New top results on HL-LHC for Snowmass

Input from the ATLAS and CMS Collaborations

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UNIVERSITY

What is Snowmass ?

- **Snowmass** is a scientific study which provides an opportunity for the entire particle physics community to come together to **identify** and **document a scientific vision for the future of particle physics** in the US and its international partners
    - Link to know more about Snowmass
- ATLAS and CMS prepared a common **white paper** to be used as input for the Snowmass process
- The paper is structured as follows: for each section, **Yellow Report (YR) results** have been summarised in 3-4 pages and subsequent **new ATLAS and CMS results** are highlighted in 1-page summaries

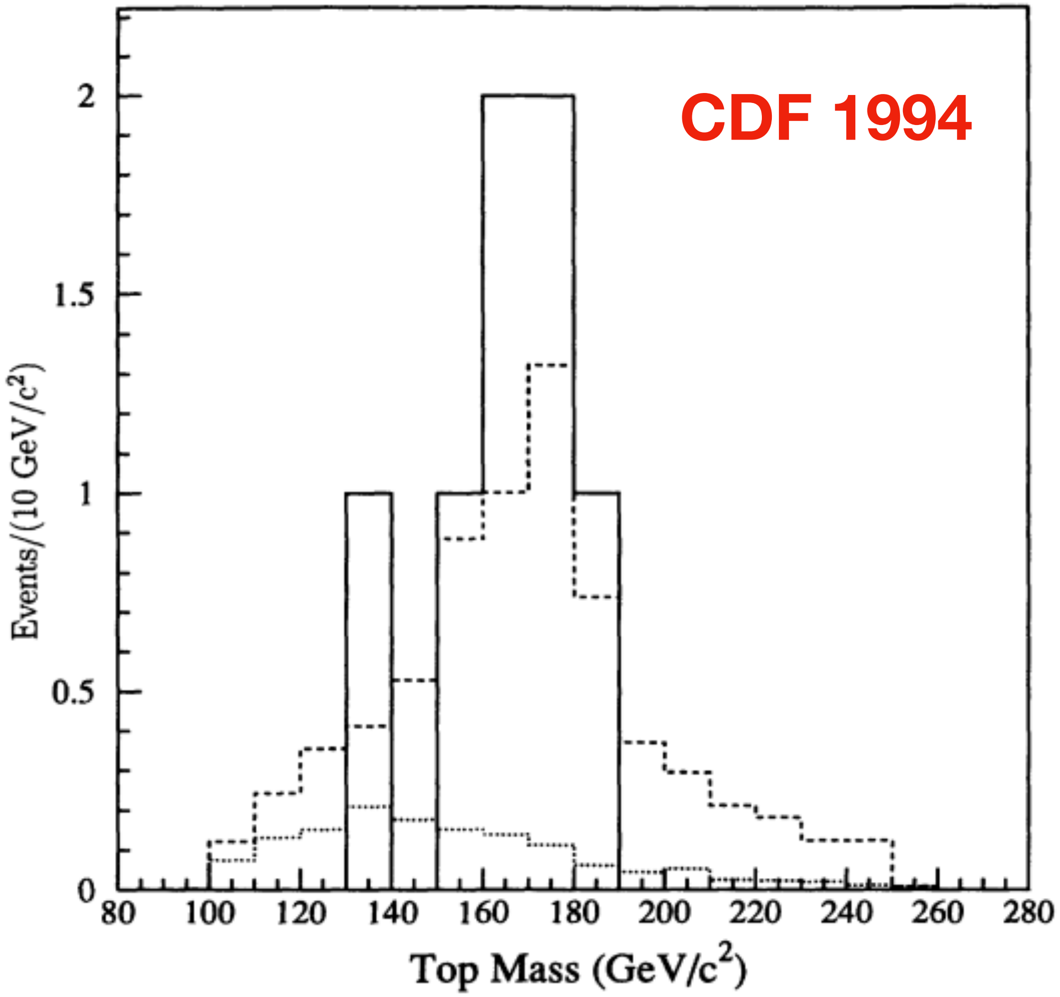
EF03: Heavy flavor and top quark physics

Link to the Note:
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001

Introduction

- We have been doing Top & SM measurements for a long time!

7 events; l+4jets



Top mass:

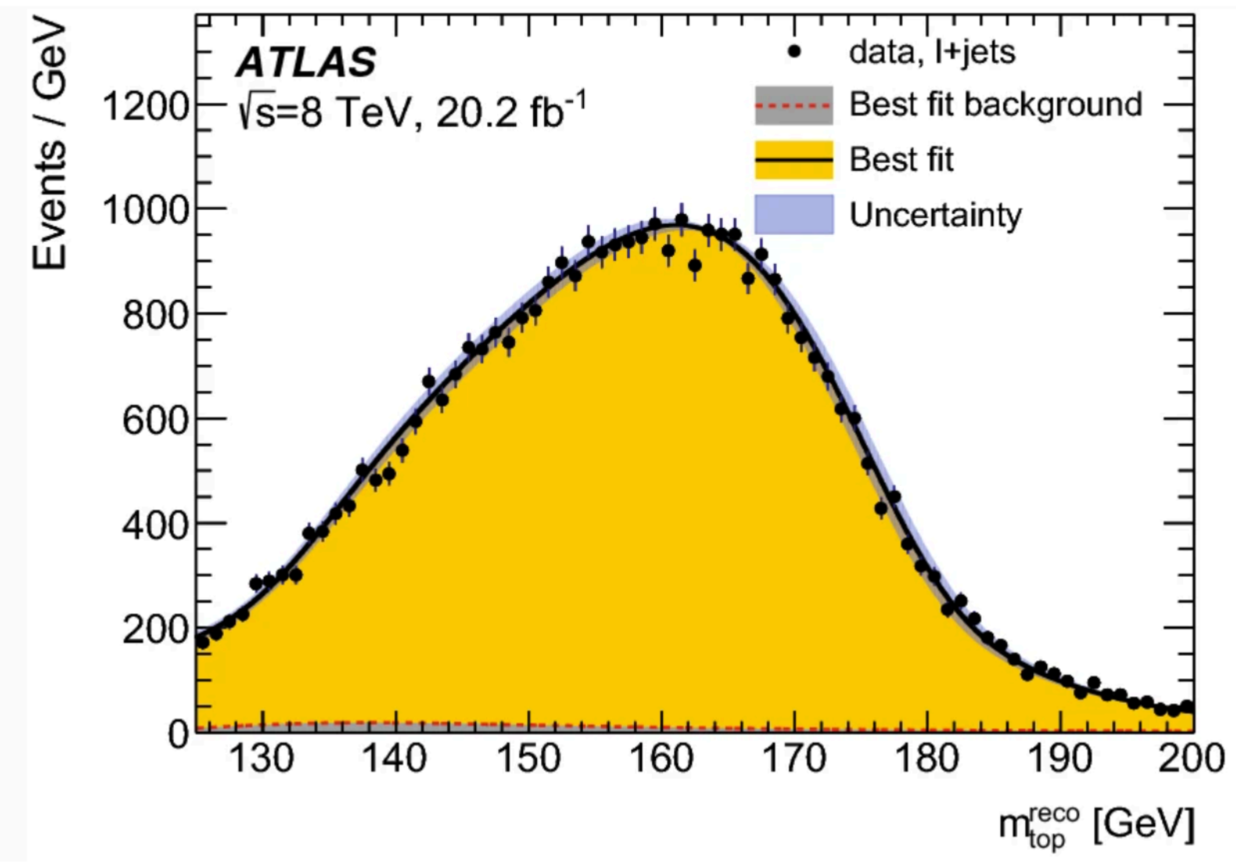
$174 \pm 10^{+13}_{-12}$ GeV/c²

with **9.4% precision**

PRD 50,2966(1994)

~38K events; l+4jets
(at least 2b-tags)

ATLAS 2019



Top mass:

