

Top physics projections for HL/HE-LHC

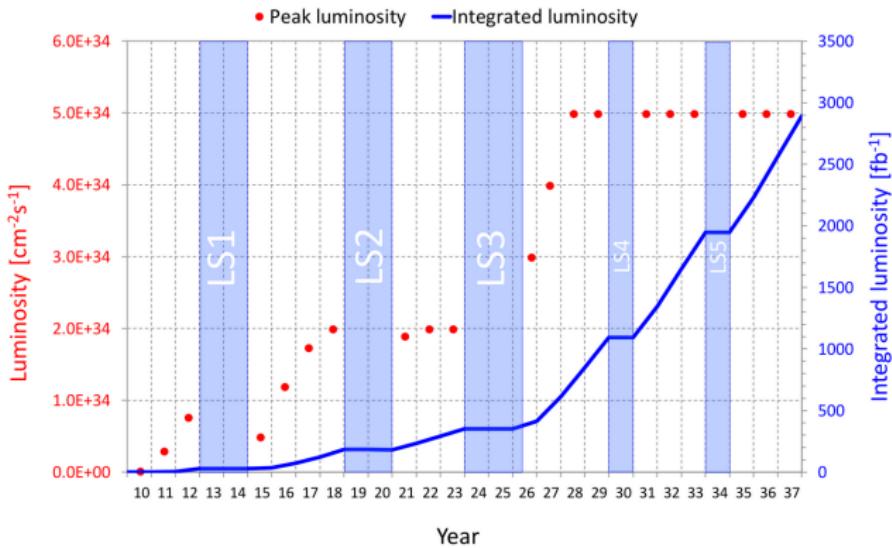


O. Hindrichs

LHCTopWG, CERN

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Expected conditions HL-LHC:

- $(5 - 7.5) \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- $250\text{--}300 \text{ fb}^{-1}$ per year.
- high pileup $\langle \mu \rangle = 140 - 200$
- $3\text{--}4 \text{ ab}^{-1}$ at 14 TeV

Expected conditions HE-LHC:

about 15 ab^{-1} at 27 TeV

Prospect of top quark physics: "Standard Model Physics at the HL-LHC and HE-LHC"
(CERN-LPCC-2018-03, arXiv:1902.04070v2)

Main changes of ATLAS detector:

- complete silicon inner tracker (ITk) $|\eta| < 4$
- Hardware trigger (L0) rate 1000 kHz (100 kHz), in addition a hardware track trigger (HTT) provides tracking information 400 kHz
- High level Trigger (EF) rate 10 KHz (1 kHz)
- ...

Main changes of CMS detector:

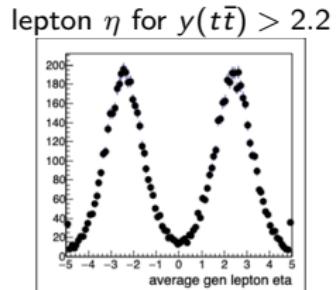
- New silicon inner tracker $|\eta| < 4$ ($|\eta| < 2.4$)
 - Hardware trigger (L1) rate 750 kHz (100 kHz) with track reconstruction ($p_T > 2 \text{ GeV}$) from stups.
 - High level Trigger rate 7.5 KHz (0.5–1 kHz)
 - high granularity endcap calorimeter (HGCal)
 - ...
- Combination of higher trigger rates and use of tracking information (electron identification, muon mom. resolution, pileup identification) allows for similar event selection as in Run 2.
- Extended η -range of the tracker facilitates measurements in new phase-space regions.

Simulation of Phase-2 CMS:

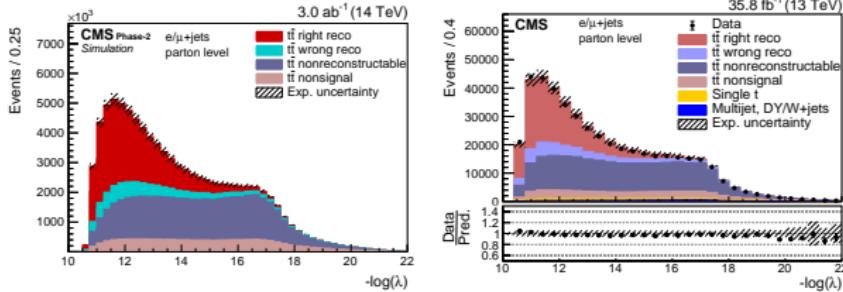
The projection is based on a DELPHES simulation of the CMS Phase-2 detector including about 200 pileup interactions.

