Recent High Luminosity LHC (HL-LHC) projections from CMS

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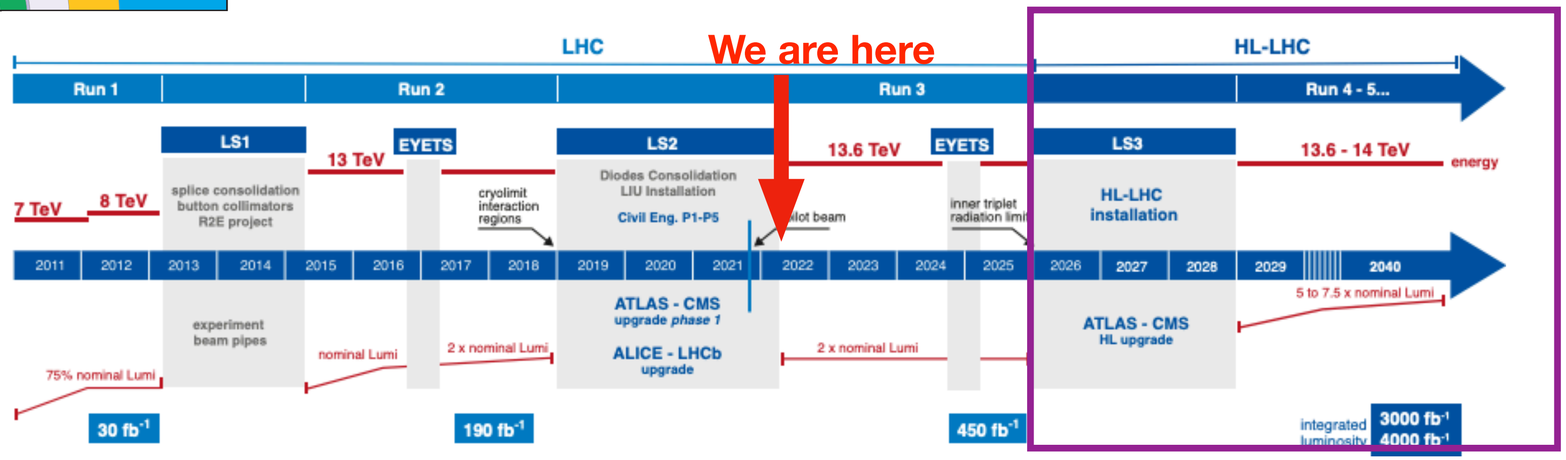
June 27, 2022 to July 2, 2022

University of Ioannina (GR)

HL-LHC planning and physics studies at CMS



18 new studies by CMS for Snowmass White Paper + 3 recently got public

Focus of studies:

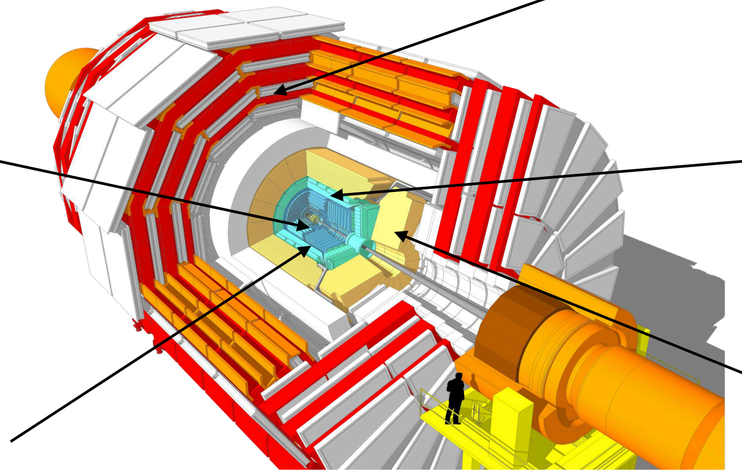
- HL-LHC: 14 TeV, 3000 fb^{-1}.
- Exploit upgraded CMS detector.

- Higgs prospects cover Higgs boson properties and couplings, BSM higgs physics
- SM prospects include EWK precision physics, QCD and strong interactions, Heavy flavor and top quark physics
- New Physics incorporate Model-specific explorations, general explorations and Dark matter at colliders

L1-Trigger/HLT/DAQ:
Tracks, machine learning in L1/HLT/DAQ

Muon system:
New readout, new GEM/RPC, Extended coverage

Tracker:
Increased granularity, extended coverage
P_T module design



Calorimeter Barrel:
ECAL/HCAL new back-end boards.

MIP Timing detector :
30-40 ps time resolution

Calorimeter Endcap:
3D showering topology

CMS Analysis approach and Systematics

CMS Analysis Approach:

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

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%

Higgs Physics

Higgs mass and width measurement

Projection in the H → ZZ → 4l and H → γγ channels from Run-2

Phase-2 Higgs mass:

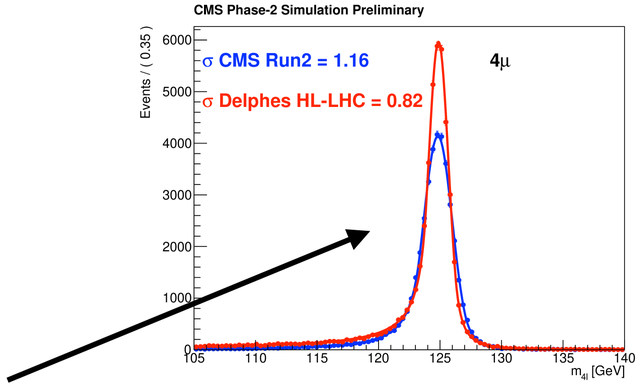
125.38 ± 0.022$^{(stat)}$ ± 0.02$^{(sys)}$ GeV (68%) **~Order of magnitude** improvement in **H → ZZ → 4l**

125.38 ± 0.07 (± 0.02 stat) GeV Improvement by **x3** in **H → γγ**

Dominant Uncertainties associated with mass resolution and lepton identification.

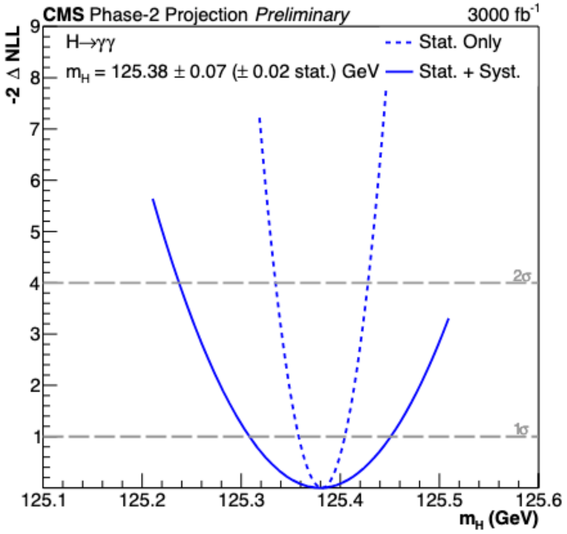
Expected ±1σ uncertainties on mass measurement in ZZ decay mode

	Mass uncertainty (MeV)				
	Combined	4μ	4e	2e2μ	2μ2e
Stat. uncertainty	22	28	83	51	59
Syst. uncertainty	20	15	189	94	95
Total	30	32	206	107	112



Completely driven by 4μ channel, thanks to improved mass resolution (25%) and extended coverage (~7%), statistical uncertainty is expected to improve.

Likelihood scan of the expected m_H (H → γγ)



Width: **Γ_H < 0.09 (0.18) GeV** at 68% (95%) CL **>x4** improvement n **H → ZZ → 4l**

