Recent HL-LHC projections from CMS

ICHEP 2022, Bologna

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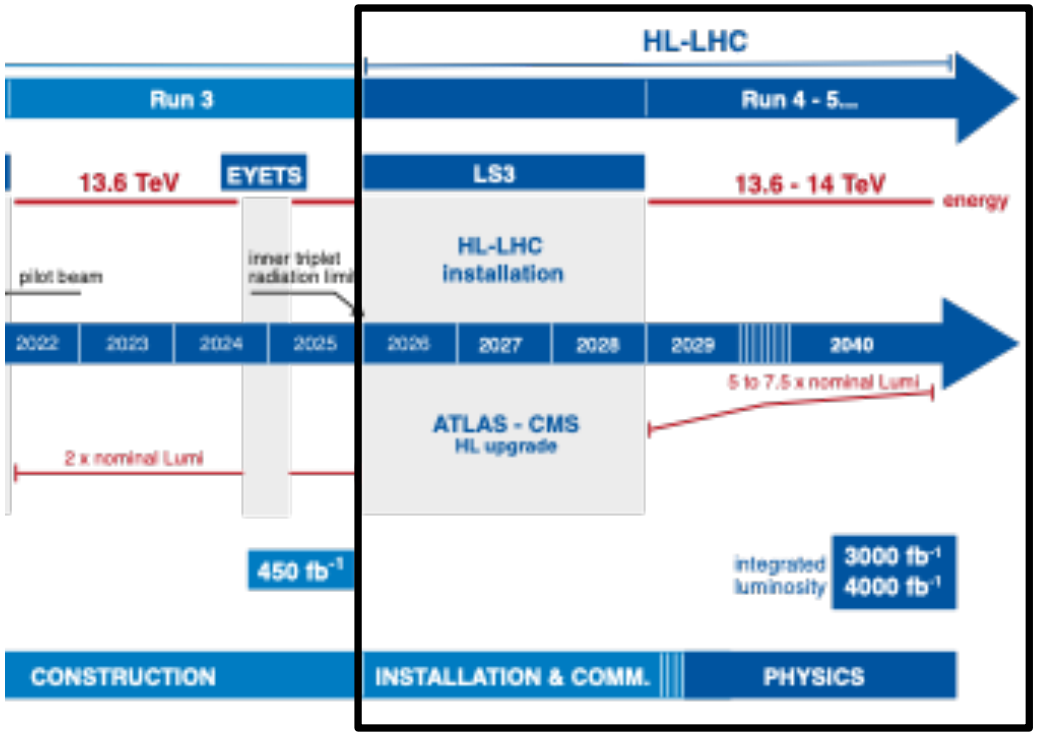
on behalf of **CMS** collaboration

High Luminosity LHC

The High Luminosity Large Hadron Collider is scheduled to begin collisions in 2029



LHC and injectors will undergo significant upgrades to boost beam intensity.

- **Instantaneous luminosity (L_{inst}) 5-7x10^{34} cm^{-2} s^{-1}**
- **Increase pileup to 140-200**
- 3000 fb^{-1} is the ultimate integrated luminosity goal.

CMS detector upgrade

HL-LHC conditions require significant upgrades of the detectors.

- Radiation hardness
- Mitigate physics impact of high pileup

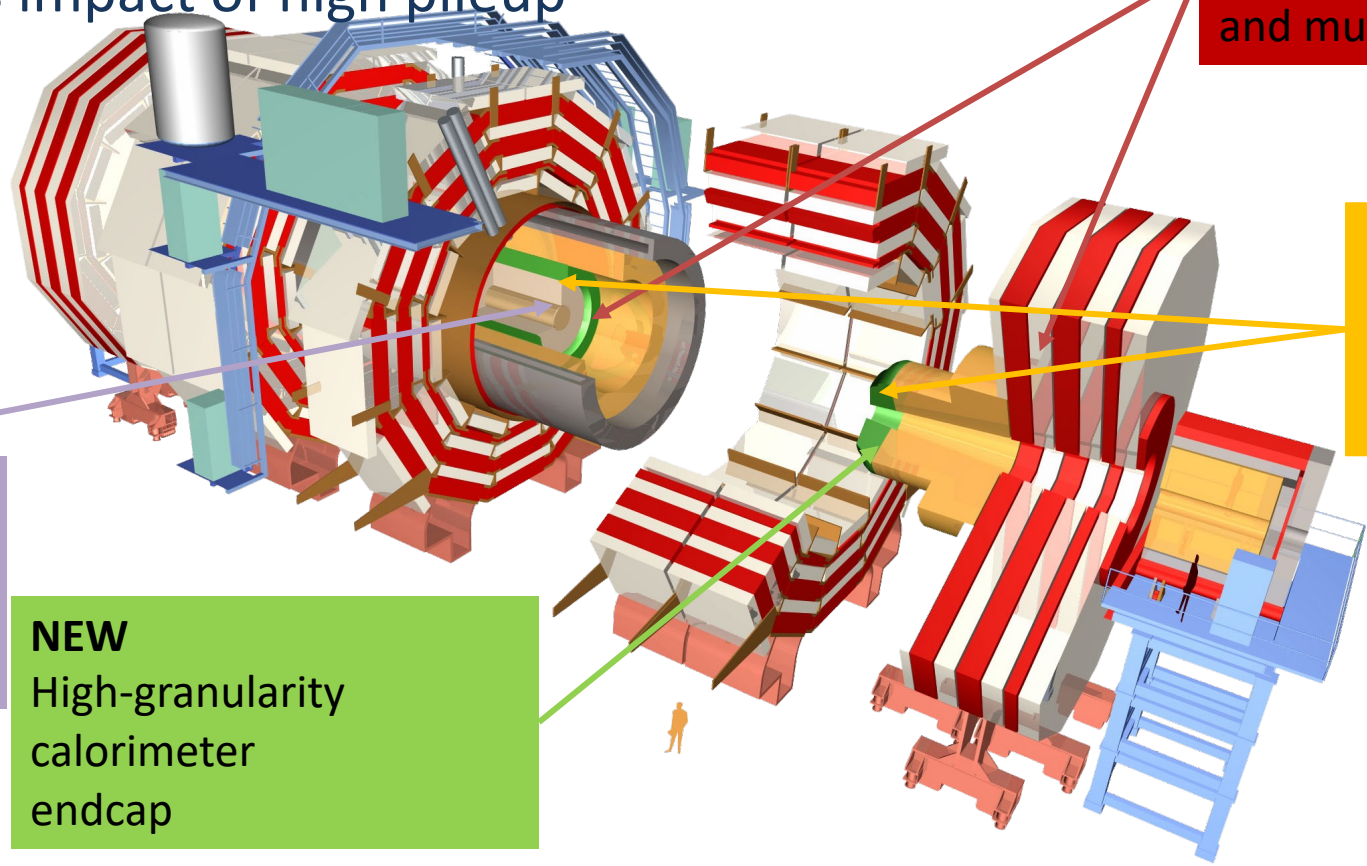
Upgraded Trigger and Data Acquisition system:
- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz

NEW
Inner Tracker, coverage up to $|\eta| = 3.8$, reduced material

NEW
High-granularity calorimeter endcap

Electronics upgrade: Barrel Calorimeter and muon system

NEW
MIP Timing detector precision timing for pileup mitigation



Physics Goals/Opportunities

- **Precision Higgs Measurements**
- **Higgs Self Coupling**
- **Precision Electroweak Measurements**
- **Extend BSM searches to smaller production cross sections**
- **Precision measurements of rare B decays**
- **Heavy Ion Physics**

Recent efforts for HL-LHC projections

European Strategy Update (2018-2020)

- "The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the science of particle physics. It takes into account the worldwide particle physics landscape and developments in related fields"

Snowmass Community Planning Exercise (2020-2022)

- "The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") ... 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 U.S. and its international partners."

This year, CMS delivered numerous new results for Snowmass, and they serve as the basis for the review I will present today.

CMS Analysis approach and Systematics

CMS Analysis Approach:

- **Projections :** Utilize existing data, scale results to cross section and higher luminosity
- **Fast simulation :** Use dedicated Phase-2 parametrized detector simulation and events from Delphes.

