators
  - 14 relevant qqtt operators
  - Cross section is a quartic function of C, due to double insertion
  - interesting because resulting constraints are already comparable with $t\bar{t}$ measurements
    - Dominant sensitivity comes from C^4 terms
    - EFT validity requires kinematic cut M_{cut} on the energy scale of the analyzed events

σ_{EFT}/σ_{SM},

for tttt operator



Constrained at 27 TeV

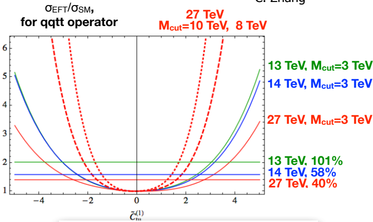
Constrained at 13 TeV

- extrapolation
  - Constraints on operator coefficients can be obtained by comparing the signal strength as a function of C with expected precision on the cross section
    - Assuming M_{cut} does not affect the projections very much
    - Constraints always come from upper bound on the cross section

- results for the constraints on $t\bar{t}t\bar{t}$ operators
  - bounds on operators coefficients improve at high energies
    - Improved precision on cross section
    - Slightly better sensitivities

Constraints from 4tops on the EFT 4-fermion operator at 14 TeV and 27 TeV

C. Zhang

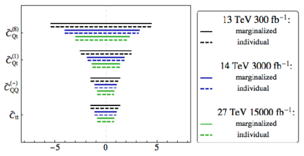


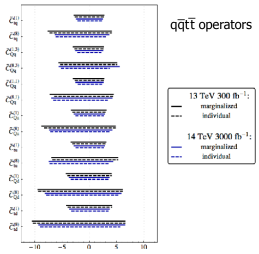
results for the constraints on $q\bar{q}t\bar{t}$ operators

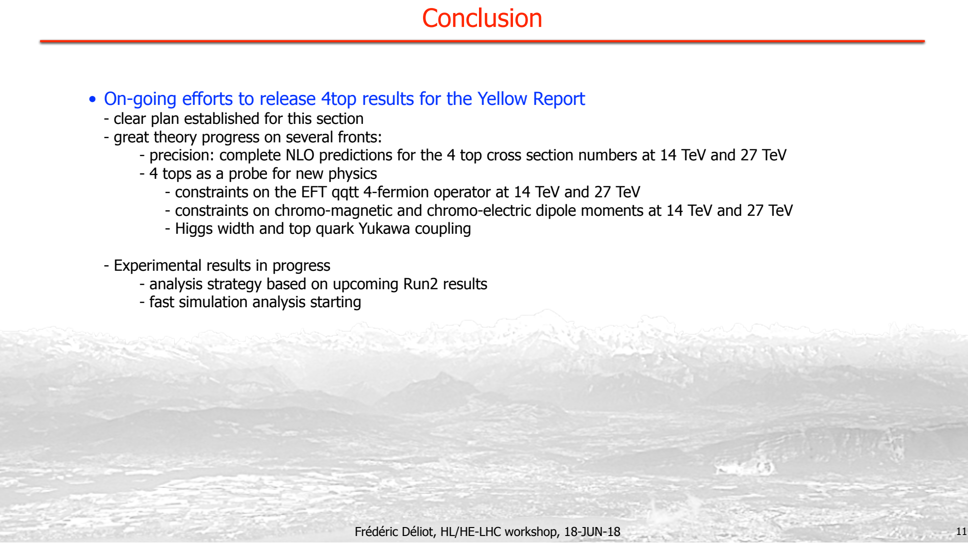
- bounds don't improve at 27 TeV: sensitivity to operators becomes smaller at 27 TeV, if M_{cut} =3 TeV is kept
- Dominant contributions at 27 TeV come from larger energy scale. M_{cut} =~10 TeV is required to capture those and reach better sensitivities. However 10 TeV is too large for EFT interpretation.
- Possible reason: double insertion diagrams dominate, but they are qq initiated.

- projected limits on operators coefficients
  - Only based on inclusive cross section (below cut). In principle a tailored analysis can yield better results (~ factor of 2). M_{cut} needs to be taken into account.

