Standard Model measurements at the High-Luminosity LHC with the CMS experiment

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**on behalf of the CMS Collaboration*

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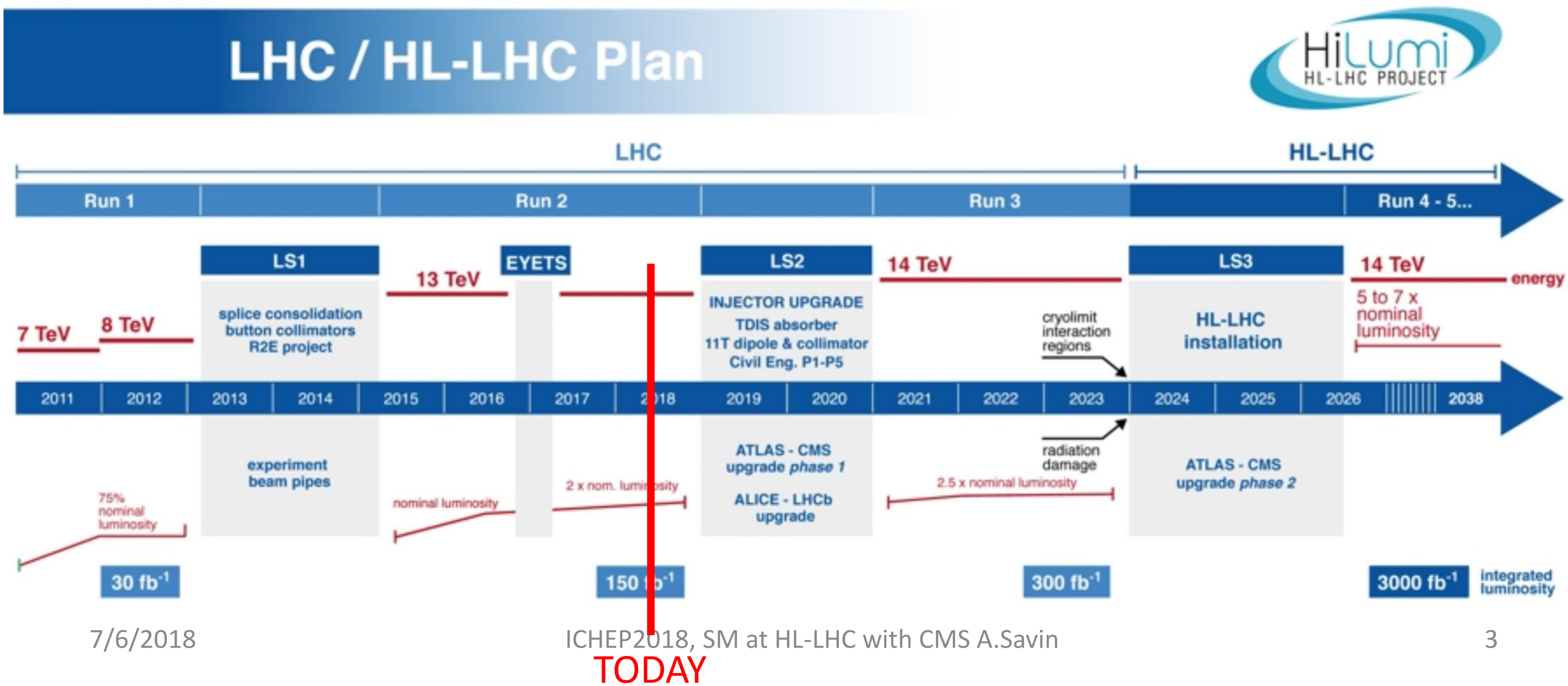
High Luminosity LHC project

- At the beginning of the next decade, many critical components of the accelerator will reach the end of their lifetime due to radiation damage and will thus need to be replaced.
- The HL-LHC will rely on a number of key innovative technologies, including cutting-edge 11-12 Tesla superconducting magnets, compact superconducting crab cavities with ultra-precise phase control for beam rotation, new technology for beam collimation, high-power, loss-less superconducting links, etc.
- Goal is to achieve instantaneous luminosities ***a factor of five larger*** than the LHC nominal value

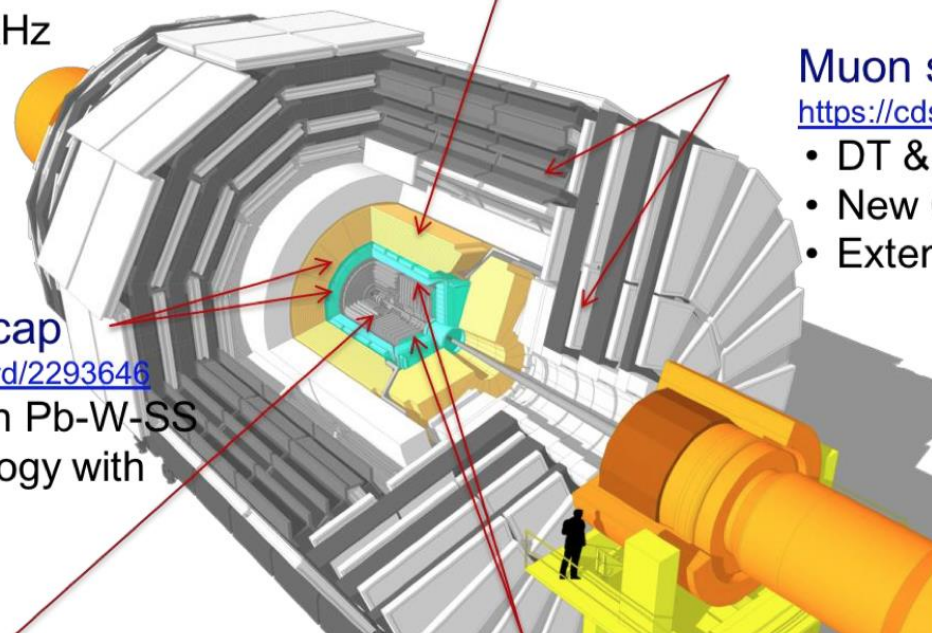


Summary of the CMS PhaseII upgrade

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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