Uncertainties treatment:

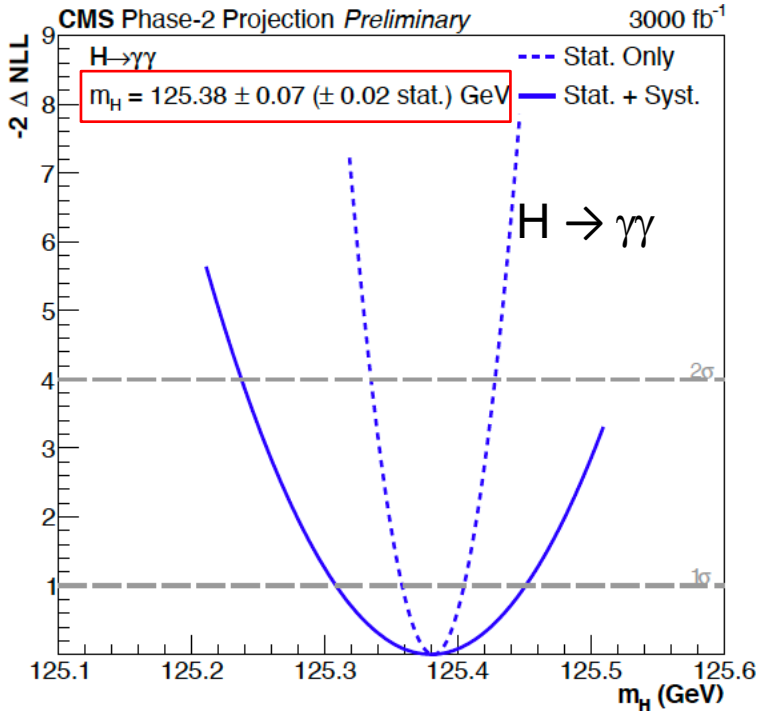
- **Run 2 systematics (S1):** Use Run 2 values
- **"YR18" systematics (S2):** A set of reduced uncertainties anticipated for Phase-2. Experimental ones based on ultimate performance and factor of half reduction for theory uncertainties.

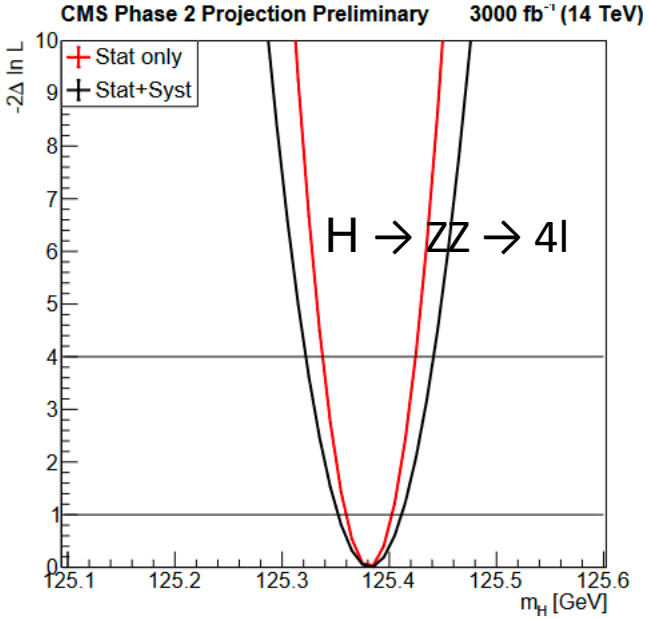
Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

FTR-21-007
FTR-21-008

Expected precision on Higgs mass and width

- The expected precision of the Higgs boson mass measurement at HL-LHC is projected in the **H → γγ** and **H → ZZ → 4l** channels.





	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	2e2μ	2μ2e	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177

The total width Γ_H is measured in H → ZZ → 4l channel.

Higgs Couplings measurements

FTR-21-006

- Expected uncertainties on signal strength and κ_μ uncertainties in H → μμ are estimated.
- H→μμ channel **provided the first evidence of Higgs couplings to 2nd generation fermions with full Run 2 data.**

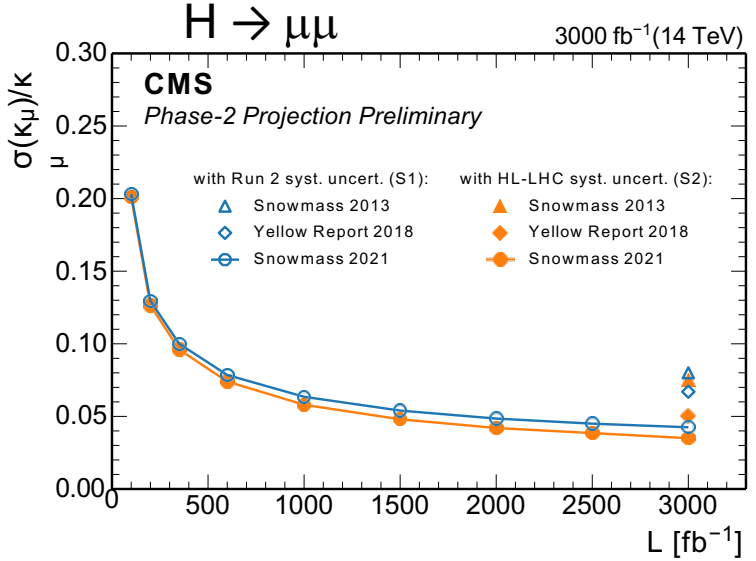
Signal strength modifier

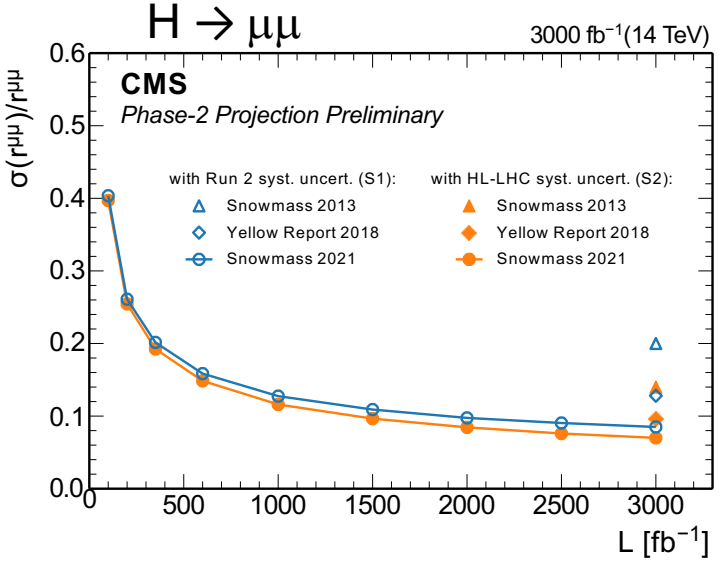
		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	20.0%
	YR 2018	9.1%	7.6%	4.8%	12.8%
	Snowmass 2021	6.4%	3.7%	4.2%	8.5%
S2	Snowmass 2013	-	-	-	14.0%
	YR 2018	9.1%	1.7%	2.7%	9.6%
	Snowmass 2021	6.4%	2.0%	2.0%	7.0%

Coupling strength modifier

		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	8.0%
	YR 2018	4.7%	2.7%	3.9%	6.7%
	Snowmass 2021	3.2%	1.9%	2.2%	4.3%
S2	Snowmass 2013	-	-	-	7.5%
	YR 2018	4.7%	1.5%	1.1%	5.0%
	Snowmass 2021	3.2%	1.1%	0.8%	3.5%

~30% improvement from the previous projection

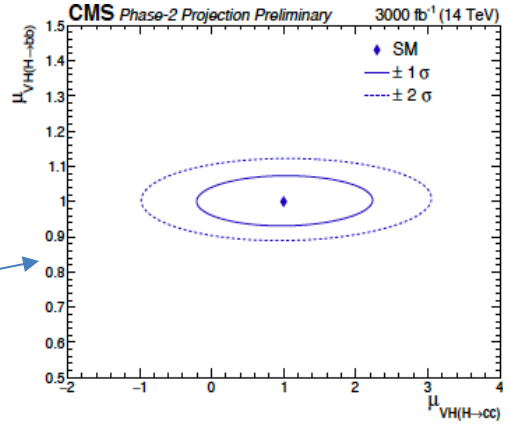


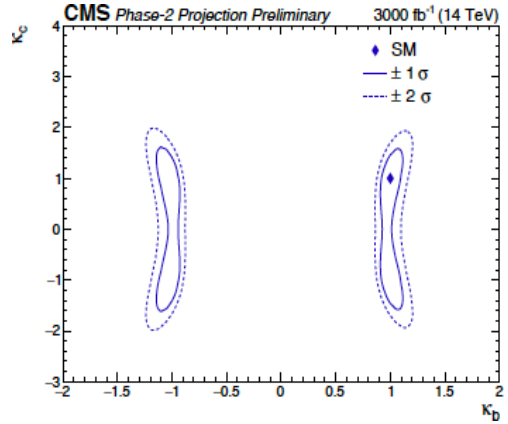


Higgs Couplings measurements

HIG-21-008
FTR-21-009
FTR-21-002

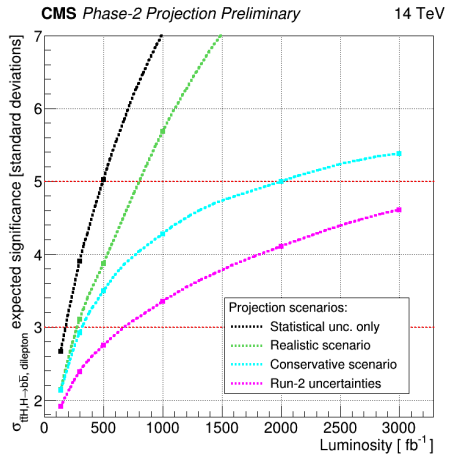
- **A direct measurement of H → cc in association with W and Z.**
- This is extremely difficult due to the small branching fraction, challenging c-quark identification in hadronic environment and very large multi-jet QCD background.

