Future Physics with the CMS Experiment

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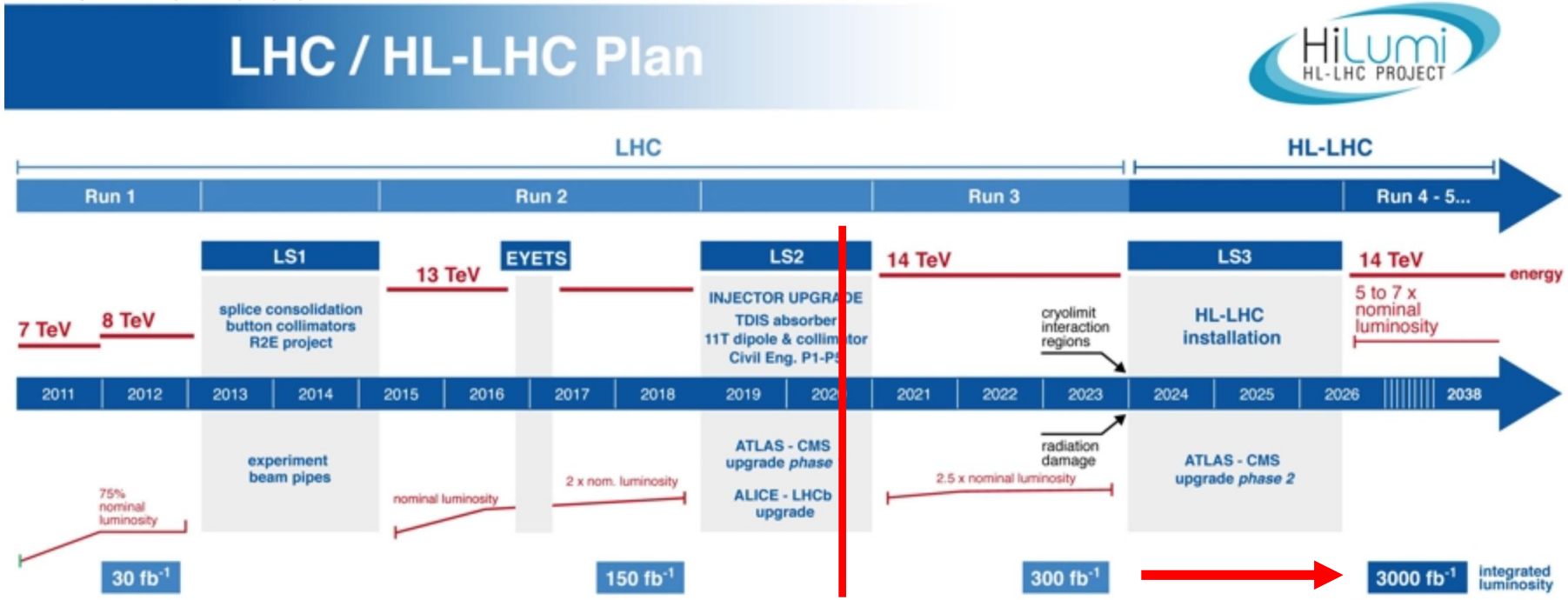
High Luminosity LHC project

- The HL-LHC will extend the LHC program to the second half of the 2030s with pp collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} , and PbPb and pPb collisions with integrated luminosities of 13 nb−1 and 50 nb−1, respectively
- The HL-LHC will rely on a number of key innovative technologies: cutting-edge 11-12 Tesla superconducting magnets, superconducting crab cavities, new beam collimation, etc.
- Goal is to achieve instantaneous luminosities ***a factor of five larger*** than the LHC nominal value



TODAY

Summary of the CMS Phase-2 upgrade

Trigger/HLT/DAQ

- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $\eta < 3$

New Endcap Calorimeters

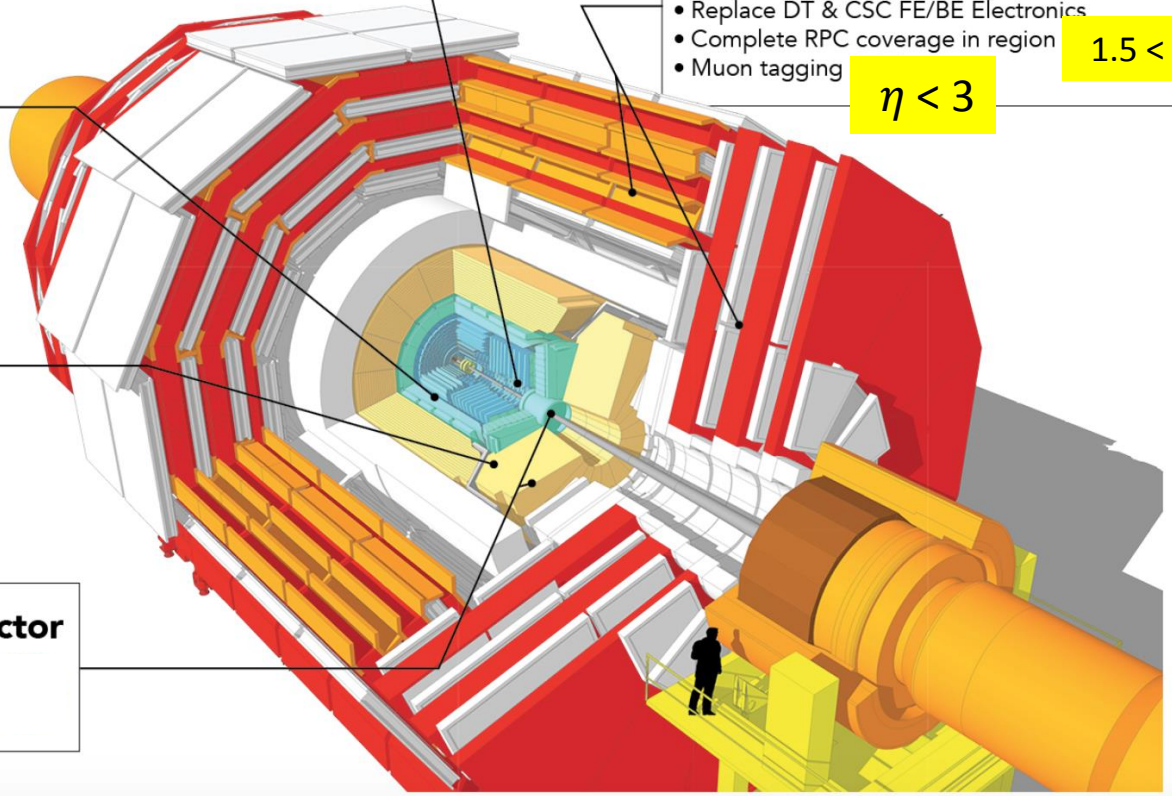
- Rad. tolerant – high granularity
- 3D capable

New Tracker

- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $\eta < 4$

MIP Precision Timing Detector

- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes



Physics at the HL-LHC

Recently summarized in CERN Yellow Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC (2019)

https://cds.cern.ch/record/2703572

Snowmass 2021 has been just started

https://snowmass21.org

This talk will present selected topics on

- Higgs Physics
- SM Physics (not Higgs)
- Beyond SM Physics

Both CMS and ATLAS collaborations demonstrated very similar physics programs for the HL-LHC, but this talk presents only selected CMS results !

Assumptions for CMS Future analyses

The HL-LHC physics analyses use different techniques based on simulated MC samples:

- Full simulation of the Phase-2 detector response ;
- DELPHES, parametrization of detector response ;
- Projections of existing Run 2 results ;
- Combination of above .

Uncertainties:

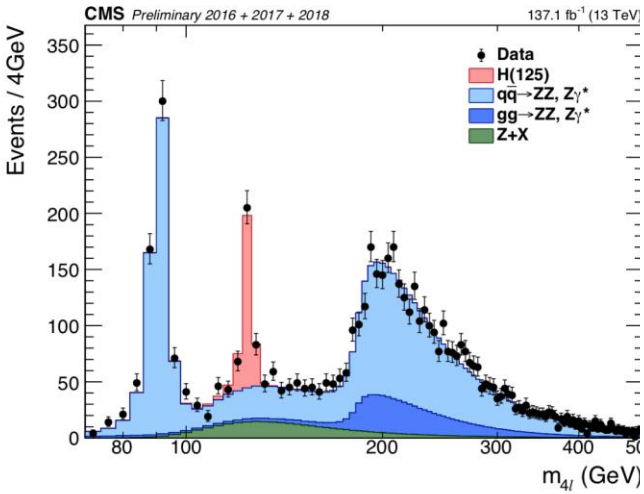
- The theoretical uncertainties are assumed to be reduced by a factor of two ;
- The intrinsic statistical uncertainty reduced by a factor $1/\sqrt{L}$;
- Detector systematics left unchanged, or revised according to detailed simulation ;
- Uncertainties on methods are kept at the same value as in the public results ;
- The uncertainty in the integrated luminosity reduced down to 1% (currently 2.5%).

Higgs measurements at the HL-LHC

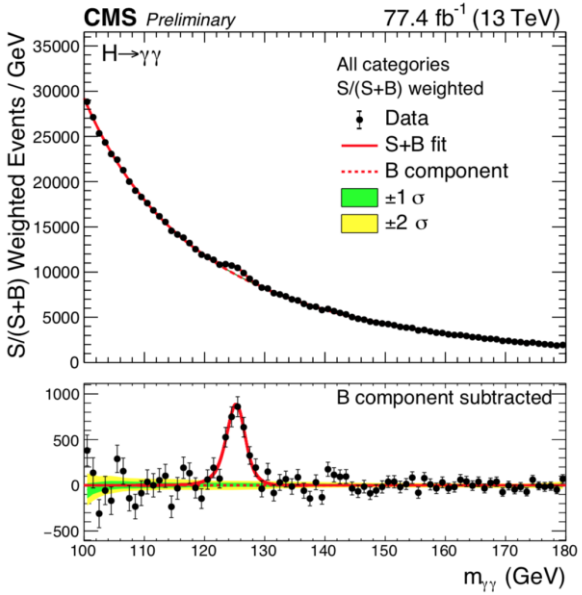
- HL-LHC as a Higgs factory
  - High Precision measurements:
    - Mass and width
    - Cross sections
    - Couplings
  - HH and Higgs self-coupling
  - BSM Higgs searches

Few recent CMS Higgs results

CMS-PAS-HIG-19-001

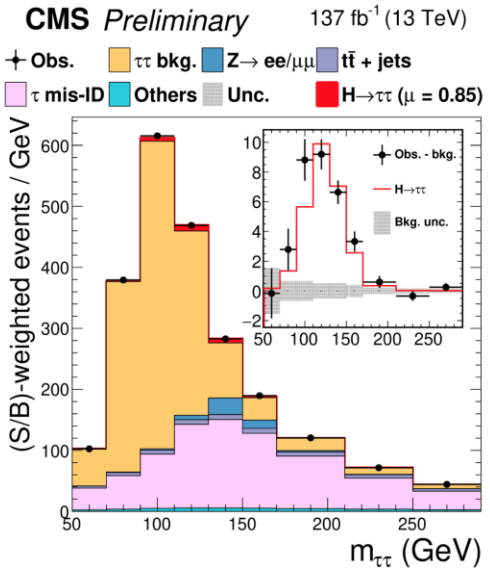


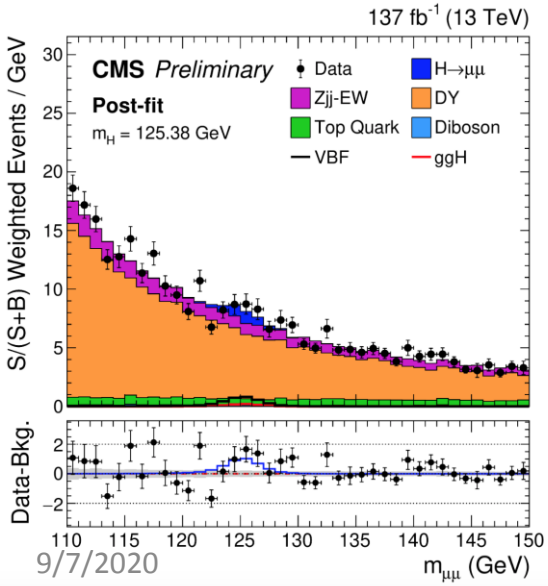
CMS-PAS-HIG-18-029



CMS-PAS-HIG-19-010

Measurement of Higgs boson decay to a pair of taus.