$t\bar{t}t\bar{t}$ operators







Conclusion

- On-going efforts to release 4top results for the Yellow Report
  - clear plan established for this section
  - great theory progress on several fronts:
    - precision: complete NLO predictions for the 4 top cross section numbers at 14 TeV and 27 TeV
    - 4 tops as a probe for new physics
      - constraints on the EFT qqtt 4-fermion operator at 14 TeV and 27 TeV
      - constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV
      - Higgs width and top quark Yukawa coupling

  - Experimental results in progress
    - analysis strategy based on upcoming Run2 results
    - fast simulation analysis starting

TopFCNC at HL/HE-LHC Status and Plans.

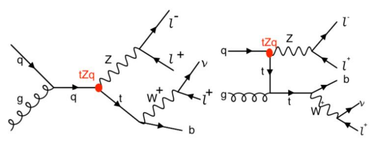
A.Savin

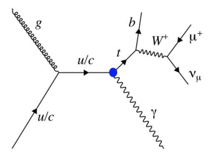
University of Wisconsin, Madison, USA

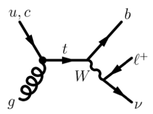
High-Luminosity LHC Workshop, CERN, June 18-20, 2018

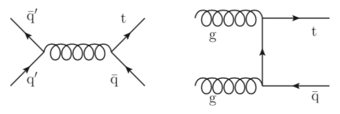
FCNC process in top production

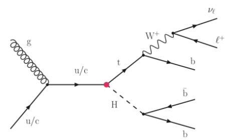
- Forbidden at tree level and highly suppressed at higher order
- Br ~ $10^{-12/-16}$ (NP)
- tZq
- tγq
- tgq
- tHq











Effective Lagrangian

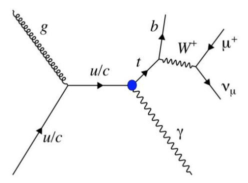
$$\mathcal{L} = \sum_{q=u,c}\Big[\sqrt{2}g_s\frac{\kappa_{gqt}}{\Lambda}\bar{t}\sigma^{\mu\nu}T_a(f^L_{Gq}P_L+f^R_{Gq}P_R)qG^a_{\mu\nu}+$$

$$+\frac{g}{\sqrt{2}c_W}\frac{\kappa_{zqt}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^L_{Zq}P_L+f^R_{Zq}P_R)qZ_{\mu\nu}+\frac{g}{4c_W}\zeta_{zqt}\bar{t}\gamma^{\mu}(f^L_{Zq}P_L+f^R_{Zq}P_R)qZ_{\mu}-$$

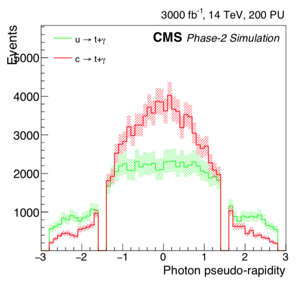
$$-e\frac{\kappa_{\gamma qt}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^L_{\gamma q}P_L+f^R_{\gamma q}P_R)qA_{\mu\nu}+$$

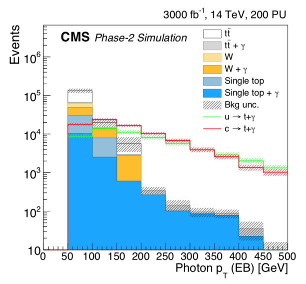
$$+\frac{g}{\sqrt{2}}\bar{t}\kappa_{Hqt}(f^L_{Hq}P_L+f^R_{Hq}P_R)qH\Big]+h.c.,$$