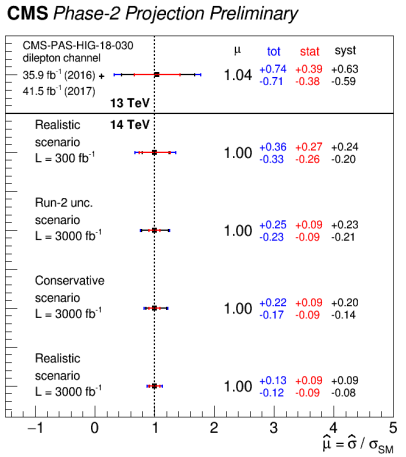




$\mu_{VH(H \to bb)}$	$\mu_{VH(H \to cc)}$
0.03(stat) ± 0.04(syst)	0.06(stat) ± 0.05(syst)

- Higgs boson coupling to the top quark in bb channel.
  - Expected uncertainty on the signal cross-section is estimated to be **12%**
  - This translates to the similar order of uncertainty on the top-Higgs Yukawa coupling (y_t).





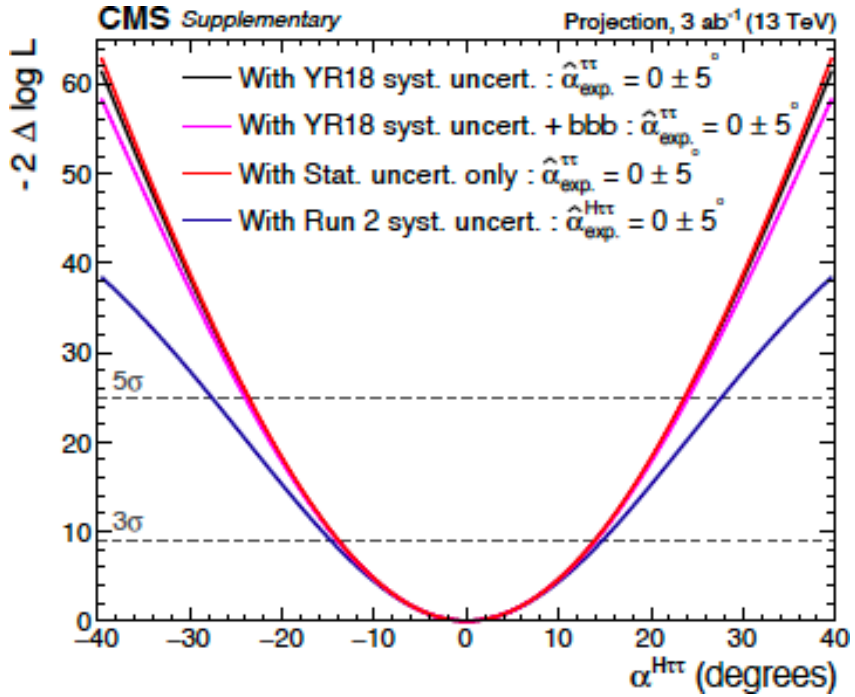
- T

Channel	3000 fb^{-1}	($\times$SM)	4500 fb^{-1}	($\times$SM)
	$H \to ZJ/\psi$		$H \to \Upsilon(mS)\Upsilon(nS)$	
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)

Higgs CP properties measurements

HIG-20-006

- Projections for the measurement of the CP properties of the Higgs boson coupling to τ leptons at HL-LHC.
- The CP nature is described in terms of effective mixing angle $\alpha^{H\tau\tau}$.



$\alpha^{H\tau\tau}$ = 0 (90)° corresponds to a pure scalar (pseudoscalar) coupling

Any intermediate value denotes a mixed coupling
- implying CP violation

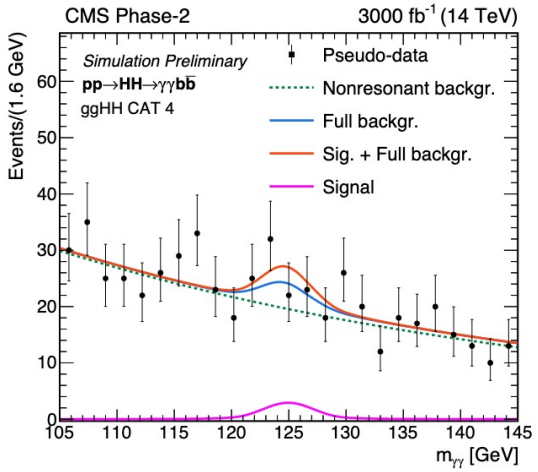
Expected uncertainty on $\alpha^{H\tau\tau}$ is 5°

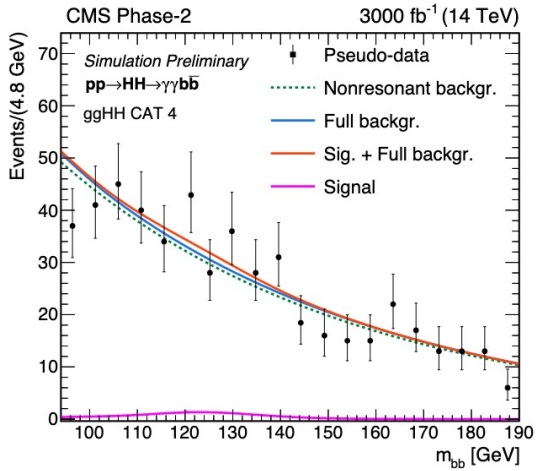
Di-Higgs prospects for HL-LHC

FTR-21-003
FTR-21-004

Projection of HH → bb γγ

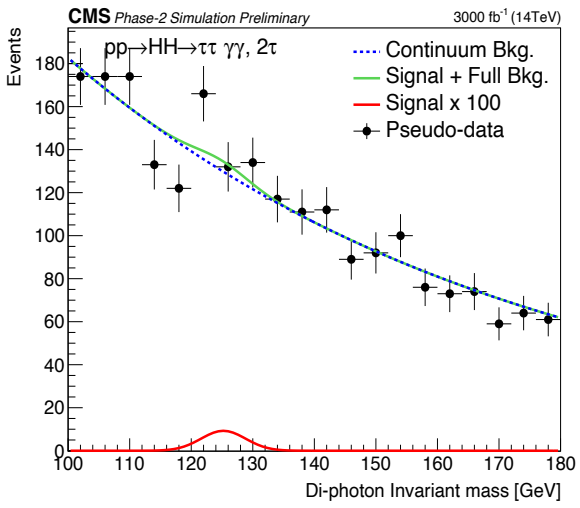
- **2.16σ expected significance**

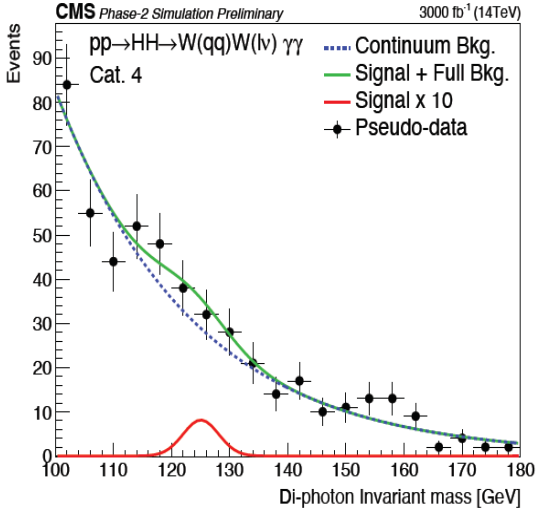




Also Explored $W^+W^-\,\gamma\gamma$ and $\tau^+\tau^-\gamma\gamma$ channels

- **Combining all final states, the expected significance for the SM ggHH signal is estimated to be 0.22σ .**