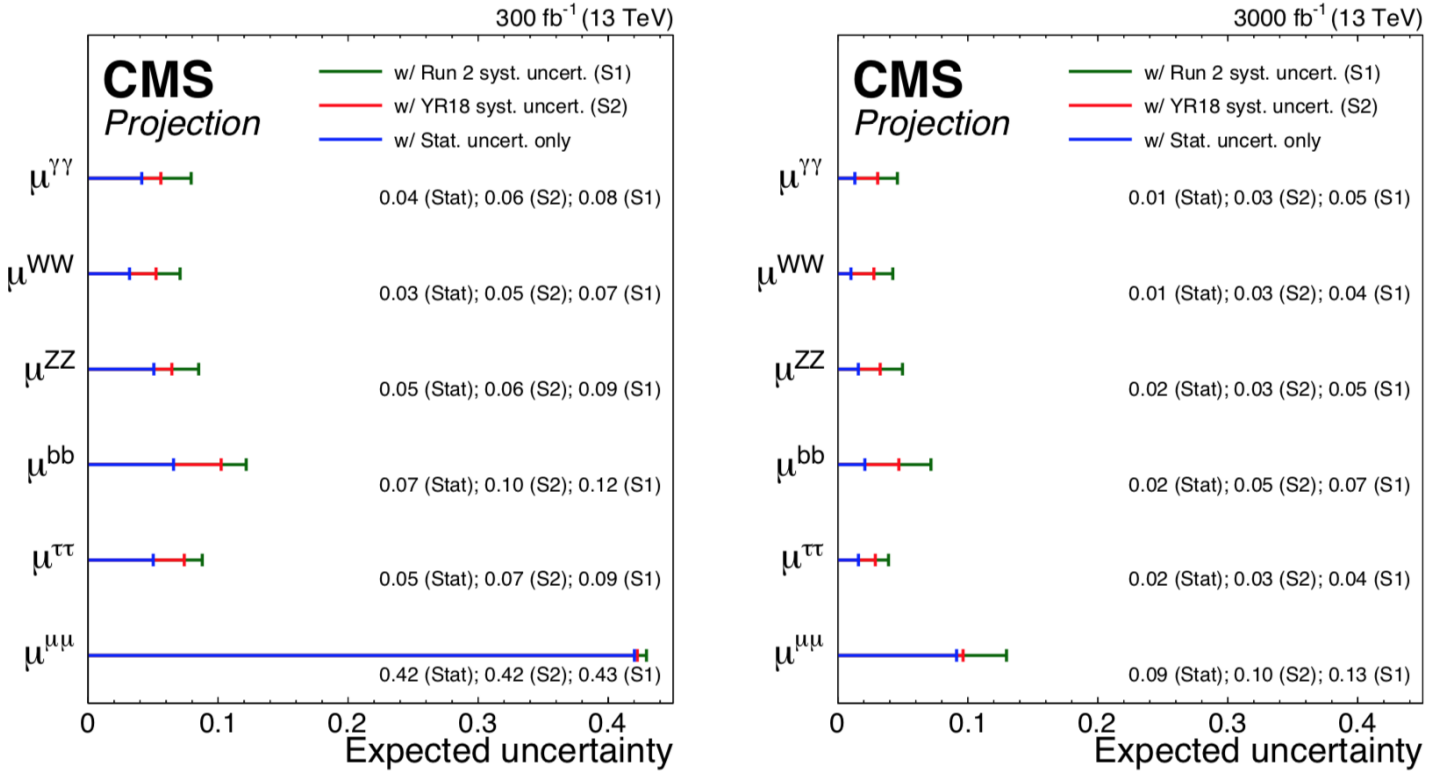
CMS-PAS-HIG-19-006

First evidence of the Higgs boson decay to a pair of muons.

Precision of the Higgs cross section

CMS-PAS-FTR-18-011

300 fb^{-1} corresponds to the total LHC luminosity before the HL-LHC or to 1 year of the HL-LHC



The expected ±1σ uncertainties **per-decay-mode** on signal strength parameters

- with Run 2 systematic uncertainties
- with YR18 systematic uncertainties

Precision of the Higgs cross section

CMS-PAS-FTR-18-011

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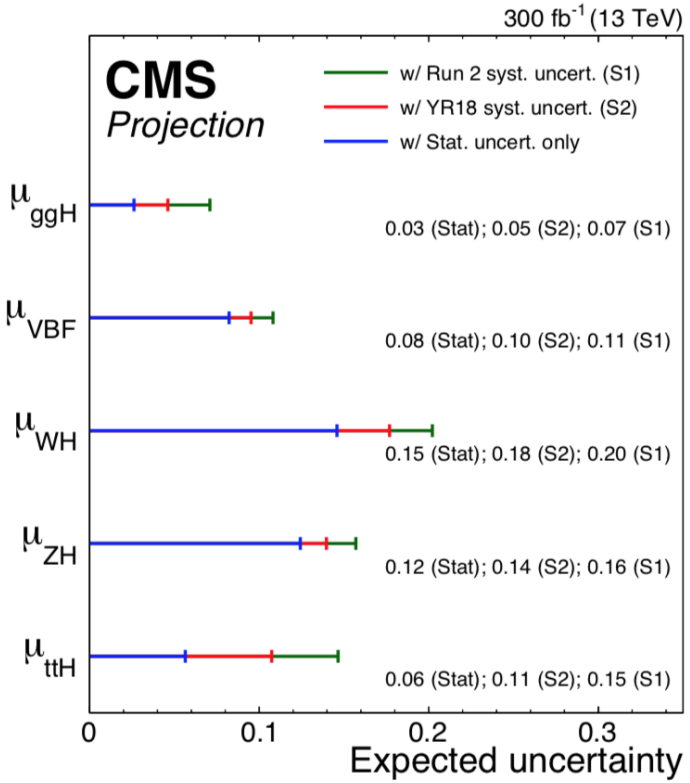
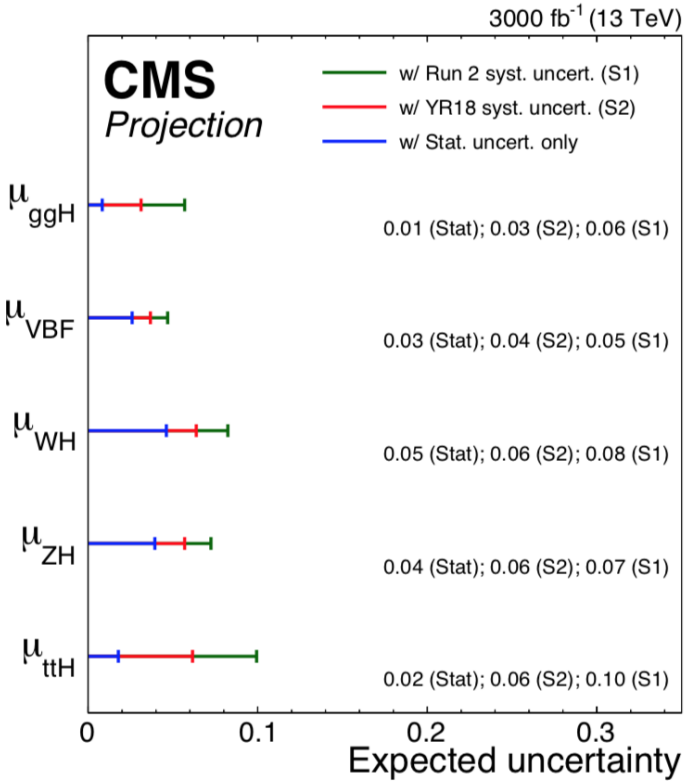




The expected ±1σ uncertainties **per-production-mode** on signal strength parameters

- with Run 2 systematic uncertainties
- with YR18 systematic uncertainties

Higgs boson couplings

Production mode

Decay mode

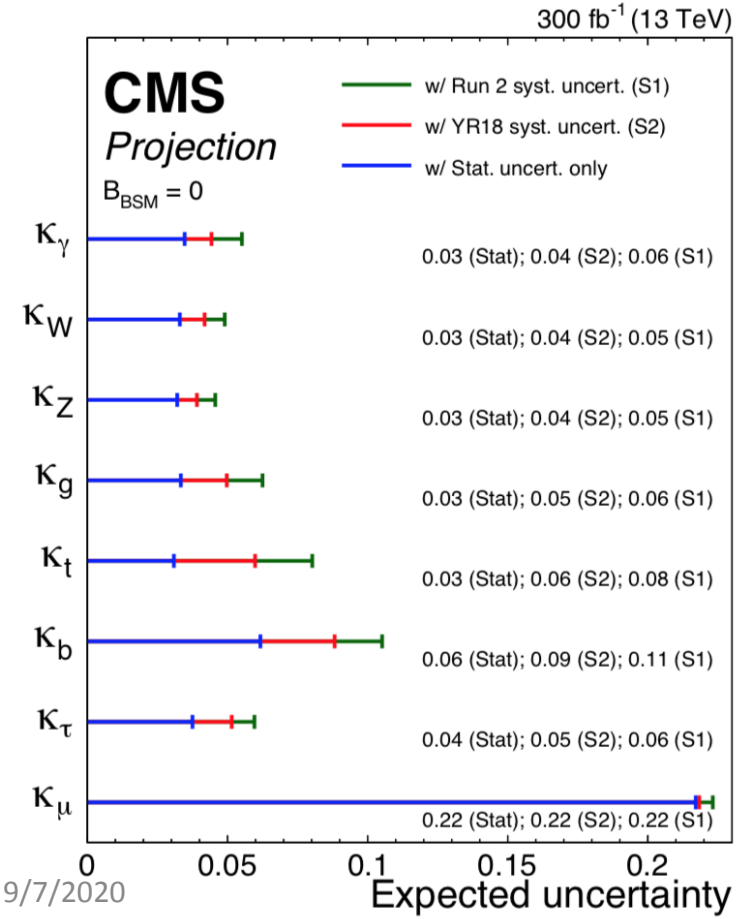
$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