FTR-21-007

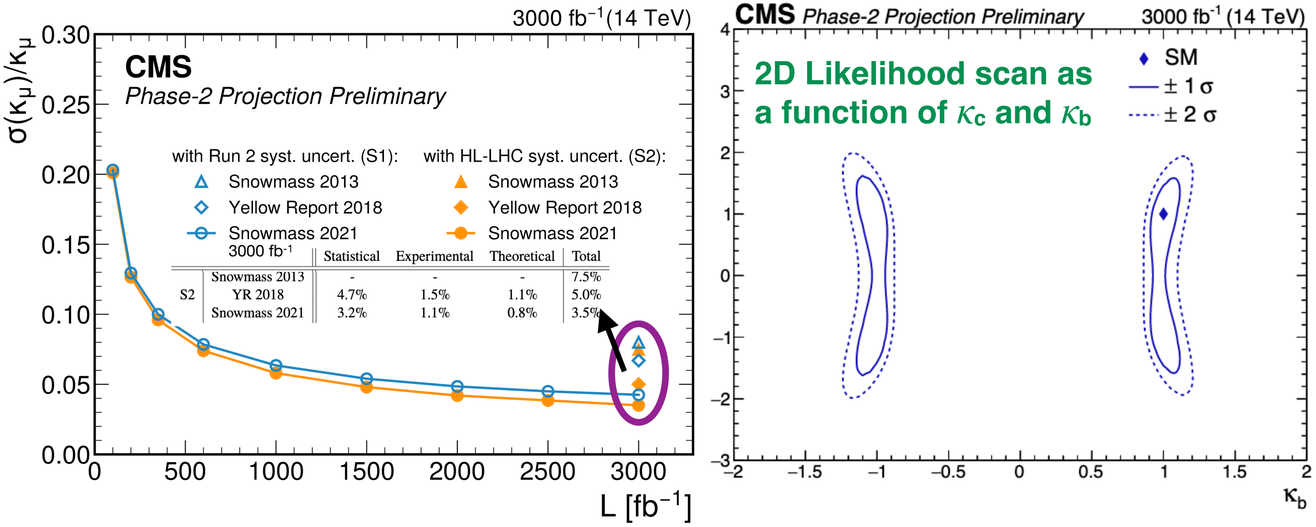
FTR-21-008

Higgs Coupling measurements

HIG-21-008
FTR-21-002
FTR-21-006
FTR-21-009

Projection in H → μμ (ggF+VBF) and VH(H → cc) channels from Run-2

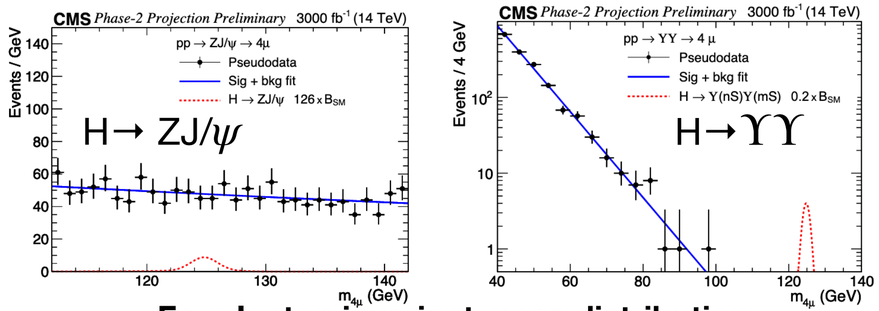
First evidence in H → μμ with full Run 2 significance of 3(2.5)σ obs (exp)



Uncertainty in Coupling modifier κ_μ vs. luminosity

- Largest impact from improvement in dimuon mass resolution after Phase-II tracker upgrade.
- VH challenging due to the small branching fraction, c-quark identification in hadronic environment and very large multi-jet QCD background. Powerful merged jet analysis

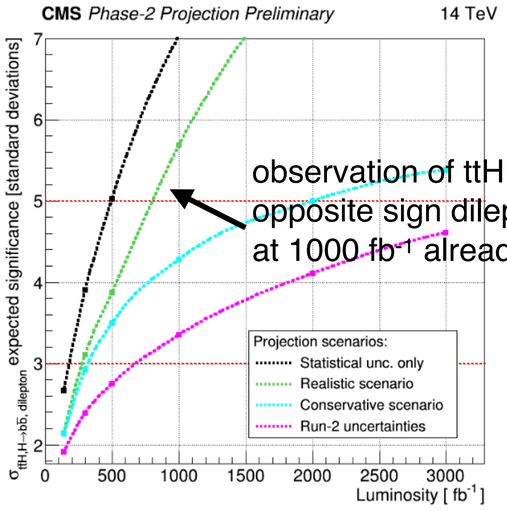
Projection in Two rare decays of Higgs to mesons

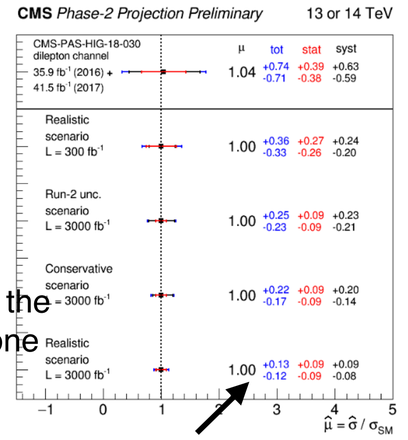


Four lepton invariant mass distribution

Expected gain in upper limit >x6 in ZJ/ψ and >x27 in $\Upsilon\Upsilon$ channel

Projection of Higgs boson coupling ttH(→bb) channel





Measurement with 12% total uncertainty on the signal cross-section, translating to similar level of precision in measuring top-Higgs coupling y_t

Sensitivity to the CP structure of H-τ Yukawa coupling

13 TeV Projection based on Run-2

CP nature of the H → ττ coupling is described by the effective mixing angle $\alpha^{H\tau\tau}$

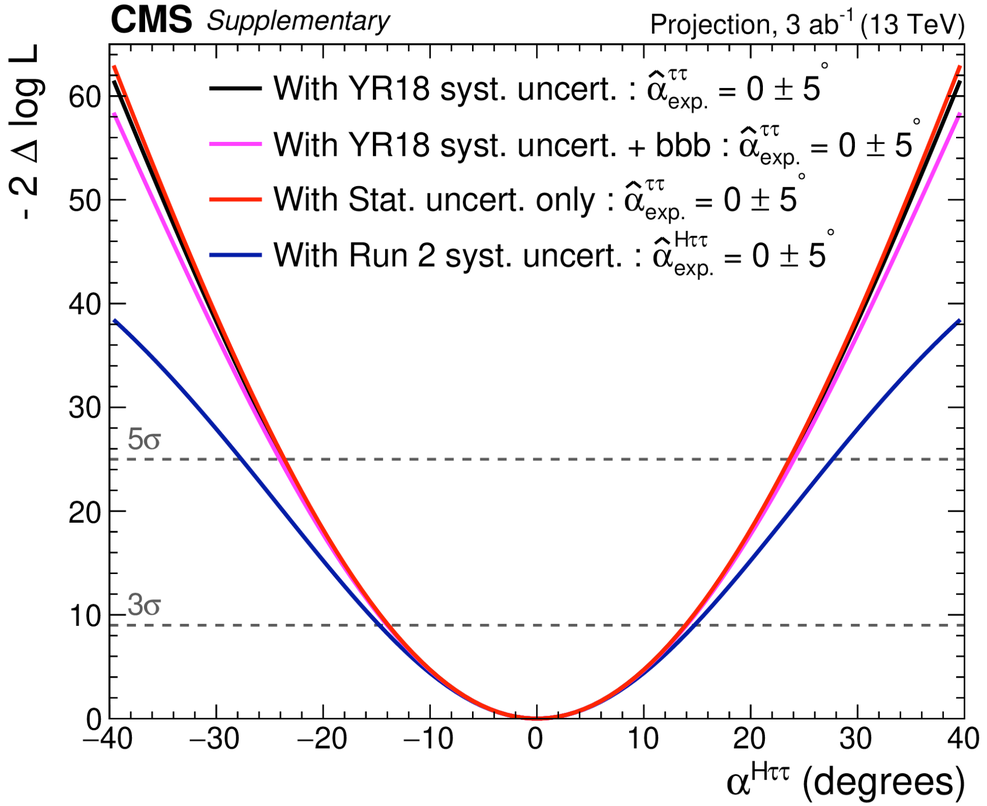
$\alpha^{H\tau\tau}$ = 0 (90)° corresponds to a pure scalar (pseudoscalar) coupling

Any intermediate value indicates a mixed coupling - implying CP violation

Phase-2 expectation:
$\alpha^{H\tau\tau}$ = 0 ± 5° at 68% CL.

(sensitivities to larger $\alpha^{H\tau\tau}$ are different due to effects of systematics.)

~x4 improvement wrt Run 2 observation:
$\alpha^{H\tau\tau}$ = -1 ± 19° (± 41°) at 68% (95%) CL

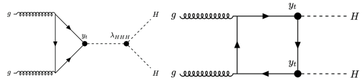


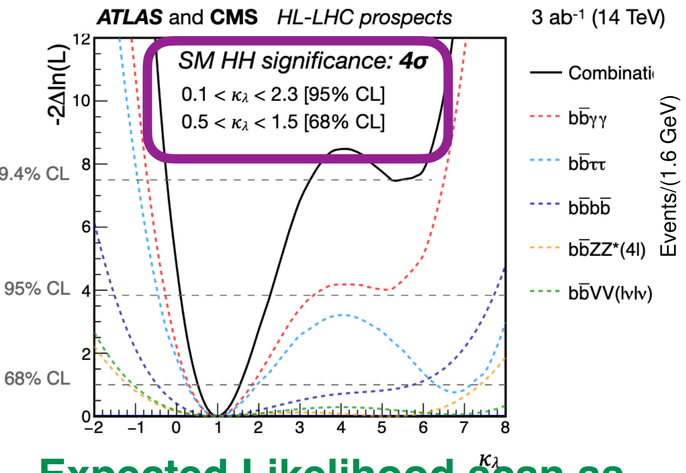
Projections of the expected negative log-likelihood scans as a function of the CP mixing angle