Main differences compared to Run 2:

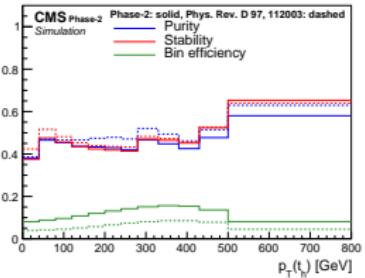
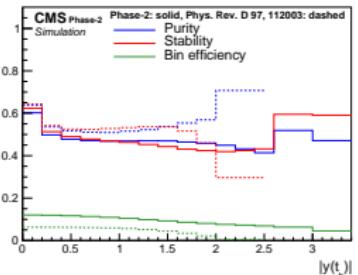
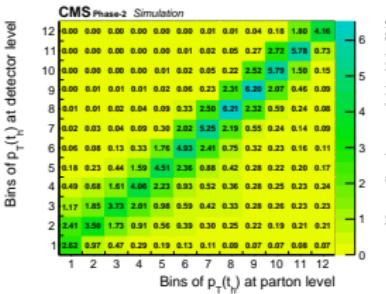
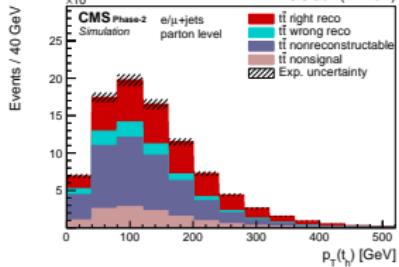
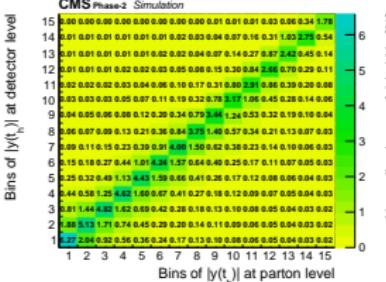
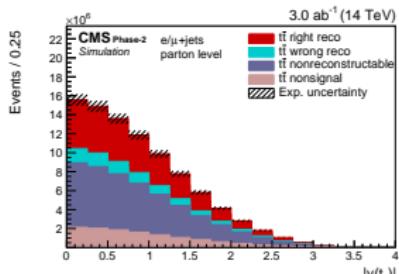
- exactly 1 isolated electron or muon with $p_T > 30 \text{ GeV}$, $|\eta| < 2.8$ (increased from $|\eta| < 2.4$)
- at least 4 jets $p_T > 30 \text{ GeV}$, $|\eta| < 4.0$ (increased from $|\eta| < 2.4$), at least 2 b-tagged ($|\eta| < 3.5$).
using PUPPI jets and p_T^{miss} is essential for pileup mitigation.



Resulting likelihood distribution



$t\bar{t}$ reconstruction performance



- Very similar performance
- Rapidity range increased for HL-LHC \rightarrow higher bin-efficiency.

Purity: correct fraction in bin at detector level.
 Stability: correct fraction in bin at parton level.

Experimental systematics follow the CMS Phase-2 upgrade recommendations (Run-2 values in parentheses):