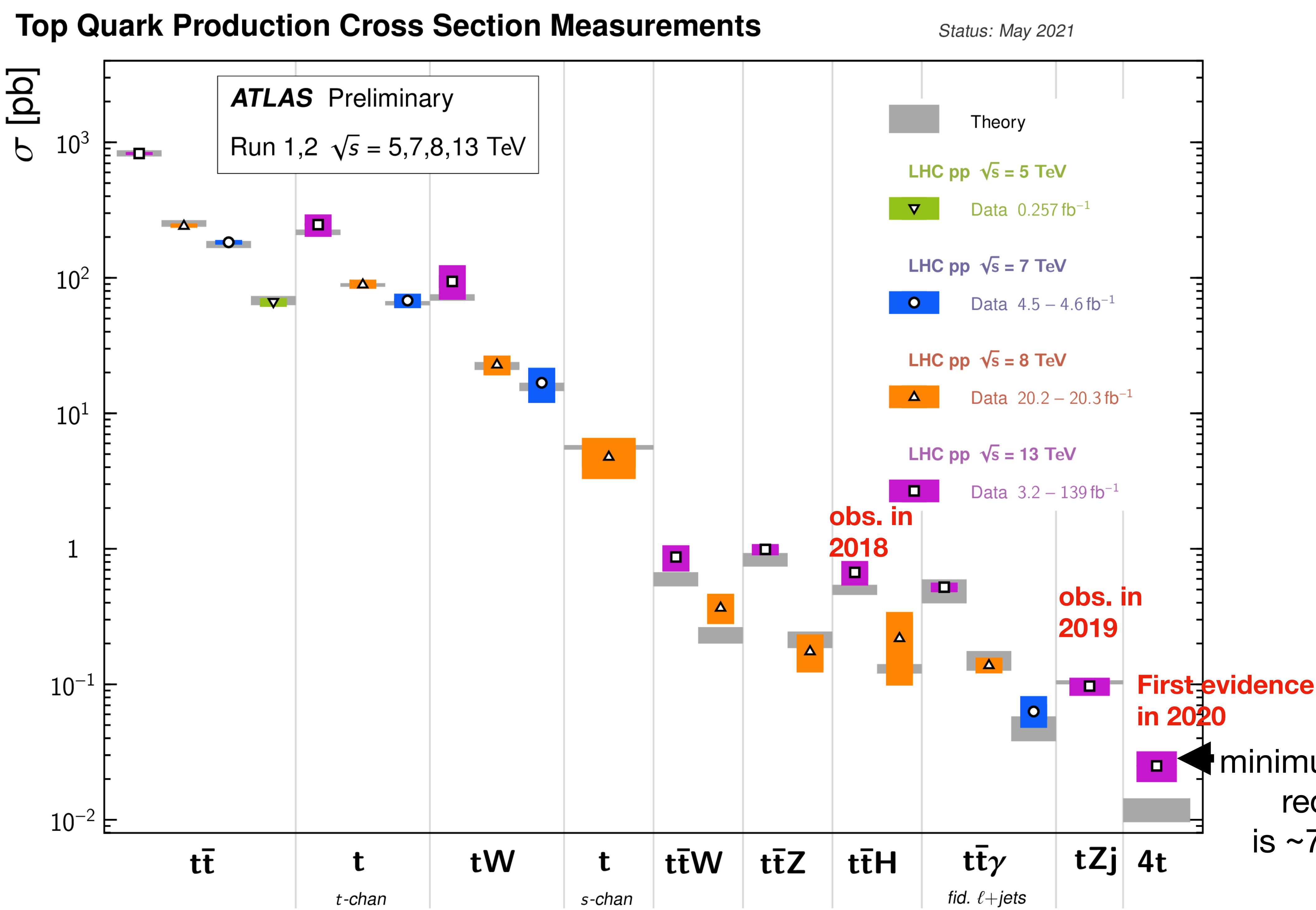
$172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})$ GeV/c²

with **0.5% precision**

Eur. Phys. J. C79(2019) 290

Introduction

- Run 2 brought us to an unprecedented centre-of-mass energy of 13 TeV
- Opened up measurements to new rare SM processes



minimum energy required is ~700 GeV

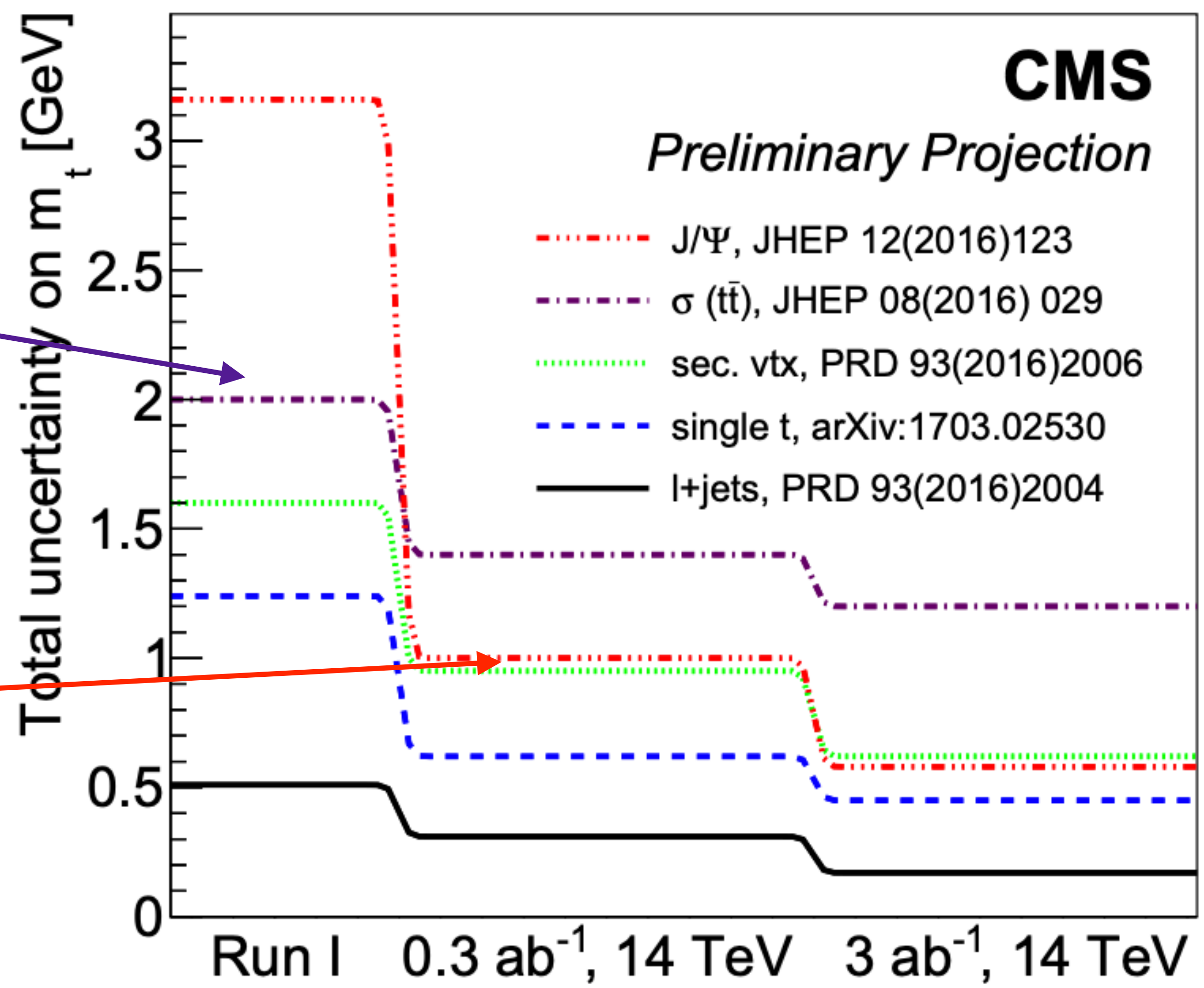
Introduction

- Why keep doing Top & SM measurements?
  - Teach us about the SM
  - Improves our theoretical calculations, MC modelling, and understanding of CP calibrations and uncertainties
  - Measurements will be important for constraining PDFs, understanding electroweak symmetry breaking (EWSB), and measuring fundamental properties of the SM
  - Can uncover unexpected deviations from the SM
- The HL-LHC will provide the opportunity for more precision, particularly at high energies which are currently limited by statistical uncertainties

Top mass

- Top quark plays a crucial role in EWSB and offers a gateway to searching for new physics beyond the SM
- m_{top} is a fundamental parameter related to other EWK parameters - stringent tests of SM
  - Most precise measurements exploit kinematic information of the decay products
- Current uncertainties are ~600 MeV, projected to be reduced to 200 MeV at the HL-LHC
- Indirect extraction of pole mass, e.g. $\sigma_{t\bar{t}}$
  - limited by theory uncertainty and lumi measurements
- less dependence on JES, e.g. $m(lJ/\psi)$
- Room for more reduction via future techniques

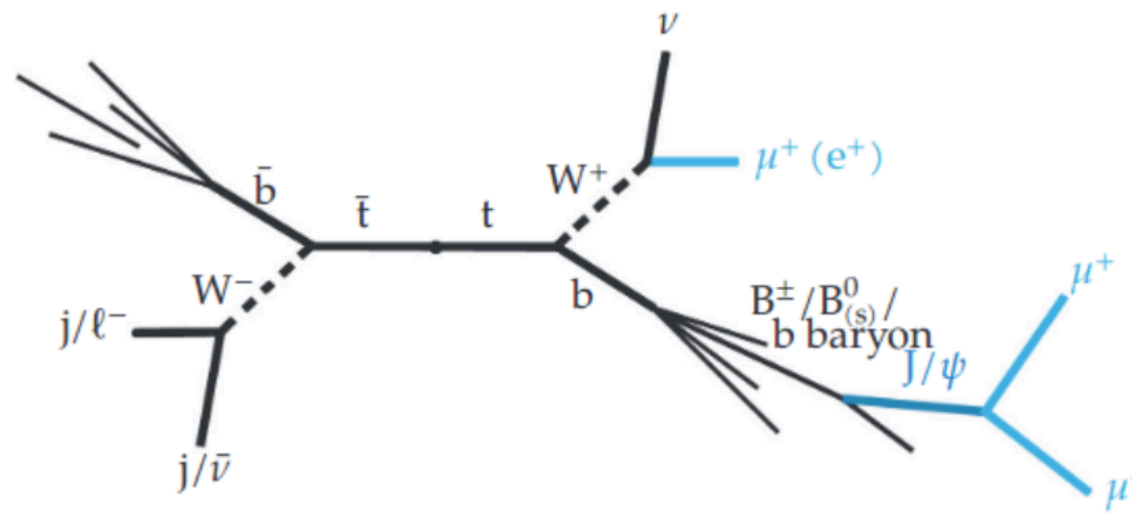
m_{top} measurement uncertainty for different methods as a function of integrated luminosity



CMS-PAS-FTR-16-006

Top quark mass measurement using $t\bar{t}$ pairs with a J/ψ

- Measurements using $t\bar{t}$ pairs with a $J/\psi \rightarrow \mu\mu$ in final state using the strong correlation between m_{top} and $m(lJ/\psi)$
  - BR $(b \rightarrow J/\psi(\rightarrow \mu\mu) + X)$ ~10^{-3}
    - Will benefit from larger data samples from the HL-LHC



