Standard Model measurements at the High-Luminosity LHC

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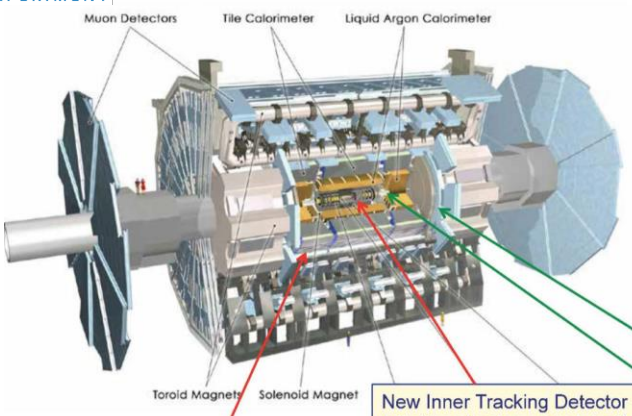
LHC / HL-LHC Plan

TODAY

ATLAS EXPERIMENT

CMS



New muon chambers
in the inner barrel region

New Inner Tracking Detector
(all silicon tracker, up to |η| =4)

Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

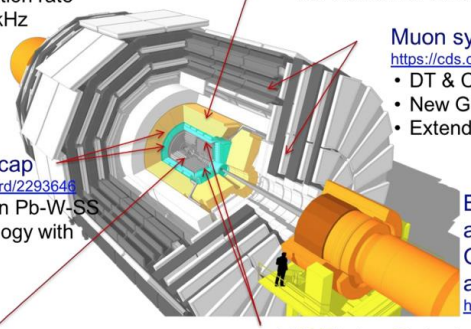
- LAr Calorimeter
- Tile Calorimeter
- Muon system

Options:
- High granularity timing detector (forward region)
- High-η muon tagger
- Forward detectors, incl. luminosity

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
- ≃ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

SM measurements at the HL-LHC

- Precise measurements
  - Should profit from
    - new methods
    - improved systematics
    - improved statistics
- Measurements with very low cross sections
  - Should profit from increased statistics
- Measurements that profit from new detectors capabilities

Physics results are summarized in Yellow Reports 2019:

WG1: **Standard Model Physics at the HL-LHC and HE-LHC,** CERN-LPCC-2018-03, https://cds.cern.ch/record/2650160/

WG4: **Opportunities in Flavour Physics at the HL-LHC and HE-LHC,** CERN-LPCC-2018-06, https://cds.cern.ch/record/2650175/

Yellow Report systematics assumptions

It is a significant challenge to predict the expected systematic uncertainties of physics results at the end of HL-LHC running "YR18 systematics uncertainties"

Trigger: despite the more challenging conditions, most of the trigger thresholds for common objects are expected to either remain similar to the current ones or to even decrease.

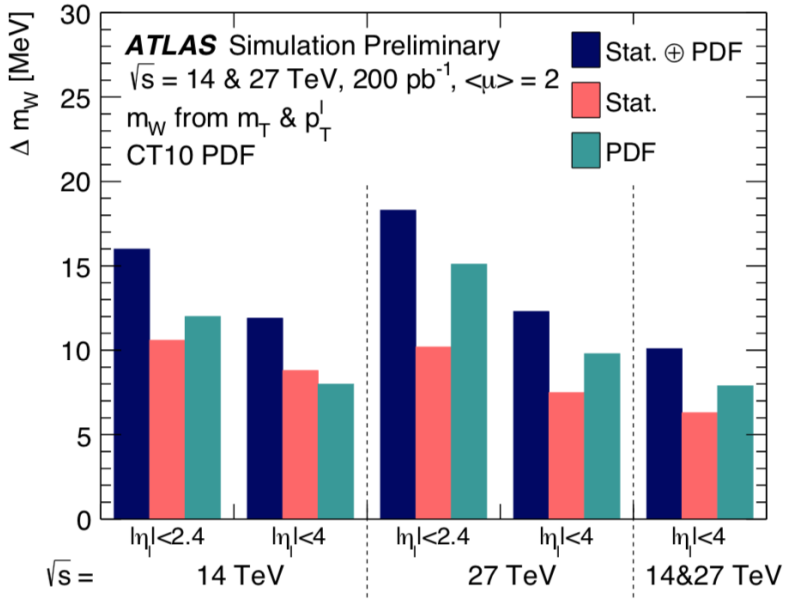
Theoretical uncertainties are assumed to be reduced by a factor of two with respect to the current knowledge, thanks to both higher-order calculation and reduced PDF uncertainties

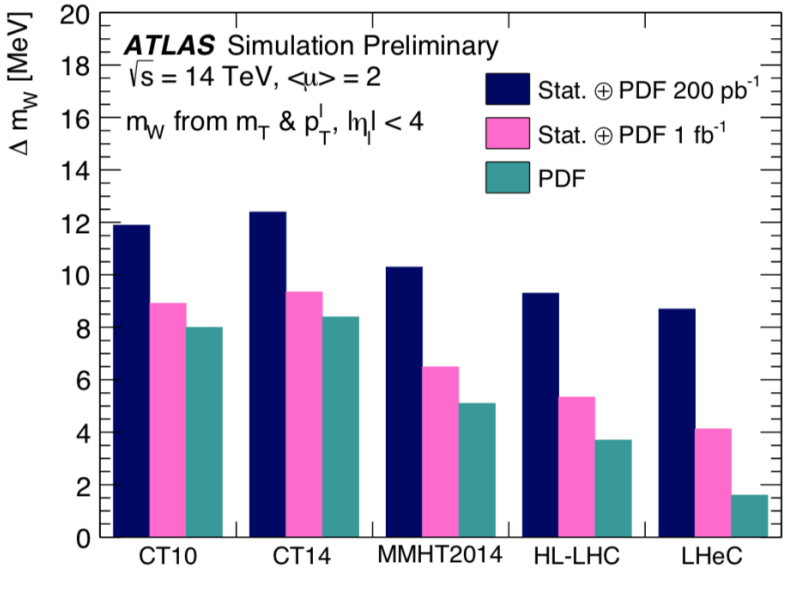
All the MC uncertainties related to the limited number of simulated events are neglected. The statistical uncertainty in the measurement is reduced by a factor 1/sqrt(L), where L is the projection integrated luminosity divided by that of the reference Run-2 analysis.

Systematics driven by intrinsic detector limitations are left unchanged, or revised according to detailed simulation studies of the upgraded detector. Uncertainties on methods are kept at the same value as in the latest public results available, assuming that the harsher HL-LHC conditions will be compensated by method improvements.
The uncertainty in the integrated luminosity of the data sample is expected to be reduced down to 1% .