HIG-20-006

HH production : Benchmark for HL-LHC

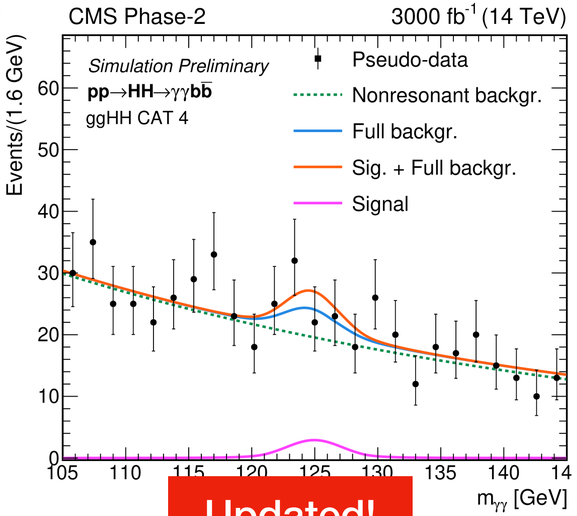
Delphes based analysis





Expected Likelihood scan as a function of κ_λ (λ_{hhh} / λ_{hhh}^{SM})

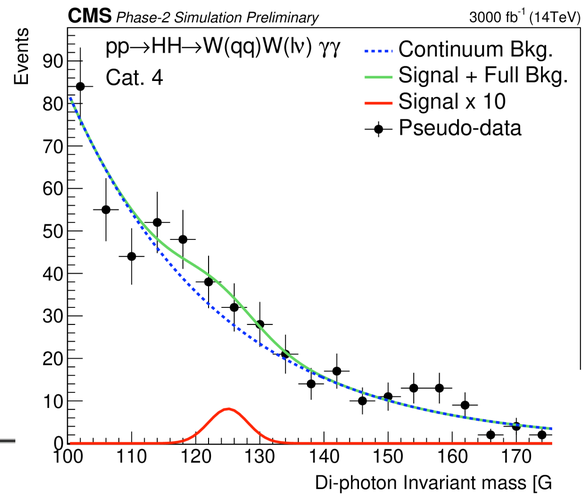
Updated results on HH → bbγγ



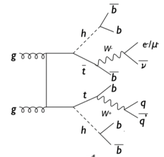
Updated!

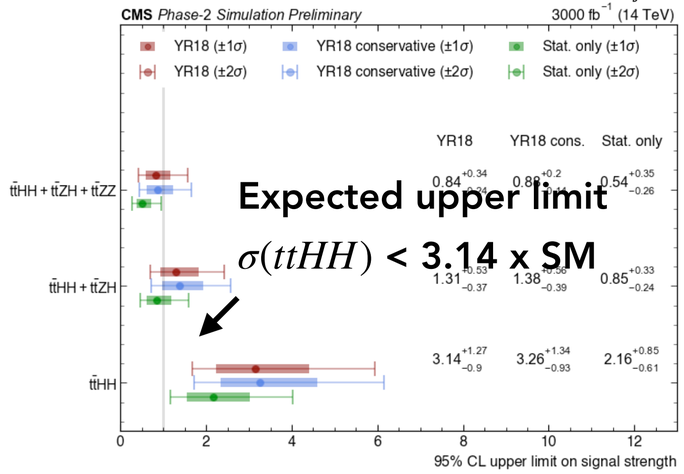
Channel	Significance	
	Stat. + syst.	Stat. only
bbbb	0.95	1.2
bbττ	1.4	1.6
bbWW(ℓνℓν)	0.56	0.59
bbγγ	~~1.8~~ 2.16 σ	~~1.8~~
bbZZ(ℓℓℓℓ)	0.37	0.37
$WW\gamma\gamma + \tau\tau\gamma\gamma$	0.22 σ	

Explored WWγγ, ττγγ channels



Search for ttHH in SM

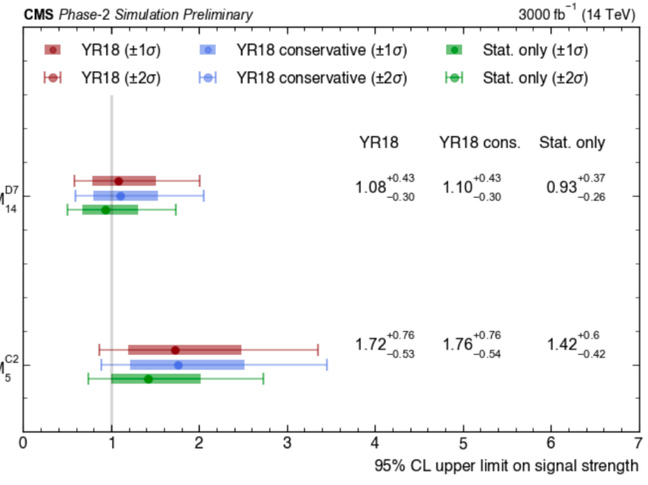




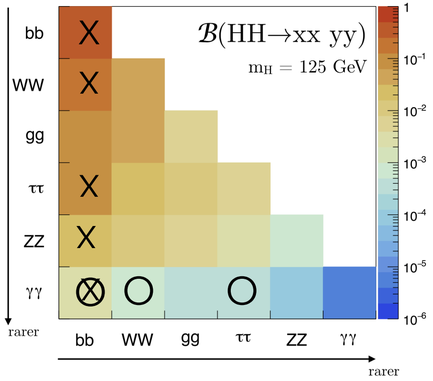
Expected upper limit

$\sigma(ttHH) < 3.14 \times SM$

ttHH in Minimal composite Higgs Model (MCHM)



X: explored in the YR
O: explored in the WP



Combination foreseen for snowmass report

FTR-21-003

FTR-21-004

FTR-21-010

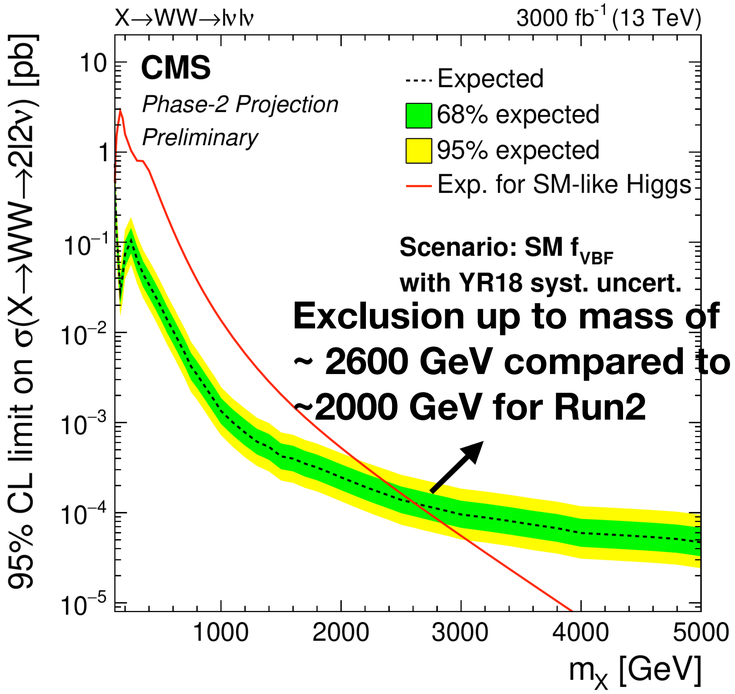
Snowmass White Paper

Higgs as portal to new physics

HIG-20-016
FTR-22-006
FTR-22-005

13 TeV Projection of high mass resonance to W+W- with dileptons from Run-2

Model-independent limits on σ x BR of a new resonance.

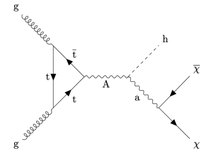


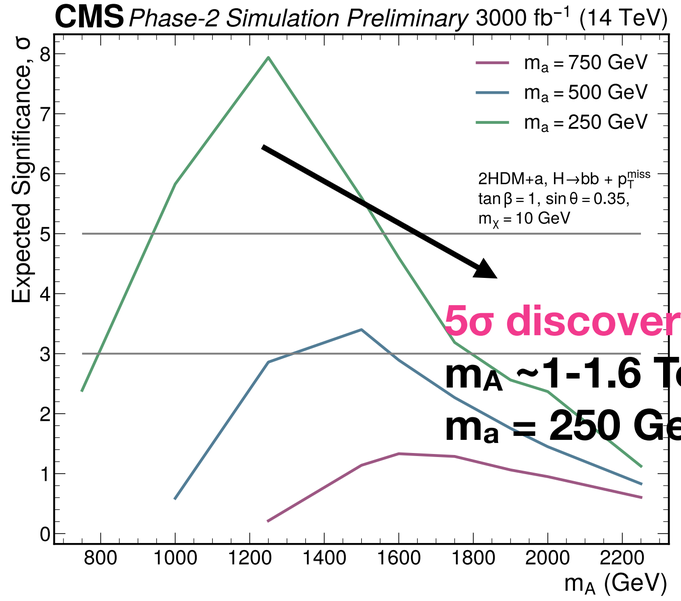
Exclusion up to mass of ~ 2600 GeV compared to ~2000 GeV for Run2

Assumes ggF & VBF contribution of same order as expected from a SM-like Higgs at high mass.