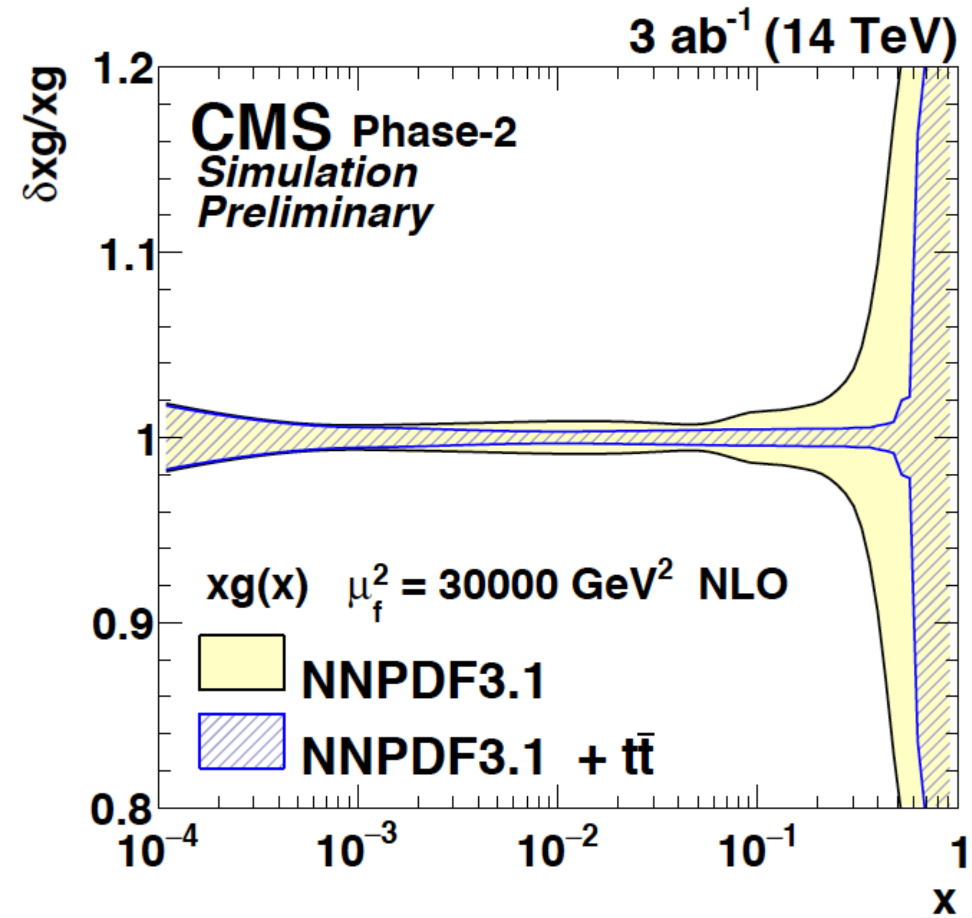
- A reduction of $t\bar{t}$ modeling uncertainties by a factor of two and a reduction of some of the experimental uncertainties by up to a factor two are assumed for these projections
  - Main result of this study is a statistical projection of the measurement
- ATLAS [ATL-PHYS-PUB-2018-042]: **a statistical uncertainty of ~0.14 GeV is expected with a systematic uncertainty of 0.48 GeV**
  - Dominant uncertainties are from **signal modeling** (fragmentation functions / b-hadron fractions) and from **JES/JER**
- CMS [CMS-PAS-FTR-16-006]: **expected to yield an ultimate relative precision below 0.1% at the HL-LHC**

m_{top} measurements will be an important element of HL-LHC

Differential $t\bar{t}$ cross-section measurements

- Done in e/μ+jets channels
- Most significant reduction of uncertainty is expected to come from:
    - Improved jet energy calibration
    - Reduced uncertainty in the b-jet identification
- Final projected uncertainty is estimated below 5%
- Precision in the measurement will profit from the **enormous amount of data** and the **extended η-coverage** of the Phase-2 CMS detector, which enables fine-binned measurements at high rapidity that are not possible with the current detector
- Uncertainties of the gluon distribution are drastically reduced and depend directly on the uncertainty of the integrated luminosity (assumed to be 1%)

Prospects at HL-LHC of the relative gluon uncertainties of the original and profiled NNPDF3.1 PDF set



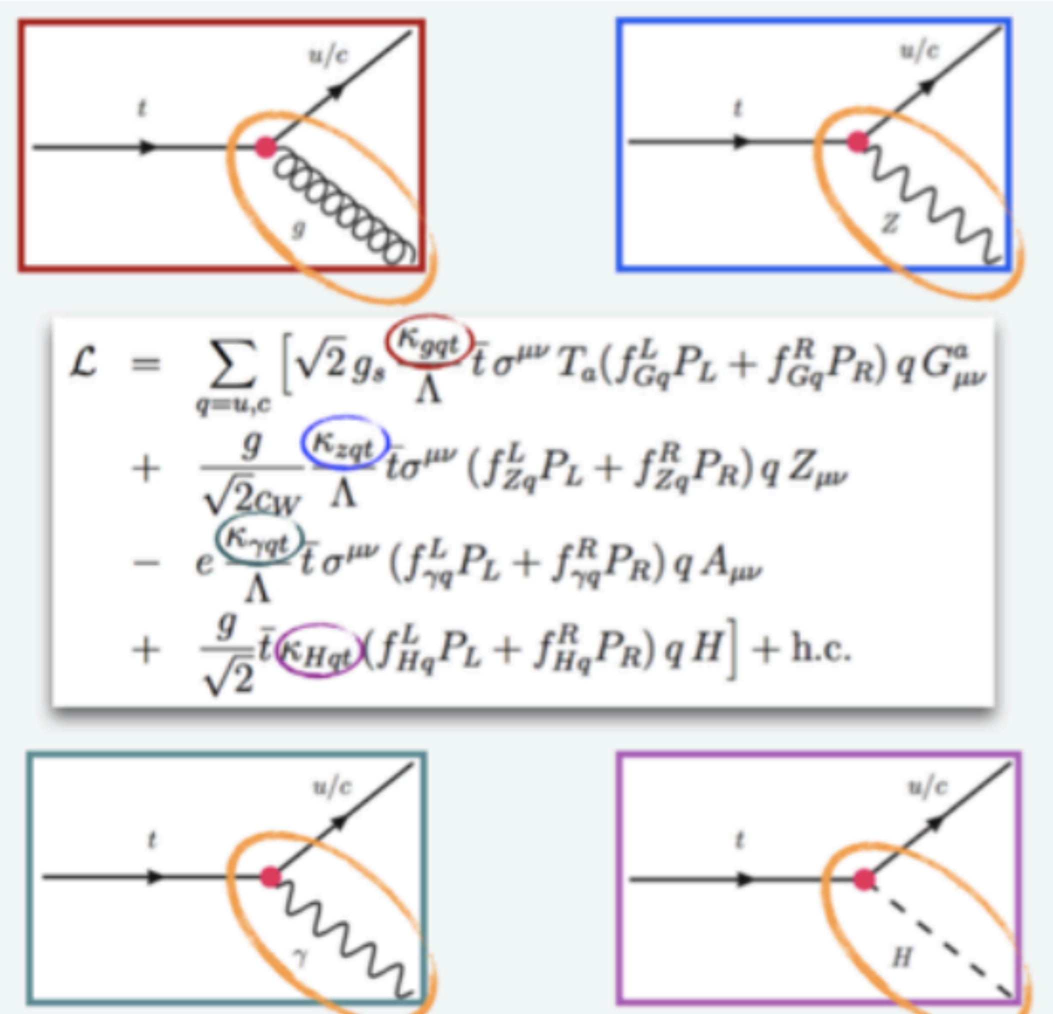
CMS-PAS-FTR-18-015

Flavor Changing Neutral Currents (FCNC)

- FCNC in the SM is forbidden at tree-level: heavily suppressed in loops by GIM mechanism BRs ~10^{-14}
- BSM can enhance FCNC up to ~10^{-4}
  - Many potential models: 2HDM, MSSM, RPV SUSY, …
- Any observation of FCNC can hint to new physics
- FCNC probe can be done in both top quark **production**, and **decay**

top quark+ gluon

top quark+ Z boson



$$\begin{aligned}\mathcal{L} = \sum_{q=u,c} \Big[& \sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R) q G^a_{\mu\nu} \\ & + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} \\ & - e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) q A_{\mu\nu} \\ & + \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R) q H \Big] + \text{h.c.}\end{aligned}$$