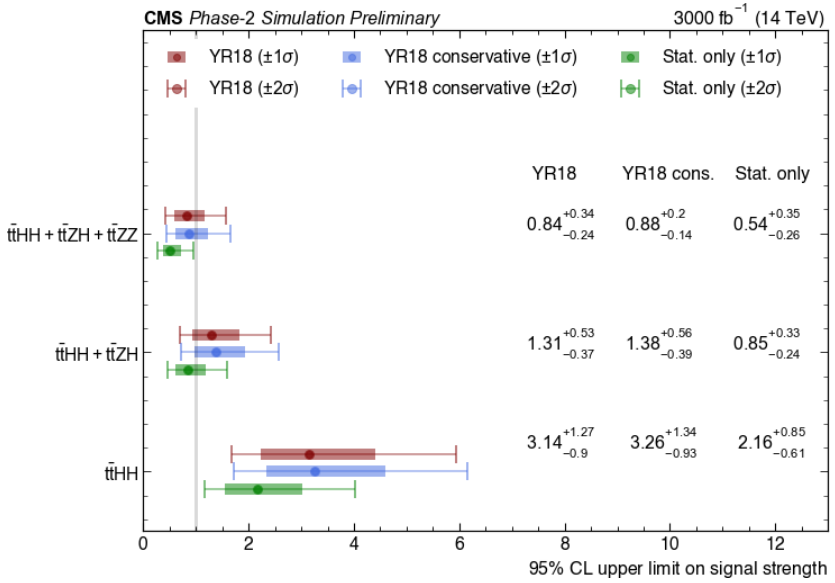
Di-Higgs prospects for HL-LHC

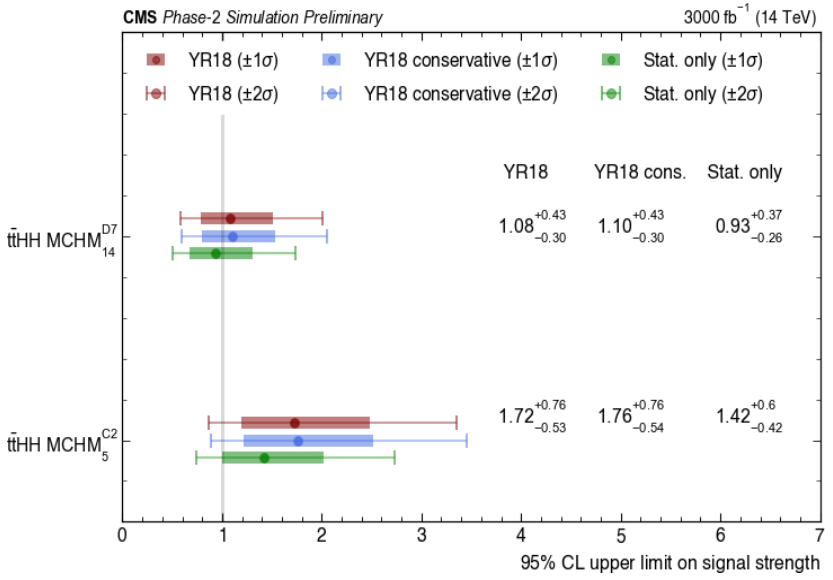
FTR-21-010

Projection of $t\bar{t}HH$

The top pair decay semi-leptonically and Higgs boson decays in b-quarks.

Upper limit on $t\bar{t}HH$ alone is expected to become $3.14^{+1.27}_{-0.9} \times$ SM



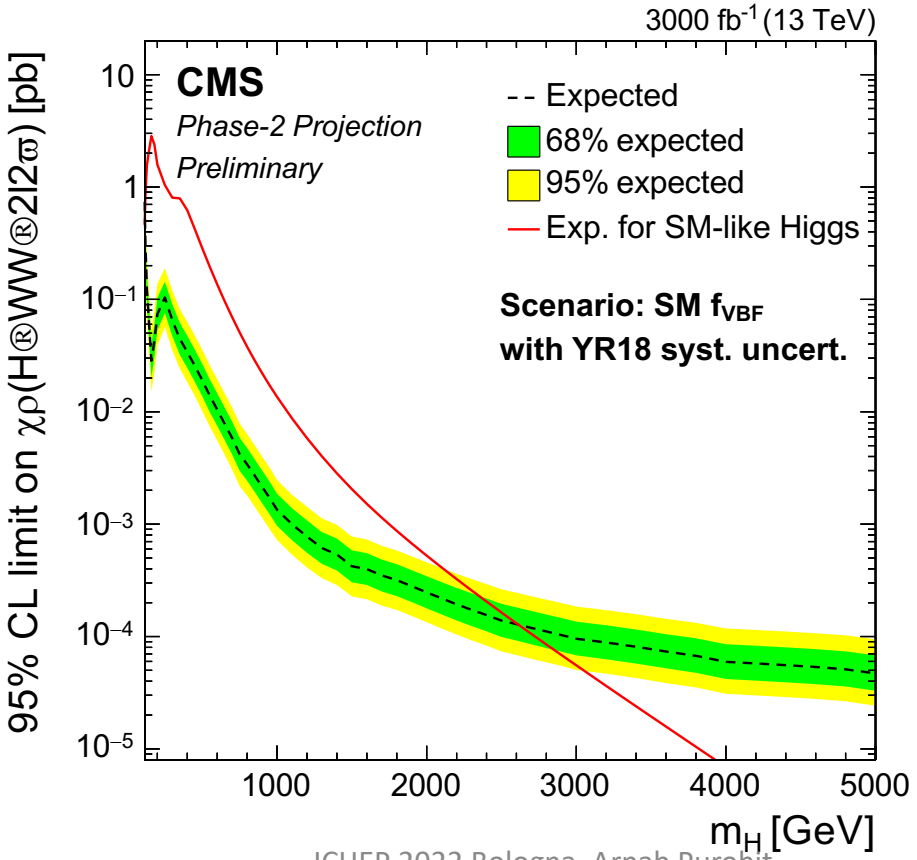


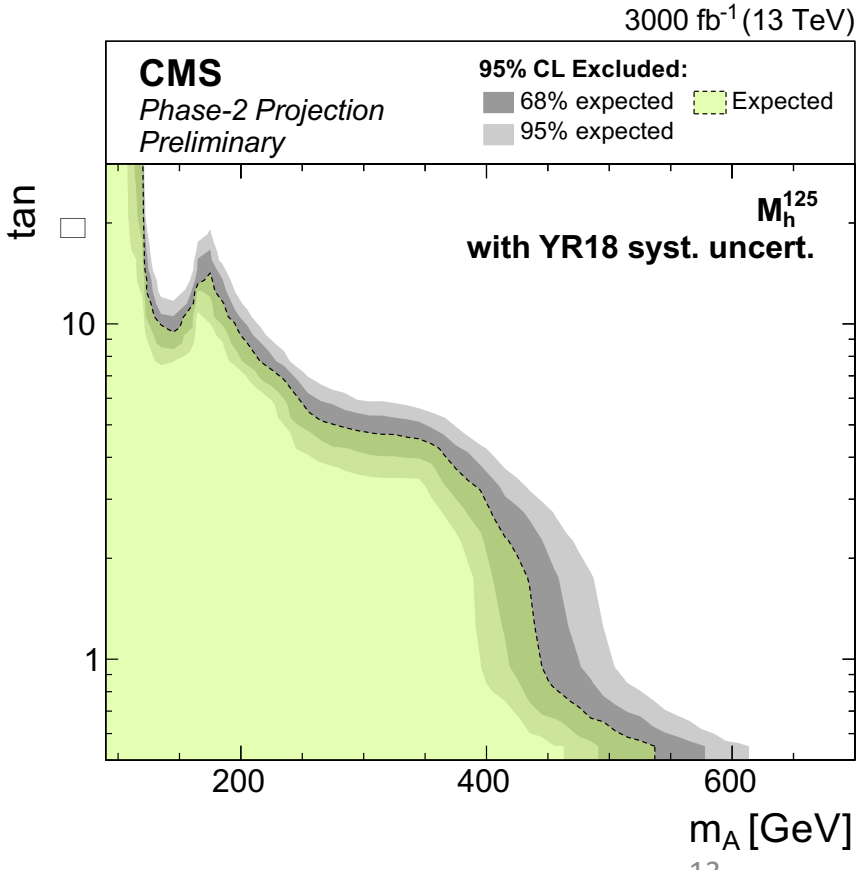
Higgs boson as a portal to new Physics

FTR-22-006

Projection of heavy resonance search in WW^{-} (→ di-lepton) channel.

- The projection predicts an exclusion up to mass of about **2600 GeV**.
- In Run 2 the limit was at ~2000 GeV.