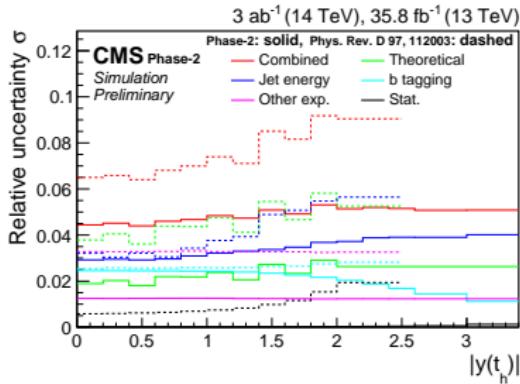
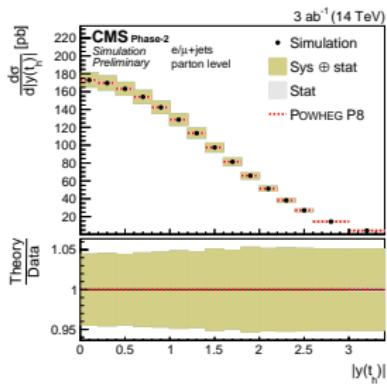
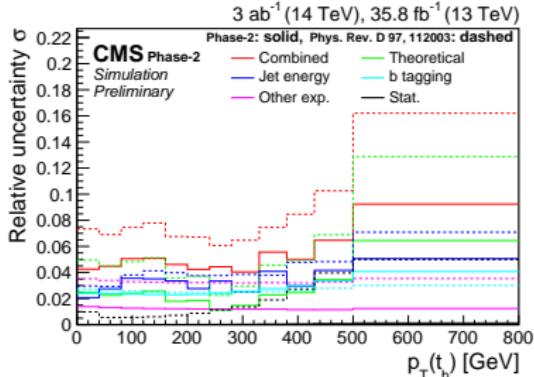
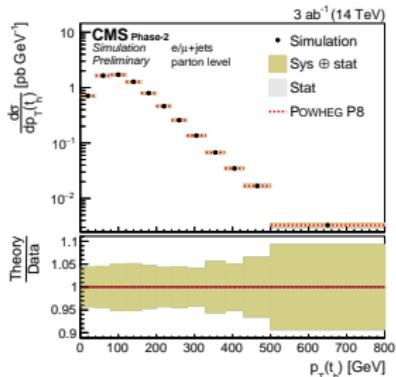
- luminosity measurement: 1% (2.5%)
- muon reconstruction and identification: 0.5% (1–2%)
- electron reconstruction and identification: 1% (1–2%)
- b-tagging efficiency: p_T dependent 1–5% (1–3%)
- b-tagging mistagging efficiency: p_T dependent about 10% (8%) for u, d, s, and gluon jets and 2–14% (2–6%) for c jets.
- jet energy calibration: for jets in the typical p_T -range of $30 < p_T < 300 \text{ GeV}$, the uncertainty of the jet energy decreases from 1.7% (2.7%) to 0.45% (0.5%).

All other uncertainties are taken from the 2016 analysis (Phys. Rev. D 97, 112003).

Theoretical uncertainties are reduced by factor two: initial/final state parton shower scales, h_{damp} , NNPDF30 variations, tune, m_t , b-decay, b-fragmentation, renormalization/factorization scales, color reconnection model

[“Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC”, CMS-NOTE-2018-006]

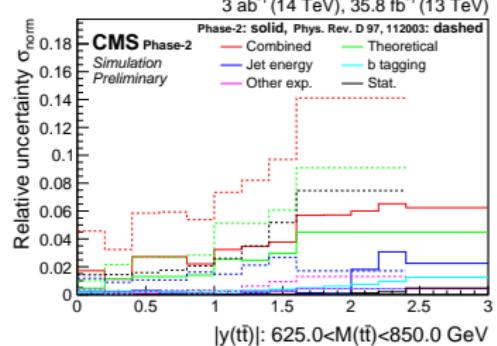
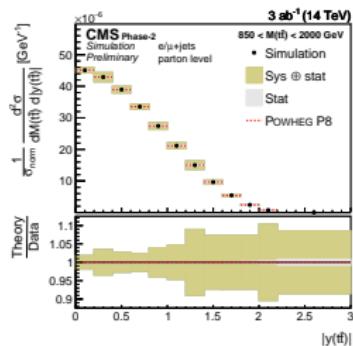
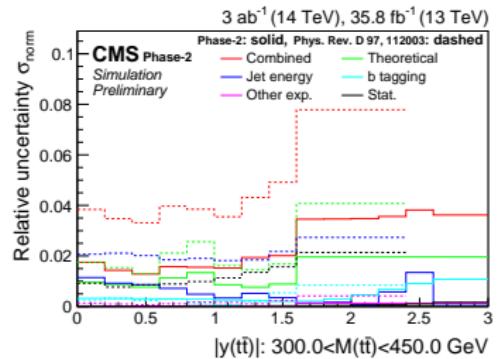
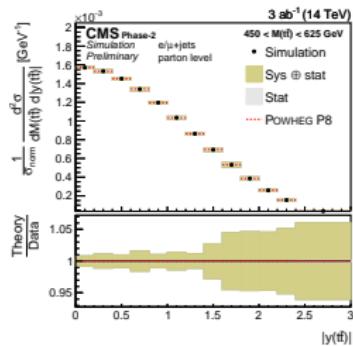
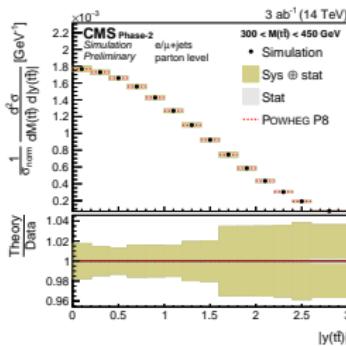
Cross section results