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 $\eta \simeq 3.8$

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

SM measurements at the HL-LHC

- Precise measurements (new methods + syst + stat)
  - Top mass
  - Weak mixing angle measurement
- Measurements with low cross sections
  - Flavor Changing Neutral Current in top production
  - VV VBS and polarized cross sections
- Measurements that profit from new detector
  - $B_S^0 \to \phi\phi \to 4K$
  - $\tau \to 3\mu$

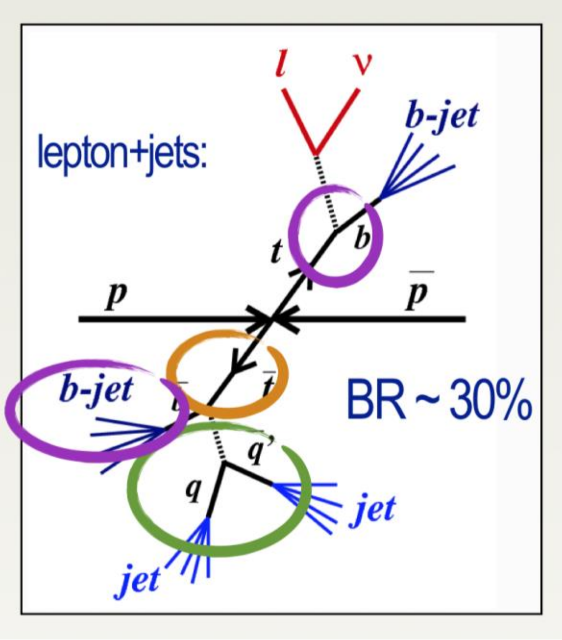
Recent publications:

- CMS-TDR-17-014 (tracker), CMS-TDR-17-015(barrel calorimeter), CMS-TDR-17-016(muon system), CMS-TDR-17-019 (HGCAL)
- CMS-PAS-FTR-16-006, CMS-PAS-FTR-17-001
- Yellow Report – CMS+ATLAS+LHCb+Theory – end of 2018

Top Mass

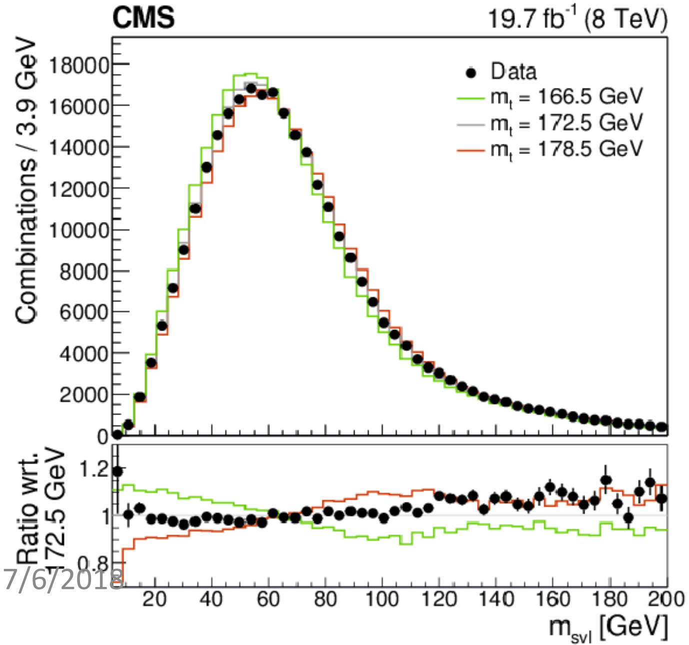
- CMS-PAS-FTR-16-006, CMS-TDR-17-014
- Top quark mass - fundamental SM parameter
- Different measurement methods: l+jets mass, single top, track- and vertex-based distributions, the "J/ψ" method (see next page), cross section
- l+jets measurement at 8 TeV:

$$172 \pm 0.77(stat)\ ^{+0.97}_{-0.93}(sys)\ GeV$$

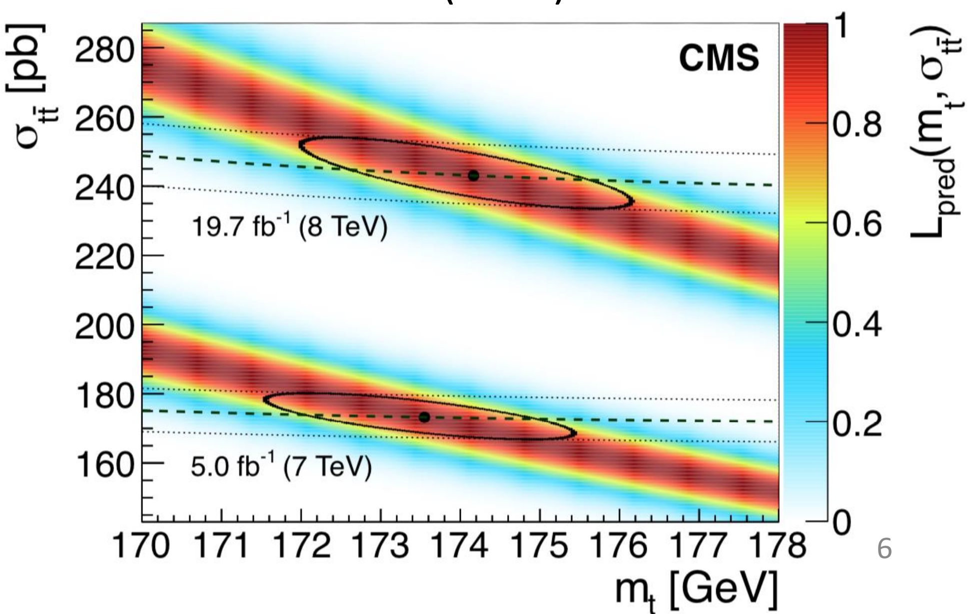


CMS 7+8 TeV combined: $(172.44 \pm 0.13 \pm 0.47)\ GeV$

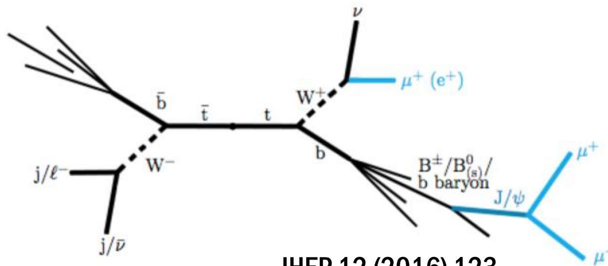
PRD93 (2016) 092006



JHEP08(2016)029

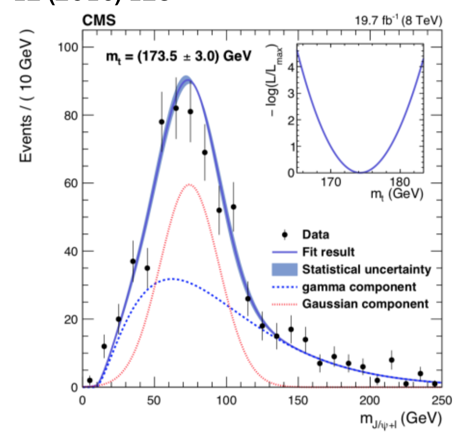


Top Mass

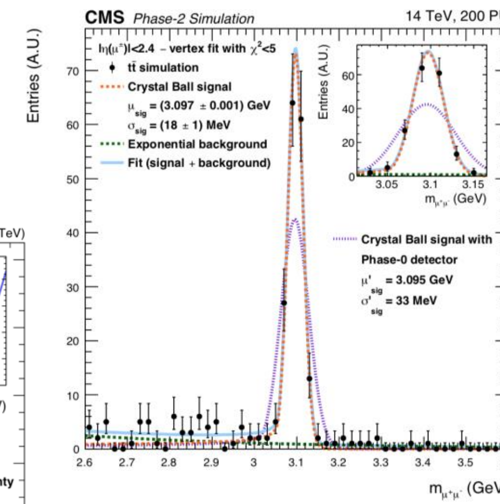


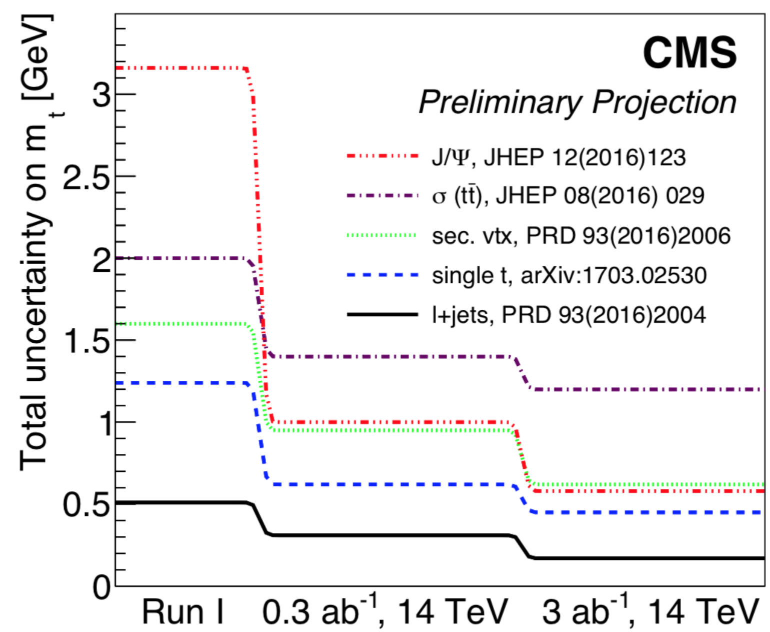
- "J/ψ" method should benefit from statistics
  - Nice reconstruction even at PU200
- Moderate improvement for pole mass from cross sections
  - Ultimately limited by lumi. uncertainty and theory uncertainty (no N3LO assumed)
- Single top:
  - Benefit from statistics and modelling improvements
- l+jets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

JHEP 12 (2016) 123



CMS-TDR-014



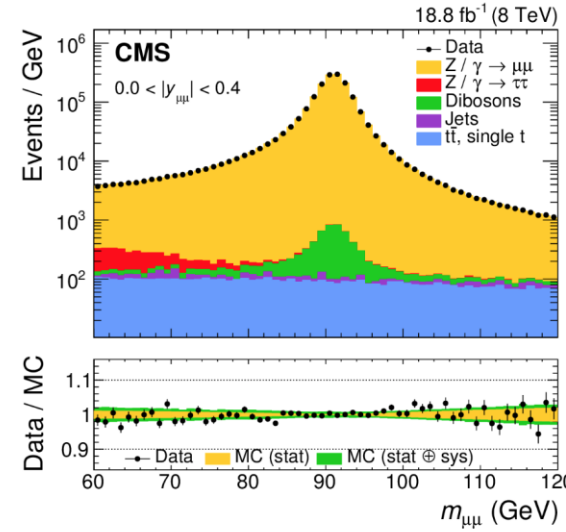


Effective mixing angle via forw.-backw. asymmetry

- Vector and axial-vector couplings in NC annihilation

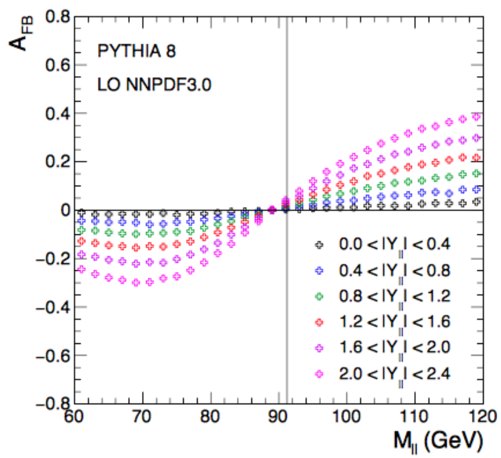
arXiv:1806.00863

$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$$



- Differential cross section

$$\frac{d\sigma}{d(\cos\theta)} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right] \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