Delphes based Search for boosted mono Higgs, with h → bb + dark matter

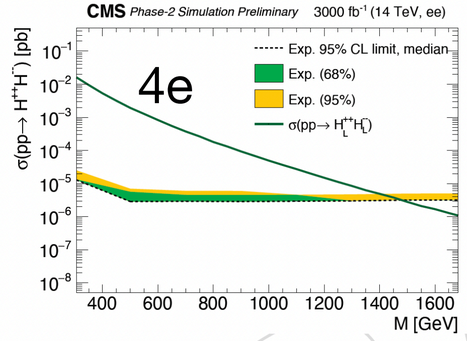
Interpretation in terms of a Type-II 2HDM+a model: tanβ = 1, sinθ = 0.35

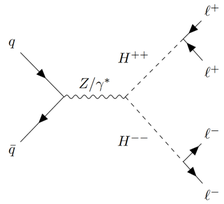


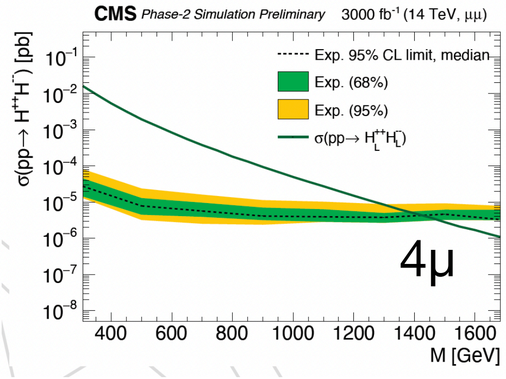


5σ discovery for m_A ~1-1.6 TeV, m_a = 250 GeV.

H±± Delphes based search in 4 same flavor leptons final state







Mass Limits of 1400 GeV for $H_L^{\pm\pm}$ pair production cross section in a left-right symmetric model for decays to 4e or 4μ.

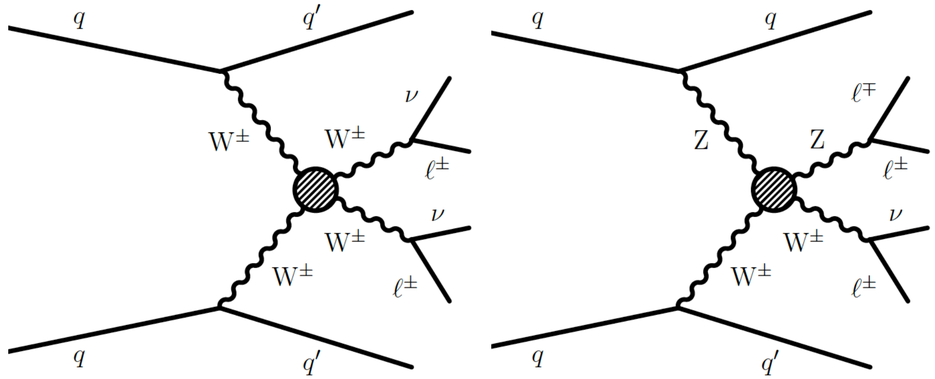
Standard Model Prospects

Vector boson scattering (VBS) in leptonic WW and WZ

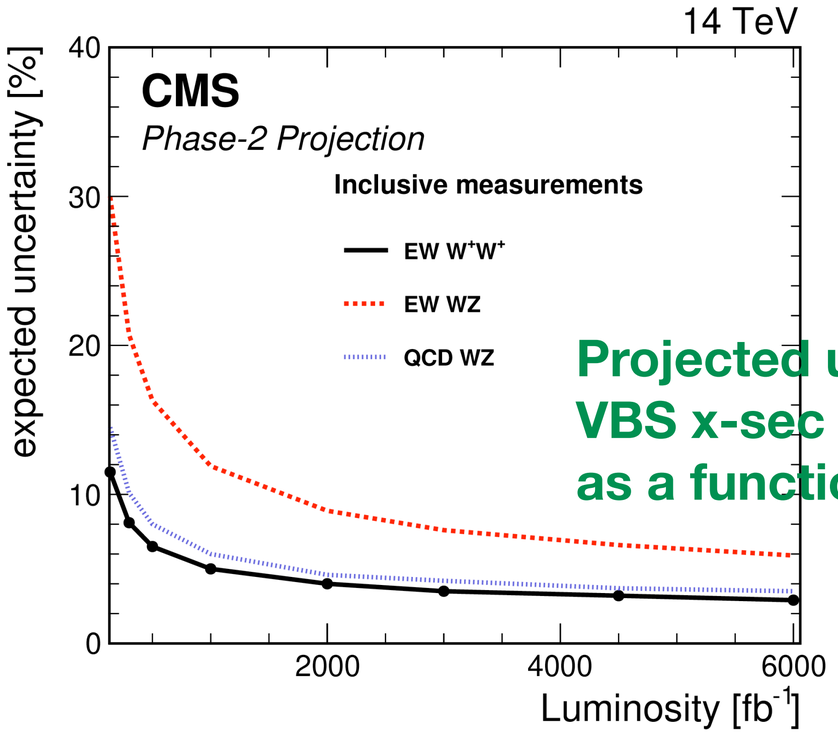
Projection based on Run-2

VBS - Important tool to probe EWSB mechanism and is sensitive to BSM.

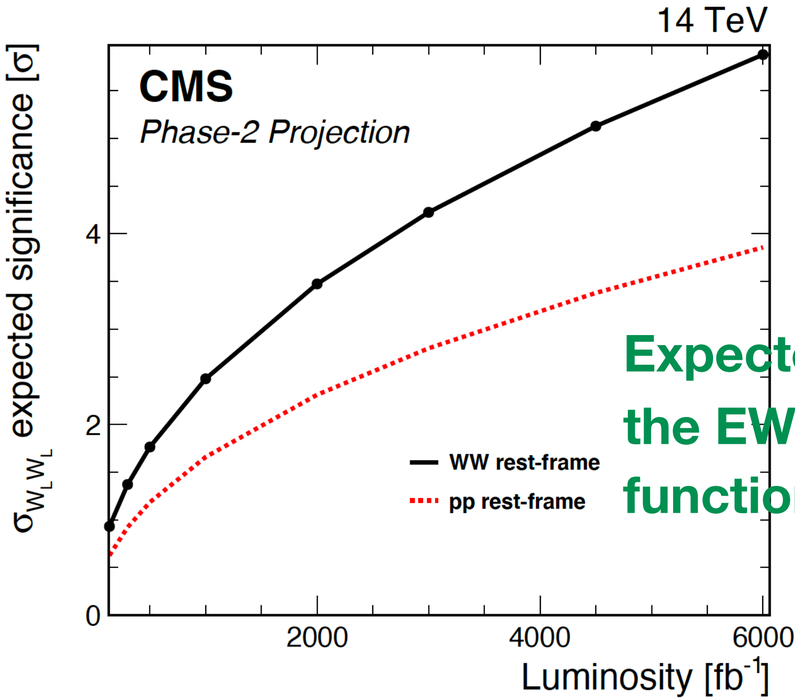
Explored sensitivity to VBS cross section and polarization.
2 same-sign leptons (WW) or 3 leptons (WZ) with total charge 1.



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



Projected uncertainty in VBS x-sec measurements as a function of luminosity



Expected significance for the EW $W_L^{\pm}W_L^{\pm}$ as a function of luminosity

FTR-21-001

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

HIN-21-009

Projection of the Run 2 search for $\gamma\gamma \rightarrow \tau^+\tau^-$ with 1 muon + 3 charged particles.

Ultra-peripheral heavy ion collisions: No hadronic interaction between the ions.
$\Longrightarrow$ Clean environment to study $\gamma\gamma$-induced processes.