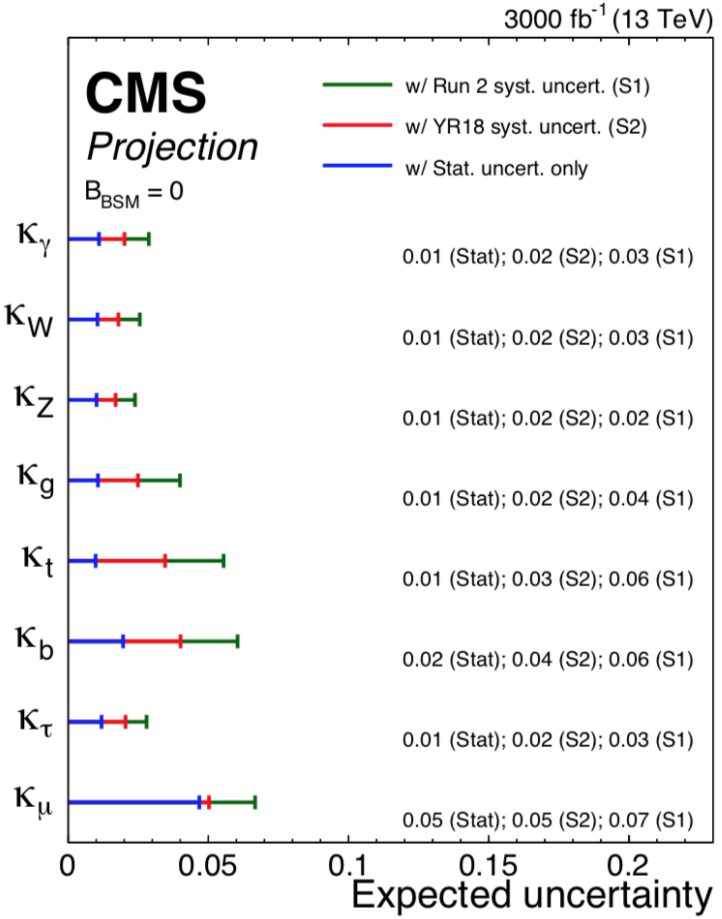
$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

https://arxiv.org/pdf/1307.1347.pdf

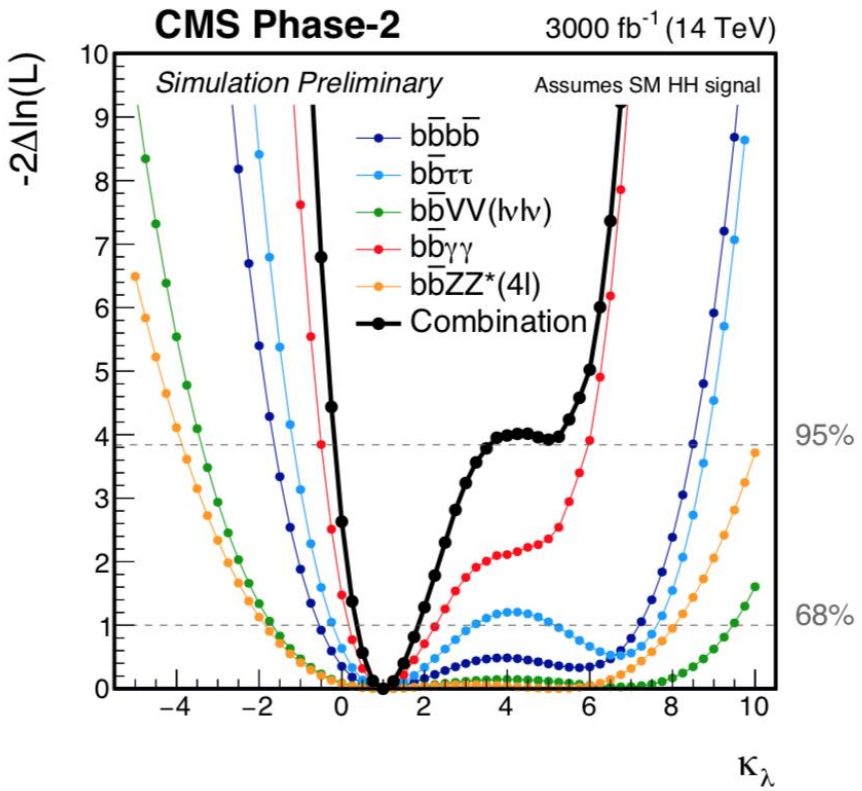
CMS-PAS-FTR-18-011





HH production and Higgs self-coupling

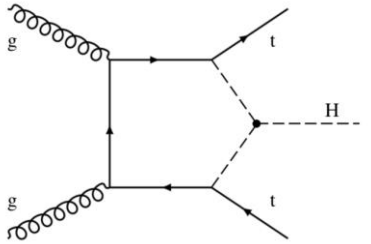
CMS-PAS-FTR-18-019



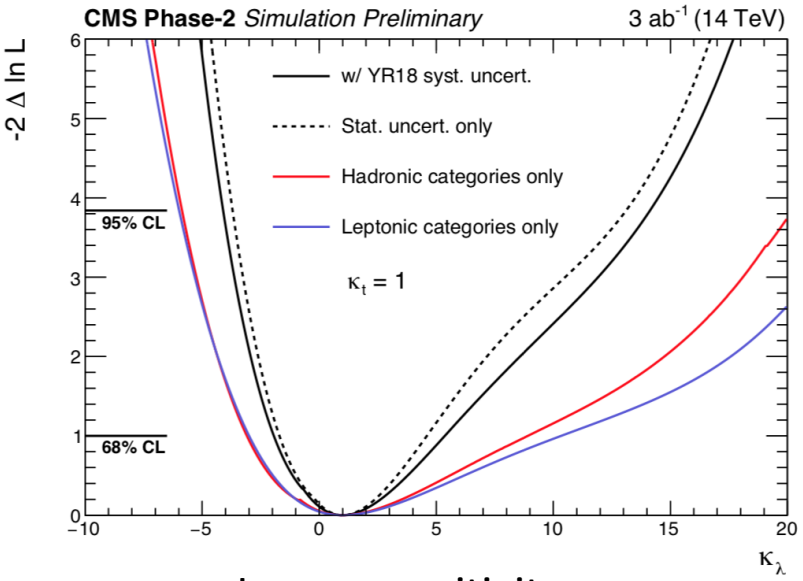
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bbττ	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bbγγ	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

The most sensitive channel is H(bb)H($\gamma\gamma$)

Alternative approach: exploiting **radiative corrections** to inclusive and differential Higgs boson production.



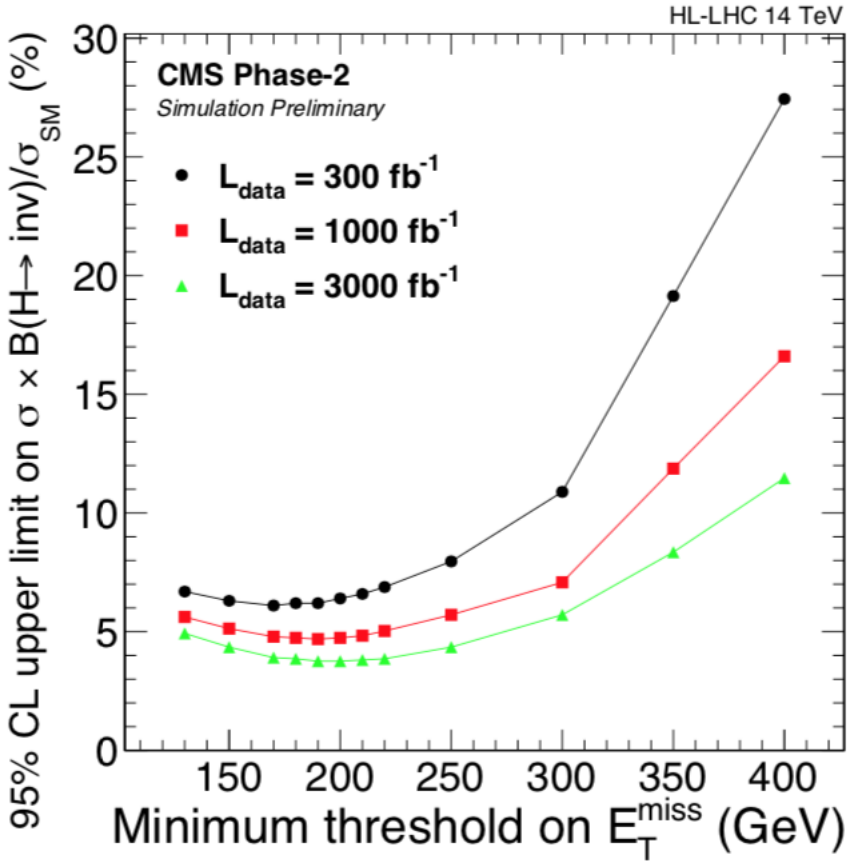
CMS-PAS-FTR-18-020
ttH($\gamma\gamma$)