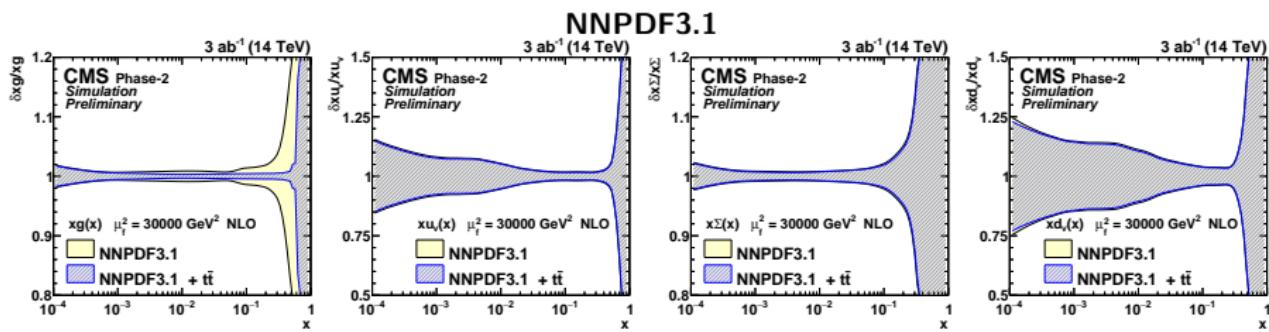
Overall reduction of uncertainty. Main improvements due to jet energy, luminosity precision, and statistics.

Double differential cross section

- Double differential cross section normalized in the measured range (uncertainties: error propagation considering full covariance matrix) is used for PDF constraints.



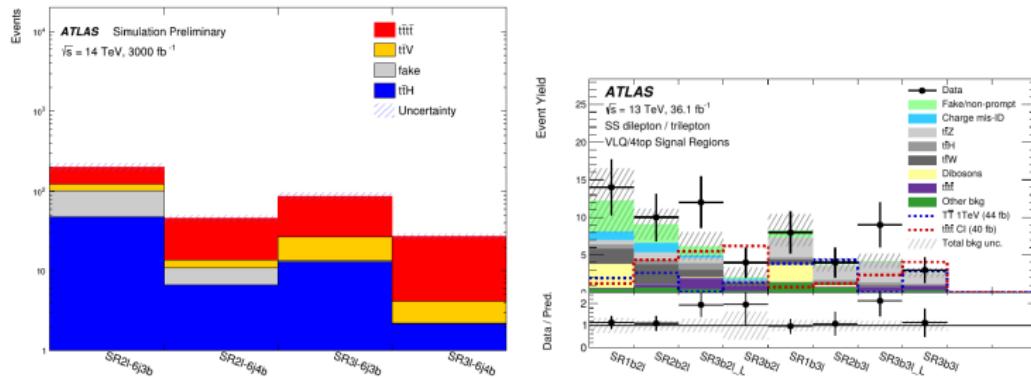
- Use normalized double differential cross section $M(t\bar{t})$ vs $|y(t\bar{t})|$ taking into account the full covariance matrix obtained for the Phase-2 projections.
- Theory prediction: NLO QCD (MG5) with scale variations.
- Fit: χ^2 minimization, include PDF uncertainties as nuisance with penalty term representing the prior knowledge.
- Expected sensitivity for $0.002 < x < 0.5$.



- Remarkable improvement of uncertainties in gluon PDF

Expected cross sections with QCD+EW contributions:

- $11.97^{+18\%}_{-21\%}$ fb (13 TeV), $15.8^{+18\%}_{-21\%}$ fb (14 TeV), $143.93^{+17\%}_{-20\%}$ fb (27 TeV)
 [JHEP02(2018)031]



- At least 2 lepton with same charge
- Simultaneous fit of H_T in four categories.
- Backgrounds estimation projected from 13 TeV measurement [JHEP12(2018)039]
- **Expected precision of cross section 11%** (main uncertainty: $t\bar{t}V$ normalization)

Projected from 13 TeV (35 fb^{-1}) CMS measurement same-sign dilepton and multi-lepton channel [EPJC78(2018)140]