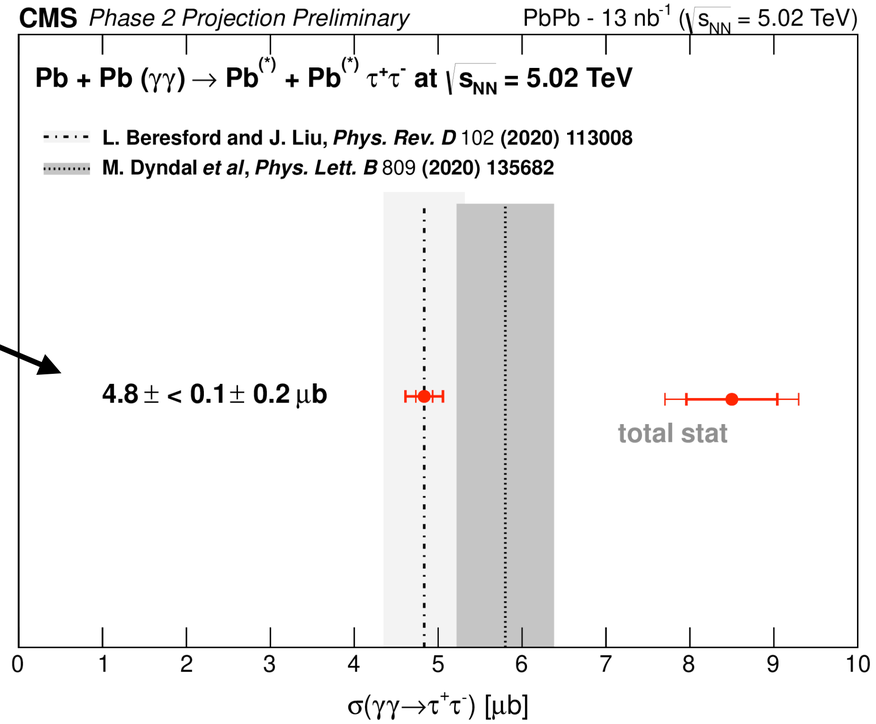
- $\gamma\gamma \rightarrow \tau^+\tau^-$ sensitive to BSM $\Longrightarrow$ improved constraints on $(g-2)_\tau$
- 13 nb^{-1} PbPb luminosity, sqrt(S_{NN}) = 5.02 TeV.

Phase-2 expected $\gamma\gamma \rightarrow \tau^+\tau^-$ 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



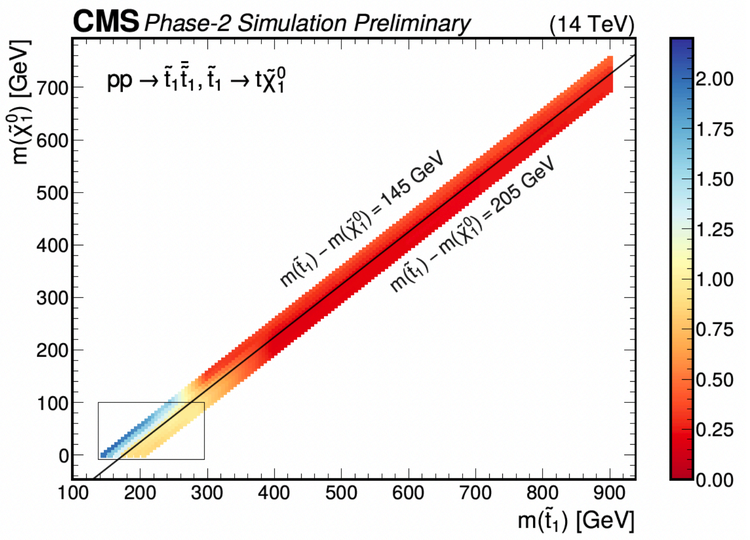
Top quark spin correlations

FTR-18-034

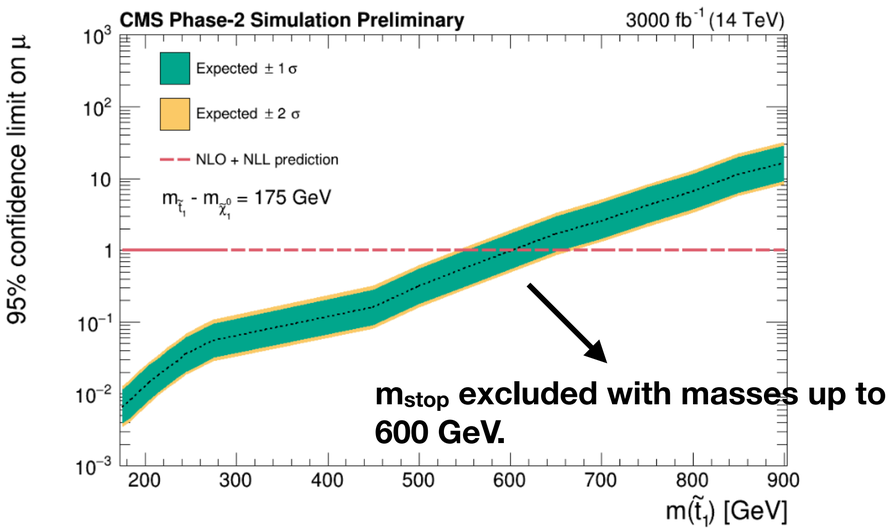
Projection analysis of precision measurement of the strength of expected $t\bar{t}$ spin correlation in eμ + ≥ 2 jets + ≥ 1 b-jet final state.

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

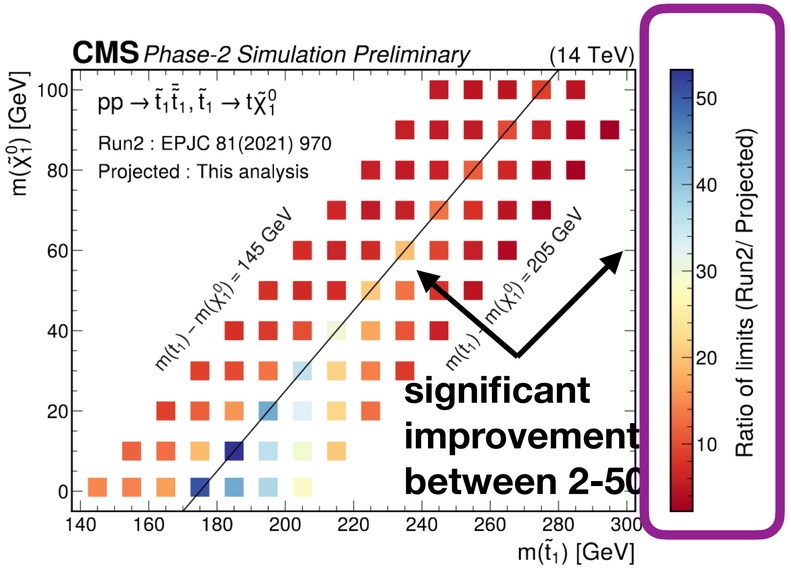
Delphes based search of top squarks in the "top corridor" using spin corr. variables in a DNN



Phase-2 exclusion limits on the stop-stop cross section in stop-neutralino mass plane.



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

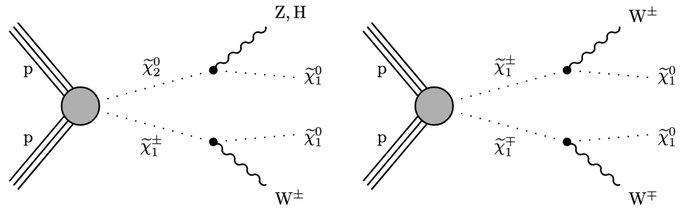


Ratio of Run 2/Phase-2 expected exclusion limits on cross section.