W mass

- Require a special low PU run at HL/HE-LHC
- Need high MET resolution and improved PDF uncertainty





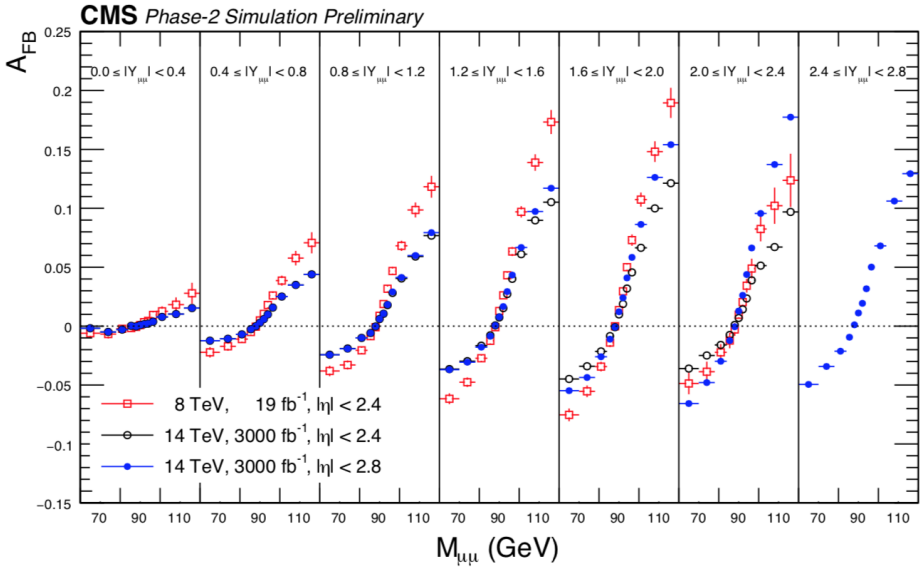
- Experimental uncertainties are expected to be kept at the level of statistical uncertainties

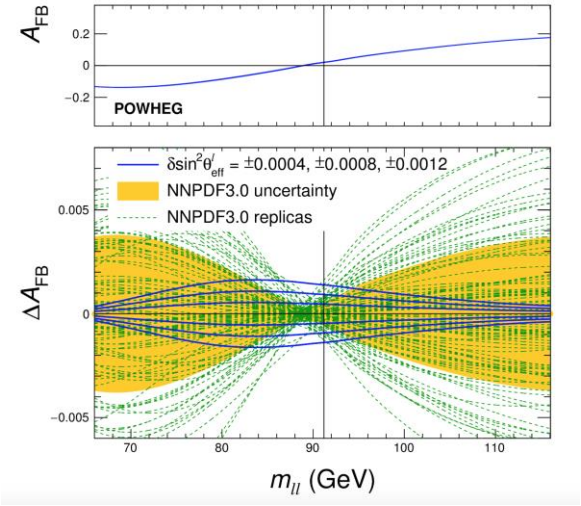
Effective weak mixing angle

- Forward-backward asymmetry, vector and axial-vector couplings in NC annihilation $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$

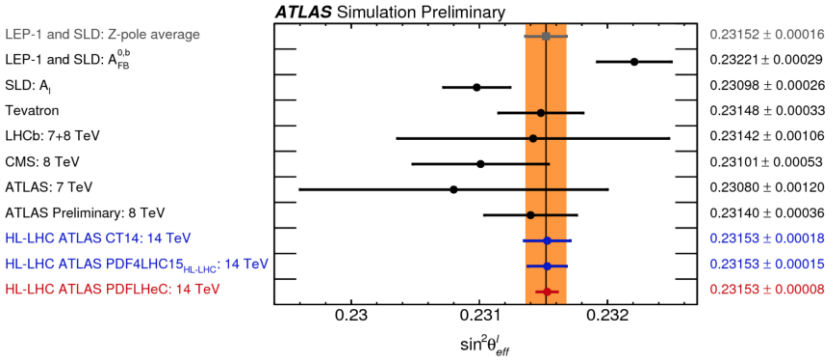
Dilution is smaller at high Y, indirect W mass measurement