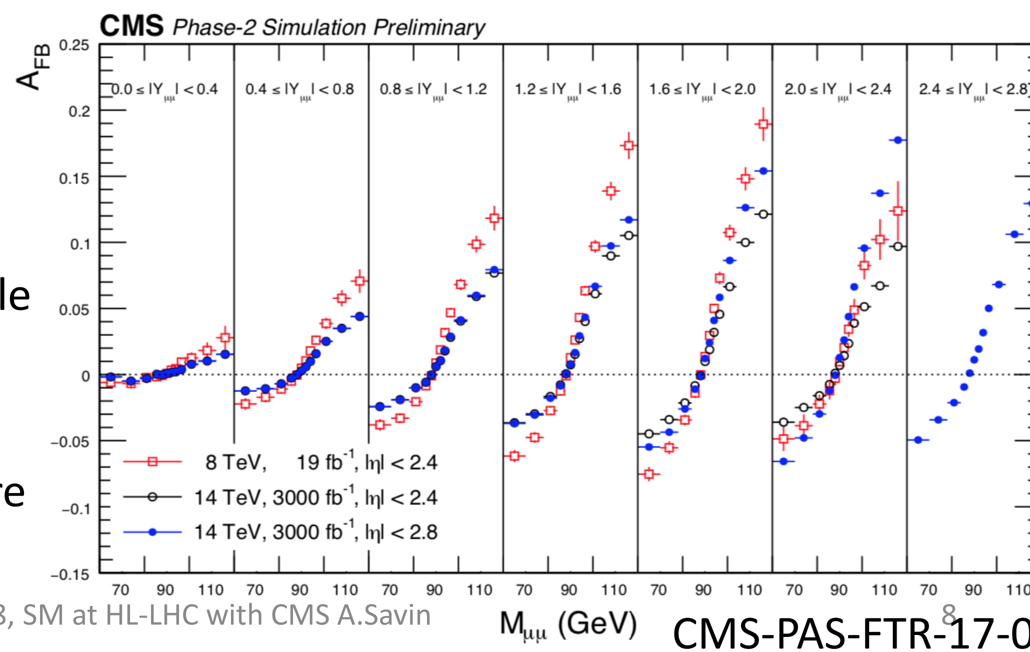
Dilution is smaller at high Y

Fit to A_{FB} to measure weak mixing angle

$$\sin^2 q_{eff}^{lept} = \mathrm{Re}[k_l(m_Z^2, \sin^2 q_W)]\sin^2 q_W$$

$$m_W^2 \sin^2 q_W = \frac{pa}{\sqrt{2}G_F}\frac{1}{1-Dr}$$

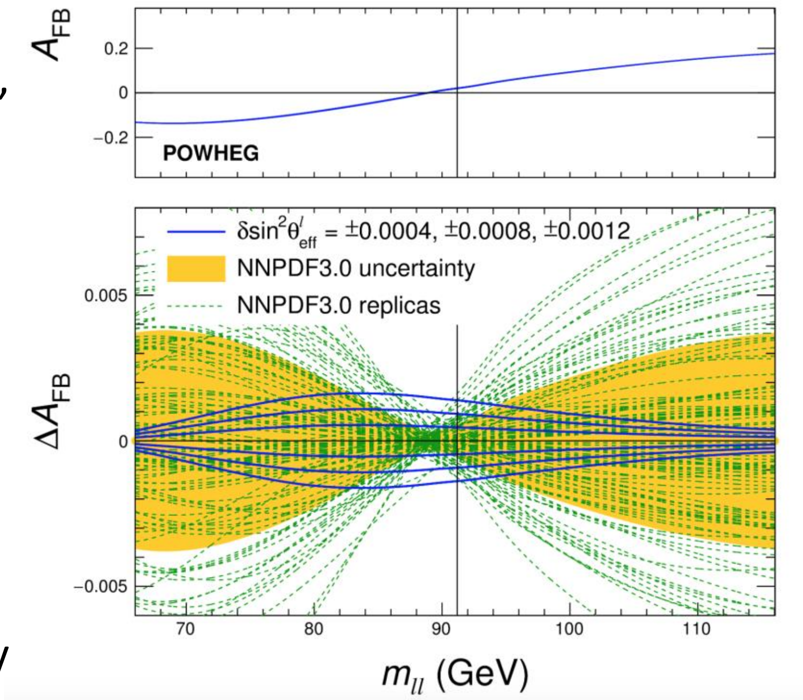
Indirect measure of m_W

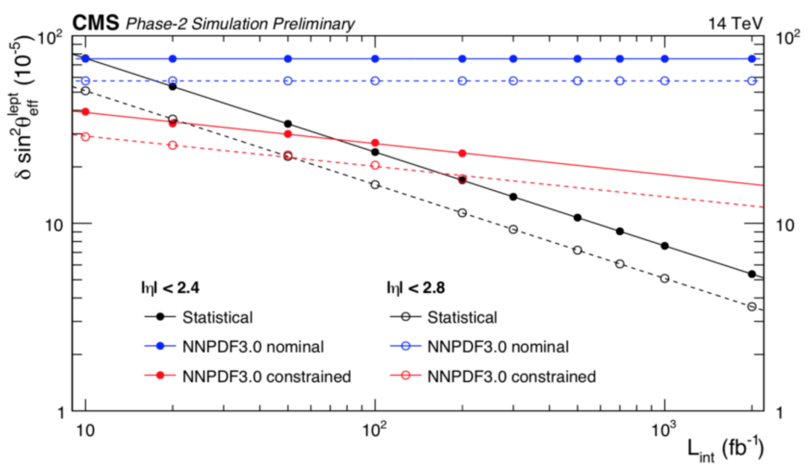


CMS-PAS-FTR-17-001

Effective mixing angle via forw.-backw. asymmetry

- Higher sensitivity at ***high pseudorapidity*** region, statistical and systematic uncertainties will be significantly reduced.
- *A*FB values depend on the size of the dilution effect and relative contributions from u and d quarks - the ***PDF uncertainties*** translate into sizable variations in the observed *A*FB values.
    - In the Bayesian $\chi 2$ reweighting method, PDF replicas that better describe the observed *A*FB distribution are assigned larger weights, and PDF replicas that poorly describe *A*FB are assigned smaller weights.
- 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 !