Beyond Standard Model Prospects

Hadronic EW SUSY Search

Projection based on Run-2

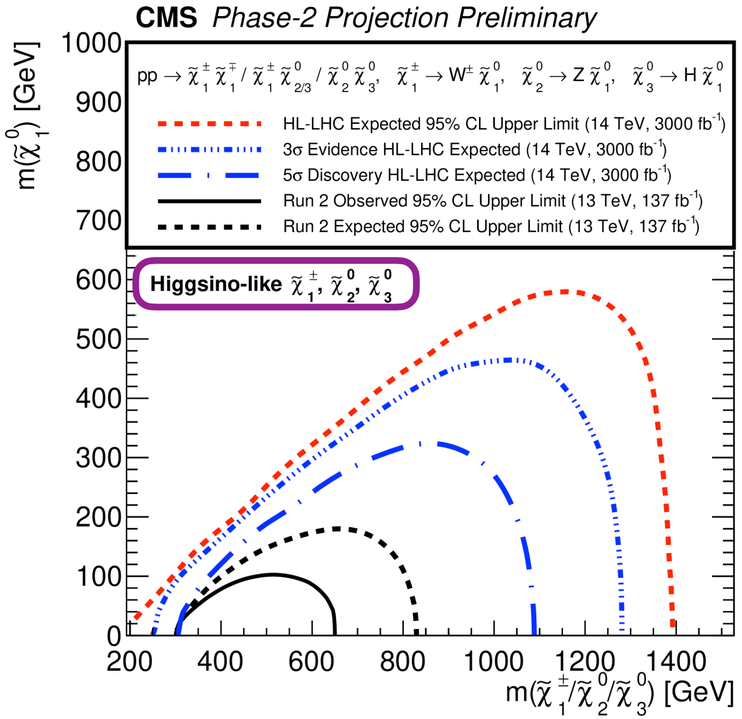


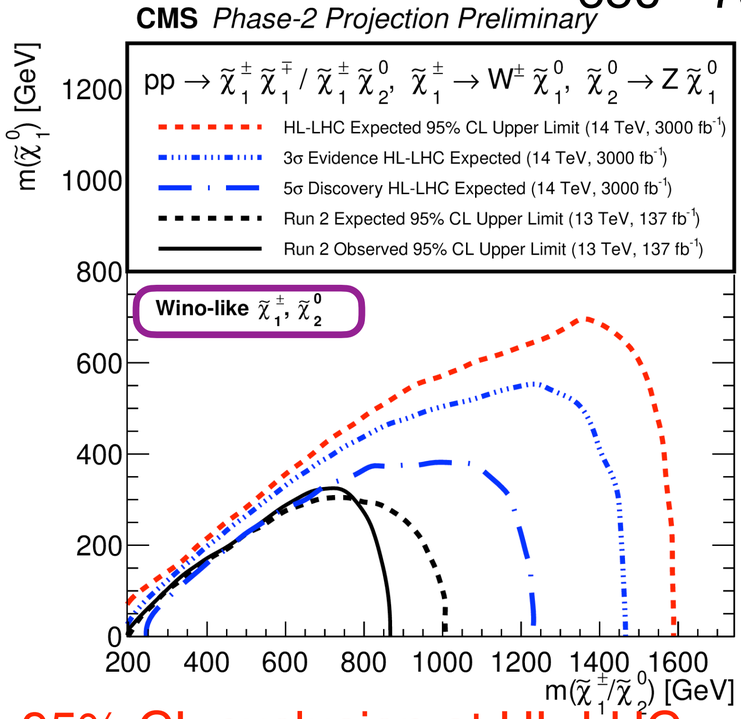
Search for EW-produced chargino / neutralino decaying to boosted hadronic W/Z/H + LSP

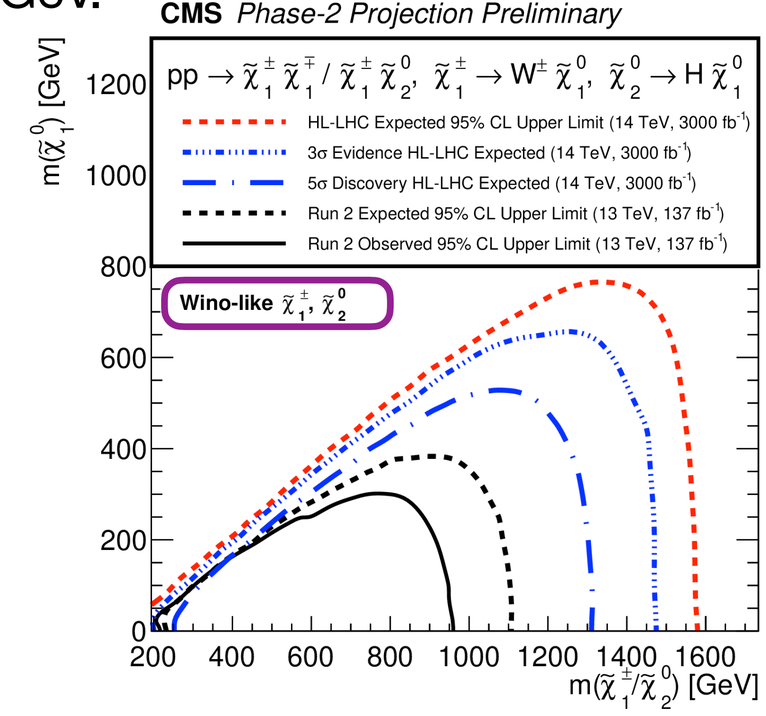
- **Final states**: WW, WH, WZ, ZH + E_T^{miss} > 200 GeV.
  $\Longrightarrow$ 2 AK8 jets with pT > 200 GeV and W/Z/H tagging.

Interpretion done 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.







95% CL exclusion at HL-LHC

SUS-21-002

Stop search with 2 tops + multijets

SUS-19-002

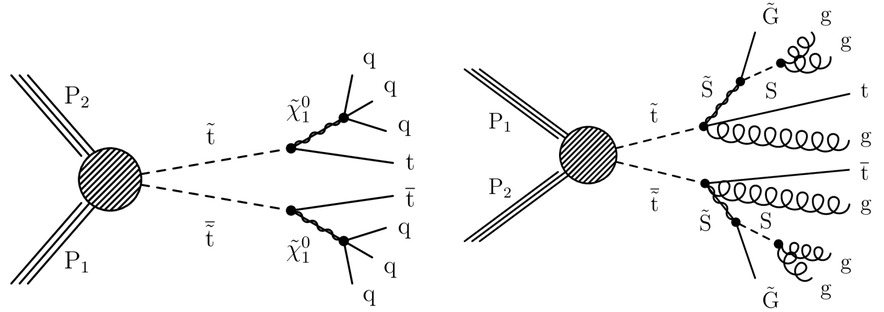
13 TeV Projection based on Run-2

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

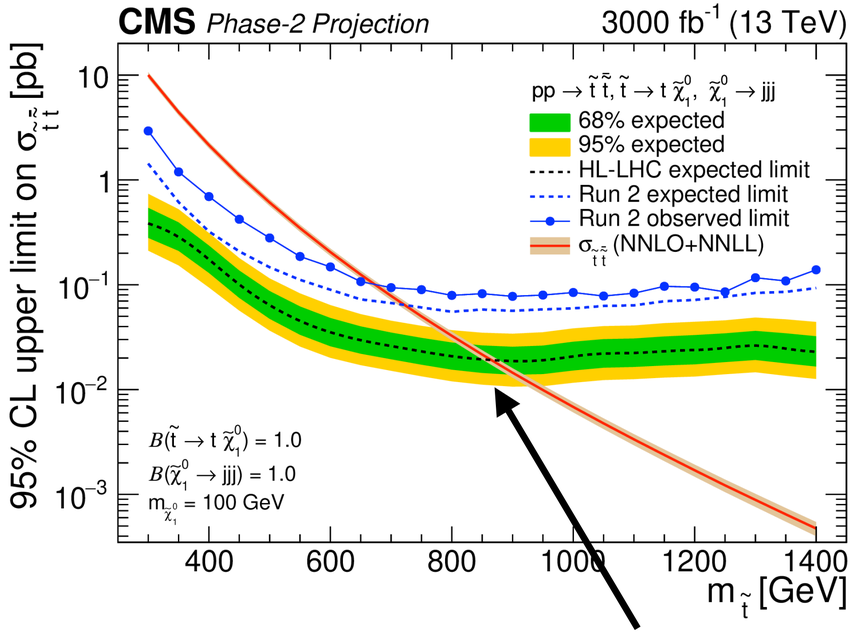
- **Final states:** 2 tops + additional jets

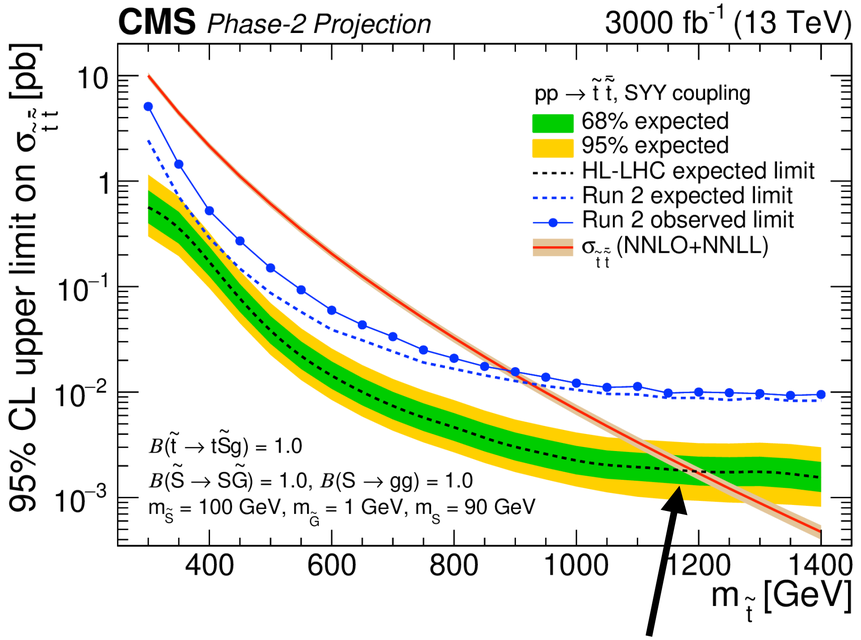
  $\Longrightarrow$ 1 lepton + ≥7 jets (no E_T^{miss})