top quark+ photon

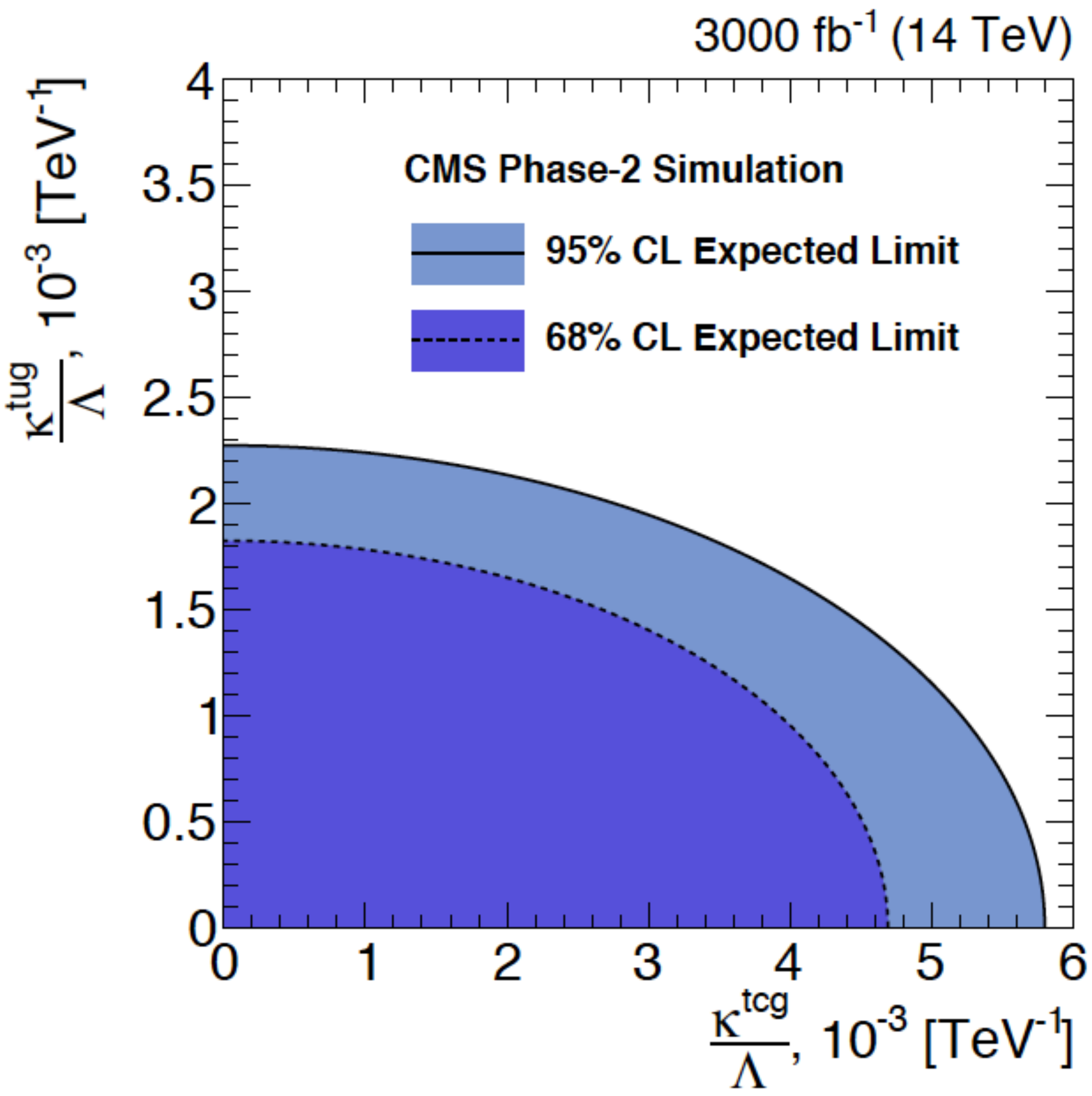
top quark+ Higgs

Flavor Changing Neutral Currents (FCNC)

- Search prospects for gluon-mediated FCNC in top quark production via *tug* and *tcg* vertices were studied with CMS HL-LHC detector

- Dominant uncertainty is normalization of multijet background

- Limits on branching fractions:
  - $B(t \to ug) < 3.8 \times 10^{-6}$
  - $B(t \to cg) < 32 \times 10^{-6}$



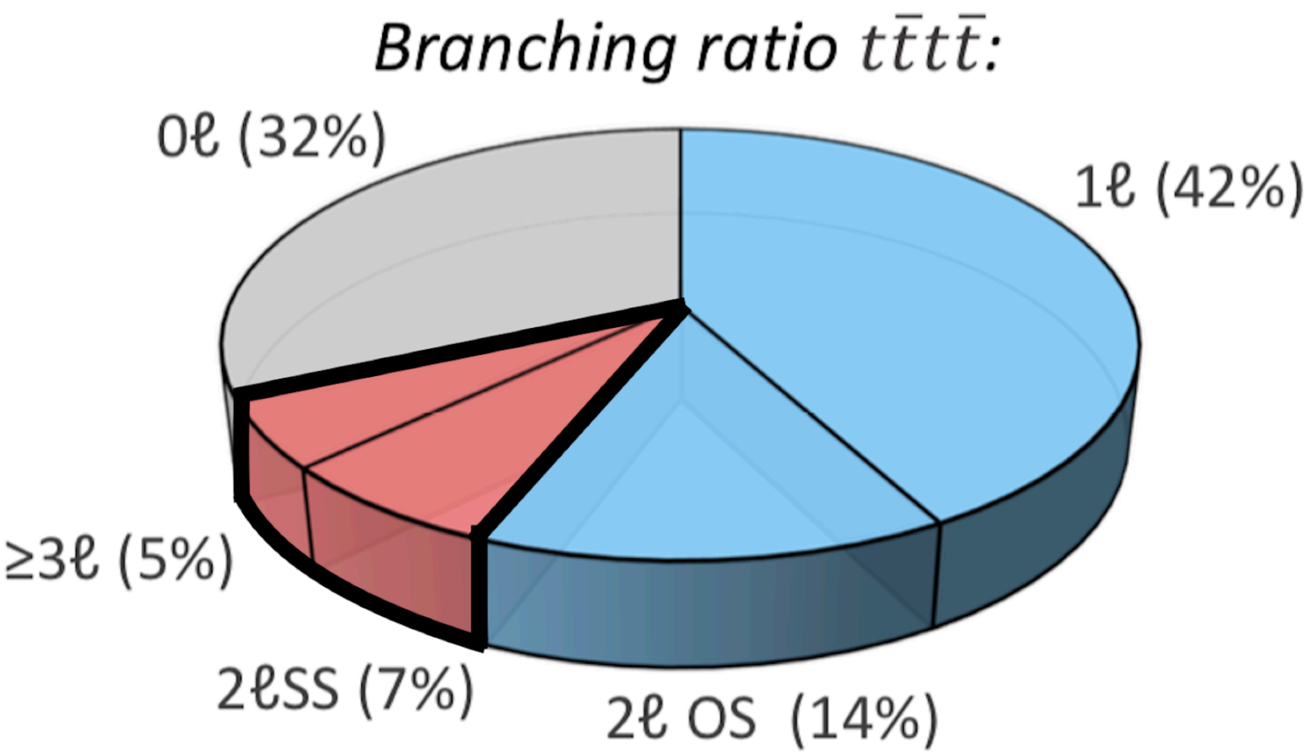
Exploiting full HL-LHC dataset will allow us to improve current limits by an order of magnitude