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



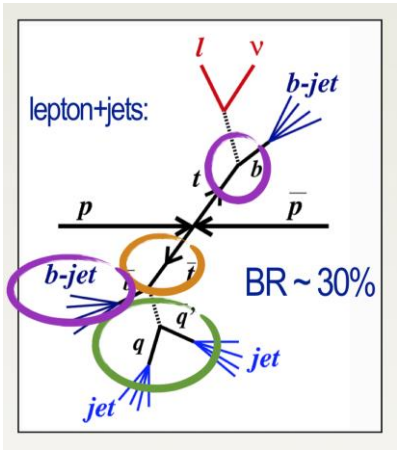


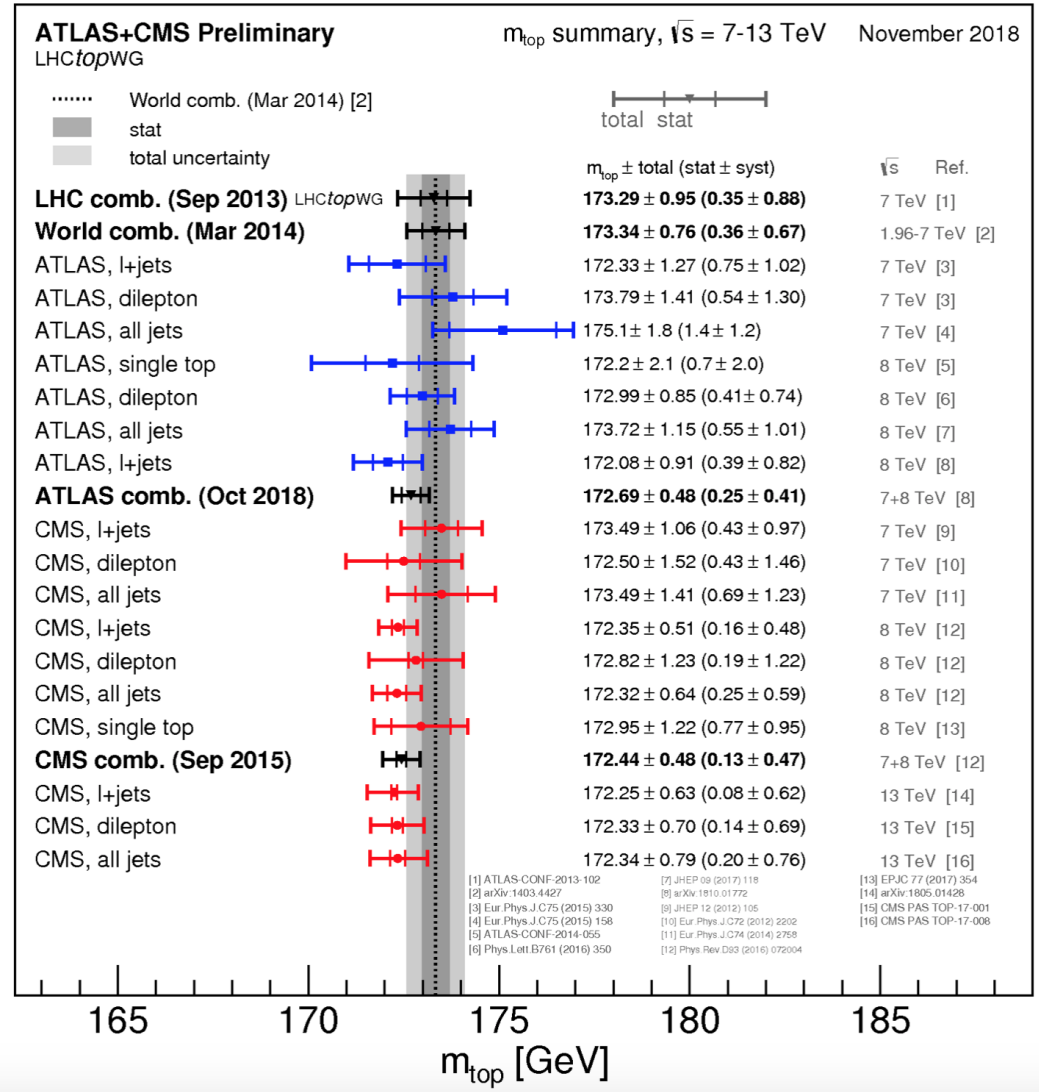
- Extending the lepton acceptance from ***|η| < 2.4 to 2.8 decreases the statistical uncertainties by about 30% and PDF uncertainties by about 20%*** Starting from about 1000fb^{-1}, a single measurement would already have a negligible statistical uncertainty and the PDF uncertainty could be constrained and improved by x2 !



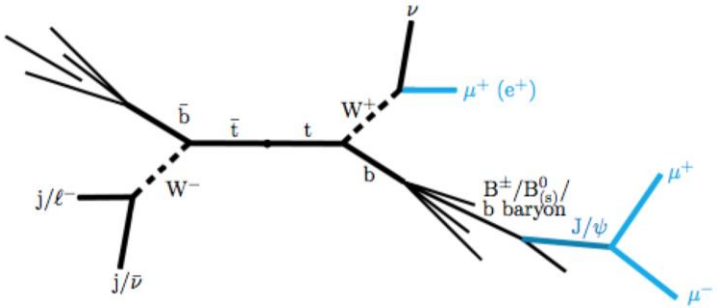
Top Mass

- Top quark mass - fundamental SM parameter
- Different measurement methods: l+jets mass, single top, track- and vertex-based distributions, the "J/ψ" method (see next page), cross section
- the reconstruction of the top mass from the final state currently (and in the future) gives the most precise experimental results.