- Binary classifier neural networks to discriminate signal from background



RPV Stealth





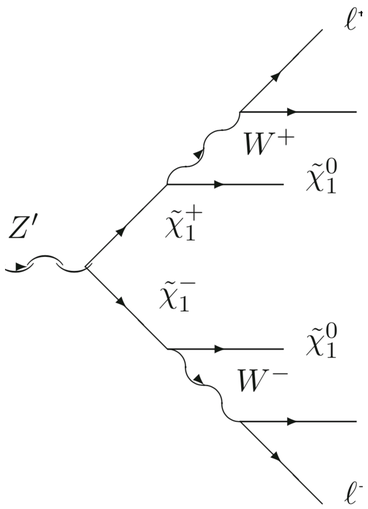
RPV: 670 GeV (Run 2) → 870 GeV (Phase-2)

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

Leptophobic Z’ to charginos

FTR-21-011

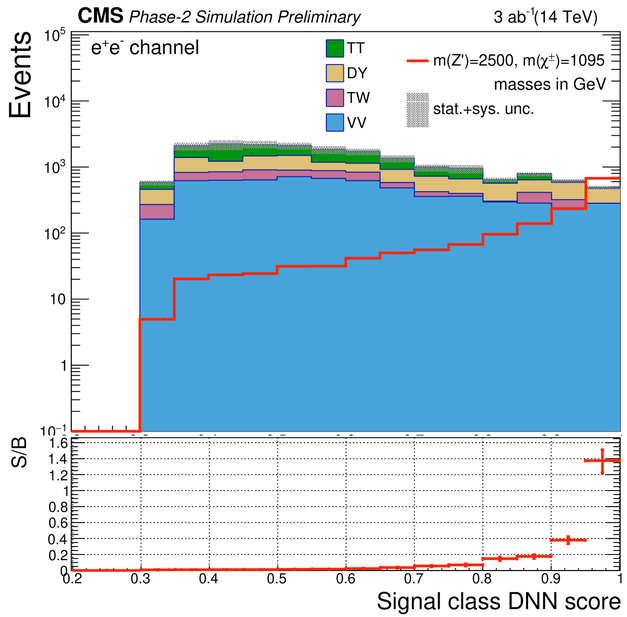
Delphes based analysis



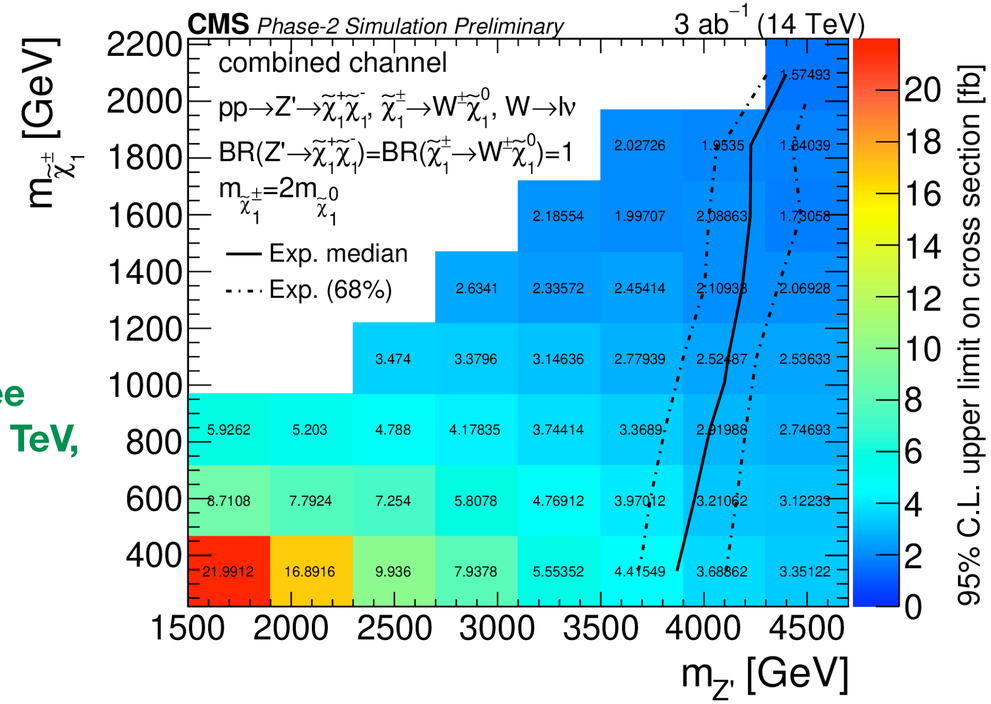
Search for leptophobic Z’ decaying to two charginos, subsequently decaying to leptonically decaying Ws and neutralinos.

- **Final states** : ee, μμ, eμ + E_T^{miss}

  $\Longrightarrow$ Select events with opposite-charged leptons and E_T^{miss} > 80 GeV
- Signal extraction via Deep Neural Networks.
  - Input variables exploiting the resonance nature of the Z’.



DNN score trained in ee final state for $m_{Z'}$ = 2.5 TeV, $m_{\tilde{\chi}_1}^{\pm}$ =1.095 TeV



Phase-2 upper limits for Z’ production xsection

Exclusion of Z’ with mass up to 4.5 TeV.

Seesaw model searches with multileptons

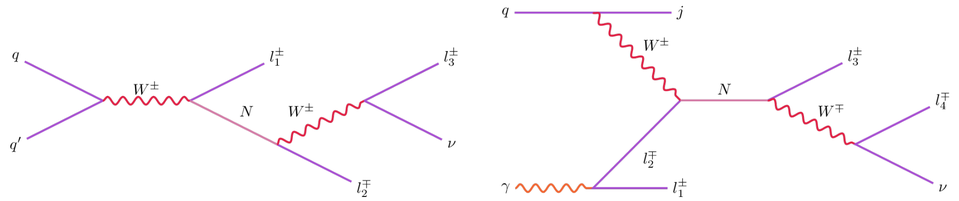
FTR-22-003

Delphes based analysis

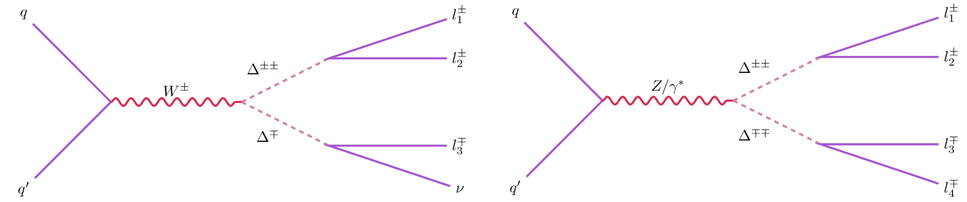
Search for Type-I and Type-II seesaw models (explaining neutrino masses).

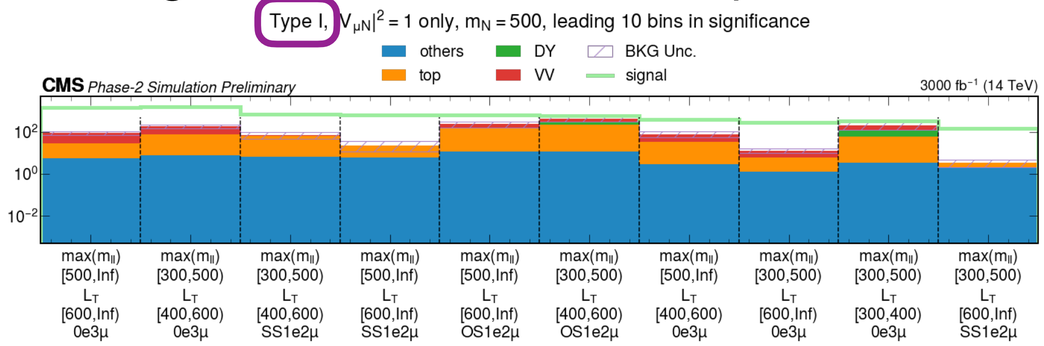
- **Final states** : Exactly 3 or 4 leptons.
- Discriminating variables: $L_T = \Sigma p_T^l$, min(m_{ll})
- Signal region : 87 bins of lepton flavor, L_T, max(m_{ll}).