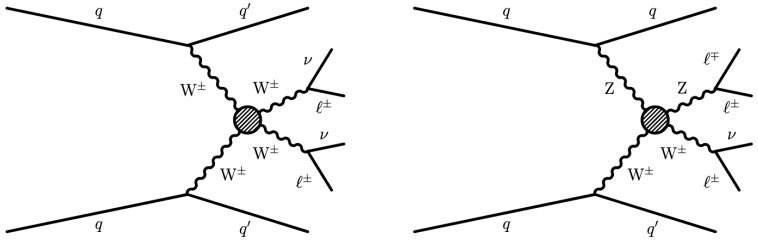




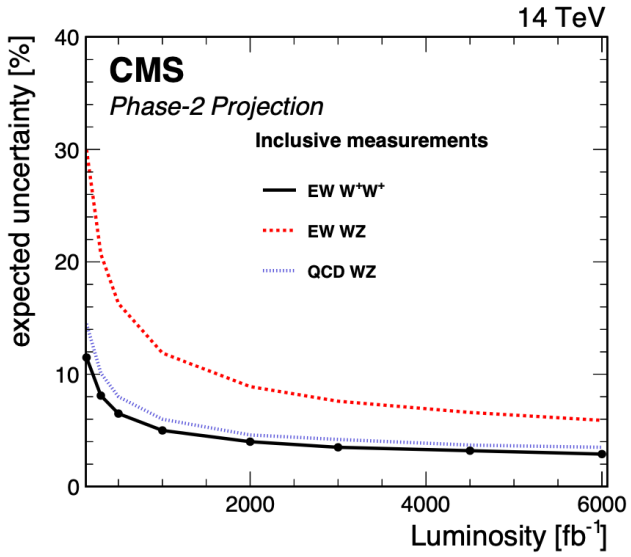
FTR-21-001

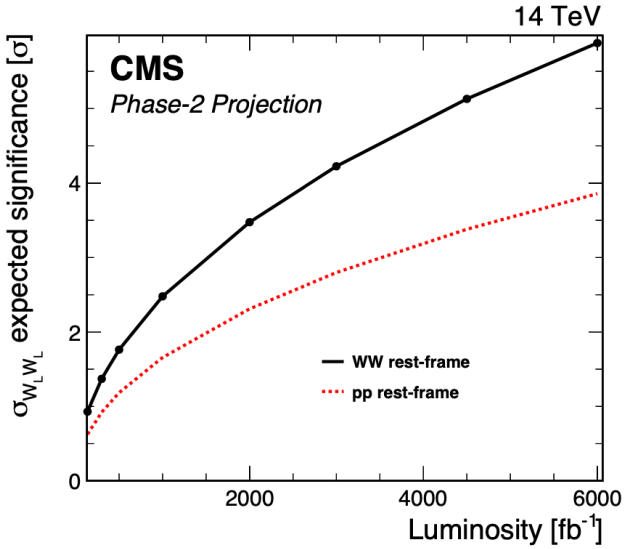
Vector boson scattering (VBS) in leptonic WW and WZ

- Important tool to probe EWSB mechanism and is sensitive to BSM.
- Explored sensitivity to VBS cross section and polarization.
  2 same-sign leptons (WW) or 3 leptons (WZ) with total charge 1.



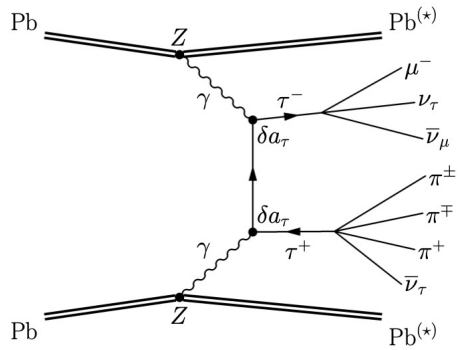
- EW WW, EW WZ and QCD WZ production cross sections are measured simultaneously.
- Simultaneous measurement of longitudinal and transverse polarized components in the WW channel.





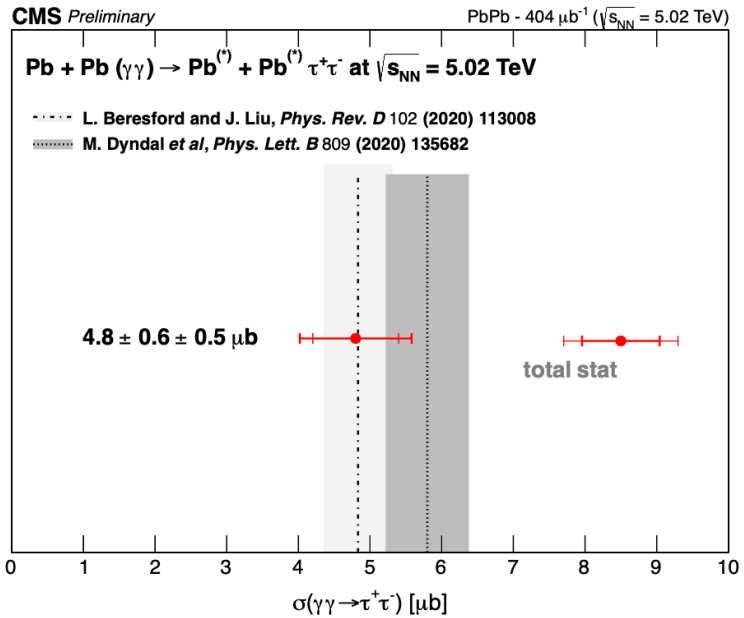
Measurement of $\gamma\gamma \rightarrow \tau^+\tau^-$

FTR-21-009



Ultra-peripheral heavy ion collisions: No hadronic interaction between the ions.
⟹ Clean environment to study γγ-induced processes.

- **γγ → τ⁺ τ⁻ sensitive to BSM ⟹ improved constraints on (g-2)τ**
- **13 nb-1 PbPb luminosity, sqrt(SNN) = 5.02 TeV.**



Phase-2 expected γγ → τ+ τ - x-section: 4.8 ± < 0.1 ± 0.2 μb.
Total Uncertainty: 4%
~x4 Improvement wrt Run 2 prediction:
4.8 ± < 0.6 ± 0.5 μb.

- Improvements originate from lepton and tracking reconstruction
- Including more decay channels and improved analyses (e.g. shape analysis), precision on (g-2)τ expected to surpass the existing measurements.

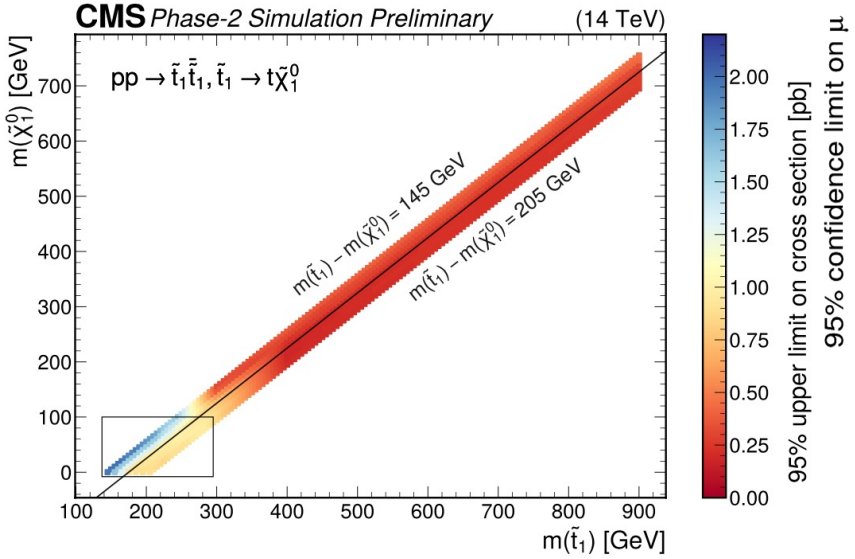
Top quark spin correlations

FTR-18-034

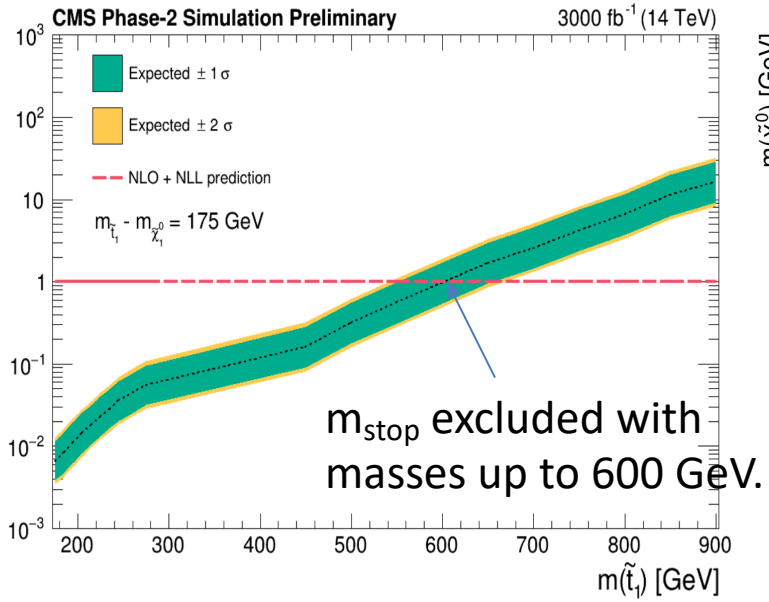
Projection analysis of precision measurement of the strength of expected spin correlation in eμ + ≥ 2 jets + ≥ 1 b-jet final state.