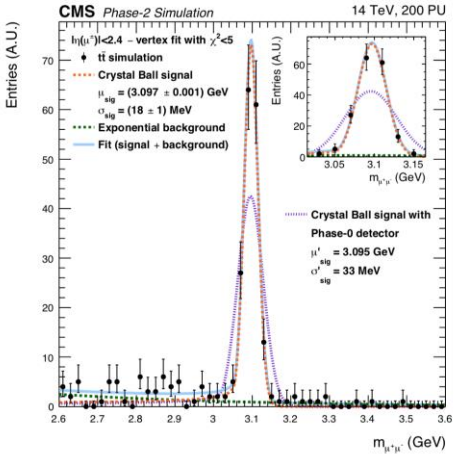




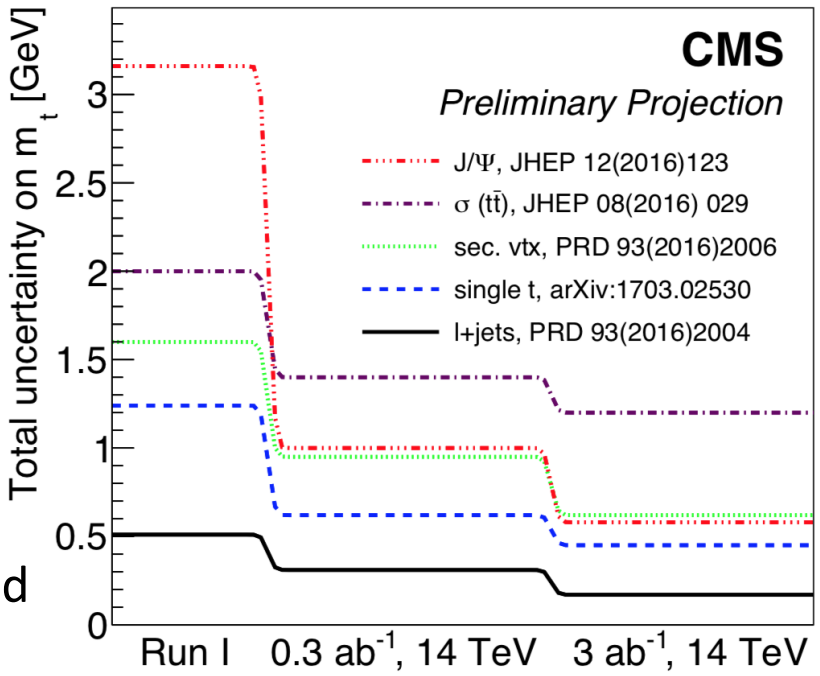
Top Mass



CMS-TDR-014



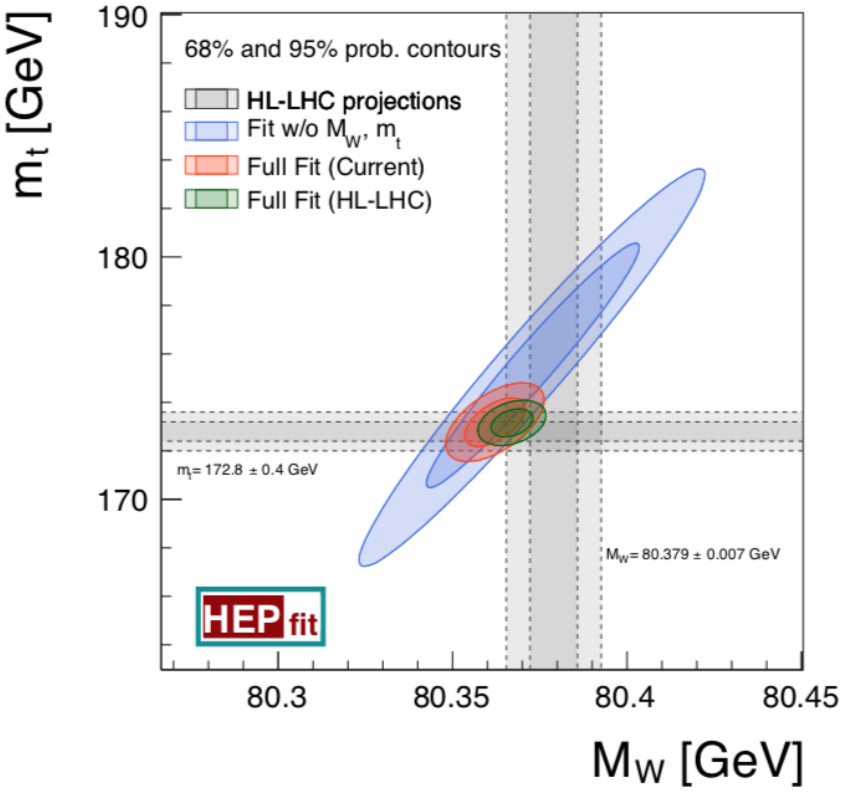
- "J/ψ" method should benefit from statistics
  - Nice reconstruction even at PU200
- Moderate improvement for pole mass from cross sections
  - Ultimately limited by luminosity and theory uncertainties (no N3LO assumed)
- Single top:
  - Benefit from statistics and modelling improvements
- l+jets
  - Benefit from differential studies constraining modelling

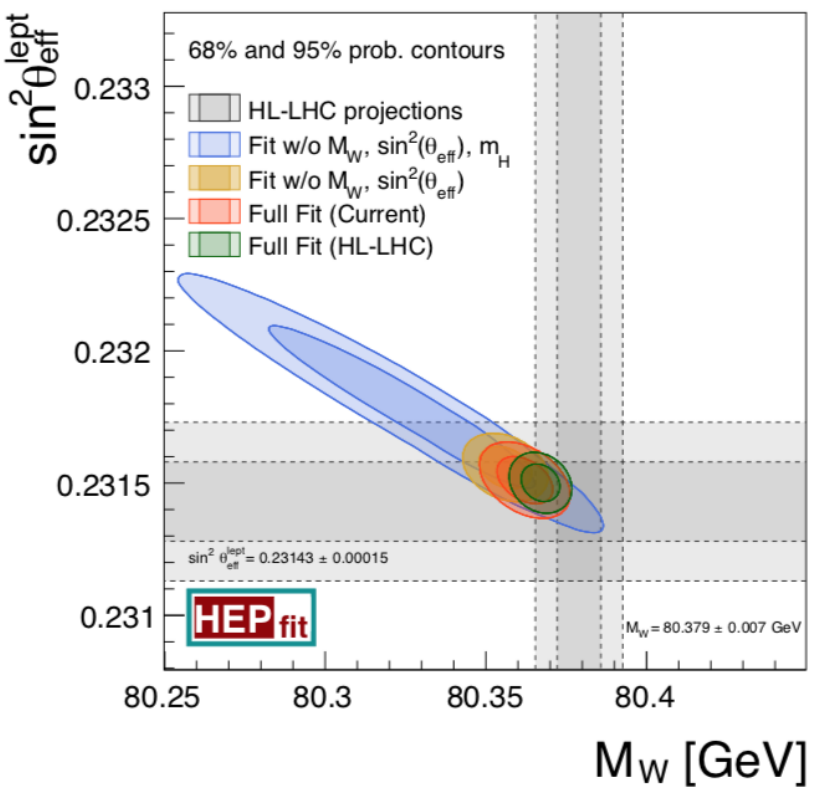


In general this measurement should be improved by pushing the experimental and theoretical uncertainties down during the next years

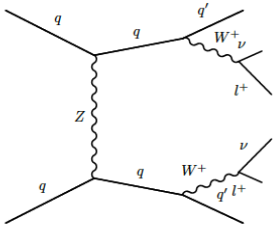
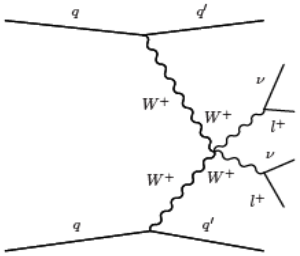
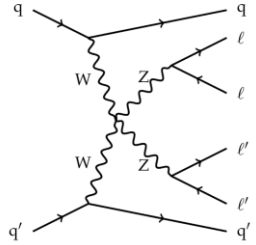
Global EW fit

- W mass uncertainty 7 MeV, width – 30 MeV
- Top mass uncertainty 0.4 GeV
- Effective angle uncertainty 0.00015
- Higgs boson mass uncertainty 0.05 GeV