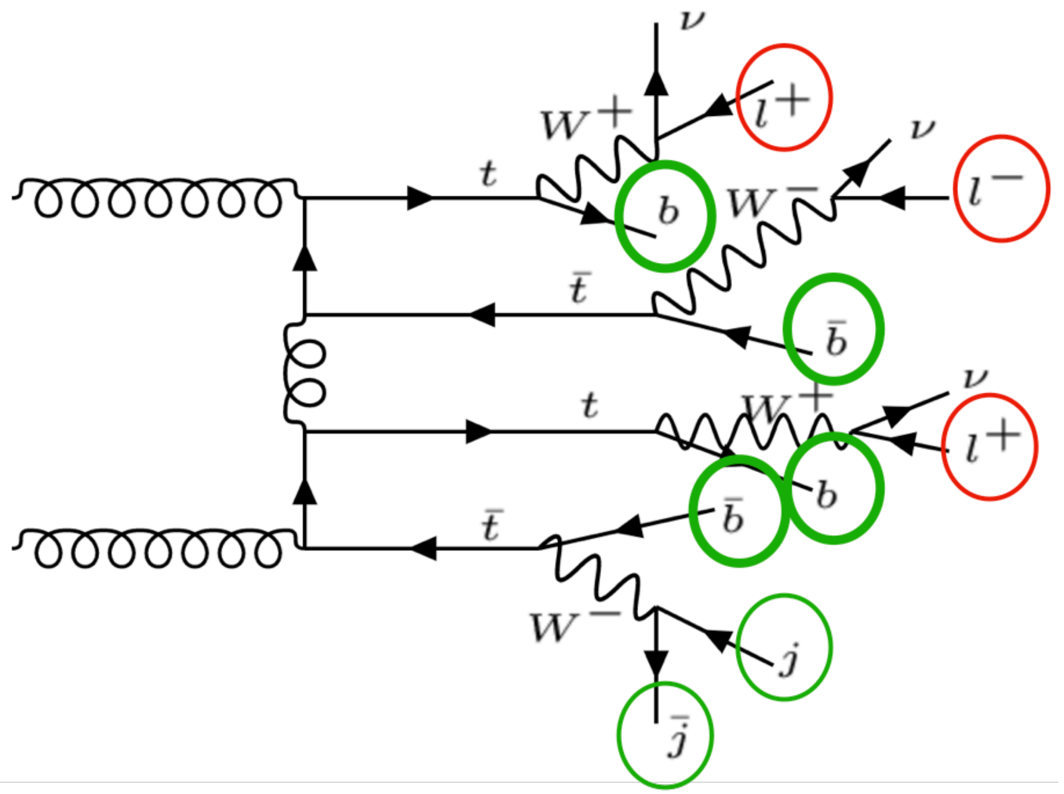
CMS-PAS-FTR-18-004

See back-up for more examples

Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

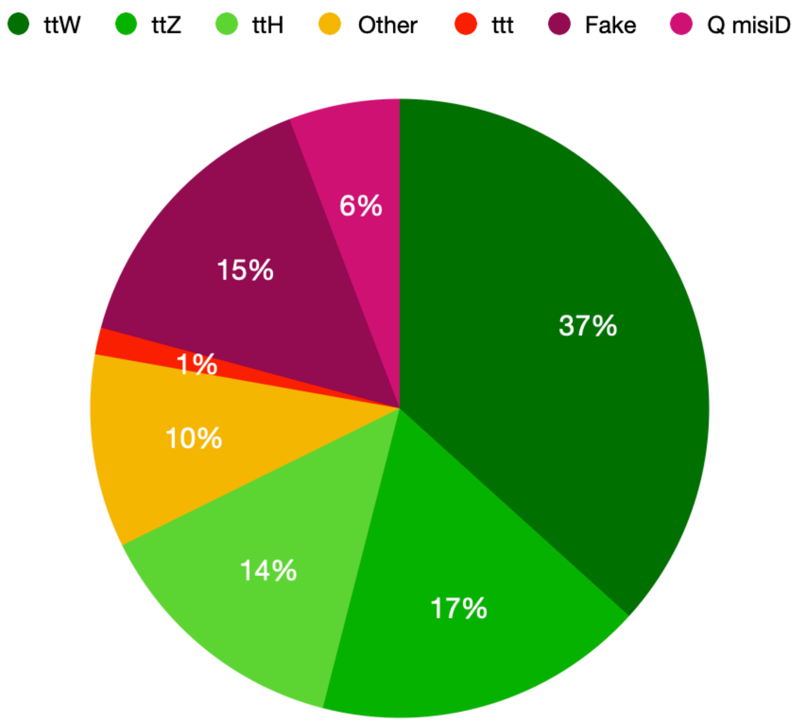
- Based on the recent evidence found in the SS/ML channel using the full run-2 dataset
- See Mathis's talk from Monday for more details





Run 2 analysis in a nutshell

- Five analysis regions: 1 Signal Region & 4 Control Regions
- Main Backgrounds:
  - ttW (37%), ttZ(17%), and ttH (14%)
  - Fake and non-prompt leptons (15%)
  - Charge mis-assignment (6%)



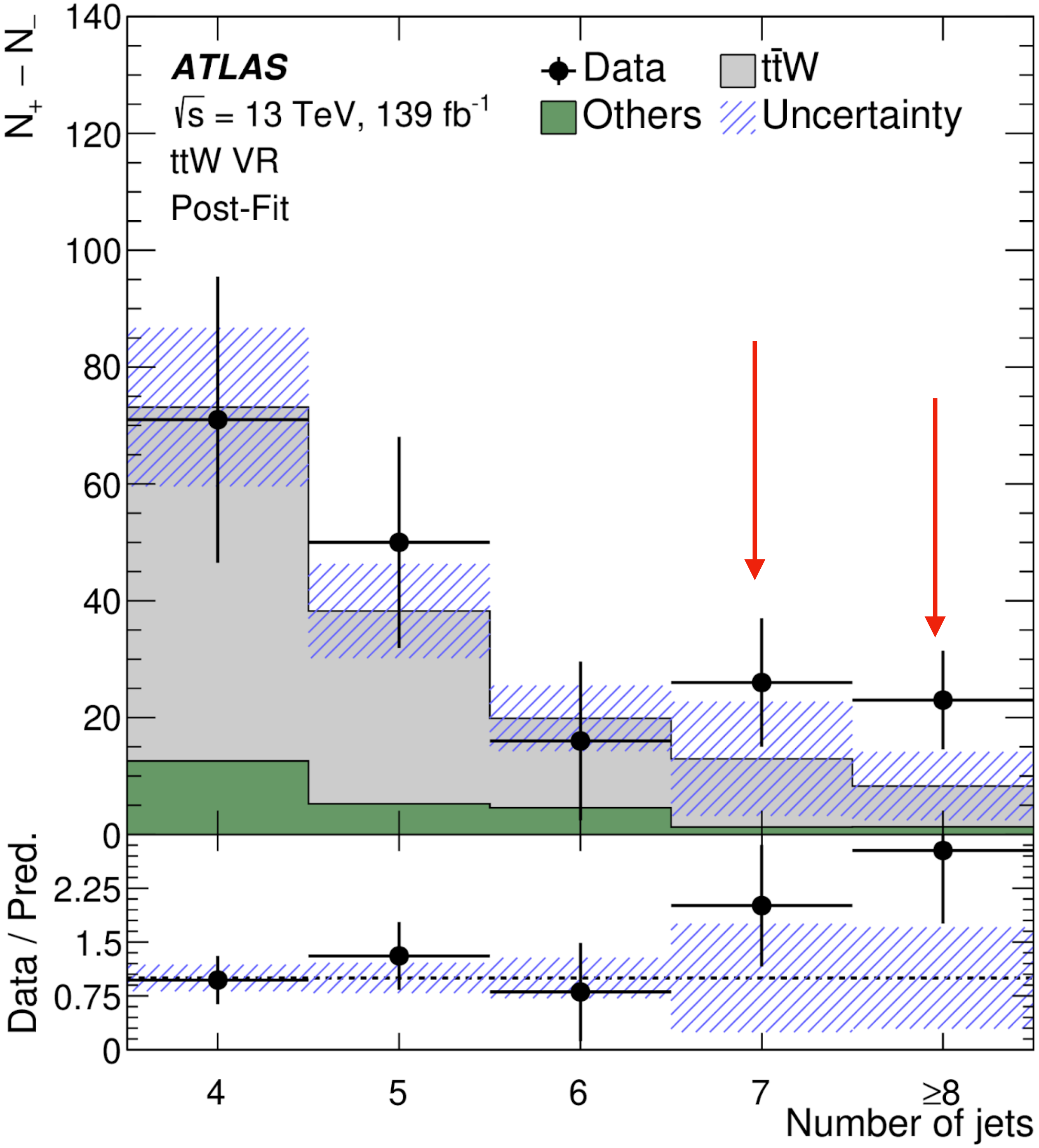
- **Template Method** is used to determine the major backgrounds
  - Background shapes are estimated from MC
  - Normalisation is obtained from the fit

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

Compatible with other ATLAS and recent CMS measurements!

ttW Validation Region

- Use Validation Region to check ttW+jets normalisation and modeling
  - Additional jets: Uncertainty of 125% is assigned to events with 7 jets and 300% is assigned to events with ≥8 jets
    - Based on Validation Region mismodeling



Results with 139 fb^{-1}

- Signal is separated from background based on a multivariate discriminant built in the signal region by combining input observables into a BDT

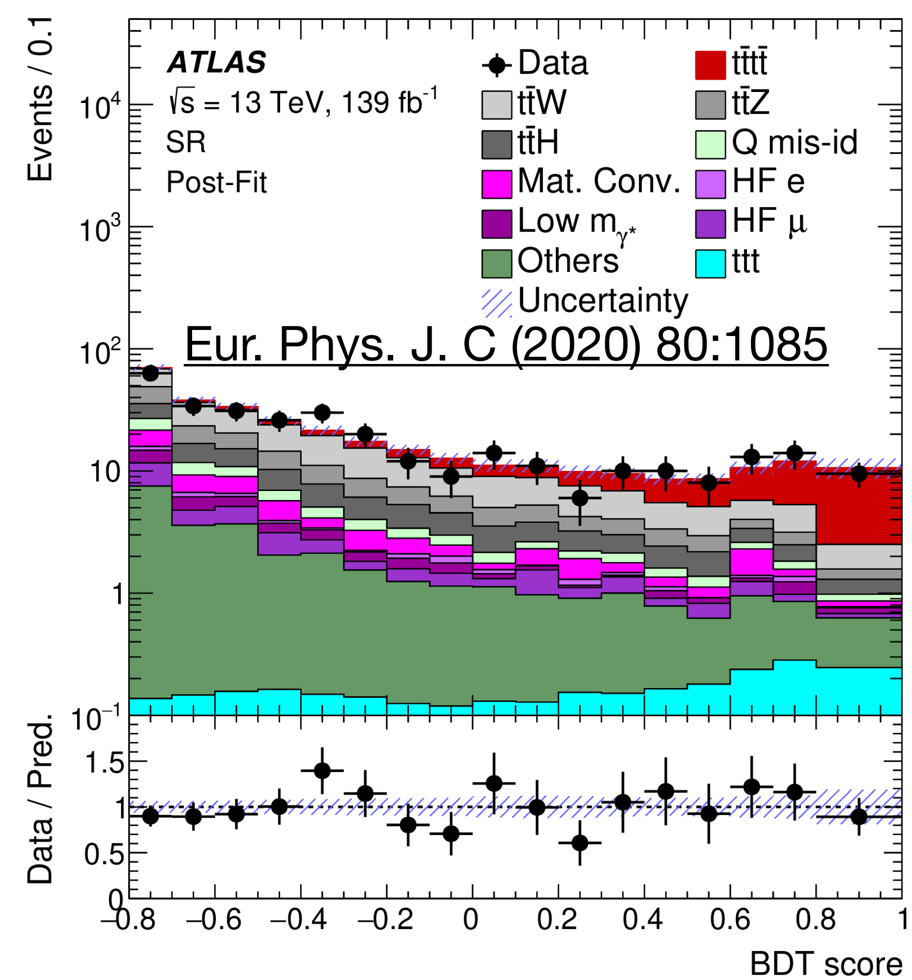
- The measured tttt signal strength is found to be:
$$\mu = \sigma_{t\bar{t}t\bar{t}} / \sigma^{SM}_{t\bar{t}t\bar{t}} = 2.0^{+0.4}_{-0.4}(stat) \ ^{+0.7}_{-0.5}(syst) \ = 2.0^{+0.8}_{-0.6}$$