Int. Luminosity	\sqrt{s}	Stat. only (%)	Run-2 (%)	YR18 (%)	YR18+ (%)
300 fb^{-1}	14 TeV	+30, -28	+43, -39	+36, -34	+36, -33
3 ab^{-1}	14 TeV	± 9	+28, -24	+20, -19	± 18
3 ab^{-1}	27 TeV	± 2	+15, -12	+9, -8	+8, -7
15 ab^{-1}	27 TeV	± 1			

- Run-2: stat scale with luminosity, syst from Run2
- YR18: stat scale with luminosity, experimental syst scale with luminosity up to 50% of Run2, theoretical unc. reduced by factor 2.
- YR18+: stat scale with luminosity, experimental syst scale with luminosity, theoretical unc. reduced by factor 2.

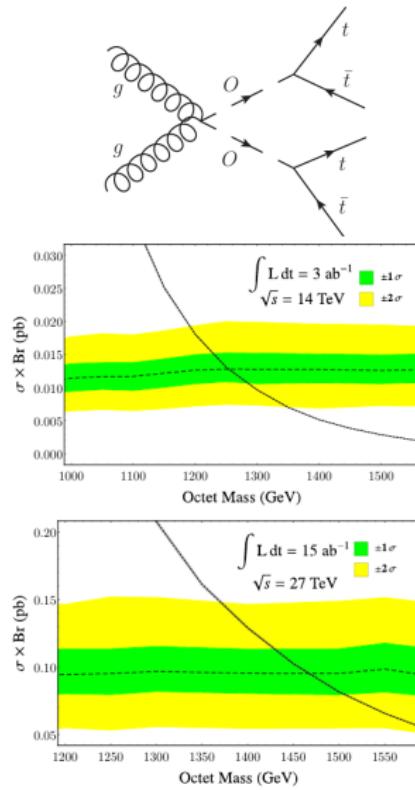
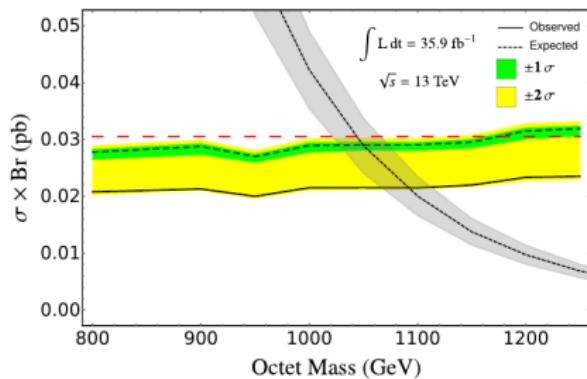
With 300 fb^{-1} first hint (3σ), stat and syst uncertainties of similar size (SS lepton channel only).

Four top interpretation

sgluon (scalar colour-octet field) pair production [PLB784 (2018) 223]

expected limits on mass:

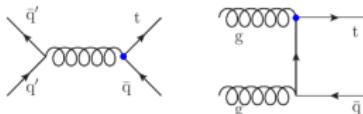
- 1060 GeV at 13 TeV
- 1260 GeV at 14 TeV
- 1470 GeV at 27 TeV



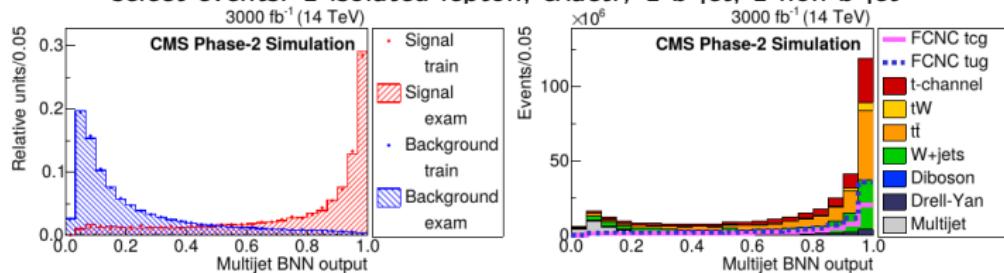
Flavor changing neutral currents

In the SM FCNC are forbidden at tree level and strongly suppressed at higher orders (BR 10^{-12} – 10^{-16}).