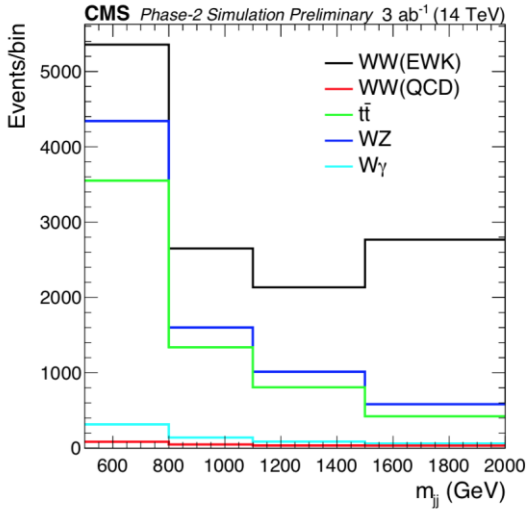


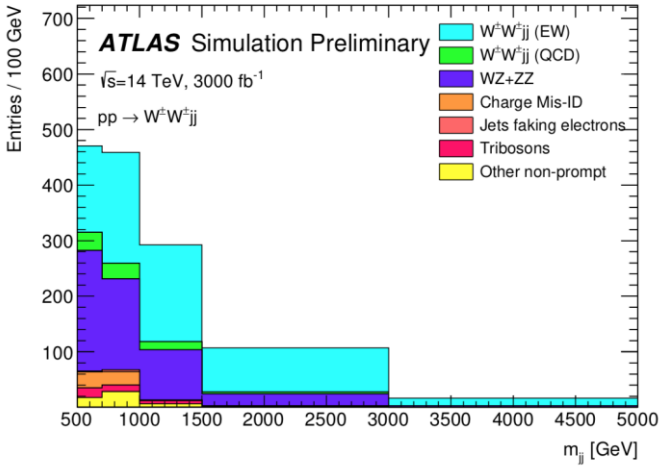


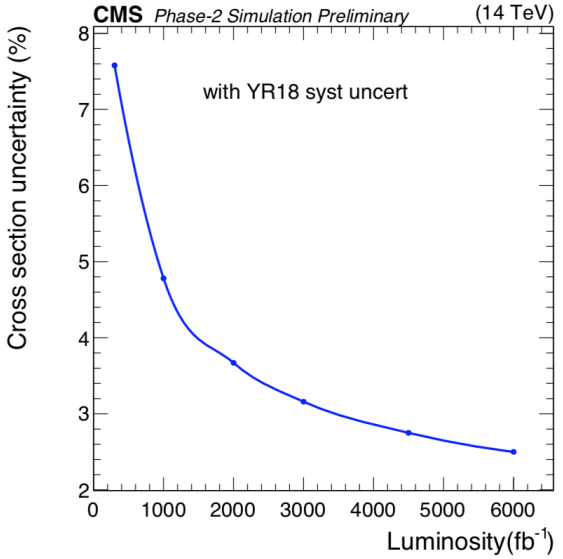
VV VBS and polarized cross section

…. etc producing WW, WZ and ZZ final states



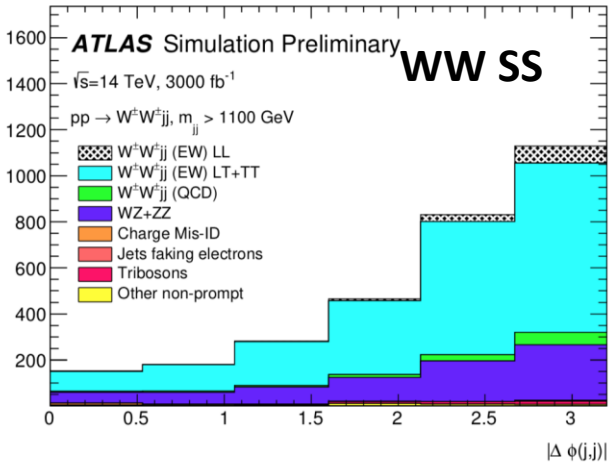


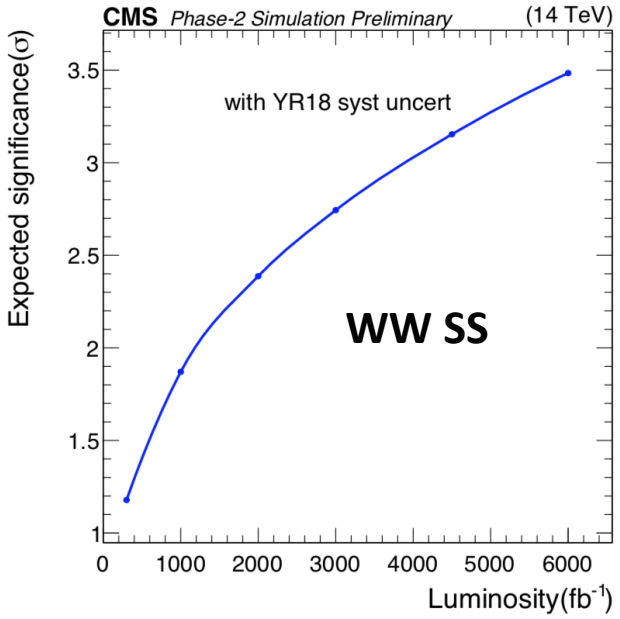


- The WW EWK is observed by both ATLAS and CMS with >5 σ significance.
- The WZ EWK is observed by
  - ATLAS 5.3 obs(3.2 exp) **arXiv:1812.09740**
  - CMS 2.2 obs (2.5 exp) **arXiv:1901.04060**
- The ZZ EWK by CMS 2.7 obs (1.6 exp) - Phys. Lett. B 774 (2017) 682

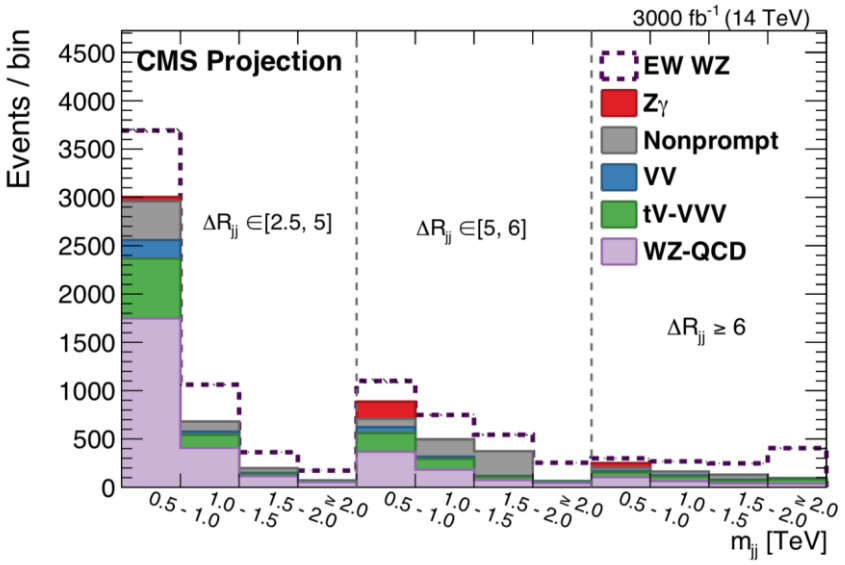
$W_L W_L$ polarized cross section

- The total vector boson scattering is composed of three components, depending on the polarization of the final-state vector bosons: both of them being longitudinally polarized (LL), both of them being transversely polarized (TT), and the mixed case (LT).
- The LL component is interesting as a direct probe of the unitarization mechanism of the VBS amplitude through Higgs and possible new physics.
- Use angular separation to measure LL signal
- Expected discovery significance for the longitudinal vector boson scattering increases as a function of the collected luminosity.