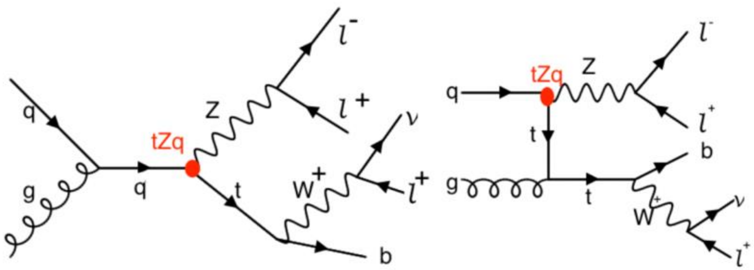


FCNC processes in top production

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

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

Single top



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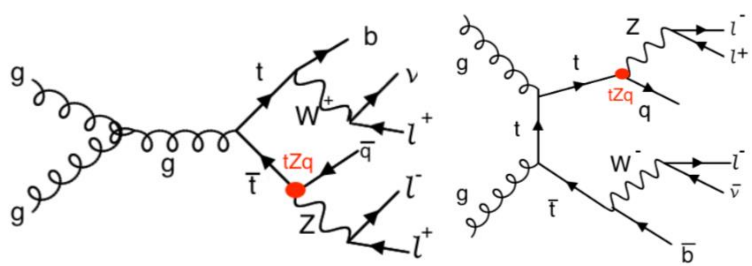
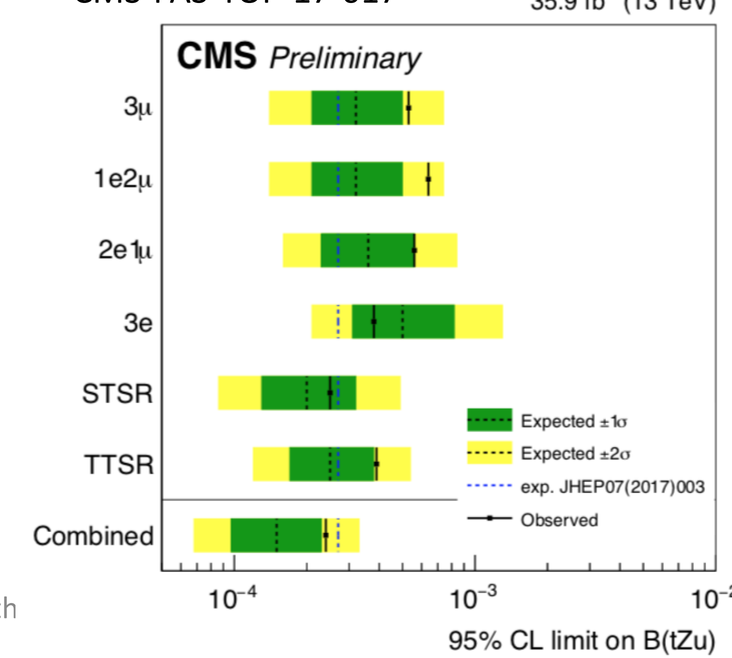
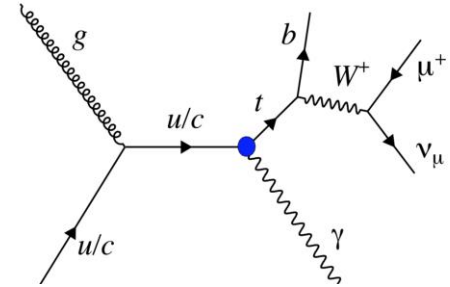