- Cross section:
$$\sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(stat) \ ^{+5}_{-4}(syst)\, fb = 24^{+7}_{-6}\ fb$$

- Compared to the theoretical prediction of
$$\sigma(t\bar{t}t\bar{t}) = 12 \pm 2\ fb$$

- Strong 4.3σ (2.4σ expected) evidence

- Consistent to 1.7σ with the Standard Model



Extrapolation Studies

- The expected cross-section of tttt at 14 TeV is 15.83 +18%/ -21% fb (JHEP 02 (2018) 031)
  - An increase by a factor of 1.3 with respect to 13 TeV
- Extrapolation studies are performed with the setup that uses HT as fitted variations in five signal regions
  - Easier to extrapolate than the result using the BDT score
  - Almost the same significances as with the BDT

Channel	Selection criteria
Common	$N_j \geq 6$, $N_b \geq 2$ and $H_T > 500$ GeV
SR2b2l	SS events with $N_b = 2$
SR2b3l	multilepton events with $N_b = 2$
SR3b2l	SS events with $N_b = 3$
SR3b3l	multilepton events with $N_b = 3$
SR4b	events with $N_b \geq 4$

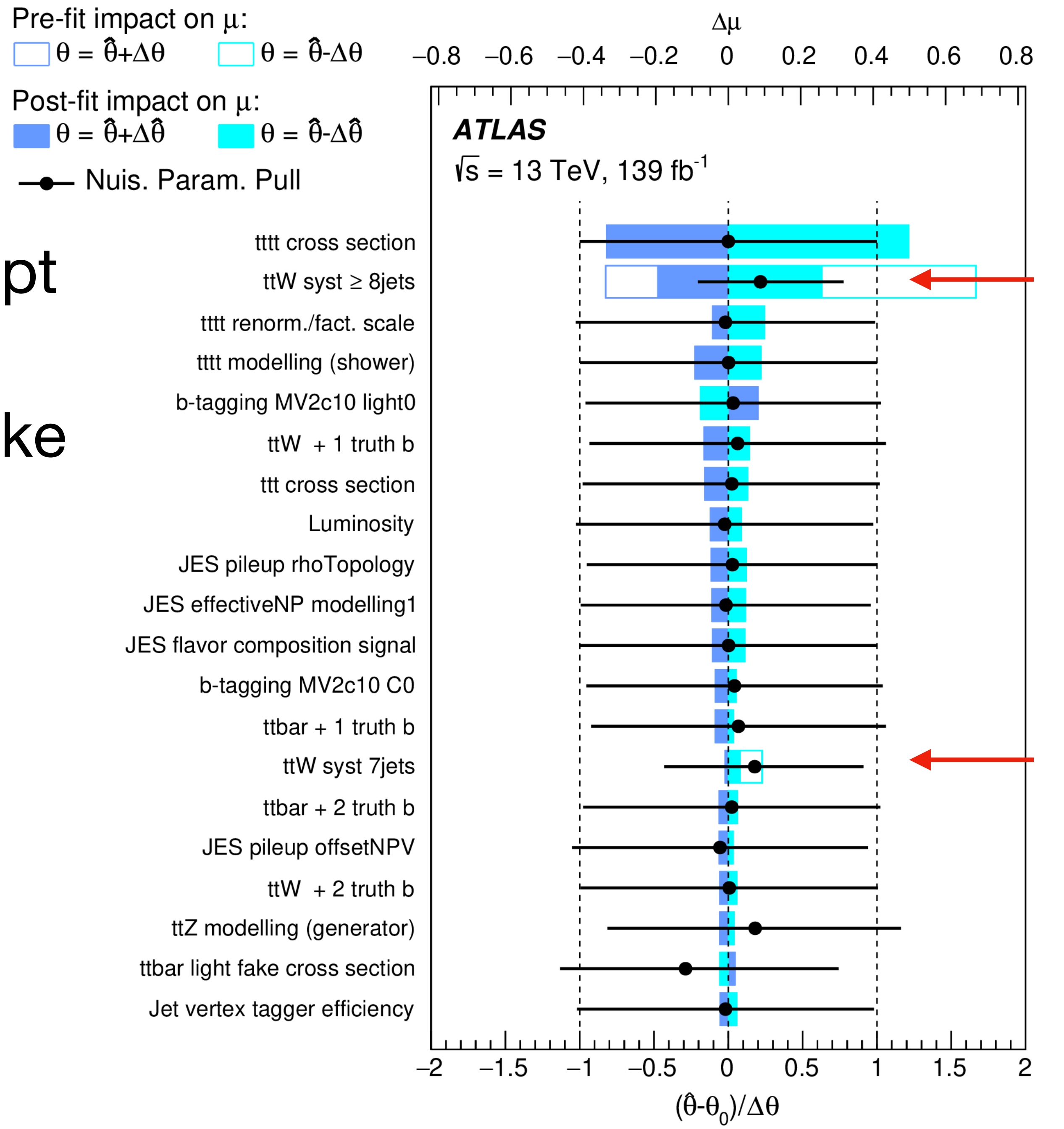
HL-LHC Recommendations

- Looked into several extrapolation scenarios based on how to scale the systematics with the assumption agreed for the 2019 Yellow Report
- Followed the recommendations explained in the High Lumi LHC Systematics
  - Modelling uncertainties could be halved (ATL-PHYS-PUB-2019-005)
  - No dedicated studies for HL-LHC expected performance, except for HF
    - Recommended way to apply flavor tagging uncertainties is to scale down the nuisance parameters from the current analyses
    - Systematics driven by intrinsic detector limitations are left unchanged, or revised according to detailed simulation studies of the upgraded detector

Two Different Scenarios

- Extrapolation is performed under two different scenarios of the evolution of detector performance and associated systematic uncertainties
- "**Run 2**" : systematic uncertainties are kept equal to their Run 2 values except uncertainties related to $t\bar{t}W + 7/8$jets (take the post-fit values of the corresponding nuisance parameters from the 139 fb^{-1} result)
- "**Run 2 Improved**": includes the $t\bar{t}W + 7/8$jets scaling and includes a decrease of the systematic uncertainties based on the "YR18 systematic uncertainties"

Ranking with 139 fb^{-1}



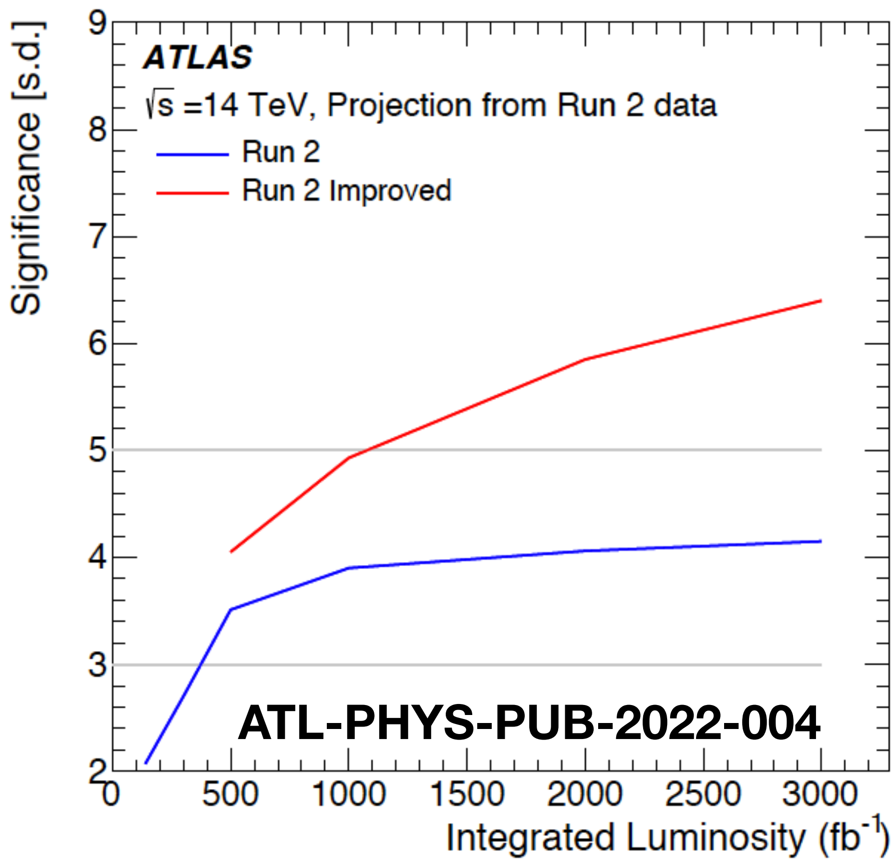
Run 2 Improved

Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}t$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