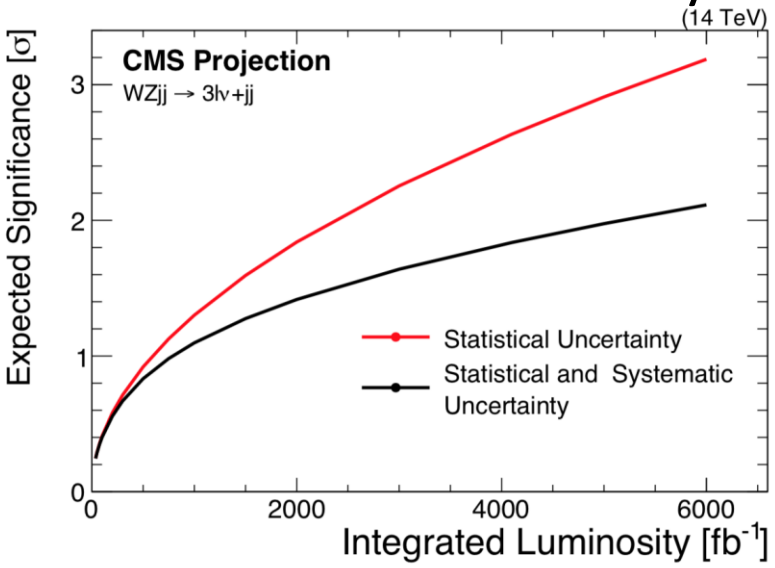


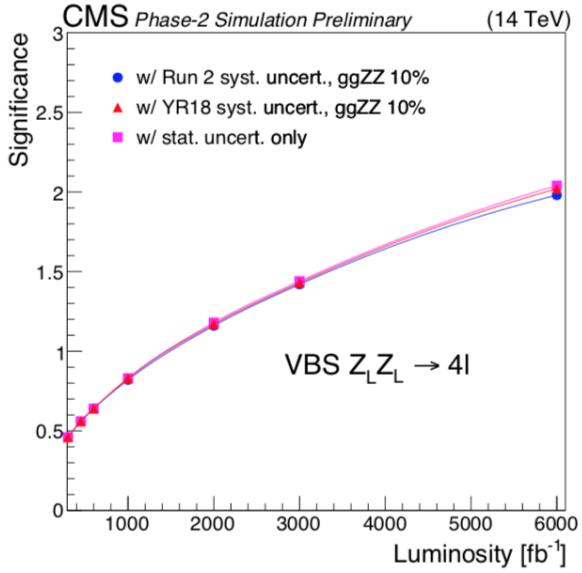
WZ and ZZ polarized cross sections



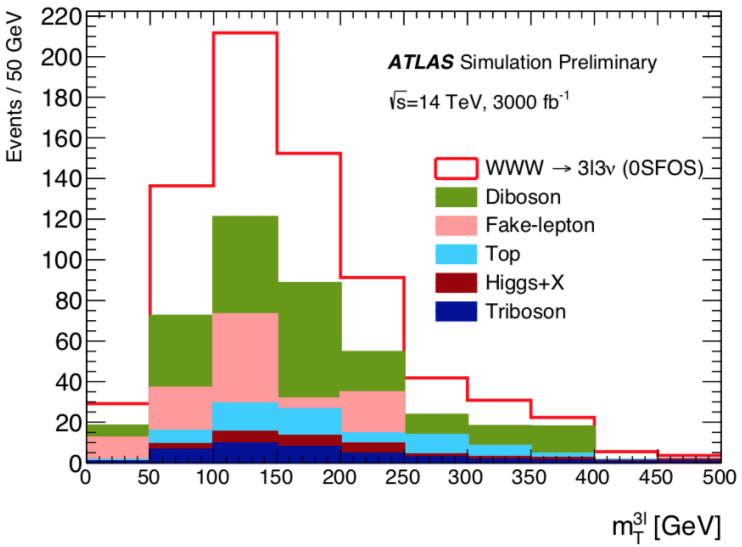
- The WZ and ZZ can be measured in similar way:
  - WZ in 2D fit m_{jj} and $\Delta\phi$ (ATLAS used BDT)
  - ZZ using BDT
- Both EWK cross sections can be measured at the HL-LHC with high accuracy

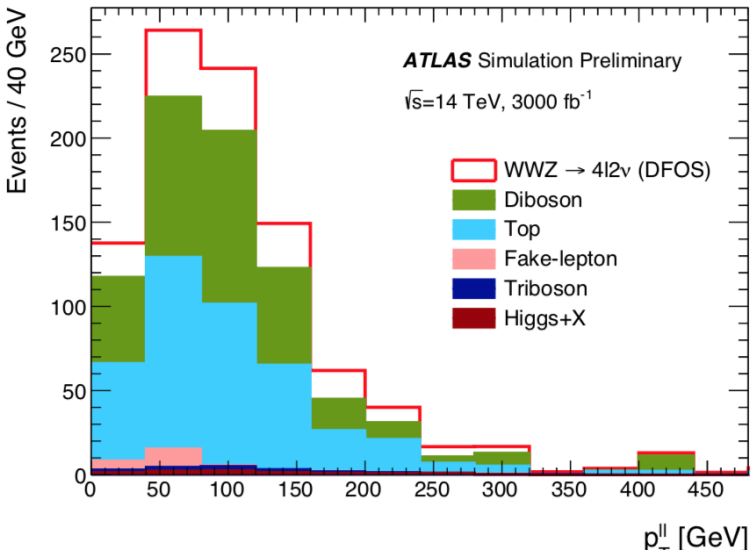
The polarized LL component is not expected to be observed in single channel and experiment –> combination

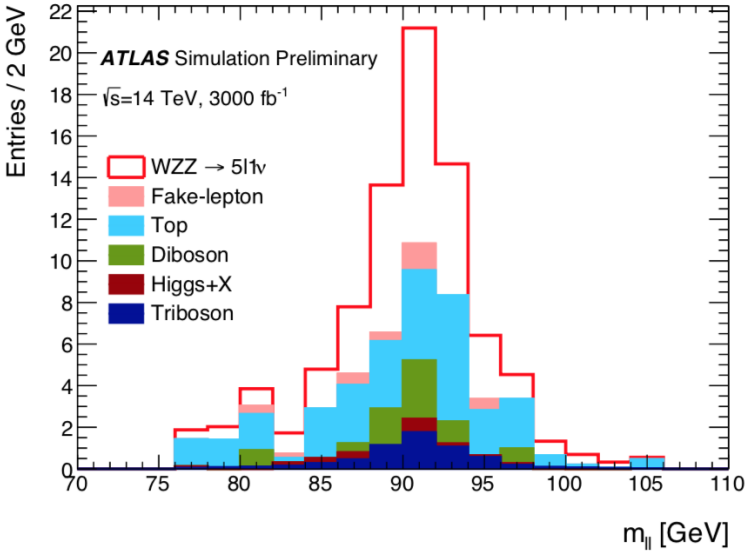




Tri-boson production







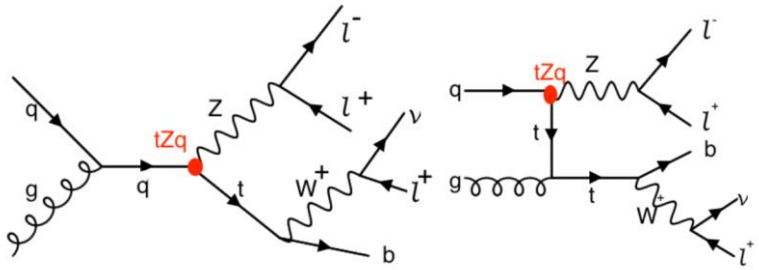
- VVV production has a low cross section but can be measured at the HL-LHC in different channels WWW, WWZ, WZZ
- At 13 TeV 4 σ obs. (3.1 σ exp.) is measured [arXiv:1903.10415](), WWW in CMS-PAS-SMP-17-013