Type-I seesaw with singlet N:

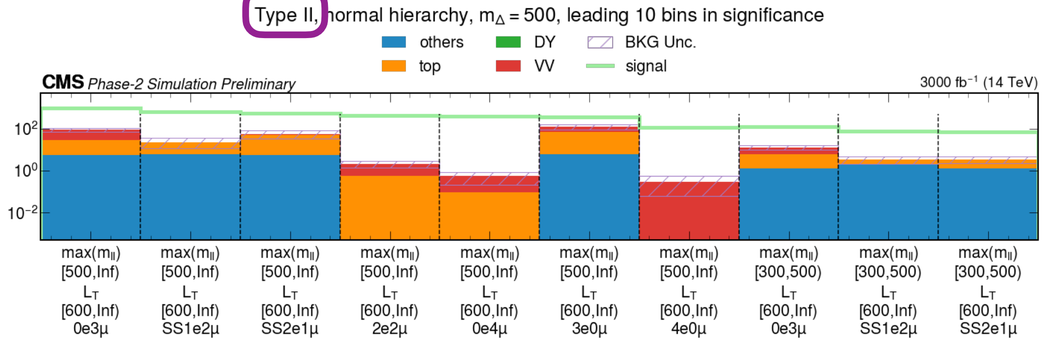


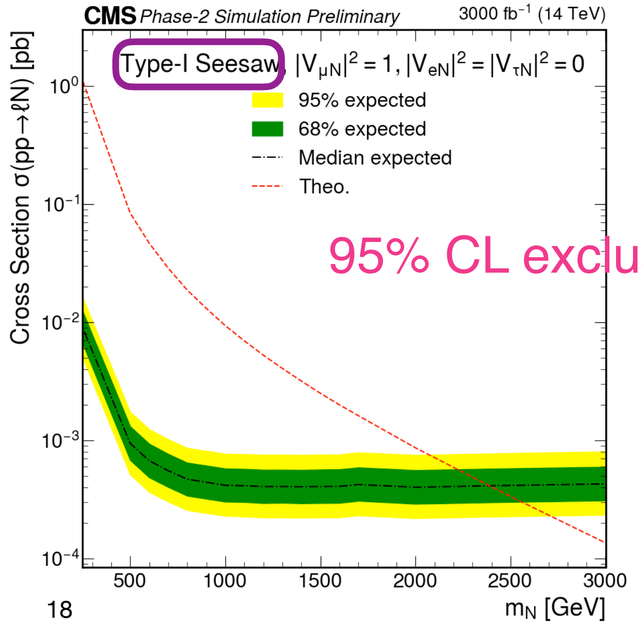
Type-II seesaw with triplet Δ:



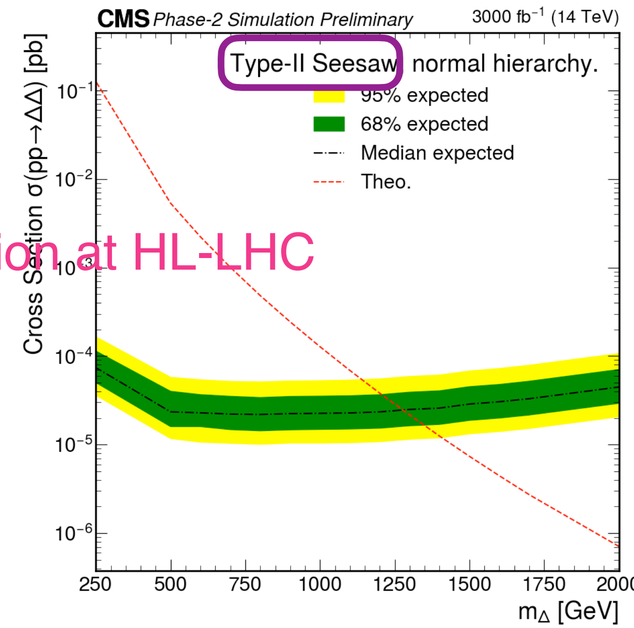


Signal and background distributions in most sensitive 10 bins





95% CL exclusion at HL-LHC



Dilepton high mass resonances

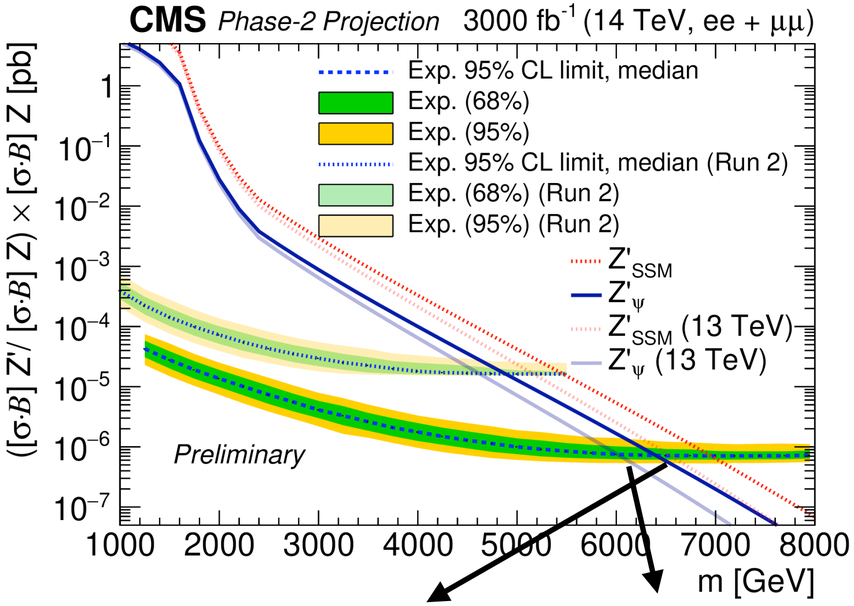
FTR-21-005

Projection based on Run-2

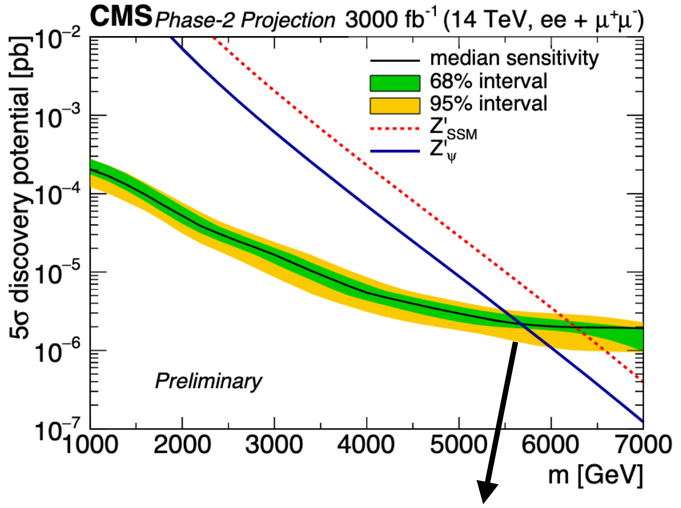
Search for high mass ee and μμ resonances & test of lepton flavor universality (LFU)

- LFU violation via measurement of cross section ratio $R_{\mu^+\mu^-/e^+e^-}$ for the DY process.

Exclusion limits on a spin-1 Z' resonance vs. mass.



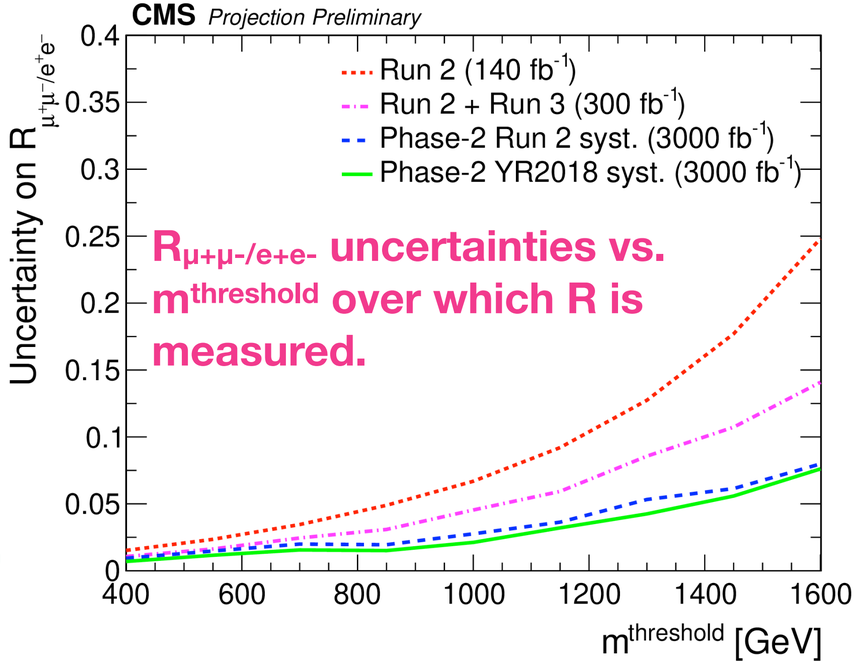
Dataset	Exp. limit (Z'_{SSM}) [TeV]	Exp. limit (Z'_{ψ}) [TeV]
Phase-2	6.83	6.28
Run 2	5.14	4.55



Discovery sensitivity showing Z' with masses upto these values can be discovered at HL-LHC

$$m_{Z'}(SSM) = 6.27 \text{ TeV}$$

$$m_{Z'}(\psi) = 5.72 \text{ TeV}$$



$R_{\mu^+\mu^-/e^+e^-}$ uncertainties vs. $m^{threshold}$ over which R is measured.

x5 improvement wrt. Run 2.

Summary & the future of future physics

- HL-LHC offers a BIG opportunity for measurements and searches in all the sectors.
- Studies for the Yellow Report and White Paper covered a substantial part of the HL-LHC physics phase space.
- CMS encourages exploring new ideas, in particular final states only accessible at HL-LHC and studies exploiting detector features and upgrades.

Stay Tuned!!