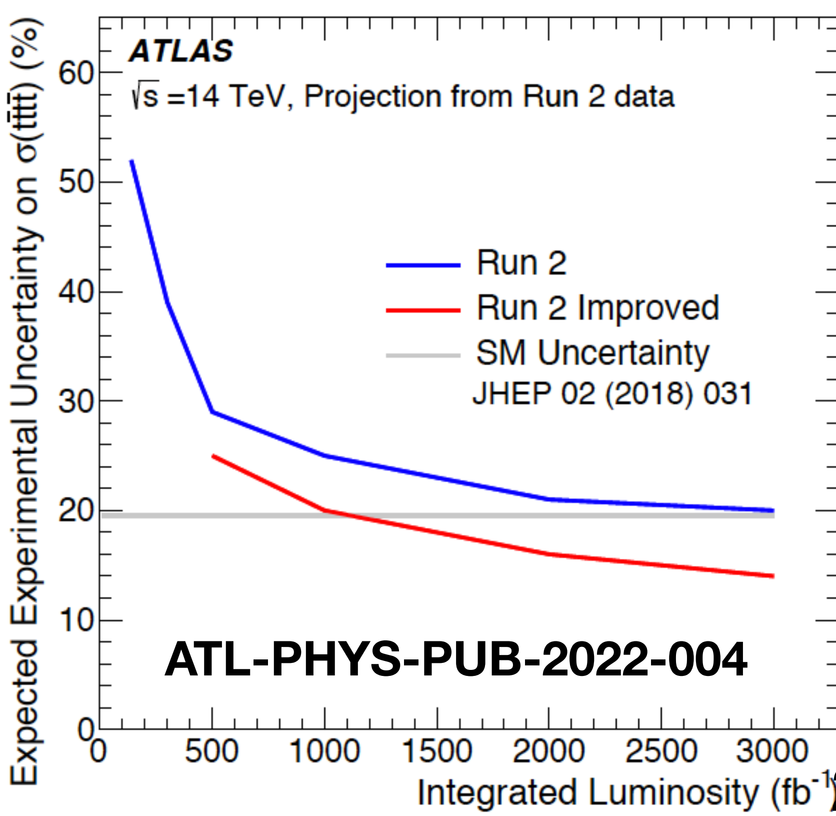
Expected Sensitivity

- A significance of 6.4σ for the SM $t\bar{t}t\bar{t}$ process is expected in the **"Run 2 Improved"** scenario
    - Expecting total uncertainty on the cross section of ~14%
    - Experimental precision is expected to be significantly better than the precision of the current SM computation
- The better sensitivity is driven by:
    - Smaller theoretical uncertainties assumed in the $t\bar{t}t$ cross section
    - Better modeling of the $t\bar{t}W/t\bar{t}Z$ + HF jets
    - Smaller b-tagging experimental uncertainties

Expected significance



Expected experimental uncertainty



Sensitivity Studies by CMS

- Based on the run-2 results with 36 fb^{-1}
- Tried various treatment of systematic uncertainties

Source uncert.	*Stat. only*	*Run 2*	*YR18*	*YR18+*
Statistical	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$
Experimental	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Int. Luminosity	None	Original	0.4	0.4
Data-driven bckgrnd	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Theory (shapes)	None	Original	0.5	0.5
Bckgrnd cross section	None	Original	0.5	0.5
Signal cross section	None	Original	0.5	0.5

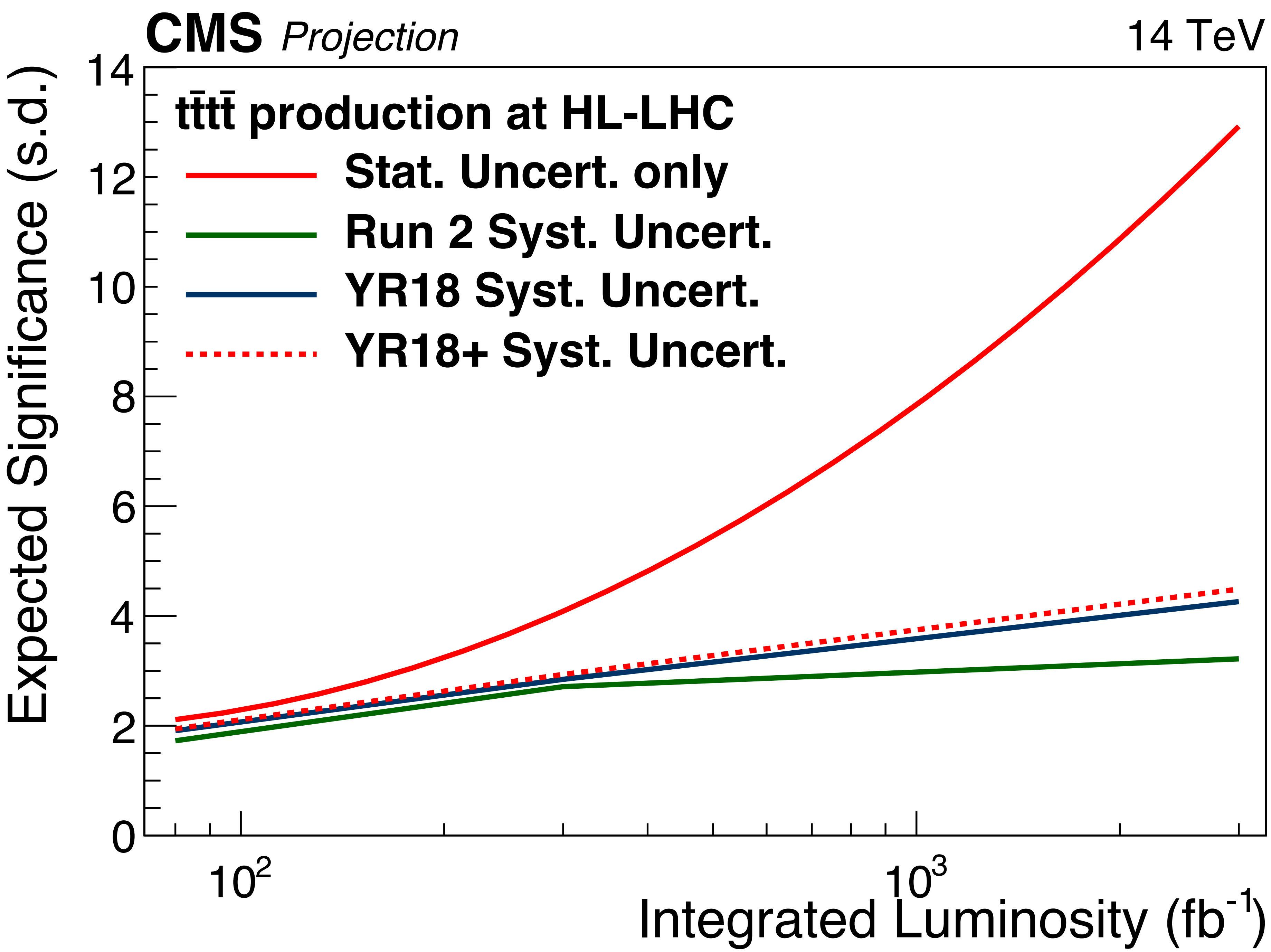
Expected significance of $t\bar{t}t\bar{t}$ signal over a background-only hypothesis

Int. Luminosity	*Stat. only*	*Run 2*	*YR18*	*YR18+*
300 fb^{-1}	4.09	2.71	2.85	2.93
3 ab^{-1}	12.9	3.22	4.26	4.49

CMS-PAS-FTR-18-031

Sensitivity Studies by CMS

- A 4.5σ significance is expected with the most optimistic systematics scenario
- Cross-section can be constrained down to 9% statistical uncertainty and 18% to 28% total uncertainty (depending on the considered systematic uncertainties)



CMS-PAS-FTR-18-031

Conclusions

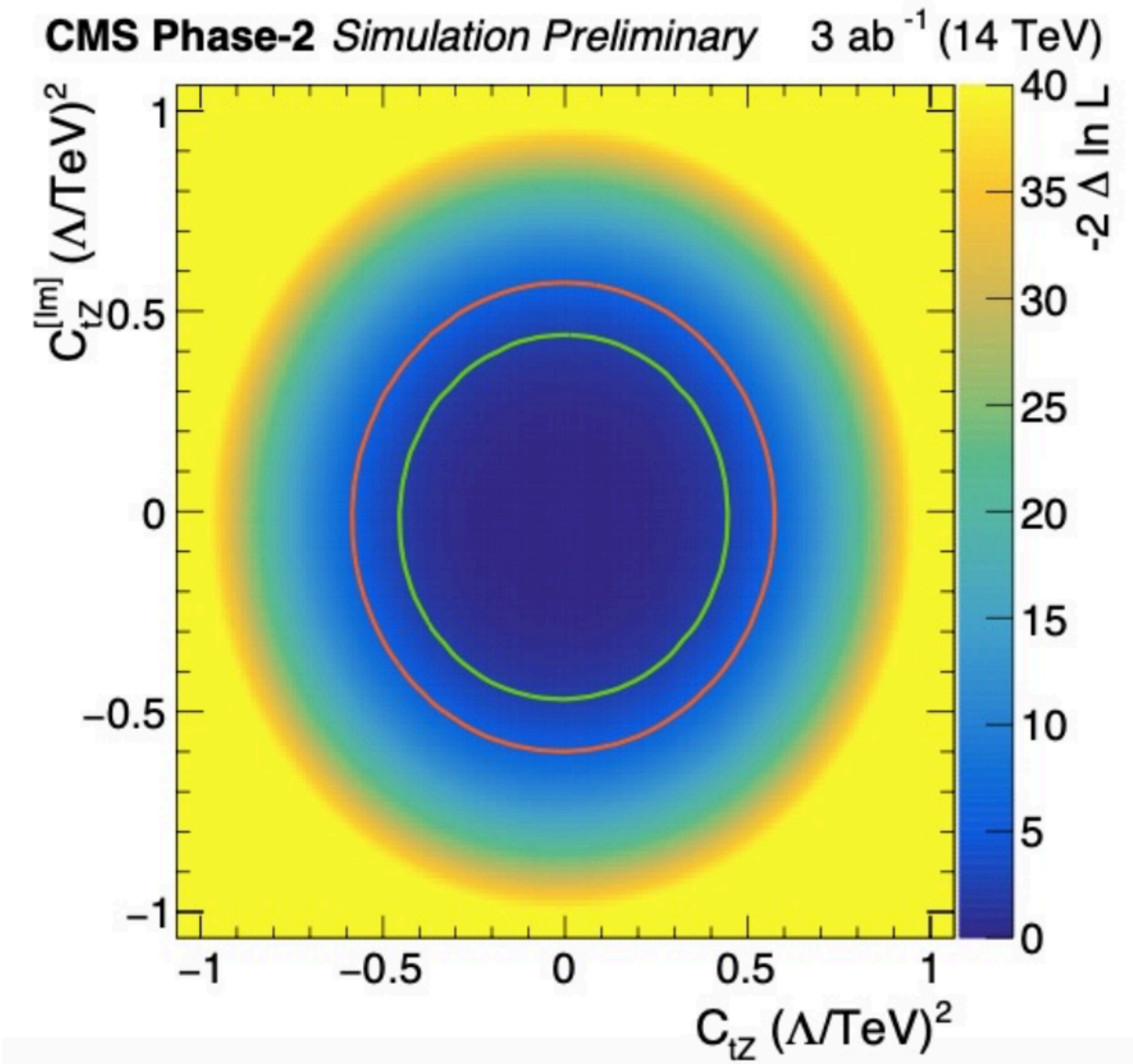
- HL-LHC will offer a great opportunity for many top measurements & top related searched
- Detector upgrades will allow for better forward jet and lepton reconstruction - essential to improve current measurements
- Will produce currently unachievable measurements
- Improve our understanding and learn more about the SM
- Can uncover unexpected deviations from the SM pointing to new physics
- Improving theoretical uncertainties is a key player to achieve better precision