FCNC processes in top production

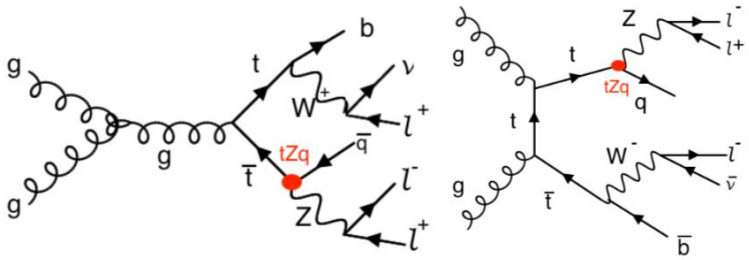
- Forbidden at tree level and highly suppressed at higher order, Br ~ $10^{-12/-16}$ (NP)
- tZq , tγq, tgq, tHq

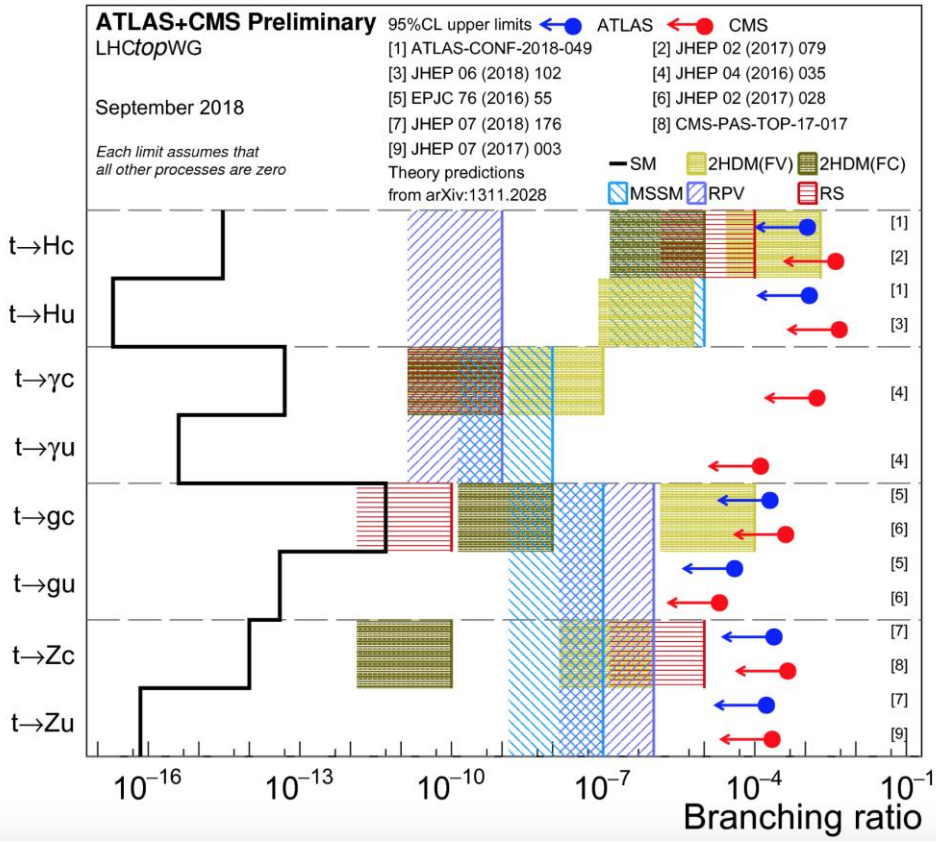
$$\mathcal{L} = \sum_{q=u,c} \Big[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R) q G^a_{\mu\nu} +$$
$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} + \frac{g}{4 c_W} \zeta_{zqt} \bar{t} \gamma^\mu (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_\mu -$$
$$- e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) q A_{\mu\nu} +$$
$$+ \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R) q H \Big] + h.c.,$$