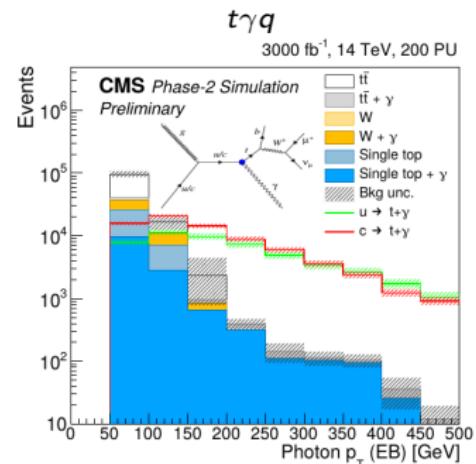
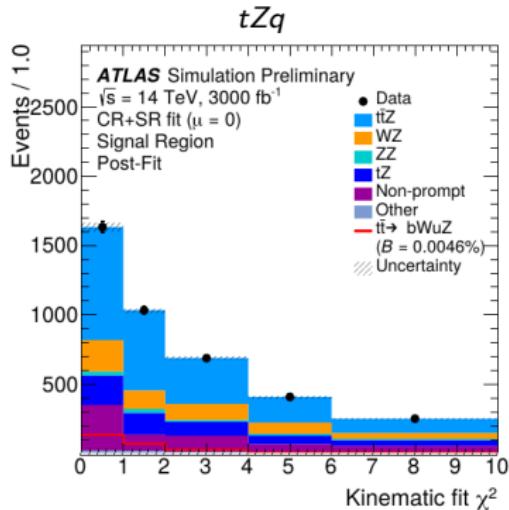
– $t\bar{q}g$



select events: 1 isolated lepton, exactly 1 b-jet, 1 non b-jet

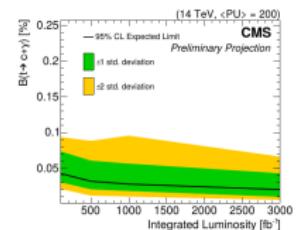
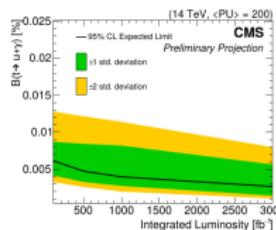


Integrated luminosity	$\mathcal{B}(t \rightarrow ug)$	$ \kappa_{tug} /\Lambda$	$\mathcal{B}(t \rightarrow cg)$	$ \kappa_{tcg} /\Lambda$
300 fb^{-1}	$9.8 \cdot 10^{-6}$	0.0029 TeV^{-1}	$99 \cdot 10^{-6}$	0.0091 TeV^{-1}
3000 fb^{-1}	$3.8 \cdot 10^{-6}$	0.0018 TeV^{-1}	$32 \cdot 10^{-6}$	0.0052 TeV^{-1}
3000 fb^{-1} Stat. only	$1.0 \cdot 10^{-6}$	0.0009 TeV^{-1}	$4.9 \cdot 10^{-6}$	0.0020 TeV^{-1}

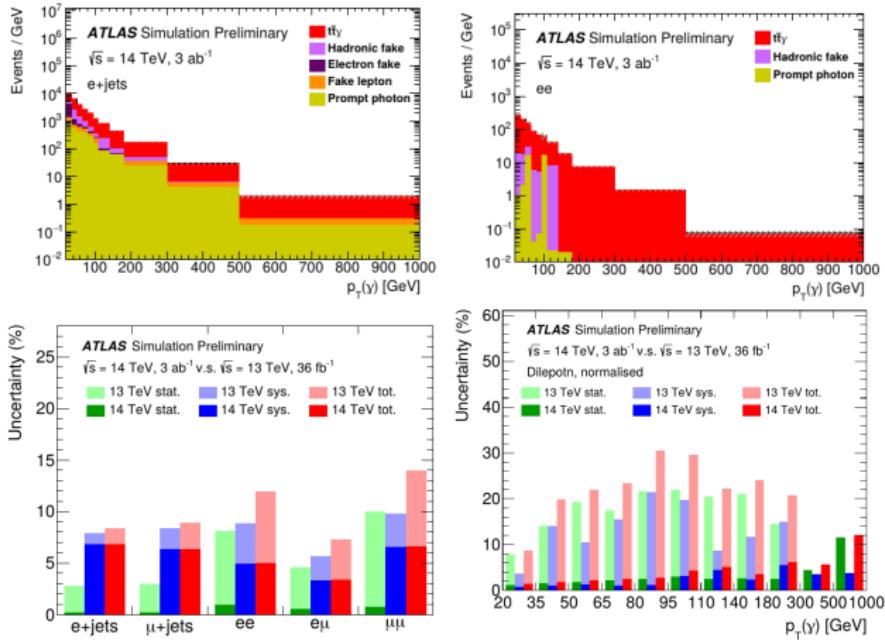


- Select $t\bar{t}$ with 3 lepton final state.
 - Depending on assumption of uncertainty in the background normalization
- $B(t \rightarrow Zq) < (4 - 5) \times 10^{-5}$
- Improvement by factor of 4 with respect to 13 TeV(2016)