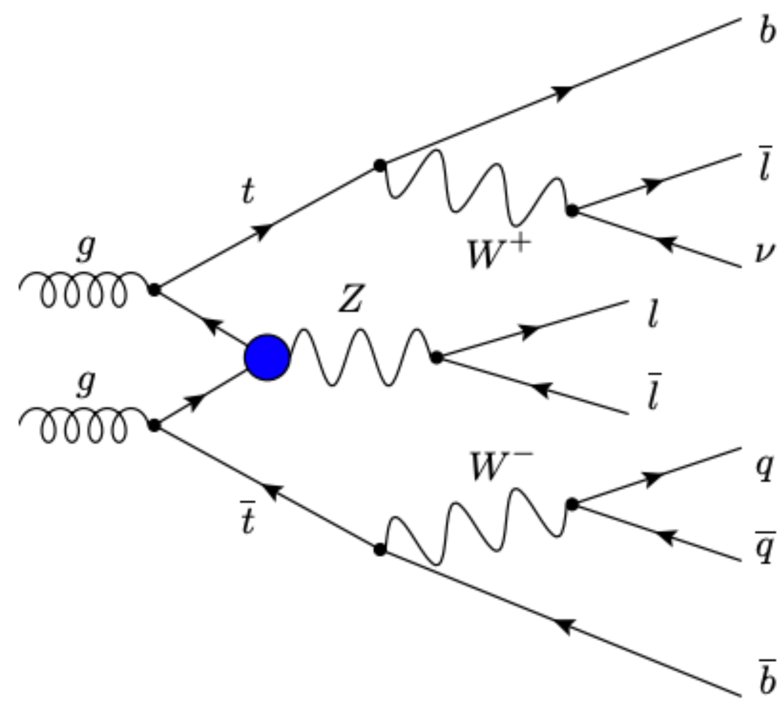
Thank you!

Extra Material

ttZ and EW top couplings at the HL-LHC

- Expected sensitivity to Wilson coefficients of top quark operators C_{tZ} in the ttZ process





Wilson coefficient C_{tZ} in SMEFT
68 % CL (Λ/ TeV)^2 : [-0.37, 0.36]
95 % CL (Λ/ TeV)^2 : [-0.52, 0.51]

CMS-PAS-FTR-18-036

FCNC - tZq

- Done in the three charged lepton final states
- The dominant sources of uncertainties, in both signal and background estimations, are from the theoretical normalization and the modeling of the background processes MC
- An improvement by a factor of four is expected over the current Run-2 analysis

	-1σ	Expected	$+1\sigma$
$\mathcal{B}(t \to uZ)$	4.9×10^{-5}	6.9×10^{-5}	9.7×10^{-5}
$\mathcal{B}(t \to cZ)$	5.8×10^{-5}	8.1×10^{-5}	12×10^{-5}

Table 6: The expected 95% confidence level upper limits on the top-quark FCNC decay branching ratios are shown together with the $\pm 1\sigma$ bands, which include the contribution from the statistical and systematic uncertainties. Presented limits are extracted from "Asimov data" in the signal and background control regions, defined as the total expected pre-fit background. Systematic uncertainty from the MC statistical uncertainty is considered as well.

Operator	Expected limit
$\lvert C_{uB}^{(31)} \rvert$	0.13
$\lvert C_{uW}^{(31)} \rvert$	0.13
$\lvert C_{uB}^{(32)} \rvert$	0.14
$\lvert C_{uW}^{(32)} \rvert$	0.14

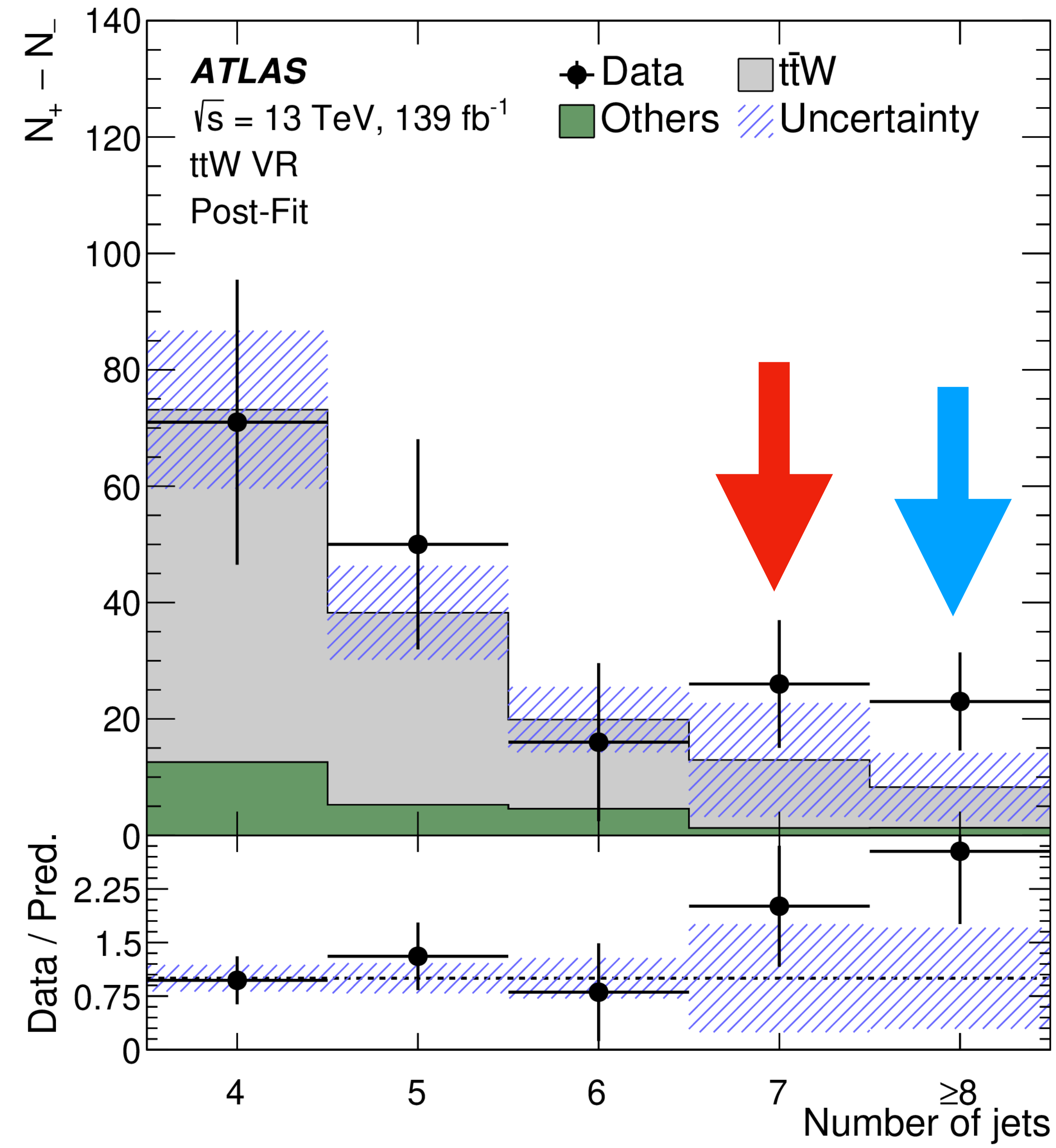
Table 8: Expected 95% CL upper limits on the moduli of the operators contributing to the FCNC decays $t \to uZ$ and $t \to cZ$ within the TopFCNC model for a new-physics energy scale $\Lambda = 1$ TeV.

ATL-PHYS-PUB-2019-001

Run 2 SM $t\bar{t}t\bar{t}$ cross section

$t\bar{t}W$ **Validation Region**: ≥4jets ≥2b-tagged

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62



Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

- The cross-section can be constrained down to 9% statistical uncertainty and 18% to 28% total uncertainty, depending on the considered systematic uncertainties, while a 4.5σ significance is expected with the most optimistic systematics scenario

- The expected sensitivity on the $t\bar{t}t\bar{t}$ cross-section is also used to provide constraints on EFT four top contact interaction operators, setting limits on their Wilson coefficients

CMS-PAS-FTR-18-031