Single top



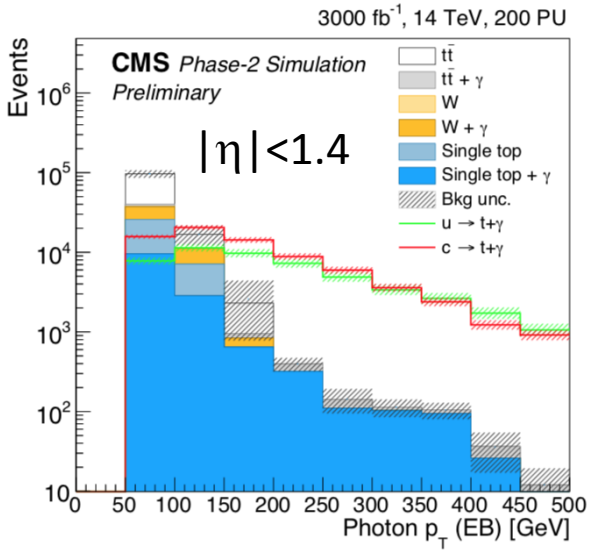
ttbar

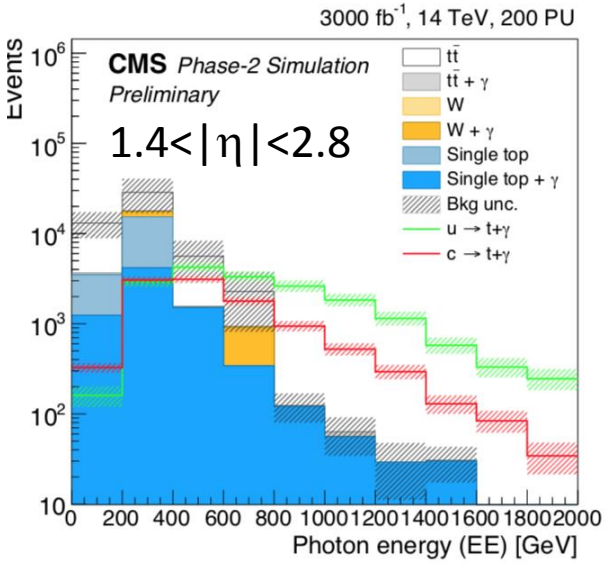




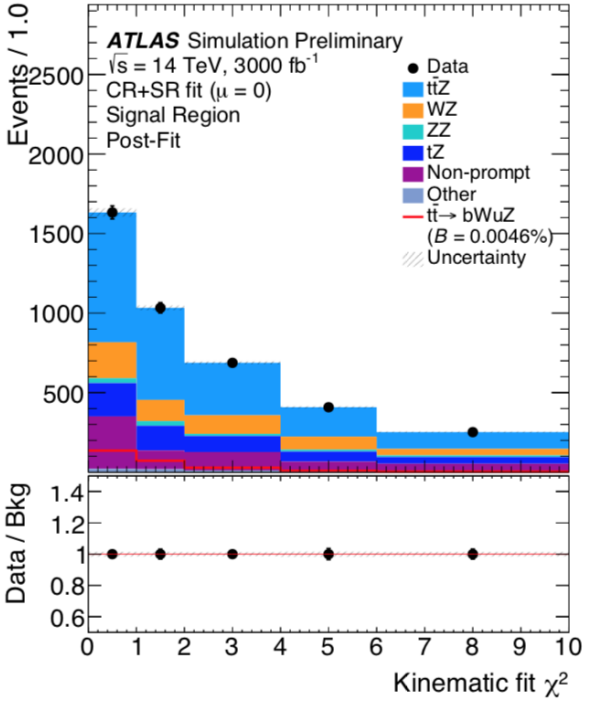
FCNC process in top production

tγq





tZq

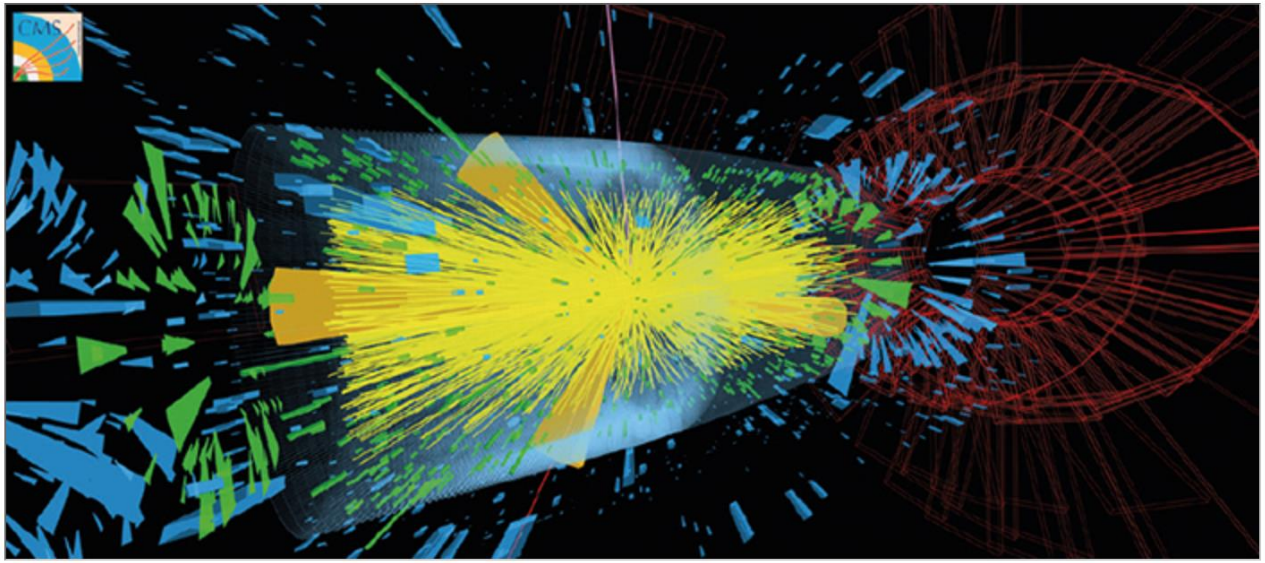


$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Run-II (36/fb)
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	2 x 10^{-5}
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	4 x 10^{-4}
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		1.7-2.4 x 10^{-4}
$t \to \gamma u$	8.6×10^{-6}		1.3 10^{-4}
$t \to \gamma c$	7.4×10^{-5}		2.0 10^{-3}
$t \to Hq$	10^{-4}		1.1 10^{-3}

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a \ell_a \ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b \ell_c \nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W}$$

Conclusions

- The HL-LHC will facilitate many important SM measurements with significantly increased precision, that is essential for understanding the underlying physics processes
- To explore new channels that are predicted by SM with extremely low cross sections and branching fractions, any deviation from predictions will be a strong indication of physics beyond SM
- The HL-LHC requires modifications of existing detectors, extending the pseudorapidity coverage, improving the trigger systems

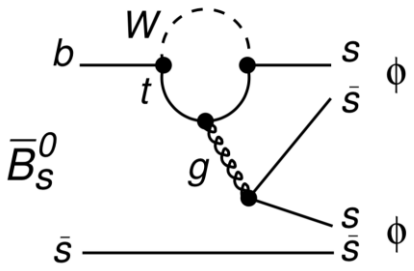


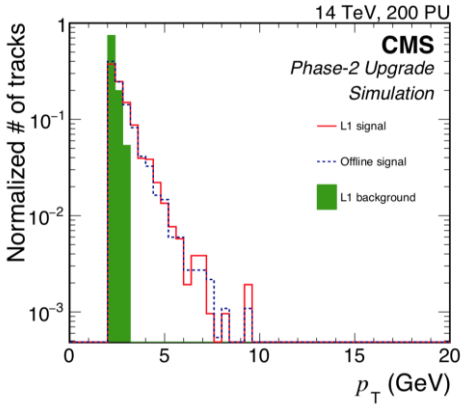
backup

L1 Trigger tracks for flavor physics

$B_S^0 \rightarrow \phi\phi \rightarrow 4K$

- CP-odd final state, determination of the CP violating phase in the CKM matrix
- FCNC - forbidden at tree level in the SM
- loop contributions from high masses





- Very low P_T tracks
- The **L1 track finder** forms φ candidates from oppositely charged tracks originating from the same vertex
- For 200 pileup events - efficiency of around 30% (to compare to 55% offline), the expected L1 trigger rate is about 15 kHz within trigger budget