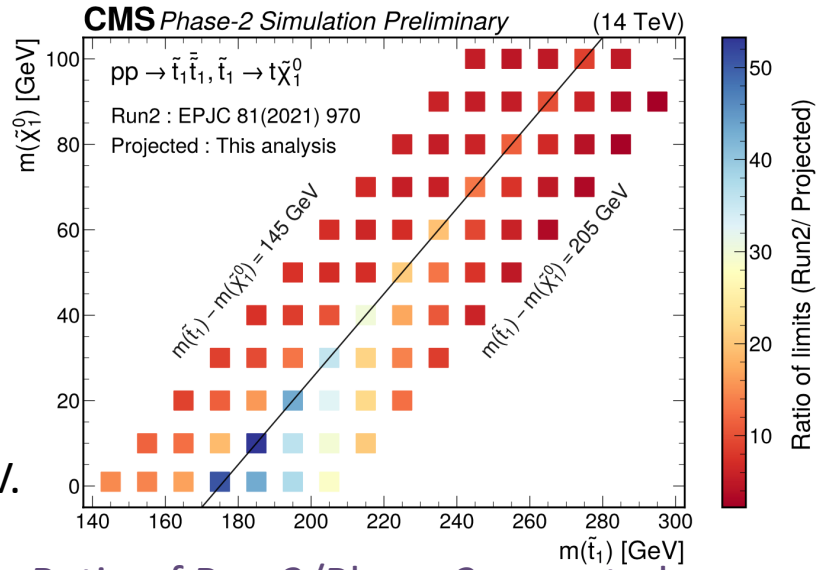
⟹ Spin correlation coefficient D is the most accurate observable with 3% precision (among 22 studied)

Delphes based search of top squarks in the "top corridor" using spin corr. variables in a DNN



Expected limits on signal strength corresponding to $\Delta M(\tilde{t}_1, \tilde{\chi}^0_1)$ = 175 GeV

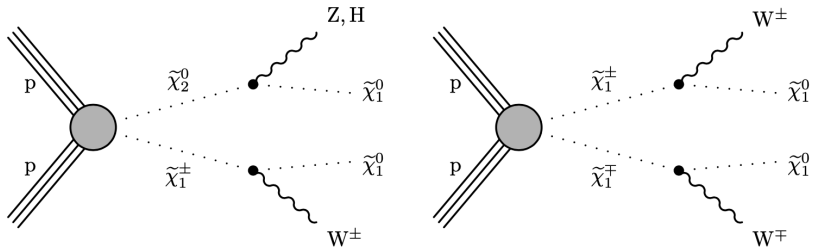




Ratio of Run 2/Phase-2 expected exclusion limits on cross section. Improvement of 2-50 times

SUS-21-002

Hadronic EW SUSY Search

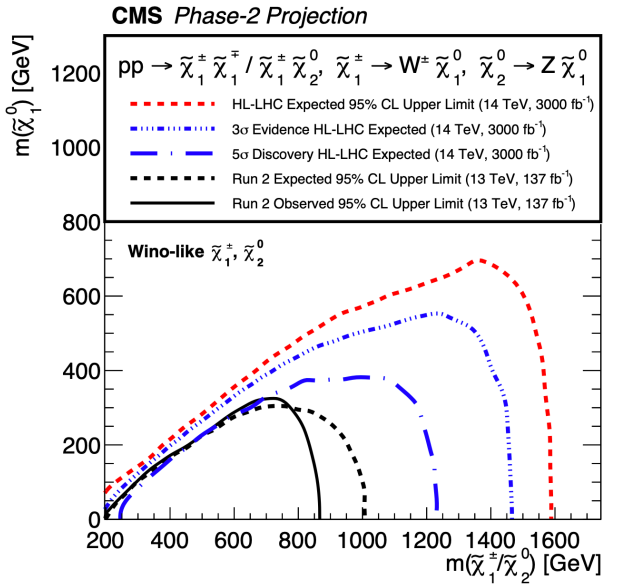


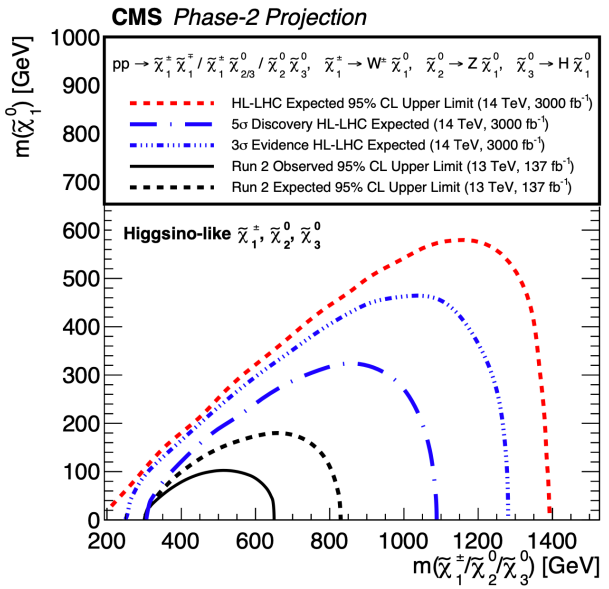
Search for EW-produced chargino / neutralino decaying to boosted hadronic W/Z/H + LSP

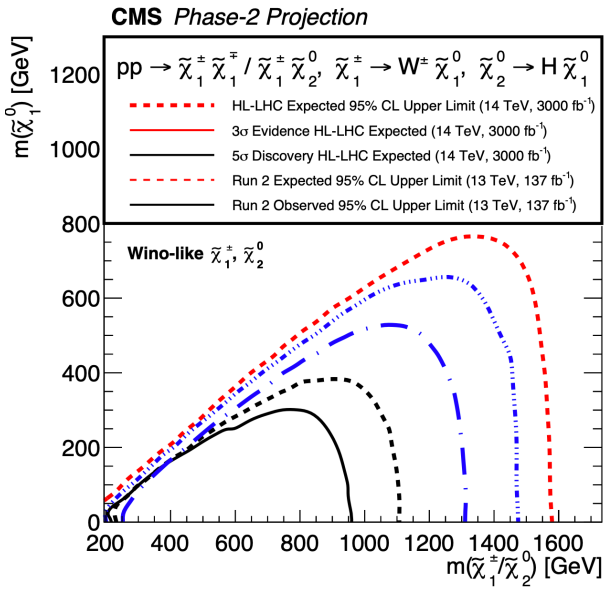
Final states: WW, WH, WZ, ZH + E_T^{miss} > 200 GeV.

$\Longrightarrow$ 2 AK8 jets with p_T > 200 GeV and W/Z/H tagging.

- Interpretation is carried out in scenarios with bino-like LSP and wino-like or Higgsino-like NSLP.
- m_{NLSP} exclusion limits difference Phase-2 expected - Run 2 observed : **650 - 750 GeV.**