Selecting single top + γ events
 $B(t \rightarrow \gamma u) < 8.6 \times 10^{-6}$ (1.9×10^{-4} @8TeV)
 $B(t \rightarrow \gamma c) < 7.4 \times 10^{-5}$ (1.7×10^{-3} @8TeV)



Measurement of $t\bar{t} +$ isolated photon with $p_T > 15$ GeV and $|\eta| < 5$
 Expected cross section 5.43 pb

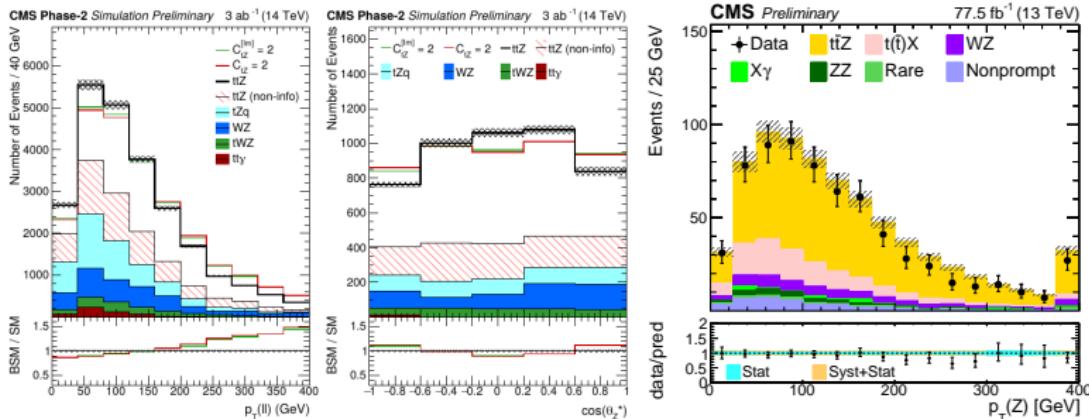


- Reduction of theoretical uncertainties including the photon fake-rate uncertainty by factor of 2.
- The cleaner di-lepton channel reaches higher precision with increasing luminosity.

EFT interpretation of $t\bar{t} + Z$

Expected cross section $1.015 \text{ pb} \pm 12\% \text{ (NLO QCD+EW) @14 TeV}$

- select $\ell + \text{jets}$ with $Z \rightarrow \ell^+\ell^-$



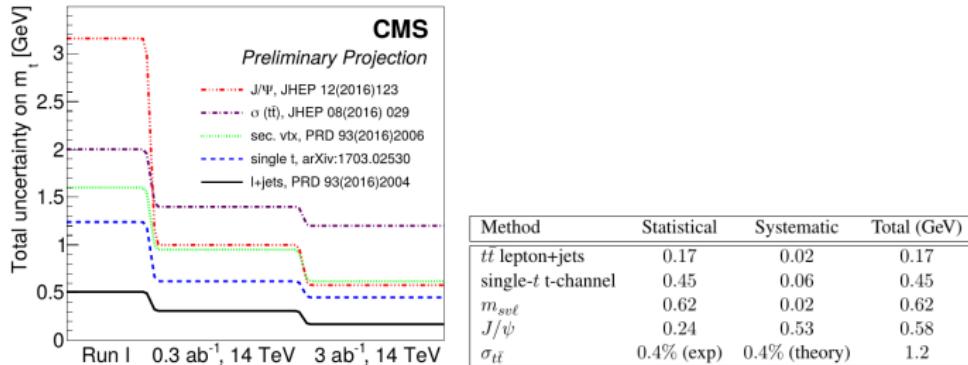
Use 2D binning in $p_T(Z)$ and $\cos(\theta^*)$ (12 bins) for extraction Wilson coefficients in SM-EFT

3 ab^{-1} at 14 TeV

Wilson coefficient	$68\% \text{ CL } (\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-0.47, 0.47]
$C_{\phi Q}$	[-0.38, 0.38]
C_{tZ}	[-0.37, 0.36]
$C_{tZ}^{[Im]}$	[-0.38, 0.36]

77.5 fb^{-1} at 13 TeV

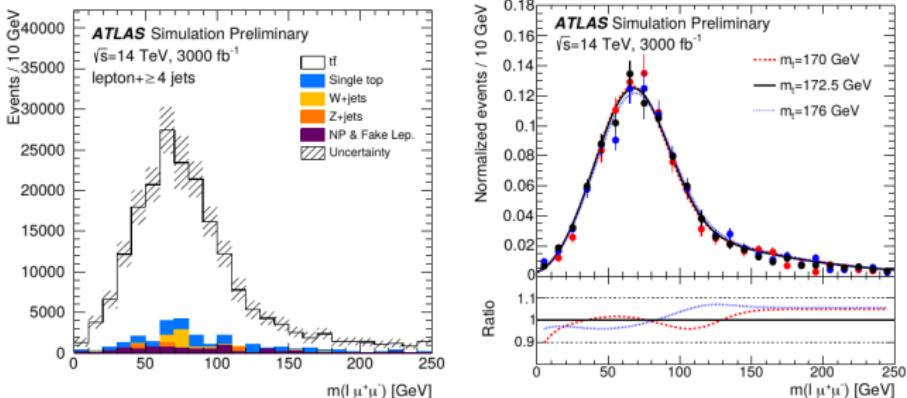
	$68\% \text{ CL}$
c_{tZ}/Λ^2	[-0.7, 0.7]
$c_{tZ}^{[I]}/\Lambda^2$	[-0.7, 0.7]
$c_{\phi t}/\Lambda^2$	[-1.6, 1.4]
$c_{\phi Q}^-/\Lambda^2$	[-1.1, 1.1]



Advantages at HL-LHC

- higher statistics for measurements using rare decays (J/Ψ)
→ measurements with different uncertainty sources
- higher statistics allows restriction to phase-space regions with low systematics.
- higher dimensional fits to constrain m_t and various systematics e.g. light/b-jet energy scales as dominant uncertainties
- extract m_t from multi-differential cross sections.
- improved understanding of modelling-uncertainties due to auxiliary measurements (reduction by 50% expected).

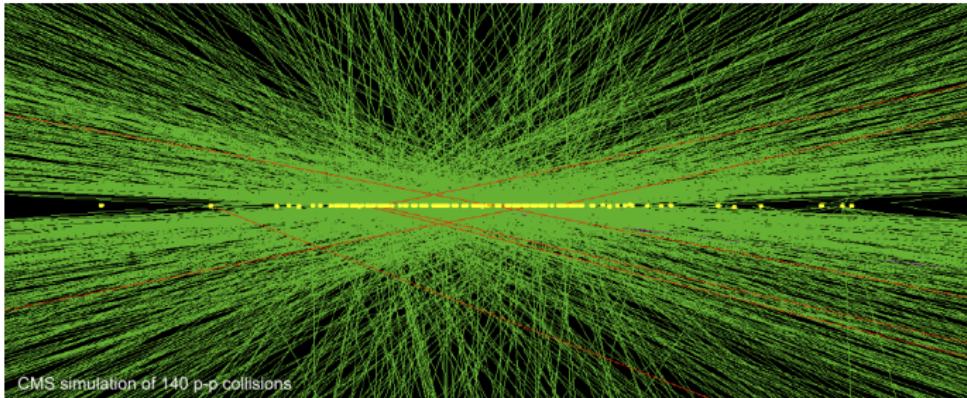
Measurement using $M(\ell J/\Psi)$



expected precision 500 MeV

- Measurements based on (partial) reconstruction of top quark mass from decay products.
 - extracted m_t^{MC} parameter, theoretical interpretation in terms well defined scheme (m_t^{pole}/\overline{MS}) difficult.
- Measurements based on comparisons of inclusive/differential cross sections to fixed order calculation

Difficult to understand m_t beyond ~ 200 MeV precision.



- In context of the Yellow-Report many studies of top quark analyses have been performed for the HL/HE-LHC
- The high statistics opens the opportunity to study rare processes with high precision
 - allows setting of stringent limits on BSM physics
 - precision measurements of SM parameters m_t
- Extended η -range of Phase-2 detectors reveals new phase-space regions.

BACK UP