FCNC in t→qγ events

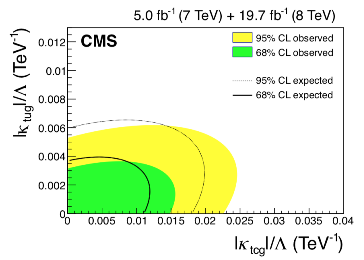


- CMS-TDR-019;CERN-LHCC-2017-023
- Current limit 1.6(18.2) x 10^{-4} u(c)
- Final state :
  - one lepton, p_T > 25 GeV |η|<2.8
  - one b-jet, p_T > 30 GeV |η|<2.8
  - one photon, p_T>50 GeV |η|<2.8
- For 3000 fb^{-1} : 8.6(74) x 10^{-6} u(c)





FCNC in gluon-mediated production



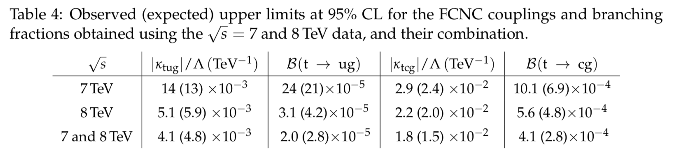


Table 4: Observed (expected) upper limits at 95% CL for the FCNC couplings and branching fractions obtained using the $\sqrt{s} = 7$ and 8 TeV data, and their combination.

$\sqrt{s}$	$\lvert\kappa_{tug}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to cg)$
7 TeV	14 (13) $\times 10^{-3}$	24 (21)$\times 10^{-5}$	2.9 (2.4) $\times 10^{-2}$	10.1 (6.9)$\times 10^{-4}$
8 TeV	5.1 (5.9) $\times 10^{-3}$	3.1 (4.2)$\times 10^{-5}$	2.2 (2.0) $\times 10^{-2}$	5.6 (4.8)$\times 10^{-4}$
7 and 8 TeV	4.1 (4.8) $\times 10^{-3}$	2.0 (2.8)$\times 10^{-5}$	1.8 (1.5) $\times 10^{-2}$	4.1 (2.8)$\times 10^{-4}$

Analysis with 3000 fb^{-1} is very close to approval, hope to show it soon !

FCNC and Anomalous couplings, EFT framework

- Jeremy Andrea, Gauthier Durieux, Cen Zhang (FCNC)
- Anomalous coupling, ttX, Y. Li, A. Onofre, M. Llacer (ATLAS) R. Shoefbeck, D. Spitzbart, D. Dobur, G. Mestdach (CMS) E.Vryonidou (Theory)

Results

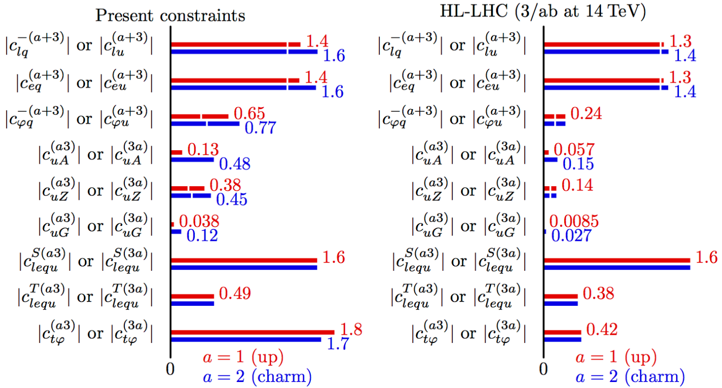


Figure 1: Current (left) and prospective HL-LHC (right) limits on top-quark FCNC operator coefficients in the conventions of Ref. [11]. Red and blue bars stand for $a = 1$ and 2, respectively, i.e. for top-up and top-charm FCNCs. White marks show individual limits, obtained under the unrealisitic assumption all other operator coefficients vanish.