CMS-PAS-TOP-17-017

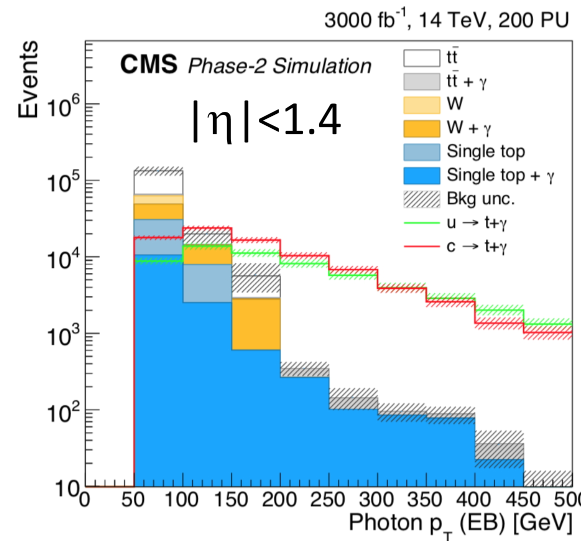


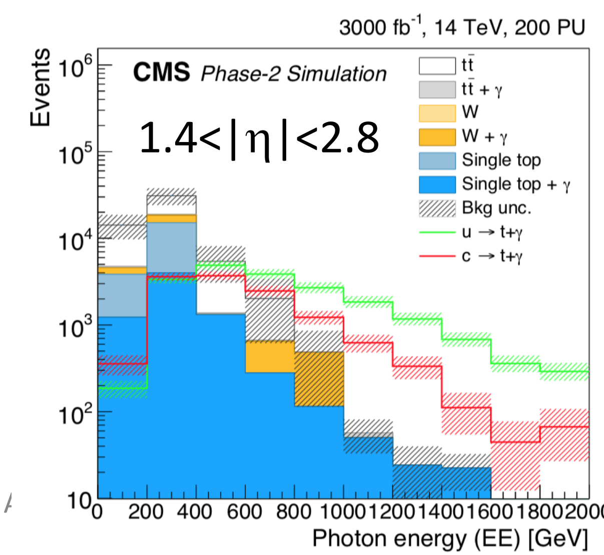
FCNC in t→qγ events



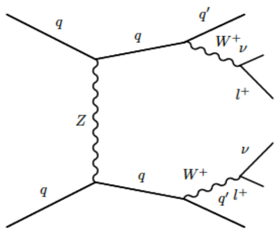
CMS-TDR-17-019

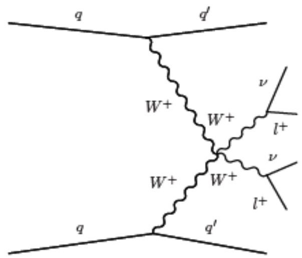
- Current limit 1.6(18.2) x 10^{-4} u(c)
- Final state :
  - one lepton, p_T > 25 GeV $|\eta|$<2.8
  - one b-jet, p_T > 30 GeV $|\eta|$<2.8
  - one photon, p_T>50 GeV $|\eta|$<2.8
- The upper limit on the single top quark production cross section via $tu\gamma$ $(tc\gamma)$ interaction of 3.4 (4.4) fb at 95% CL is obtained for an integrated luminosity of 3000 fb^{-1}.
- 95% CL upper limits on the branching fractions of $B(t \to u\gamma) < 8.6 \times 10^{-6}$ and $B(t \to c\gamma) < 74 \times 10^{-6}$, improving over the previous extrapolation to HL-LHC conditions by a factor of 3.

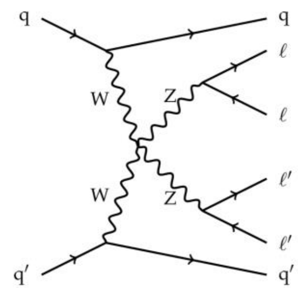




VV VBS and polarized cross section





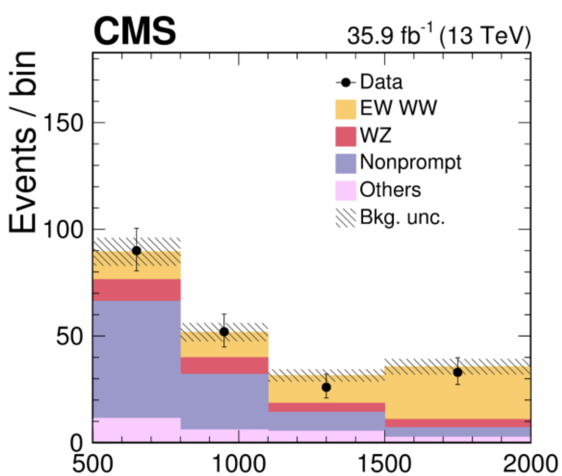


.... etc producing WW, WZ and ZZ final states

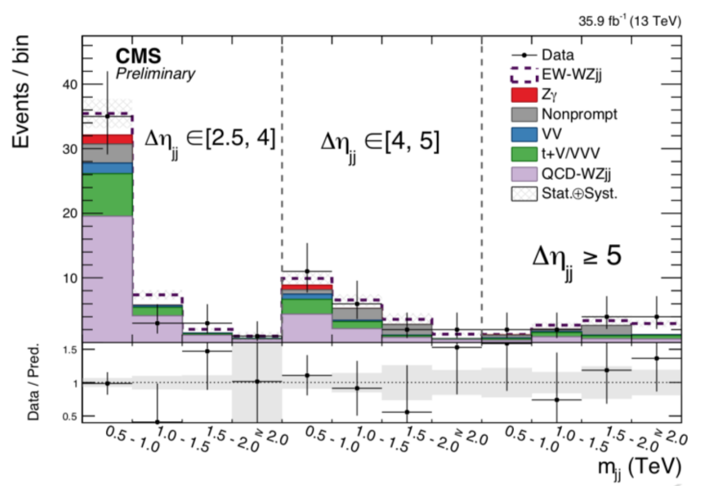
EWK observed / expected significance in standard deviations