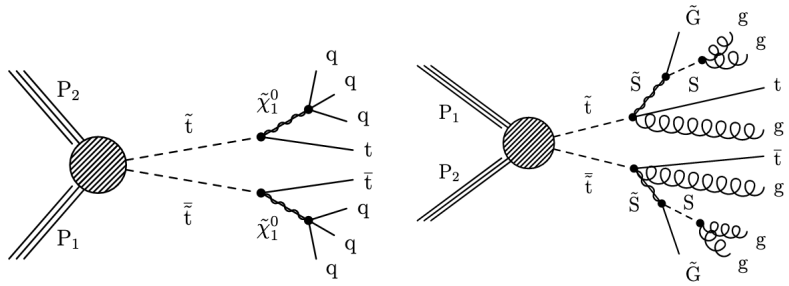






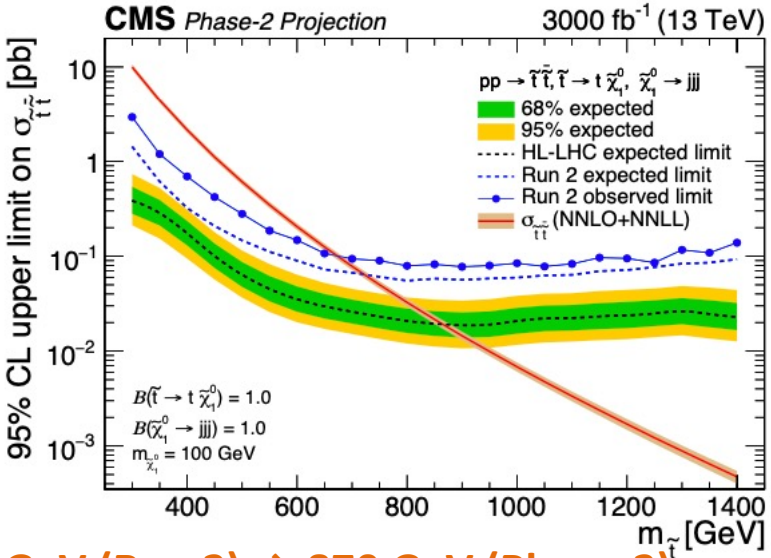
SUSY-19-002

Stop search with 2 tops + multijets

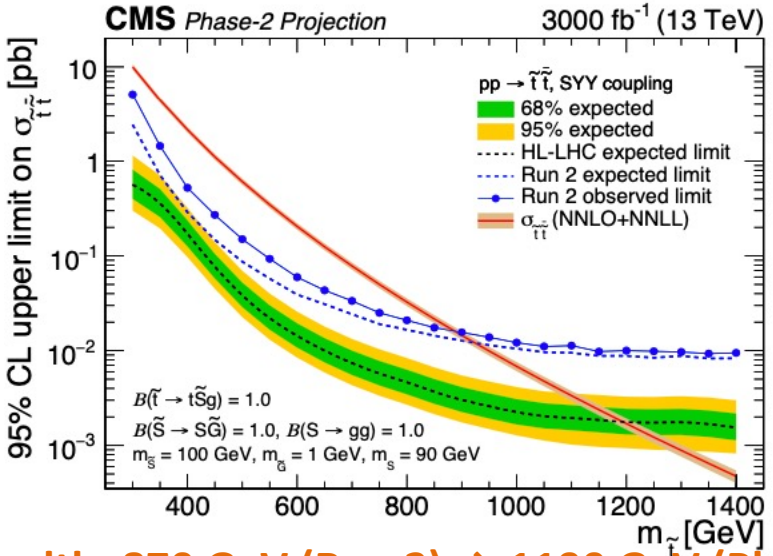


Search for stop pair production in R-parity violating or stealth SUSY models

- Final states: 2 tops + additional jets
  $\Longrightarrow$ 1 lepton + ≥7 jets (no E_T^{miss})
- ML method used for Signal extraction.



RPV: 670 GeV (Run 2) → 870 GeV (Phase-2)

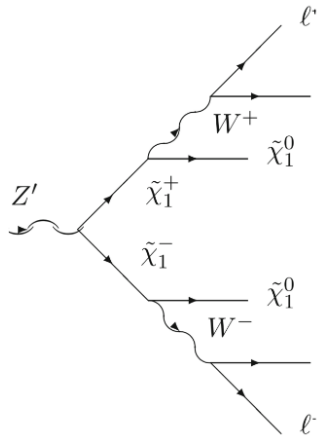


Stealth: 870 GeV (Run 2) → 1190 GeV (Phase-2)

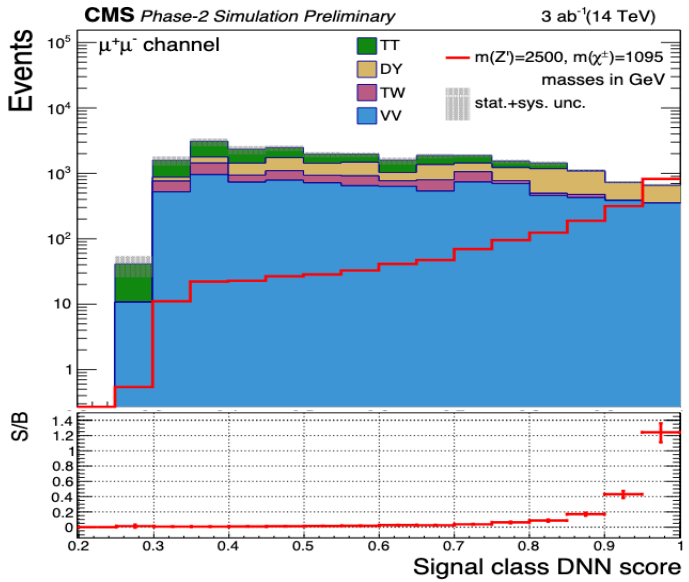
FTR-21-011

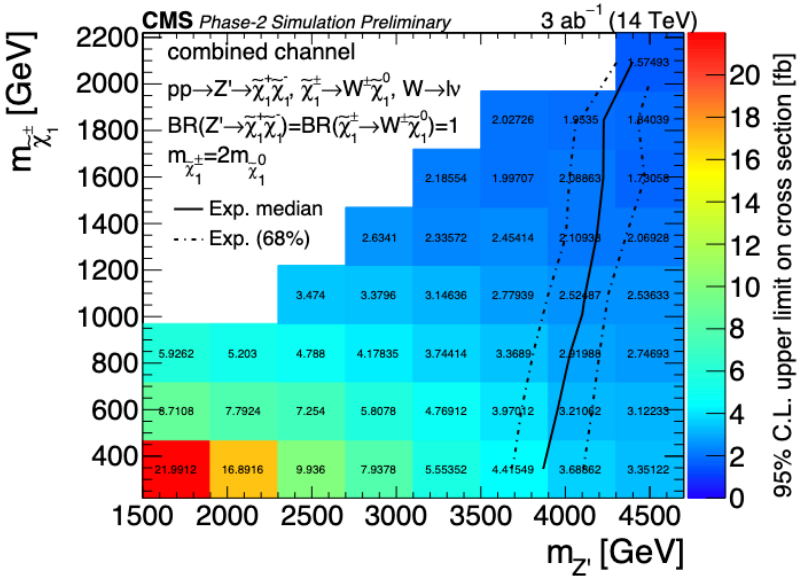
Search for leptophobic Z' resonances

Search for leptophobic Z' decaying to two charginos, subsequently decaying to leptonically decaying Ws and neutralinos.



- Final states : ee, μμ, eμ + E_T^{miss}
  ⟹ Select events with opposite-charged leptons and E_T^{miss} > 80 GeV
- ML method used for Signal extraction.
- Input variables exploiting the resonance nature of the Z'.

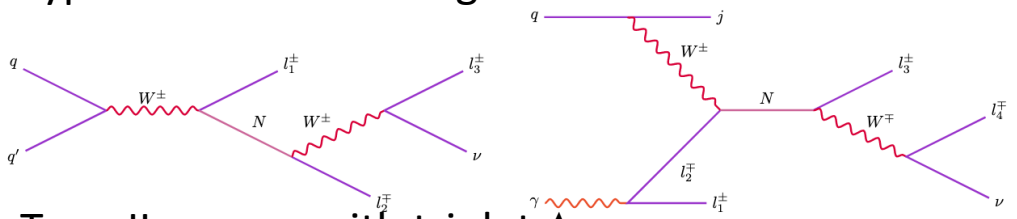




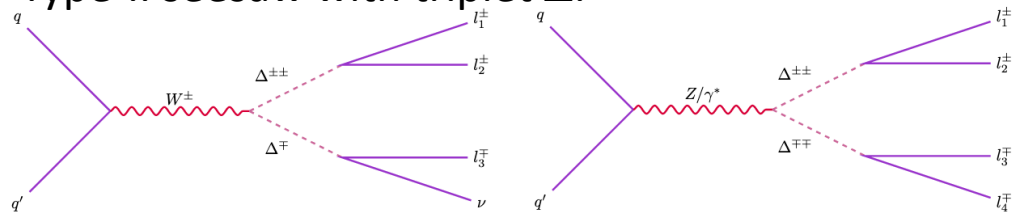
Seesaw model searches

FTR-22-003

Type-I seesaw with singlet N:

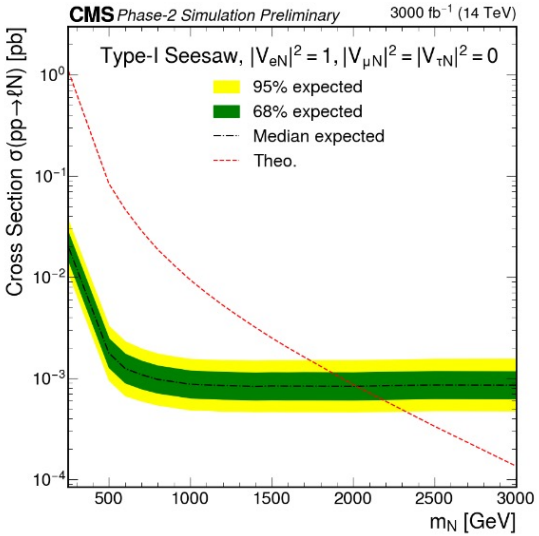


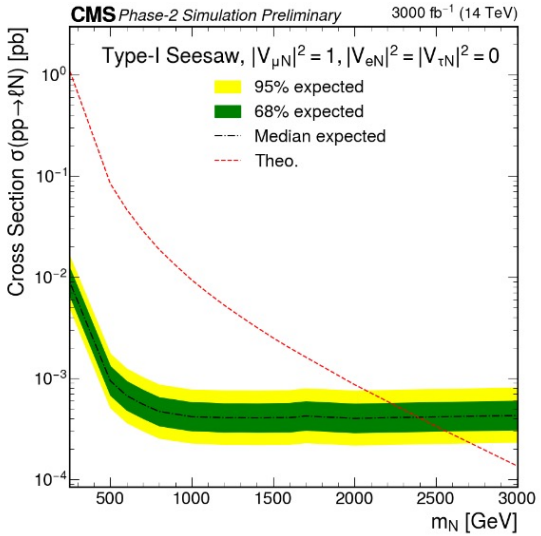
Type-II seesaw with triplet Δ:



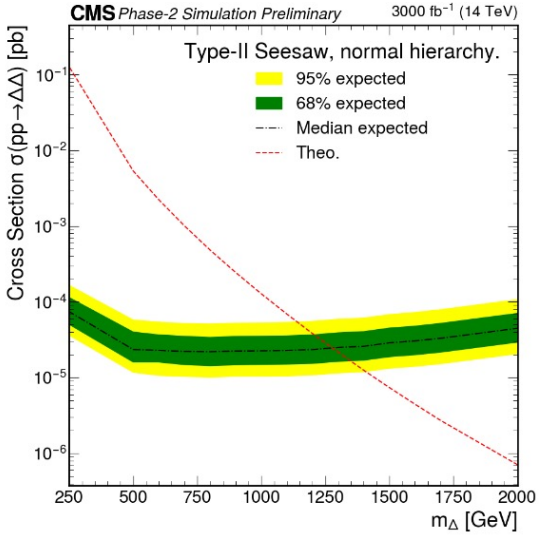
Search for Type-I and Type-II seesaw models (explaining neutrino masses).

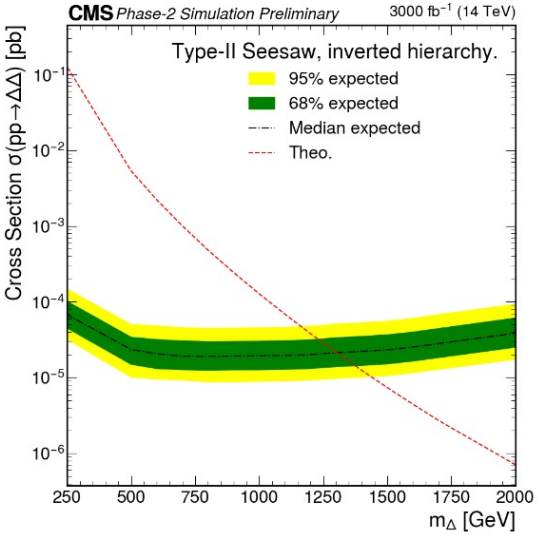
- Final states : Exactly 3 or 4 leptons.
- Discriminating variables: $L_T = \Sigma p_T^l$, $\min(m_{ll})$
- Signal region : 87 bins of lepton flavor, L_T, $\max(m_{ll})$.





Type-I seesaw





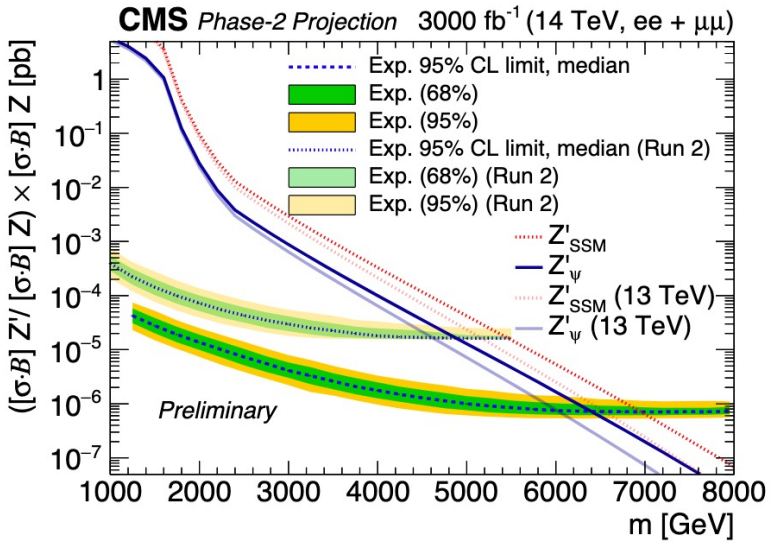
Type-II seesaw

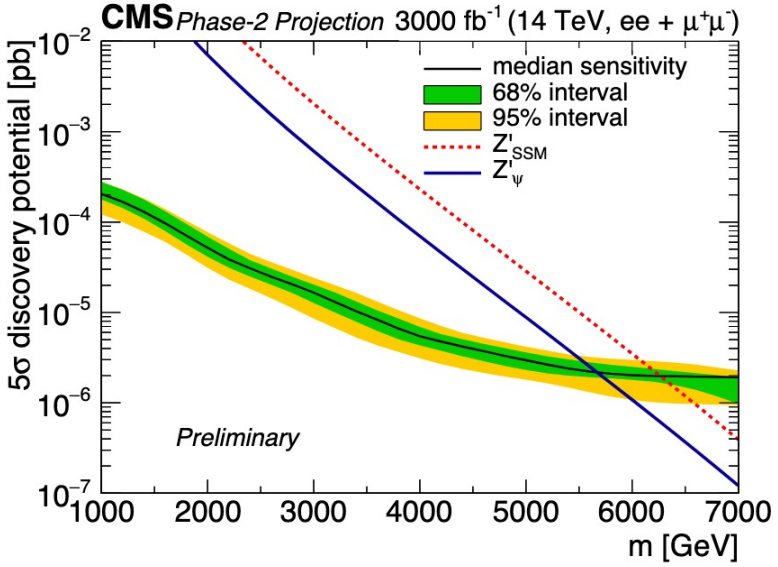
FTR-21-005

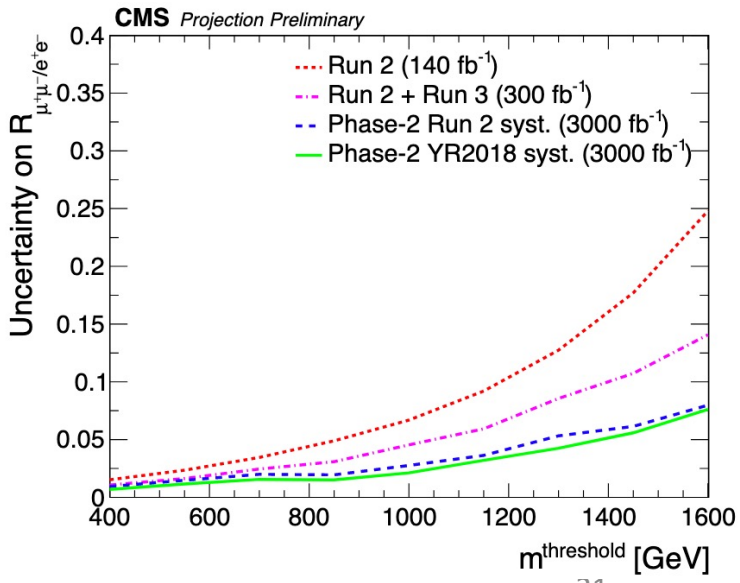
High mass dilepton resonances

Search for high mass ee and μμ resonances & test of lepton flavor universality (LFU).

- LFU violation via measurement of cross section ratio $R_{\mu^+\mu^-/e^+e^-}$ for the DY process.
- Using a Delphes simulation, the effects of acceptance adjustments on signal and BG yields were assessed.







Conclusion

- **HL-LHC will bring new challenges**
- **Comprehensive set of upgrades in progress for CMS at HL-LHC**
- **CMS encourages exploring all the exciting physics which is enabled by the upgraded detector with multiple ab^{-1} of data from HL-LHC.**
- **Presented the most up-to-date studies from the CMS Collaborations concerning the physics program for the HL-LHC.**

Thank you