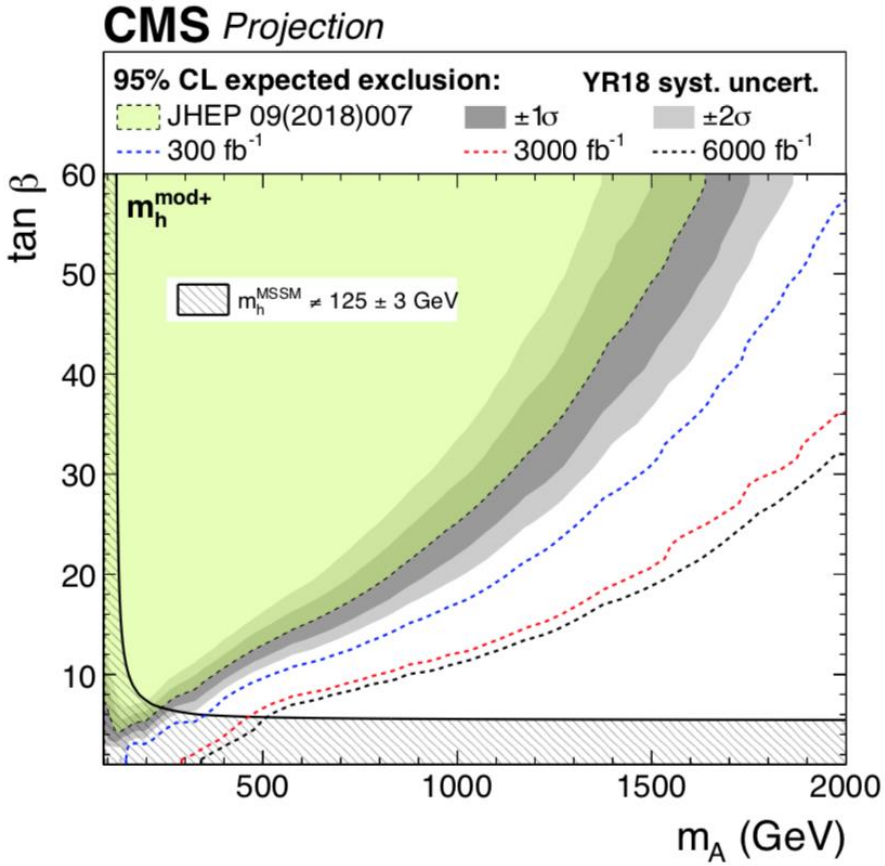
Lower sensitivity

Higgs beyond SM

Rare decays, Higgs to invisible, CMS-PAS-FTR-18-016



MSSM Higgs, CMS-PAS-FTR-18-040



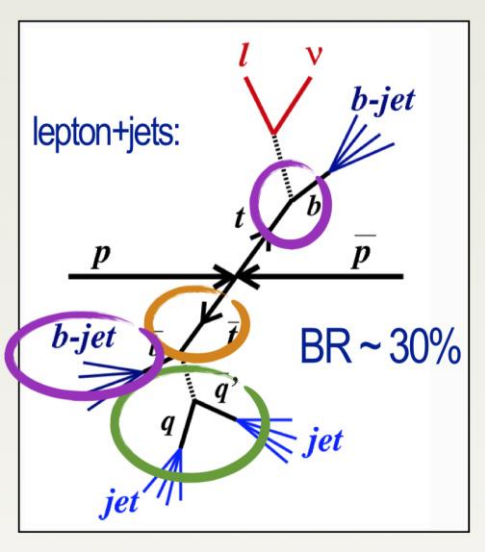
Significant extension of the currently excluded regions or discovery

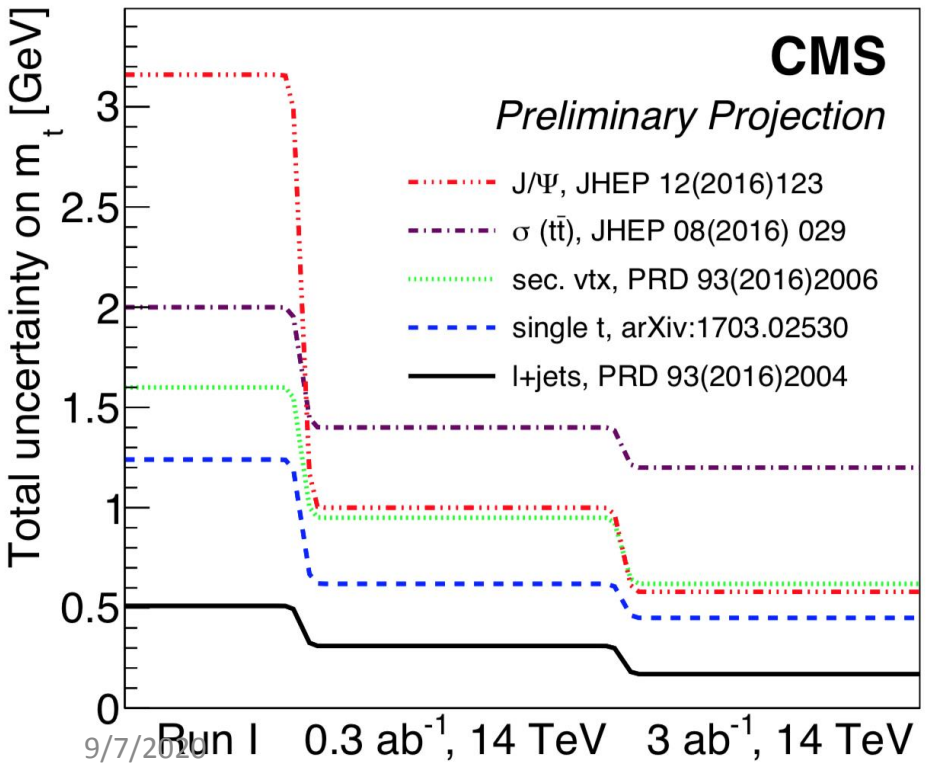
SM at the HL-LHC

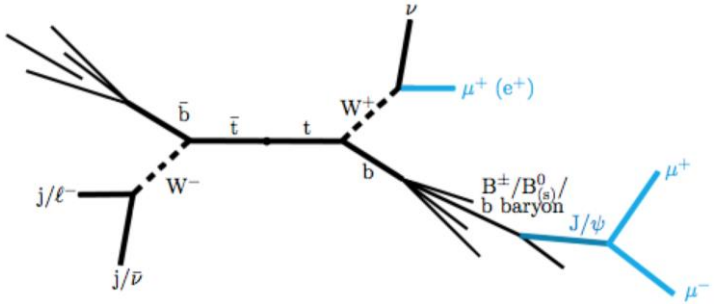
- Precise measurements (new methods + syst + stat)
  - Top mass, top properties
  - Weak mixing angle measurement
- Measurements with low cross sections
  - Top Flavor Changing Neutral Current
  - VV VBS and polarized cross sections

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, cross section



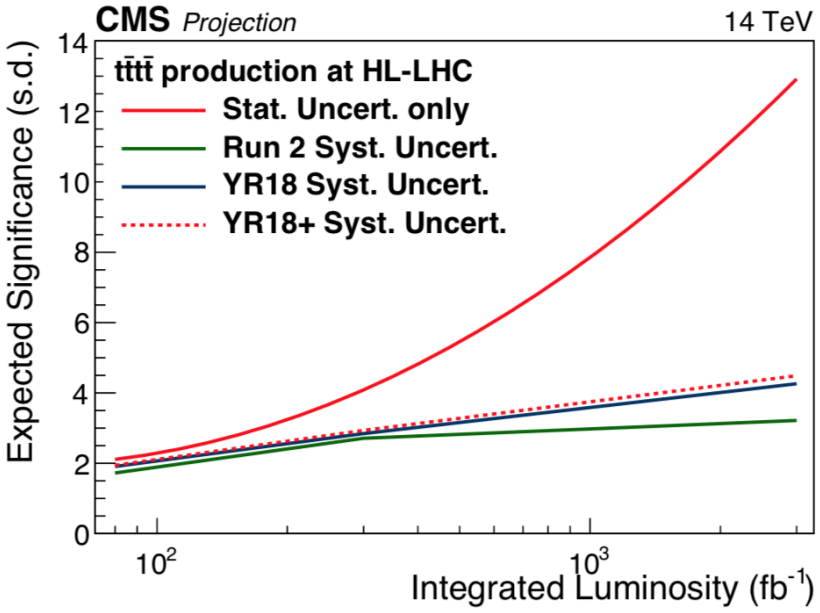




- "J/ψ" method should benefit from statistics + reco
- Moderate improvement for other methods

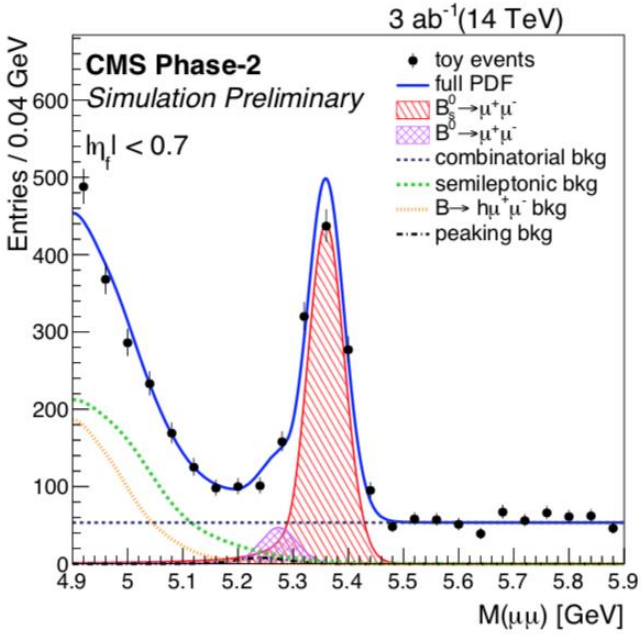
Rare SM signatures

4 top production,
CMS-PAS-FTR-18-031



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

rare $B \to \mu^+\mu^-$ decays,
CMS-PAS-FTR-18-013



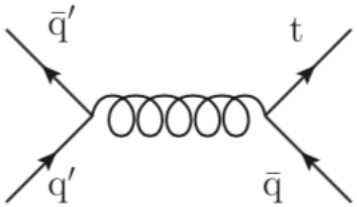
$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$
300	205	21	12%	46%	$1.4 - 3.5\sigma$
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$

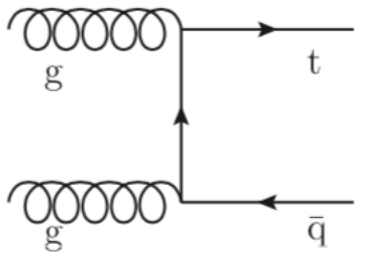
FCNC processes in top production

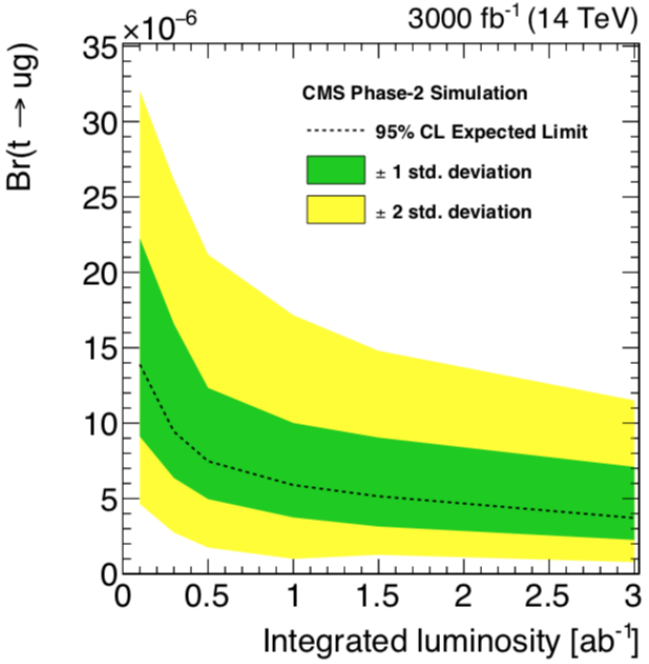
CMS-PAS-FTR-18-004

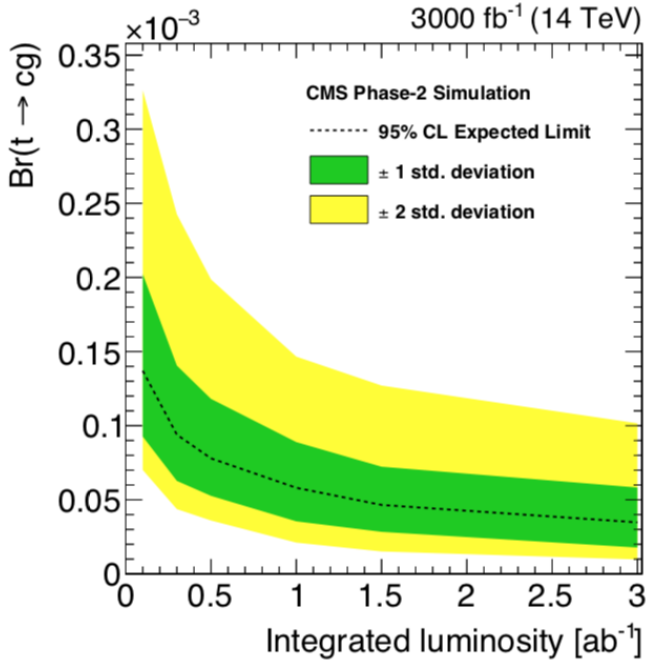
Flavour-changing neutral currents (FCNC) are absent at lowest order in the SM
FCNC couplings of the top quark are predicted to be very small $<10^{-10}$

$$\mathfrak{L} = \frac{\kappa_{tqg}}{\Lambda} g_s \bar{q} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu},$$

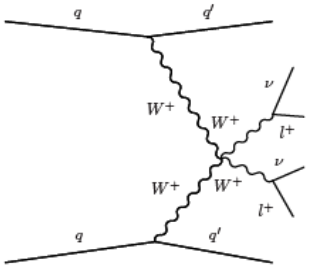


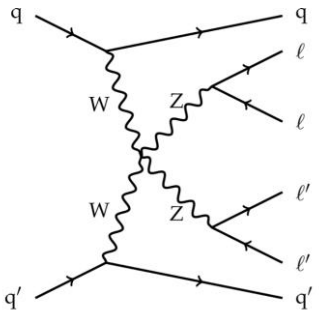






VV VBS and polarized cross section



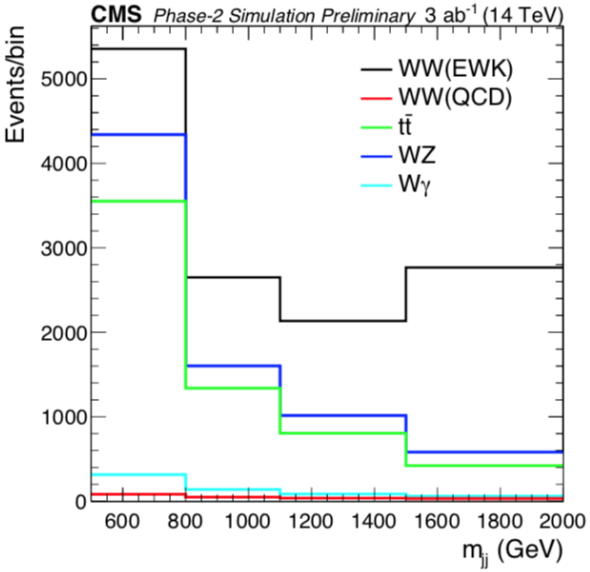


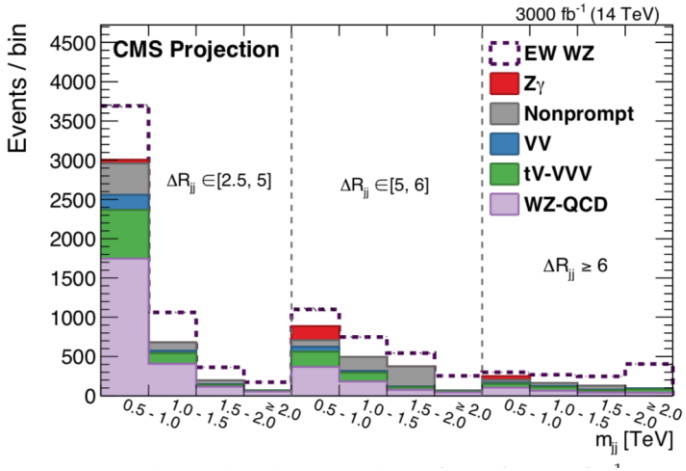
…. etc producing WW, WZ and ZZ final states

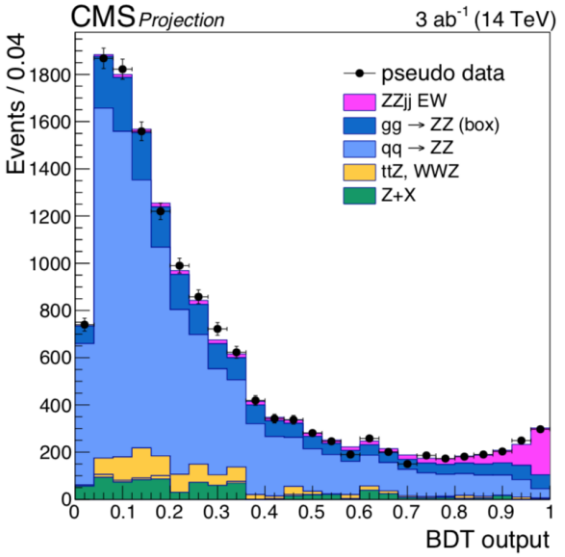
WW production, CMS-PAS-FTR-18-005

WZ production, CMS-PAS-FTR-18-038

ZZ production, CMS-PAS-FTR-18-014



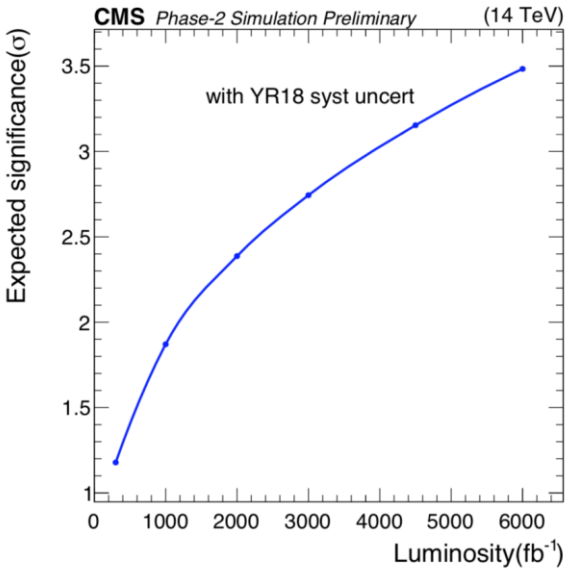




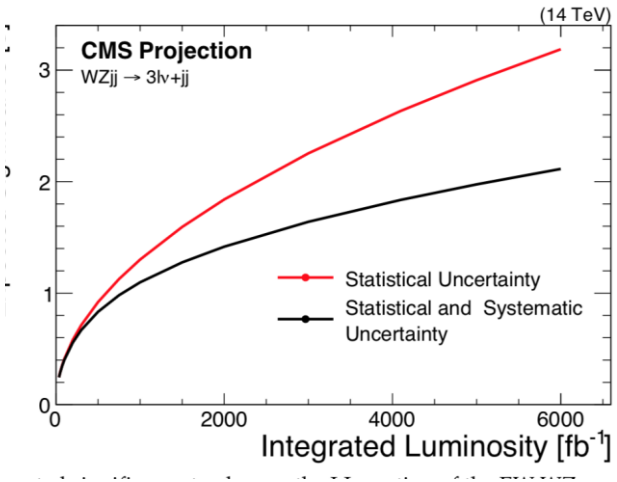
VV VBS and polarized cross section

- 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).

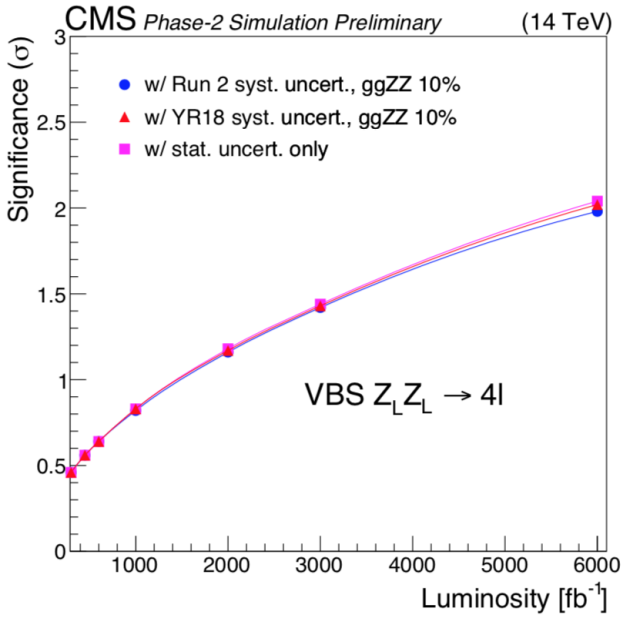
WW production, CMS-PAS-FTR-18-005



WZ production, CMS-PAS-FTR-18-038



ZZ production, CMS-PAS-FTR-18-014

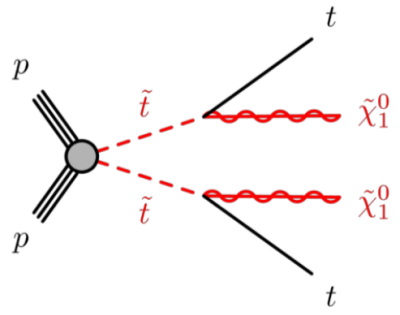


Beyond SM:

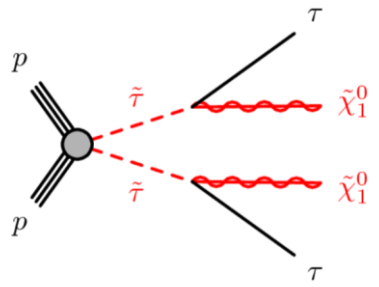
- Nothing new discovered so far ...
- Model-specific
  - SUSY
  - Leptoquarks
- More general
  - Search for high-mass resonances
- Dark matter

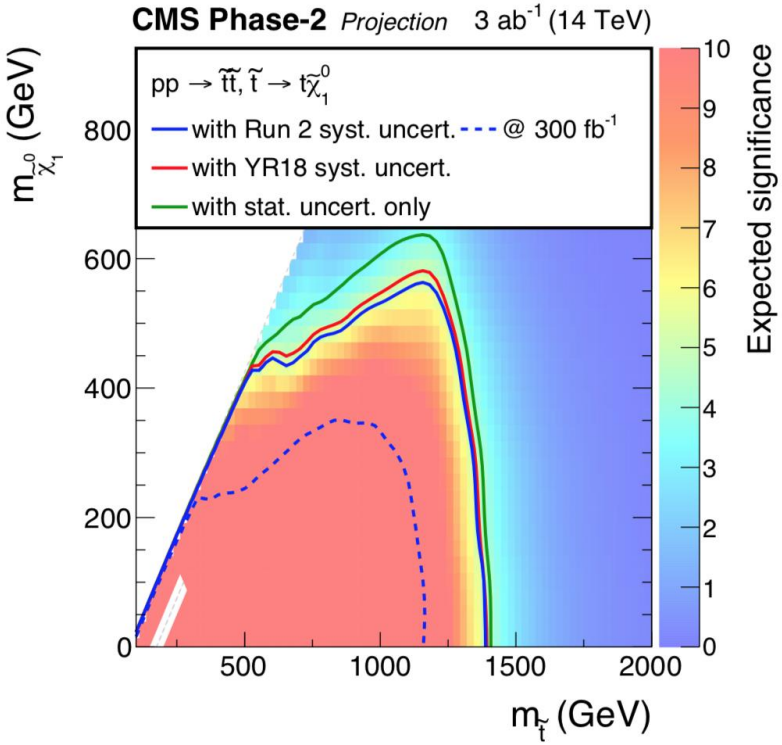
SUSY

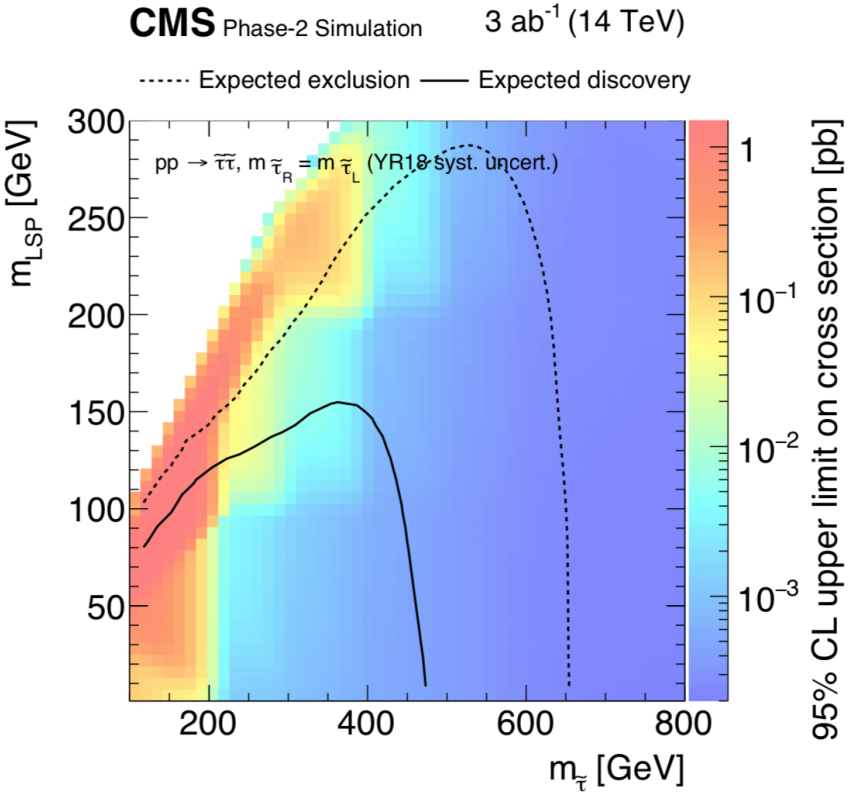
stops
CMS-PAS-FTR-18-037



staus
CMS-PAS-FTR-18-010



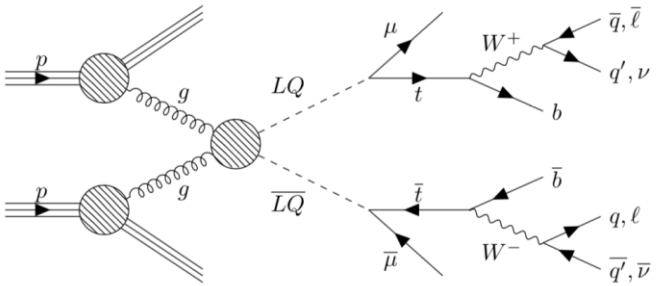


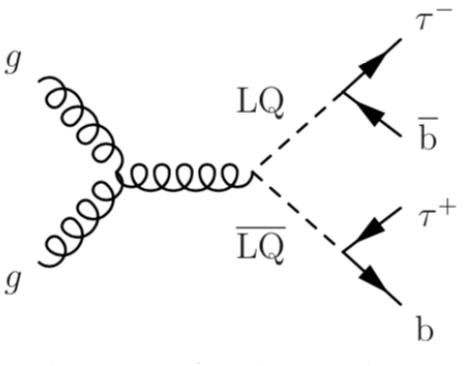


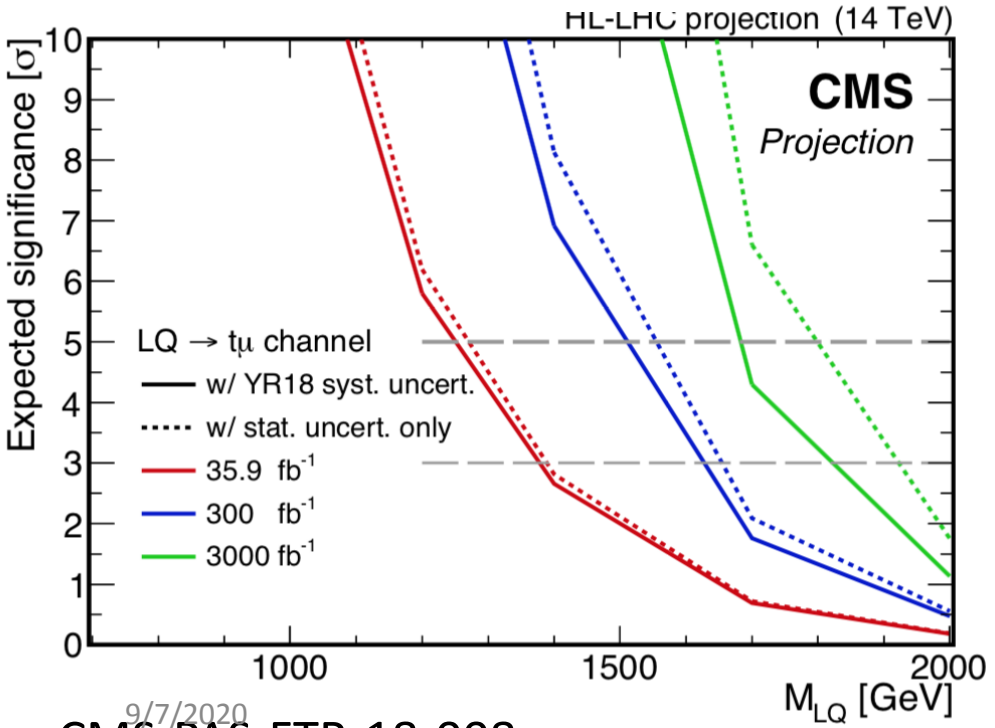
Statistics will allow to explore compressed spectra suffering from low statistics and high systematics today

Leptoquarks

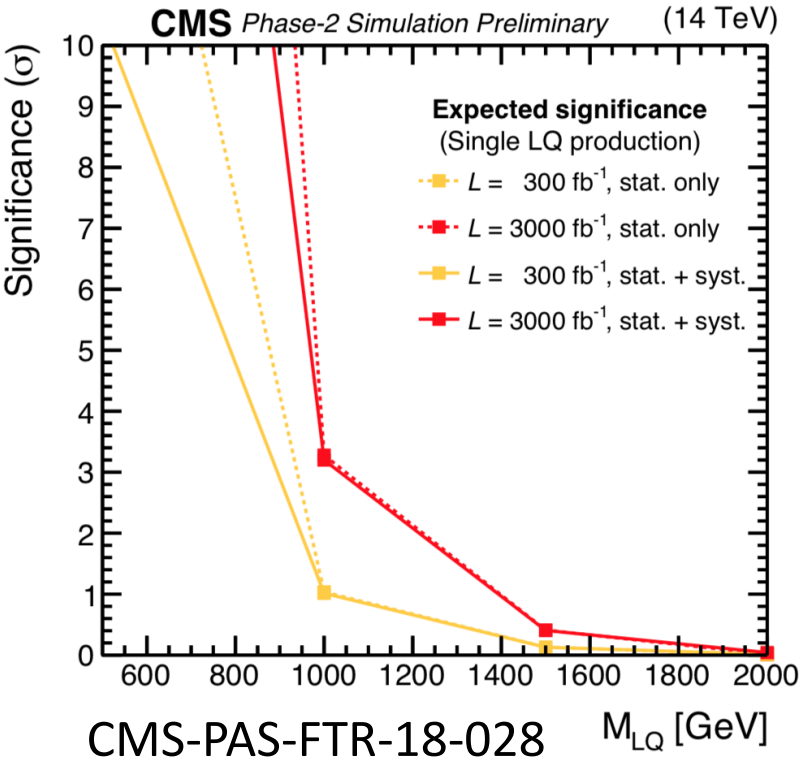
Leptoquarks carry both baryon and lepton quantum numbers and carry fractional electric charge.







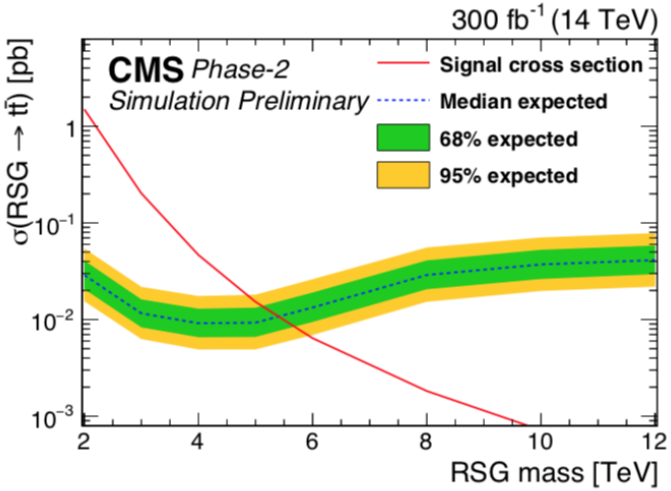
CMS-PAS-FTR-18-008

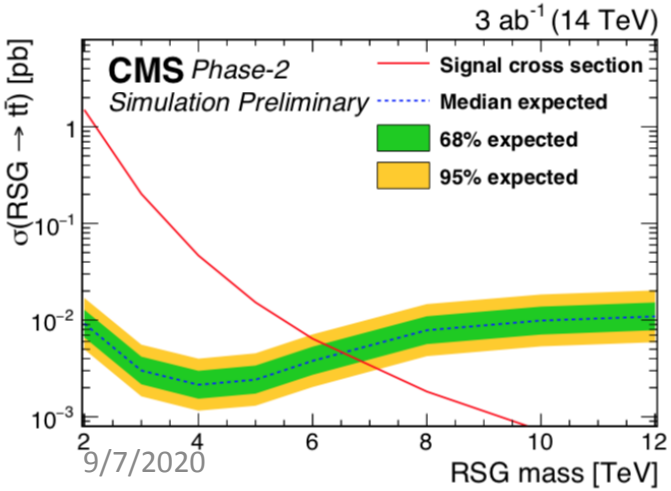


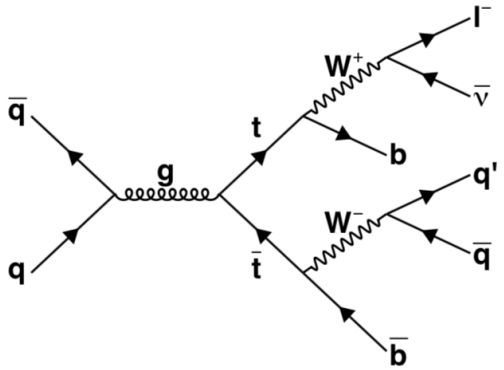
CMS-PAS-FTR-18-028

Search for tt resonances

Many models of NP predict heavy resonances with enhanced couplings to the third generation of fermions - top quark pair production to search for the presence of heavy resonances.







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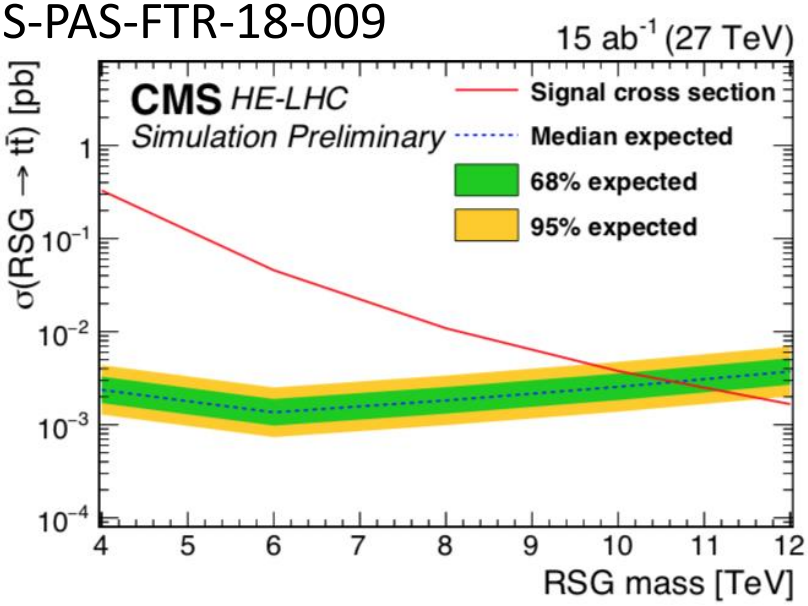

Heavy resonances

New heavy gauge bosons are predicted by various extensions of the SM

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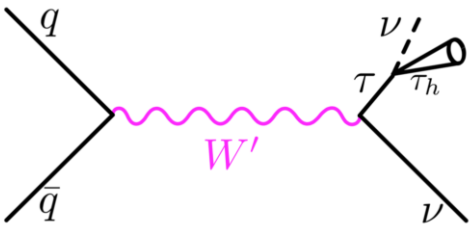

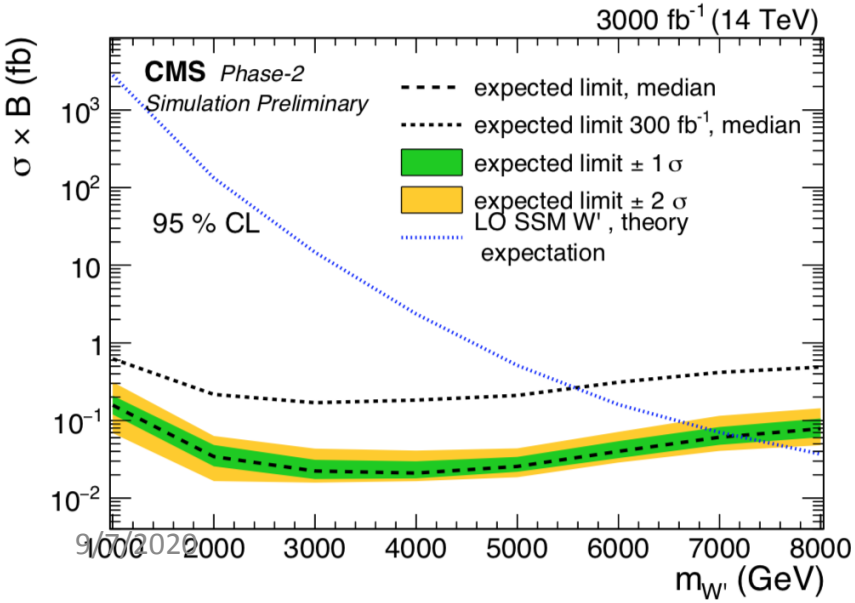

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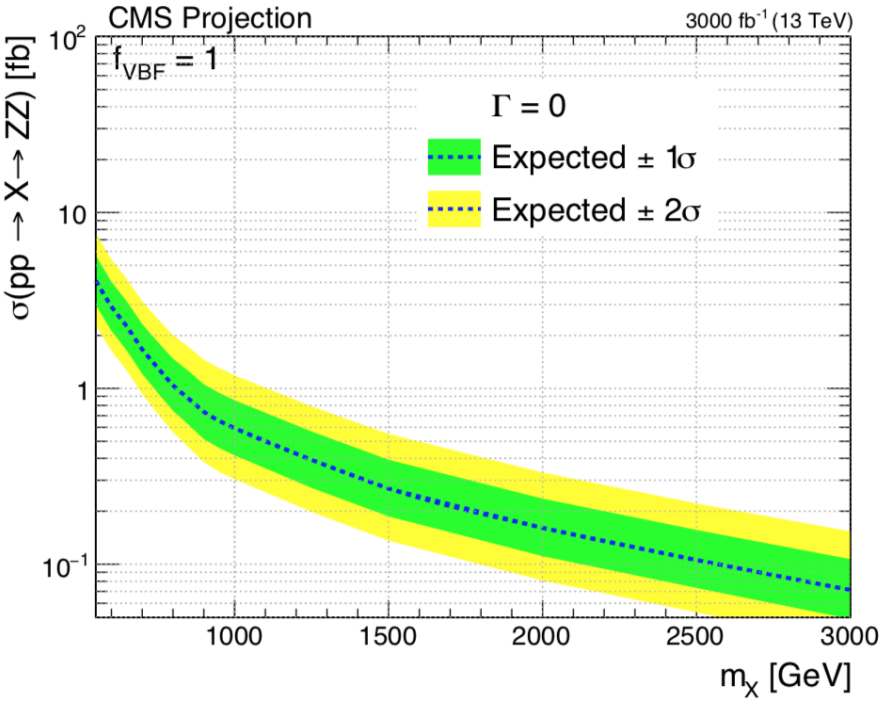
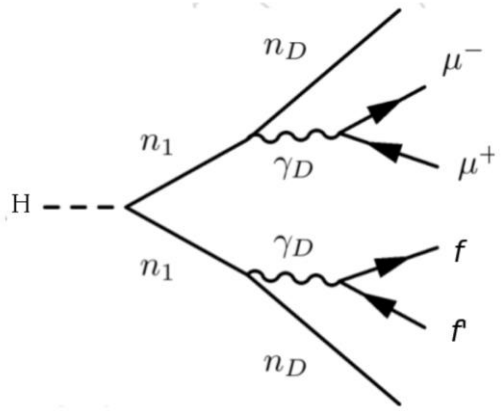
pp → X → ZZ

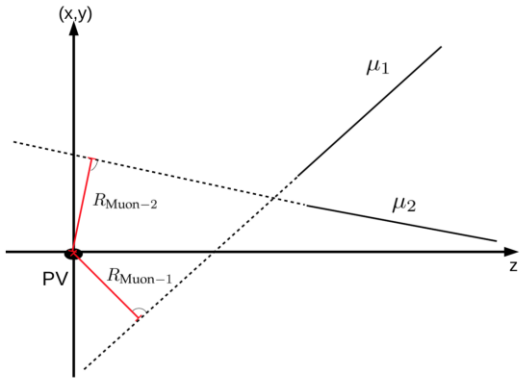


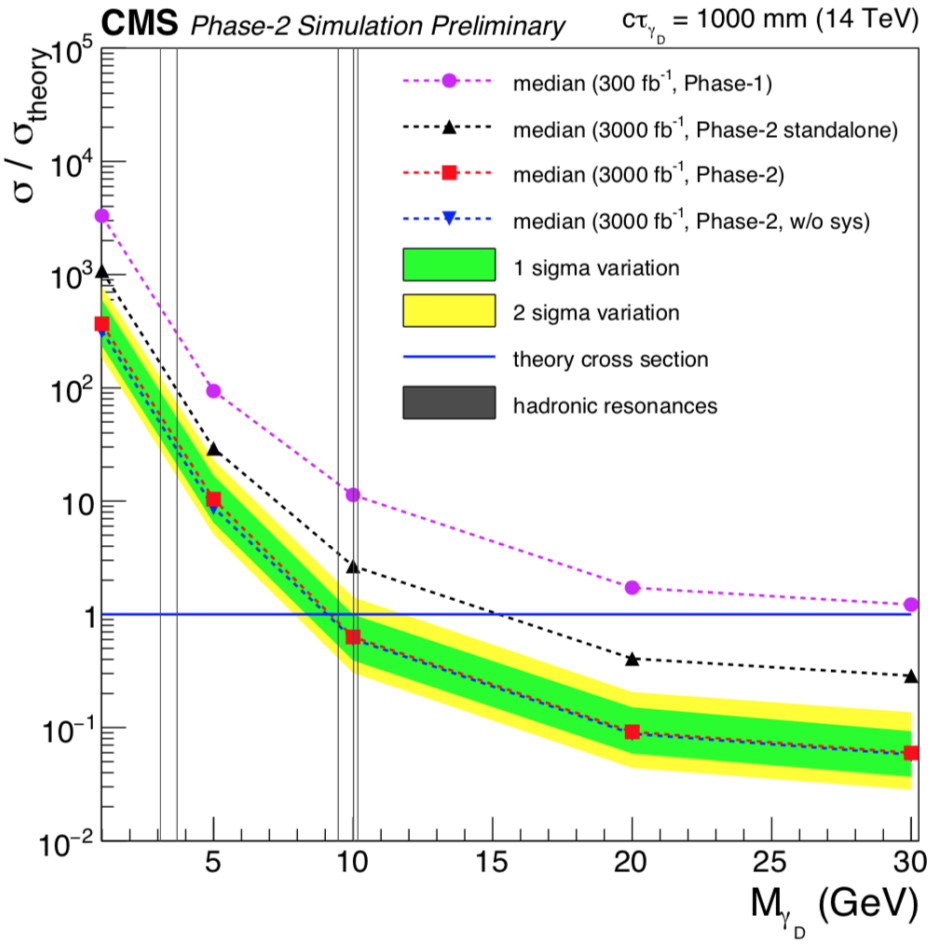
Dark matter photons

Many NP models predict long-lived particles - a large distance from the primary pp collision - search for displaced muons that emerge from the decay of long-lived particles.

CMS-PAS-FTR-18-002

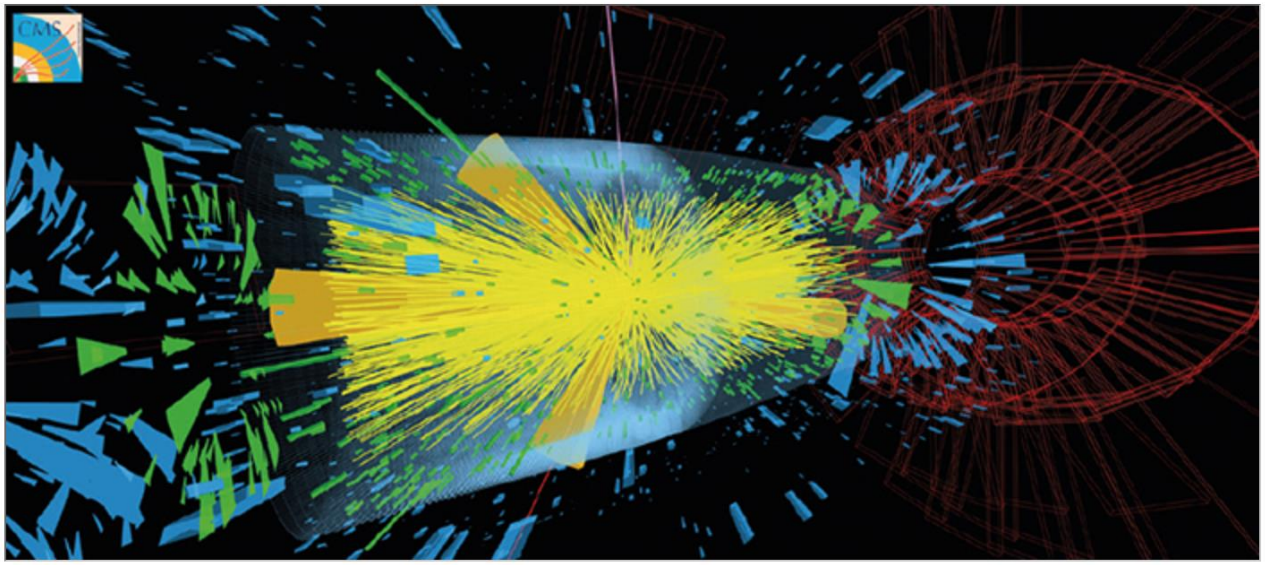






Conclusions

- The HL-LHC will allow to repeat many important measurements with significantly improved precision
- To explore new processes with extremely low cross sections and branching fractions, hopefully to find NP
- A lot of physics studies for the HL-LHC were done already and summarized in the CERN Yellow Report, new activities are already ongoing



More Higgs precision measurements

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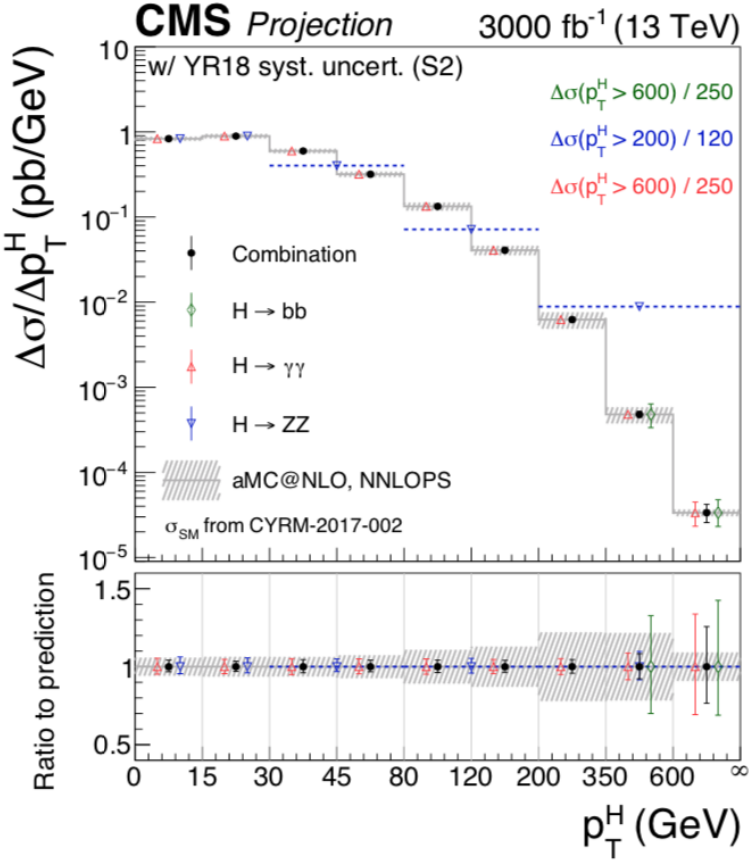
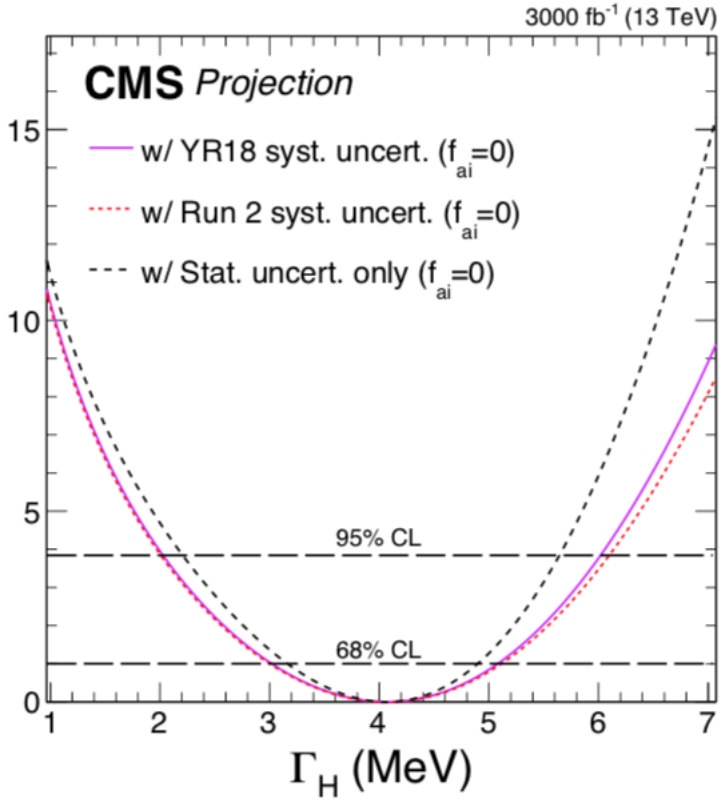
Differential Higgs cross sections



Direct and indirect Higgs width measurement



Effective mixing angle via forw.-backw. asymmetry

- Vector and axial-vector couplings in NC annihilation

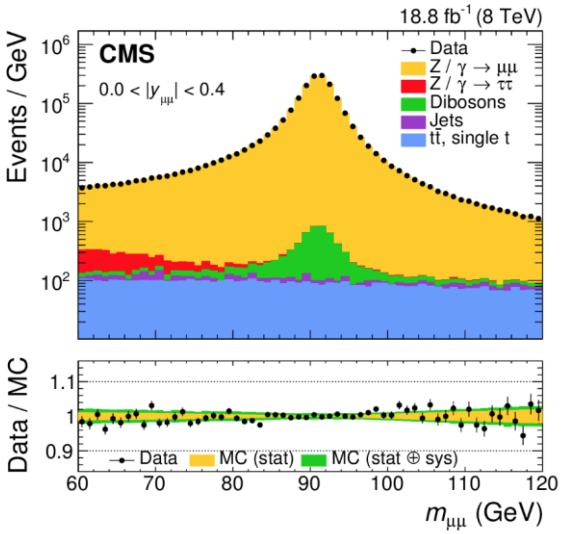
arXiv:1806.00863

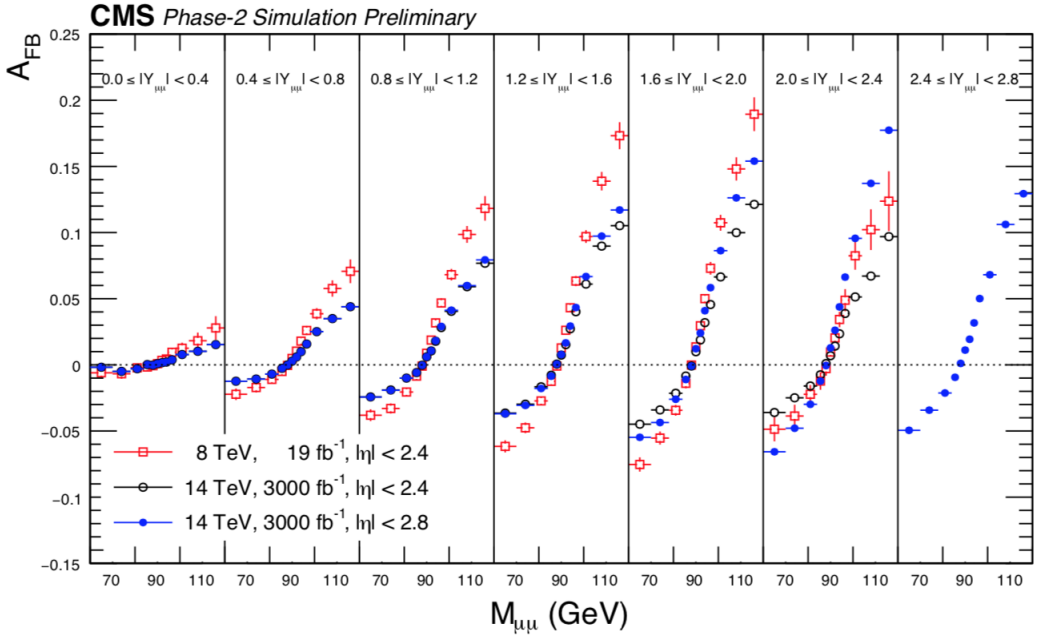
$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$$

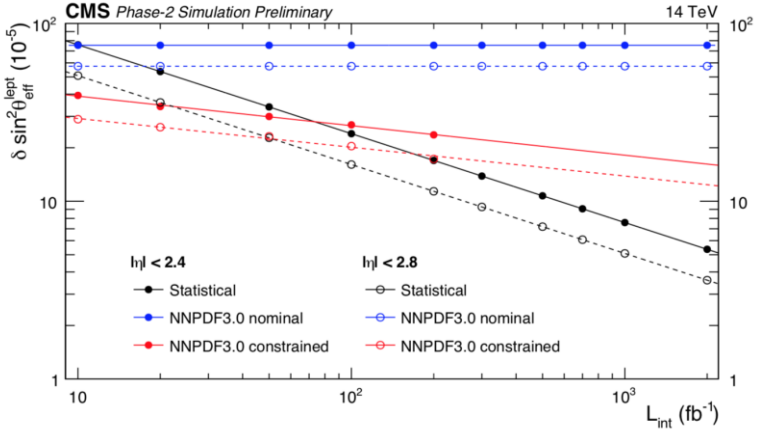
- Differential cross section

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

Fit to A_{FB} to measure weak mixing angle, indirect measure of m_W







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