Channel	ssWW+2j	WZ+2j	ZZ+2j
expected	5.7	2.7	1.6
observed	5.5	1.9	2.7

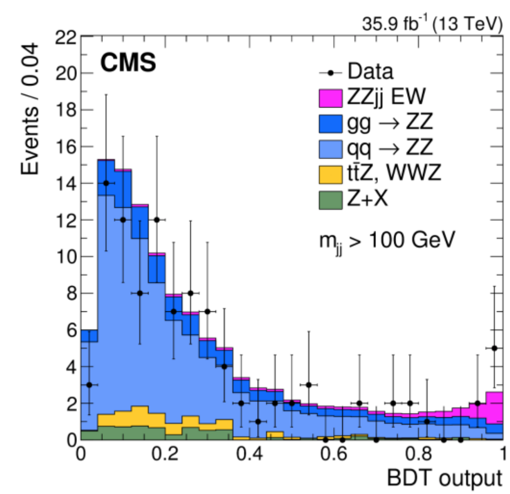
Phys. Lett. B 774 (2017) 682



CMS-PAS-SMP-18-001

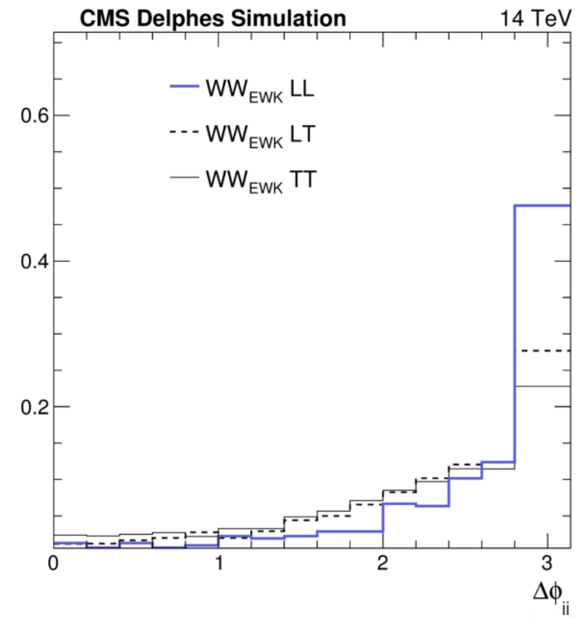


Phys. Rev. Lett. 120 (2018) 081801

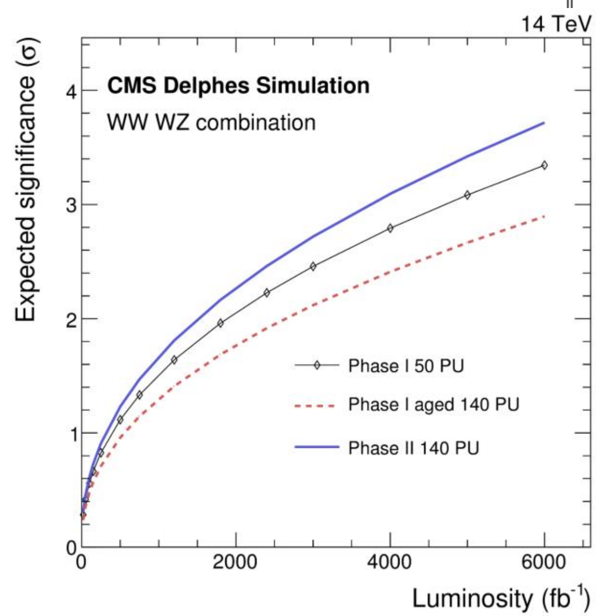


VV VBS and polarized cross section

CMS-PAS-SMP-14-008



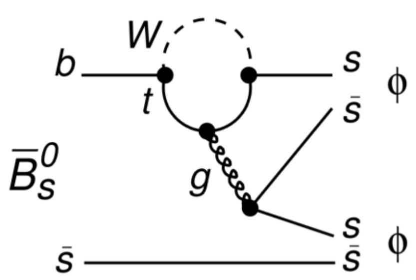
- The total vector boson scattering is composed of three components, depending on the polarization of the final-state vector bosons: both of them being longitudinally polarized (LL), both of them being transversely polarized (TT), and the mixed case (LT).
- Expected cross section uncertainty decreases with the luminosity
- Expected discovery significance for the longitudinal vector boson scattering increases as a function of the collected luminosity.
- New results are expected soon for WW+WZ+ZZ combination

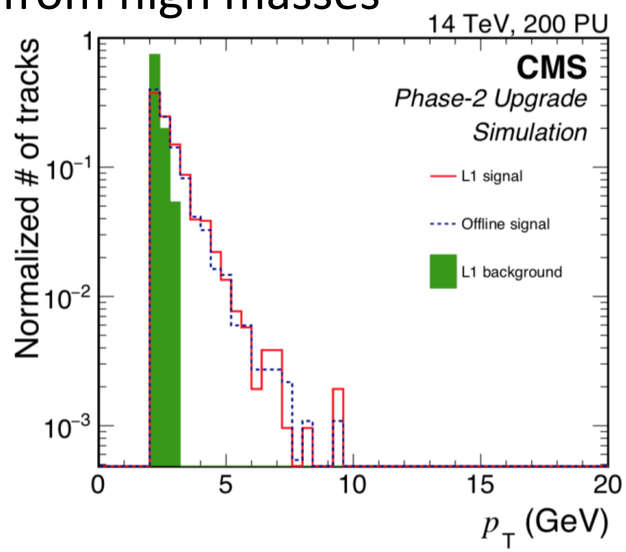


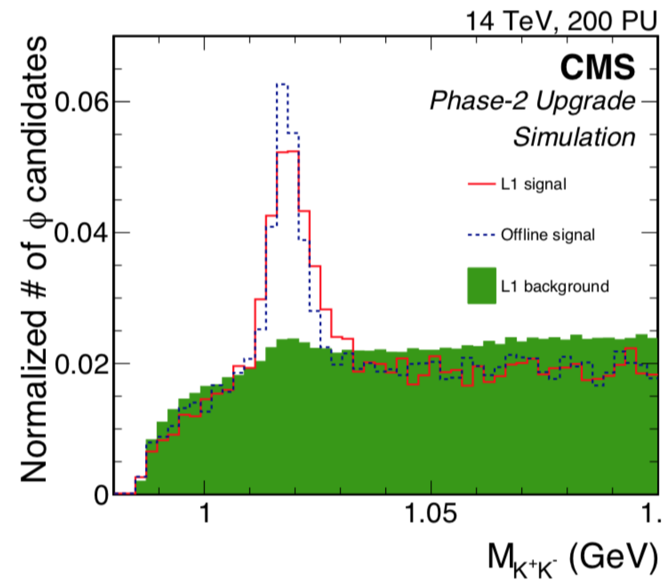
$B_S^0 \to \phi\phi \to 4K$

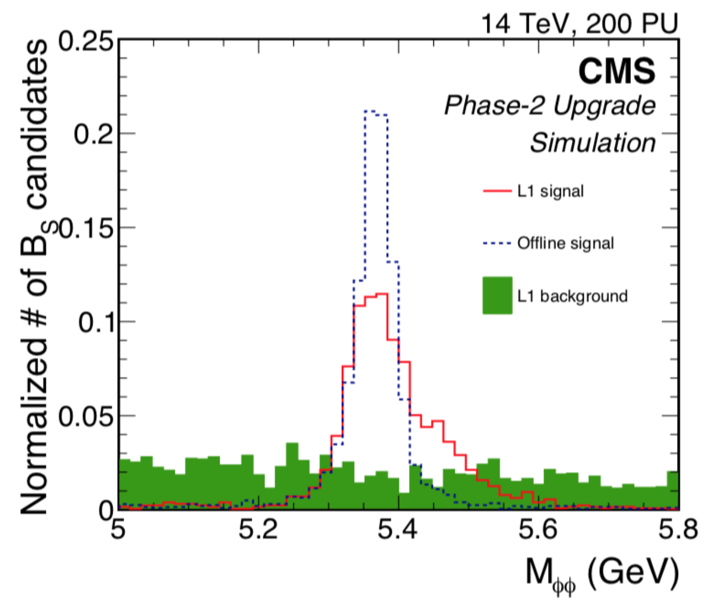
CMS-TDR-014

- 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







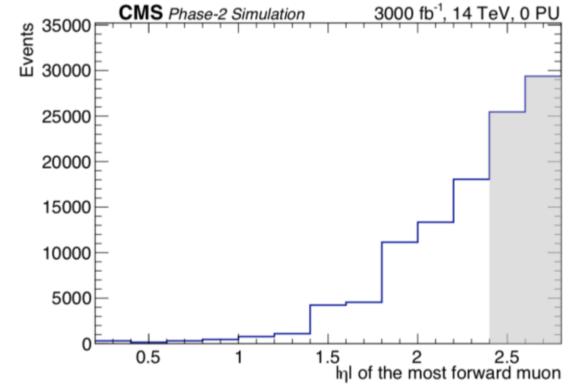


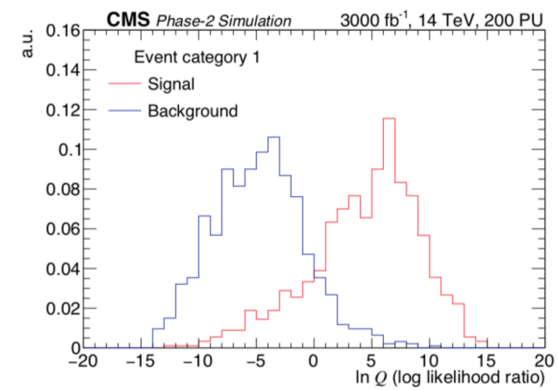
- Very low P_T tracks
- The **L1 track finder** forms φ candidates from oppositely charged tracks originating from the same vertex
- For 200 pileup events - efficiency of around 30% (to compare to 55% offline), the expected L1 trigger rate is about 15 kHz within trigger budget

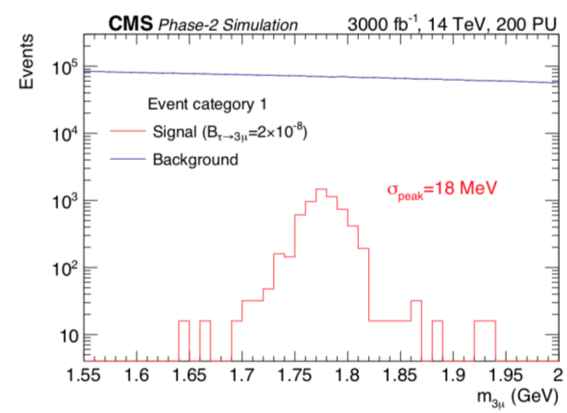
Lepton flavor violating decay $\tau \to 3\mu$

CMS-TDR-17-016

- There are no known symmetries that strictly forbid lepton-flavor violating (LFV) decays, such as $l \to 3l'$
- Small Br, at LHC, $\tau \to 3\mu$ decay is one of the "cleanest" LFV decay channel. Best experimental upper limit, set by Belle Br<2.1×10^{-8} at 90% CL
- The main source *Ds* → $\tau\nu$ decays. Very low momenta and are significantly boosted in the forward direction
- The projected exclusion limit on 3.7×10^{-9} at 90% CL, and 4.3×10^{-9} without ME0 chambers. Effective gain ~ 1.35, i.e. from 3000 to ~ 4000 fb−1





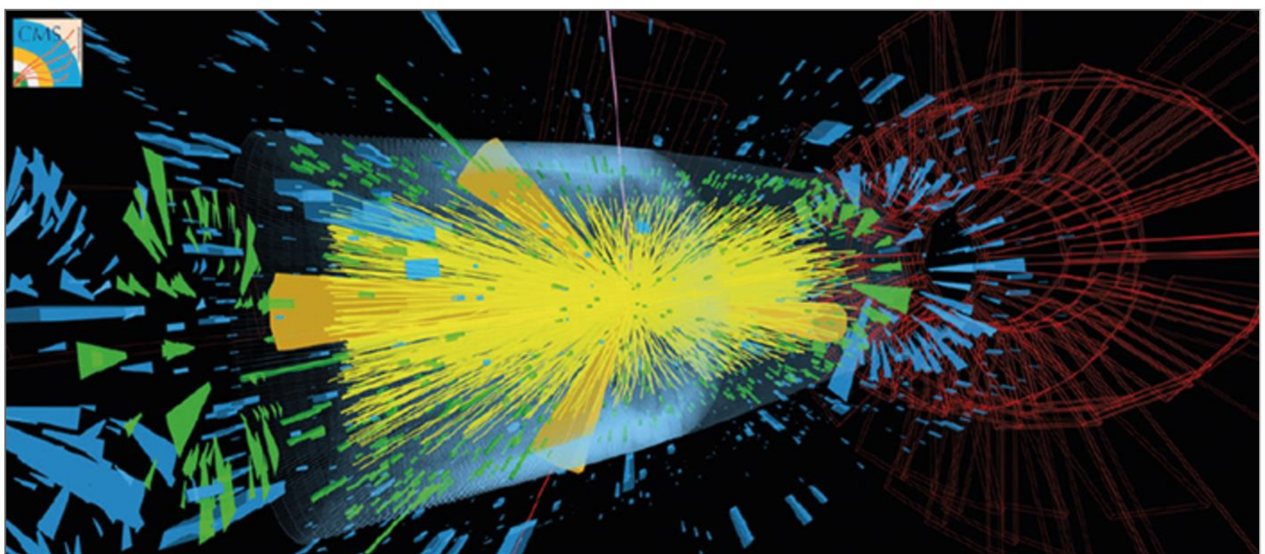


	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4 580	3 640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}	
$B(\tau \to 3\mu)$ for 3σ-evidence	6.7×10^{-9}	
$B(\tau \to 3\mu)$ for 5σ-observation	1.1×10^{-8}	

/in

Conclusions

- The HL-LHC will allow to repeat 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
- A lot of physics studies are done already, the next step is to complete the Yellow Report by the end of 2018



Backup