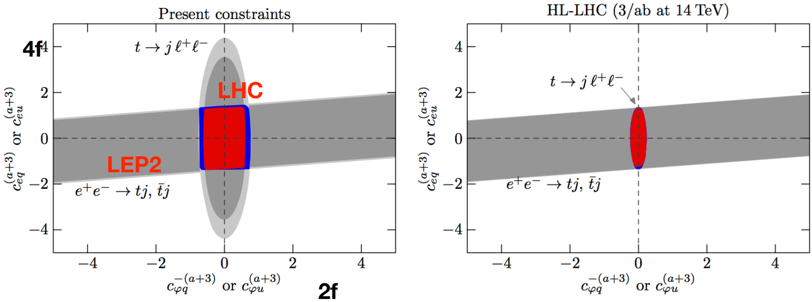


Figure 2: Current (left) and prospective HL-LHC (right) limits on top-quark FCNC operator coefficients in a two-dimensional plane. Other parameter are marginalized over, within the constraints obtained when all measurements are included. Red and blue regions stand for $a = 1$ and 2, respectively, i.e. for top-up and top-charm FCNCs. The impact of $t \to j\ell^+\ell^-$ and $e^+e^- \to tj, \bar{t}j$ is displayed separately.

REPORT OUTLINE

6. Top Physics

- **Top cross section (10 pages)**
  - **tt cross section**
    - **CMS and LHCb:**
      - Measurements of standard 1D distributions pT(t), y(t), M(tt) ...)
      - 2D distributions M(tt) vs. y(tt) and make projection for PDF constraints
  - **Single top**
    - **t-channel cross section (HL):**
      - top-charge ratio
      - differential top quark pT, rapidity
      - differential polarization angle
    - **s-channel inclusive cross section (HL/HE):**
      - inclusive, differential cross-sections
      - analysis of high-Q2 regime
    - **tZq inclusive cross section (HL)** (potentially also differential)
  - **4-tops:**
    - Table with NLO predictions for the 4 top cross section at 14 TeV and 27 TeV
    - 4 tops as a probe for new physics
      - constraints on the EFT qqtt 4-fermion operator at 14 TeV and 27 TeV
      - constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV
      - Higgs width and top quark Yukawa coupling
    - Experimental analysis (TBD)

REPORT OUTLINE

6. Top Physics (...continued)

- **Top properties (5 pages)**
  - **Spin correlations**
    - Figure of spin correlations along different spin axis vs m(tt) - di-lepton channel
  - **Charge asymmetry**
    - Figures of charge asymmetry for ATLAS and LHCb -- l+jets and di-lepton channels
- **Top couplings (5 pages)**
- **Top mass (8 pages)**
  - Discussion on top mass theoretical issues
  - A figure for the top mass measurement from the γγ spectrum at the HE-LHC
  - Top mass at HL-LHC from J/Psi
  - HE-LHC projections based on boosted top jet mass
- **FCNC (8 pages)**
  - Brief discussion of theory and motivation
  - Discussion of selection, systematics
  - Experimental results: 12 figures expected (distributions and limit plots)

REPORT OUTLINE

7. Effective coupling interpretations - 10 pages

- Common introduction with Wtb studies, identifying relevant operators
- **tt+V**
  - Discussion of experimental analysis approach for ttZ and ttphoton: assumptions on uncertainties
  - Differential distributions: Plots pT(Z), m(ll), dPhi (leptons from Z) and pT(gamma)
  - 2D exclusion contour plots
    - ctZ/ctZI @ 150/fb and @ 3/ab for ttZ and ttɣ
    - cpt/cpQM @ 150/fb and @ 3a/fb for ttZ
  - Discussion of projected sensitivity in terms of dim-6 coefficients
  - Possibility of HE studies for ttV (pheno study)
- **Wtb vertex**
  - tt: semileptonic + dileptonic ⇒ 1 per analysis (angular observable)
  - Single top: t-channel and Wt-channel (semi.+dileptonic) ⇒ 1 per analysis (angular observable)
  - Table including all analysis
  - Main results: 95% CL limits on couplings, under the SM assumption ⇒ 2 plots (with all contributions)

Status and Prospects

- Several analysis being developed
- Several waiting for approval
- Next meetings:
  17th October Top physics:
  https://indico.cern.ch/event/756456/
  (18th and 19th Weak and Strong interactions)
  These meetings will be the last opportunity for the discussion of analyses results among experimentalists and theorists in WG, before the document is finalised. We expect a significant part of these meetings to be dedicated to the discussion of the write-up for the Yellow Report.

`https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop`