Future Physics with ATLAS and CMS at the HL-LHC

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On behalf of ATLAS and CMS
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Michigan State University

Snowmass and ATLAS + CMS physics

Snowmass 2021: https://snowmass21.org/

- Particle physics community planning exercise: A scientific study bringing together the particle physics community to identify and document a scientific vision for the future of particle physics in the US and its international partners.

- The P5 (Particle Physics Project Prioritization Panel) takes the scientific input and develops a 10-year strategic plan.
- Organized in 10 frontiers: Energy, Neutrino, Rare processes & precision, Cosmic, Theory, Accelerator, Instrumentation, Computational, Underground facilities, Community engagement.
- Scientific results presented as white paper contributions (link)

ATLAS & CMS jointly contributed to the Energy Frontier

- White paper contribution: “Physics with the Phase-2 ATLAS and CMS Detectors” FTR-22-001, ATLAS-PHYS-PUB-2022-018, 17 March 2022.

Snowmass White Paper Contribution: ATLAS & CMS

Contents

WP organized in sections of frontier subtopics. Each section has:

- Summary of earlier results (mainly from the 2018-19 Yellow Reports (YRs) for the ESG).
- 1-page summaries of new results.

HL-LHC physics studies at ATLAS + CMS

ATLAS+CMS White Paper contents:

- 18 new studies by CMS: 12 new FTR PASes + 6 approved within Run2 analyses.
  - 3 more FTR PASes approved after WP,
- 7 new results by ATLAS.

Focus of studies:

- HL-LHC: 14 TeV, 3000 fb^{-1}.
- Focus on new channels not (easily) accessible with the current data.
- Exploit enhanced detectors and coverage.

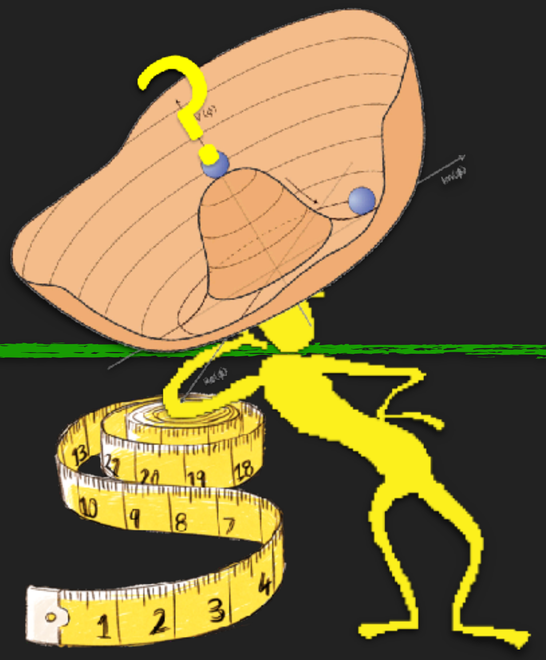
Different methods to establish sensitivity:

- Projection from a present analysis: Use existing samples, scale results to cross section and higher luminosity for different systematics scenarios. —> ATLAS and CMS
- New analysis design: Use events with dedicated Phase-2 parametrized detector simulation **`DELPHES`**. —> only CMS.

Uncertainties treatment — different options used:

- Run 2 systematics: Use Run 2 values
- “YR18” systematics: A set of reduced uncertainties anticipated for Phase-2.
- Statistical-only uncertainties: The ultimately optimistic scenario with no systematics.
- Other analysis-specific scenarios.

Higgs prospects

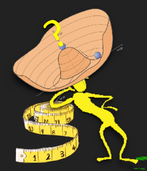


Contributions to:

- EF01: Higgs boson properties and couplings
- EF02: Higgs boson as a portal to new physics

Plenary talk on Friday morning “Higgs Physics at HL-LHC” by Michaela Mlynarikova.

I will only give a few example teaser here.



CMS-PAS-FTR-21-007 (Simulation-assisted projection from CMS-HIG-19-001 and CMS-HIG-16-041)

EF01: Higgs mass and on-shell width from H → ZZ /γγ , H → μμ

Evaluate impact of detector Phase-2 upgrade on signal modeling and acceptance (**DELPHES** simulation)

- Improved tracker lower material budget, Precision of HGCAL, PU suppress by MTD, Muon extend $|\eta| < 2.8$

Higgs mass and on-shell width results, by scaling X-section and luminosity from Run 2.

H → ZZ → 4l: Improved uncertainties associated with mass resolution and lepton ID.

H → γγ: Reduced photon E scale systematic (more accurate ECAL calibration, Improved method to measure and correct the non-linear discrepancies in E(γ) scale.)

	Mass (GeV)		Width	
	Run 2	Phase II	Run 2	Phase II
H → ZZ → 4l	125.38 ± 0.20$^{(stat)}$ ± 0.08$^{(sys)}$	**± 0.03$^{(stat)}$ ± 0.02$^{(sys)}$**	**0.41**	**0.09**
H → γγ	125.78 ± 0.26 GeV	**± 0.02$^{(stat)}$ ± 0.07$^{(sys)}$**		

H → μμ: Improved p_T resolution (tracker) ⟹ Improved mass resolution by 30% ,

Extended acceptance (sig 10%) . Increased X-sec (13 to 14 TeV)

⟹ Discovery 5σ with 400 /fb using **DELPHES** simulation

Projection from CMS-HIG-21-008 , ATLAS-CONF-2021-21

EF01: Projection of the VH(H → cc) search

- Difficult due to small X-sections, large QCD BGs, c-tagging in hadronic environments.
- Simultaneous measurement of VH(H → bb) and VH(H → cc).

CMS Run 2: $\mu_{VH(H->cc)}$: 14 ($7.6^{+3.4}_{-2.3}$) obs (exp)

new jet reco, merged jets, ML c-tagging

Event categories:

- MVA for 2 resolved jets.
- Substructure for “boosted” topology

Phase-2 Projection

- Use only the merged jet categories 3 cc + 3 bb

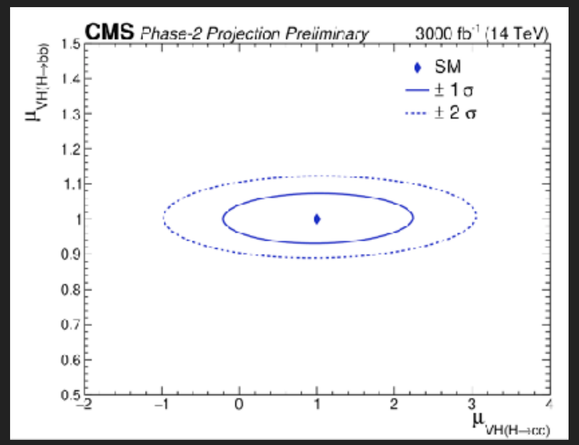
ATLAS Run 2: $\mu_{VH(H->cc)}$: 26 (31^{+12}_{-8}) obs (exp)

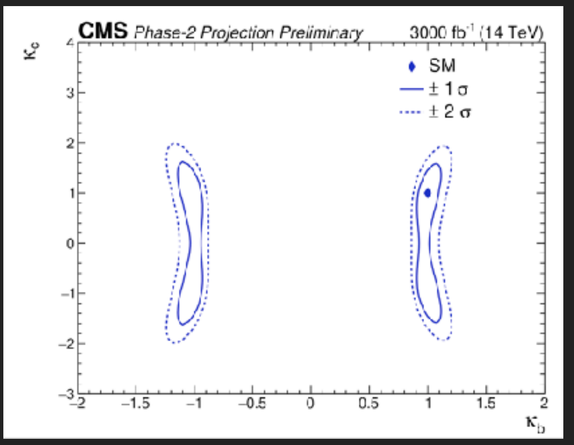
Event categories:

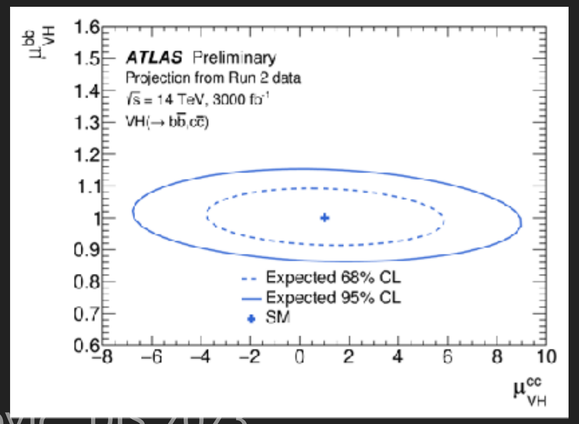
- V momentum, jet multiplicity,
- signal/control regions with BDT descriminant

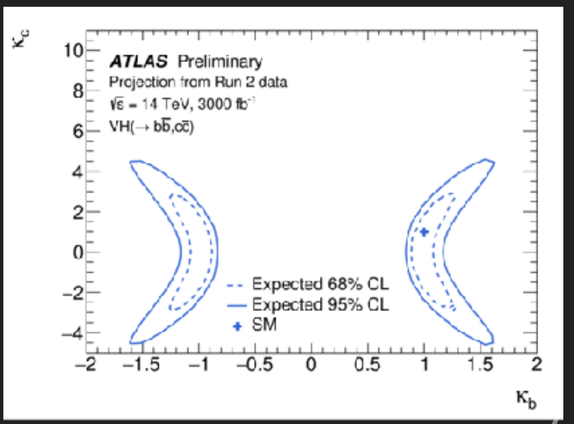
Phase-2 projection

2D profile likelihood scans of signal strength and coupling modifiers.







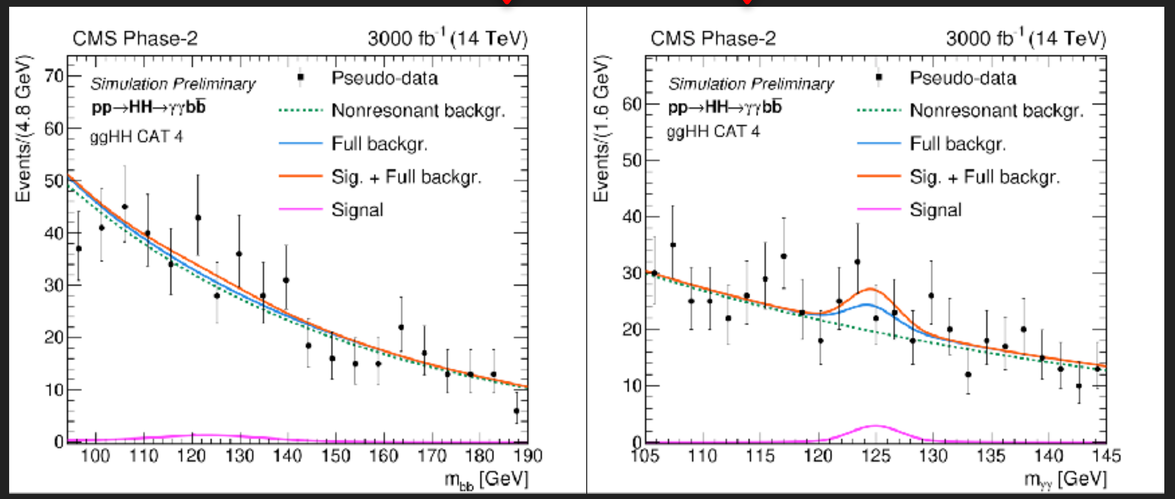


CMS-PAS-FTR-21-004, ATLAS-PHYS-PUB-2022-053)

EF01: HH → bbγγ and HH → bbττ

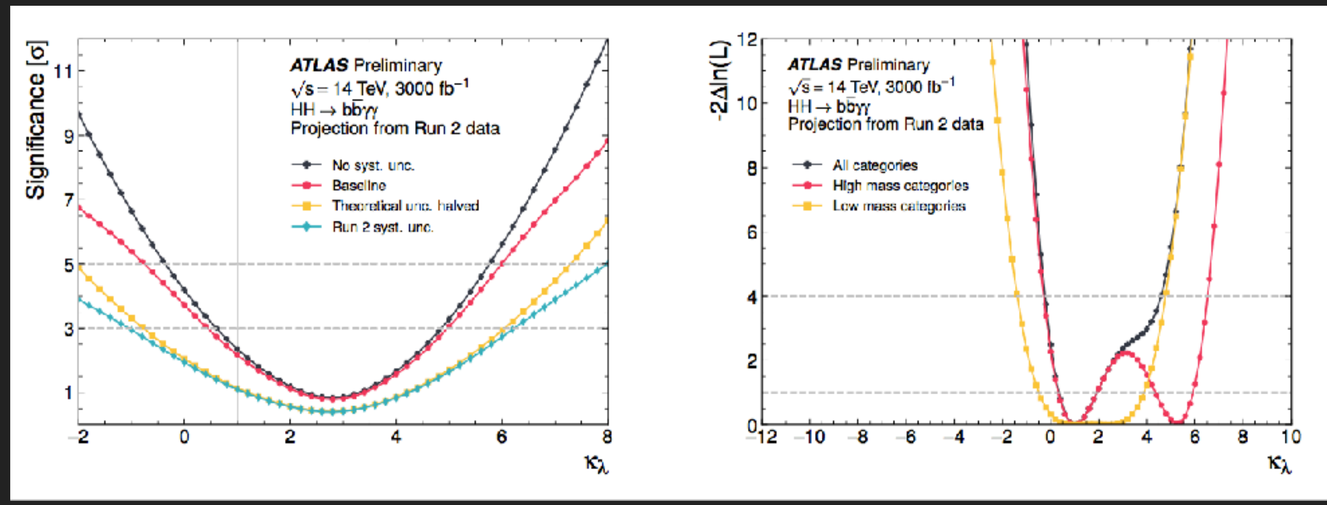
CMS: DELPHES studies of ggHH and VBFHH:

- DNNs for signal/bg discrimination in event selection.
- Signal significance extracted with a simultaneous fit to m_{bb} and $m_{\gamma\gamma}$ distributions.



ATLAS: Projections from Run2 results:

- Updated analysis (139 /fb)
- Modified mass
  $M_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$



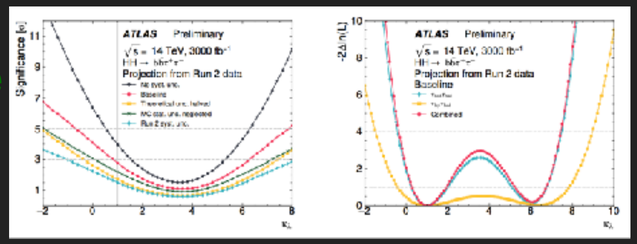
Phase-2 expected significance

HH → bbγγ : 2.16 σ. (for ggHH+VBFHH)

Phase-2 expected significance

HH → bbγγ : 2.2 σ.

Similarly **HH →bbττ : 2.8 σ**

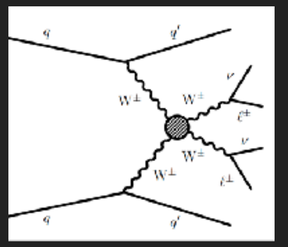


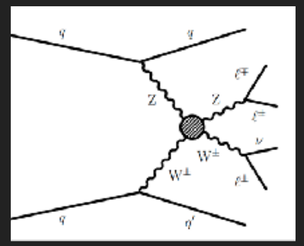
SM prospects

Contributions to:

- EF04: EW precision physics and constraining new physics
- EF07: QCD and strong interactions: Heavy ions
- EF03: Heavy flavor and top quark physics

EF04: VBS measurement in leptonic WW and WZ

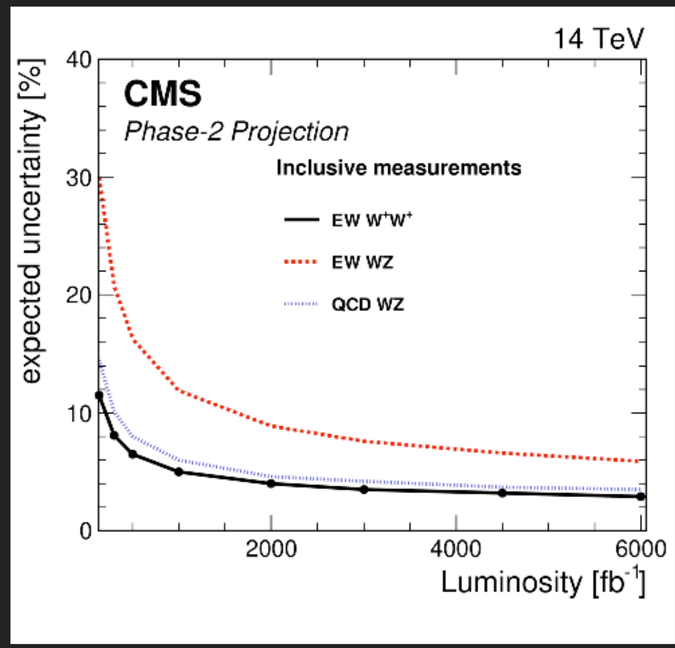




ATLAS (CMS) had first observations of several EW VBS with Run-2 data
- leptonic decays of VBS WW, WZ, ZZ.

Phase 2 projected sensitivity to VBS X-section and polarization.
with signatures: 2 same-charge leptons or 3 leptons with total charge 1.

- Simultaneous measurement of EW WW, EW WZ and QCD WZ production X-sections, with uncertainty **6%**(**3%**) and (**4%**)
  Benefit from large stats and forward acceptance of leptons and jets.

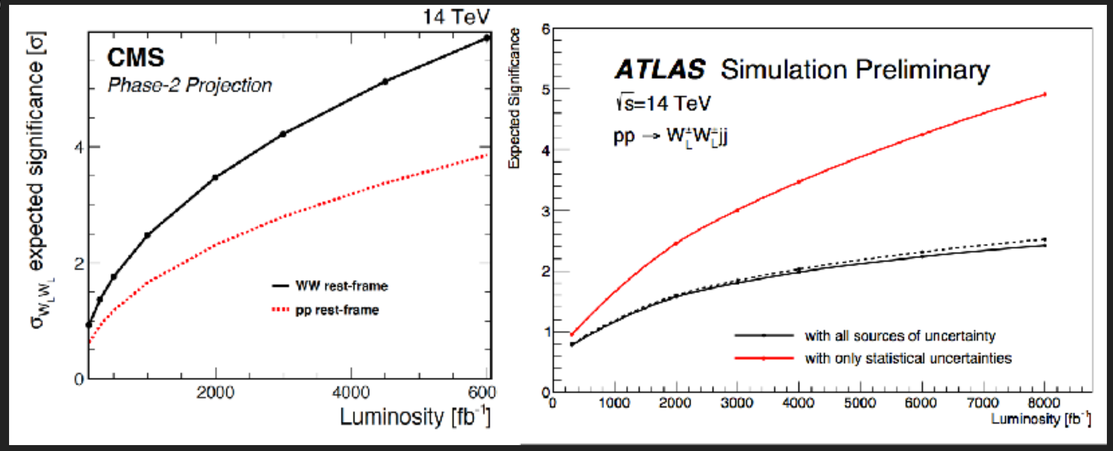


- Simultaneous measurement of longitudinal and transverse polarized components in the WW channel.
  - unitirized in SM, BSM?

Expected significance for the EW W_LW_L

1.8 σ (**2.7 σ**)

Small X-sec (7% of tot), challenge but important for ATLAS (CMS)



Projection from CMS-PAS-HIN-21-009 (Supplementary material to the PAS)

EF07: Measurement of $\gamma\gamma \rightarrow \tau^+\tau^-$

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

$\Longrightarrow$ Sensitive to BSM $\Longleftarrow$ improved constraints on $(g\text{-}2)_\tau$.

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

- 13 nb^{-1} PbPb luminosity, sqrt(S_{NN}) = 5.02 TeV.

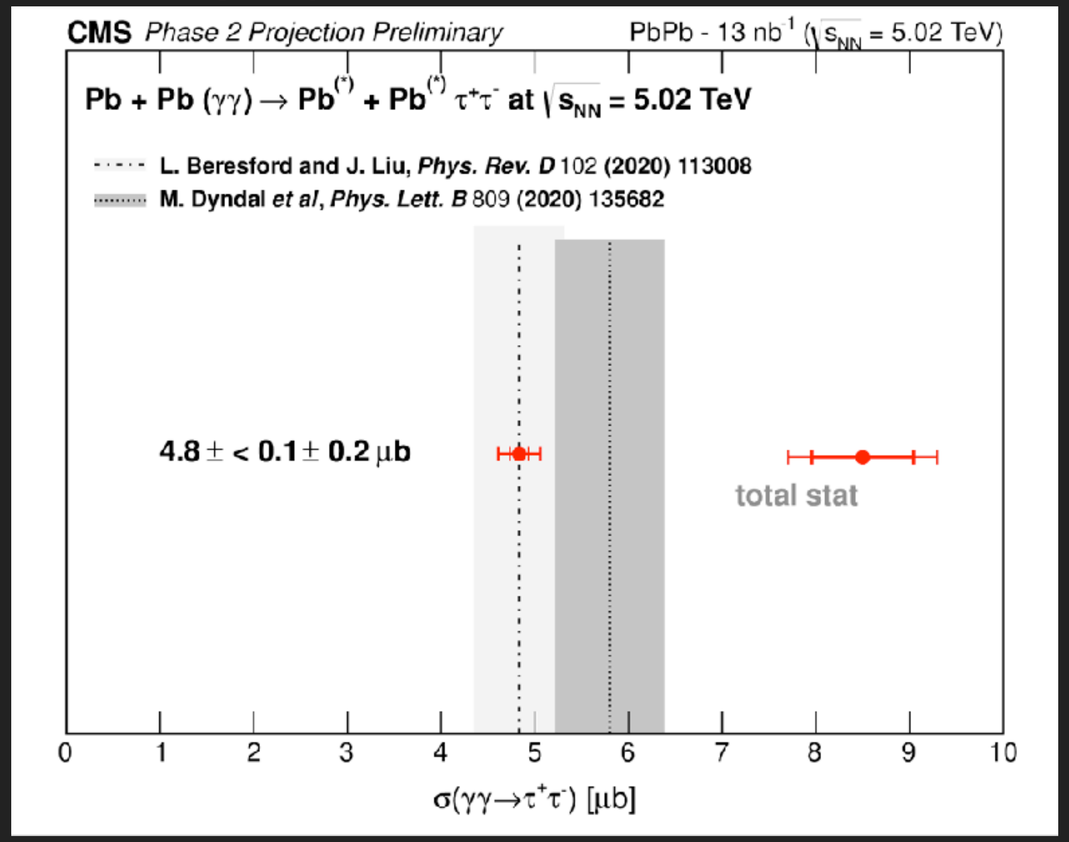
  Backgrounds (leptonic and hadronic)

  $\gamma\gamma \rightarrow l^+l^-$ supressed by track impact pararm for τ

  $\gamma\gamma \rightarrow qq^-$ estimated from data

Phase-2 expected $\gamma\gamma \rightarrow \tau^+\tau^-$ xsect. uncertainties:
4.8 **± < 0.1 ± 0.2 μb**. Total: **4%**

~x4 improvement wrt Run 2 prediction:
4.8 ± < 0.6 ± 0.5 μb.
Including more decay channels and improved analyses (e.g. shape analysis), precision on $(g\text{-}2)_\tau$ will surpass the existing measurements.



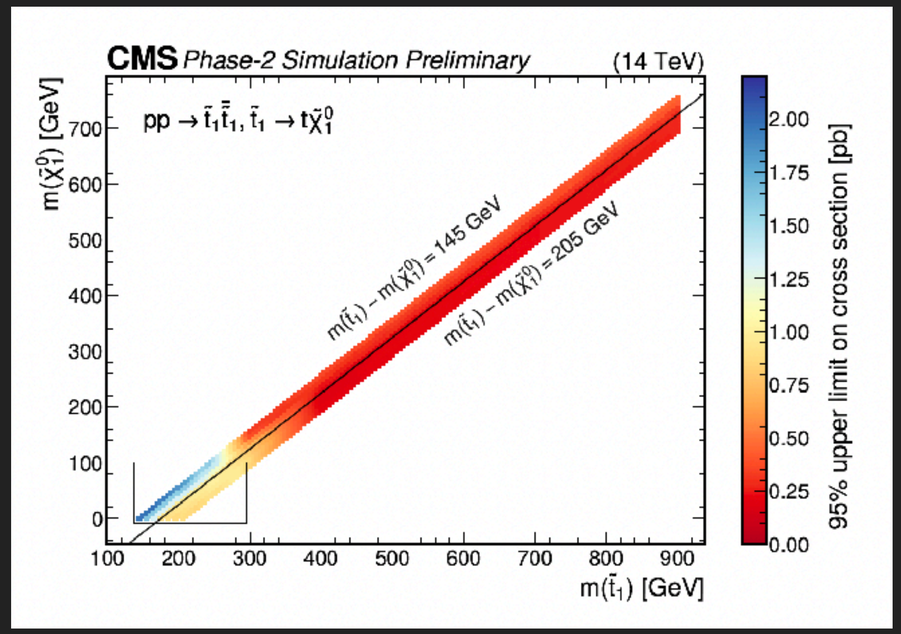
EF03: Top quark spin correlations (limit on SUSY) Not in WP, approved.

Project measurement of the top quark spin correlations with opposite charge eμ + ≥ 2 jets + ≥ 1 b-jet.

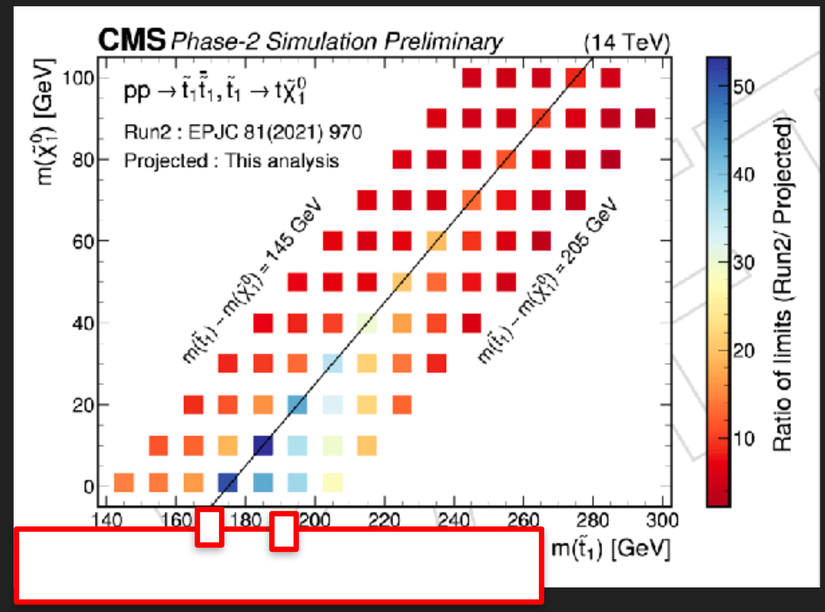
Spin correlation very sensitive to presence of **stop**.

$\Longrightarrow$ $\Delta\phi(l^+, l^-)$) the most accurate spin corr. observable with 3% precision (among 22 studied)

Use spin corr. variables in a DNN to search for top squarks in the "top corridor", $\Delta(m_{stop} - m_{LSP}) \sim m_{top}$.

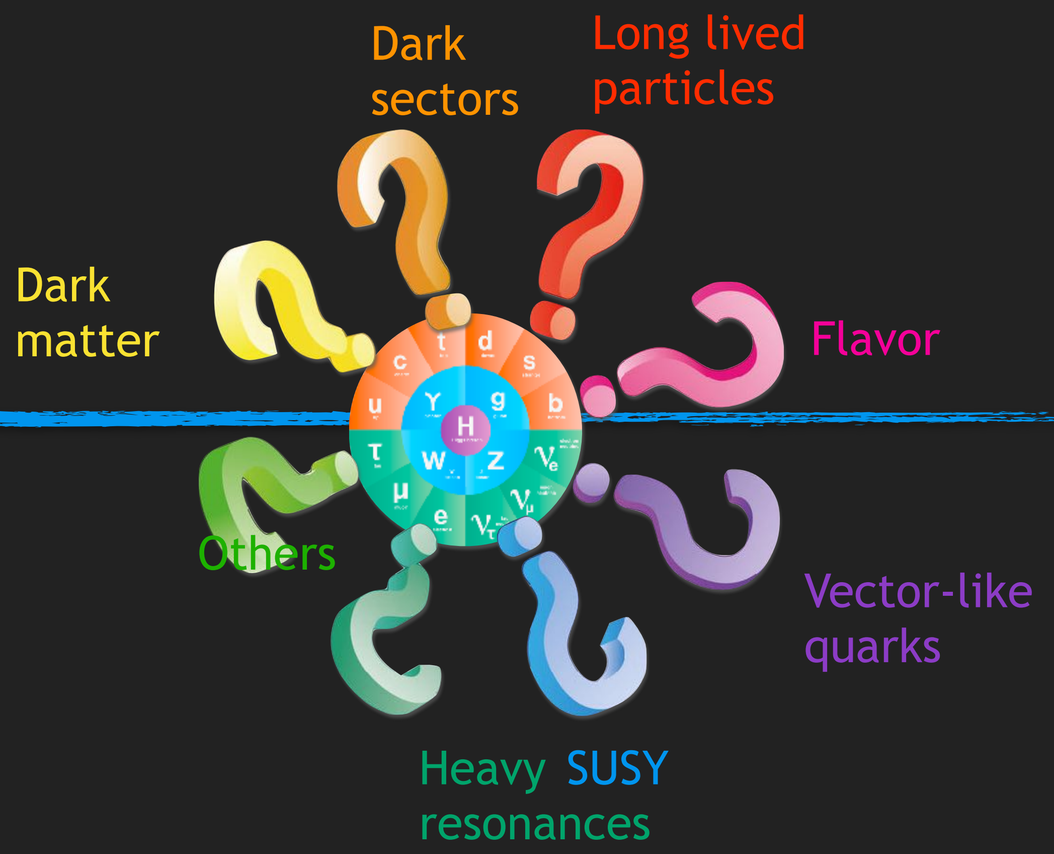


Phase-2 exclusion limits on the stop-stop cross section. m_{stop} exclusion up to **600 GeV**.



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

BSM prospects



Contributions to:

- EF08: Model-specific explorations
- EF09: More general explorations
- EF10: Dark matter at colliders

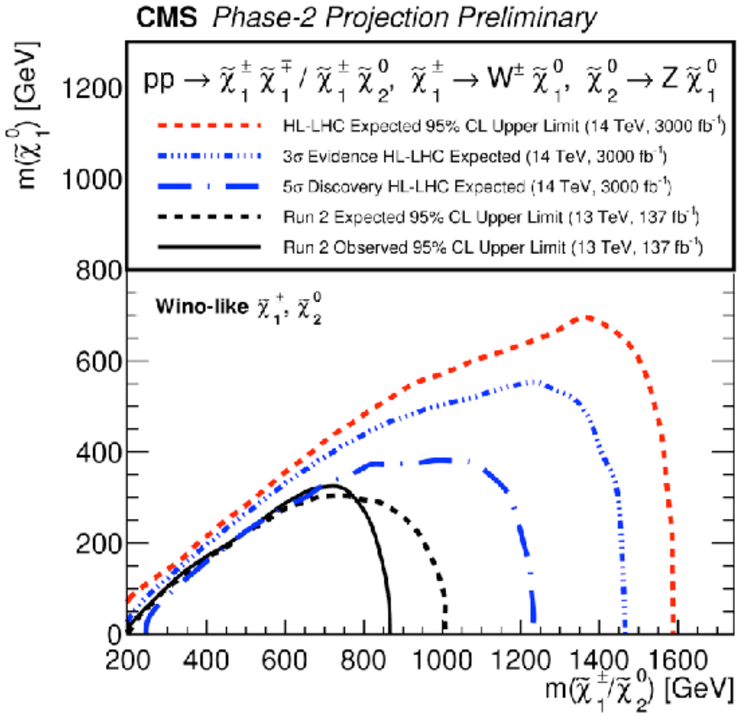
EF08: Hadronic EWK SUSY search

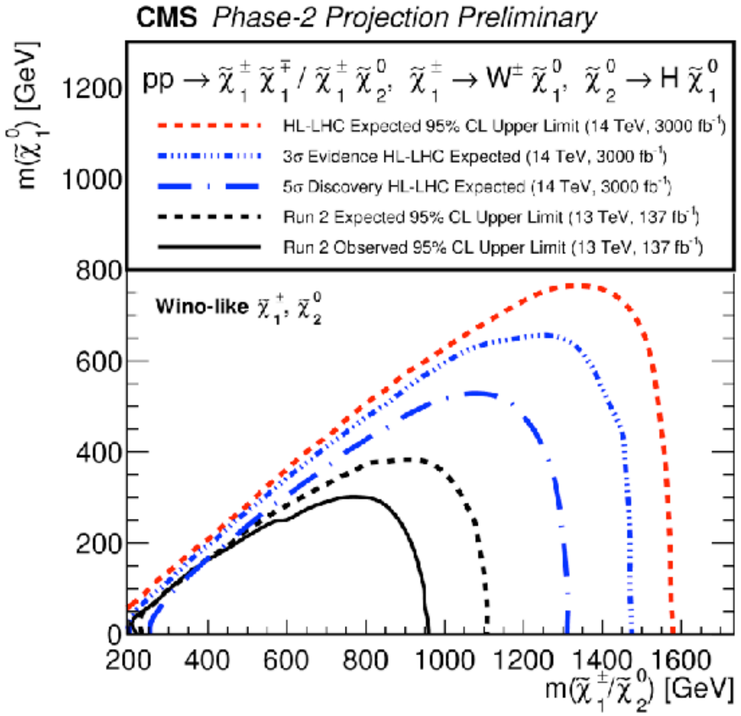
Project search for EW-produced chargino / neutralino decaying to boosted hadronic W/Z/h + LSP:

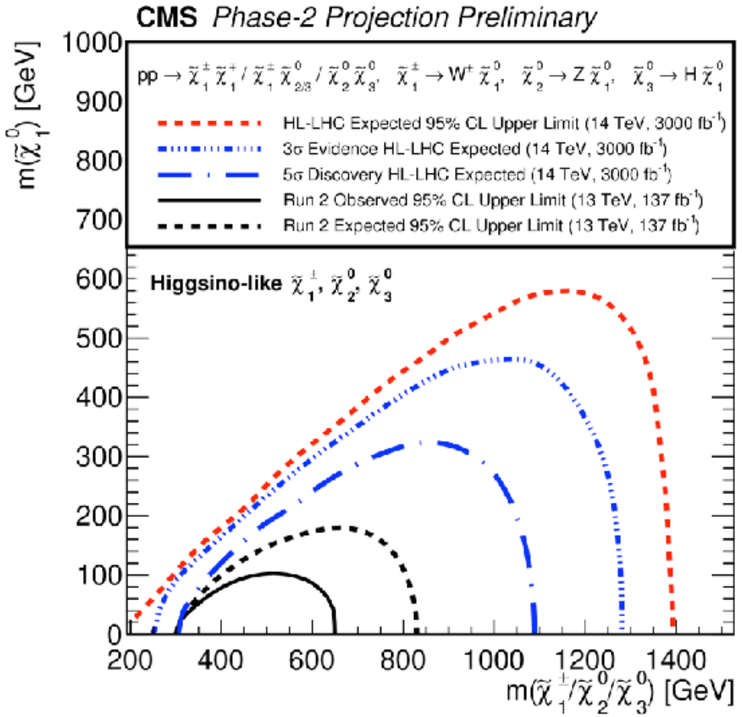
- Final states: WW, WH, WZ, ZH + E_T^{miss} > 200 GeV. 2 AK8 jets with pT > 200 GeV and W/Z/h tagging.
- Scaled luminosity and cross sections.

Interpret 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.



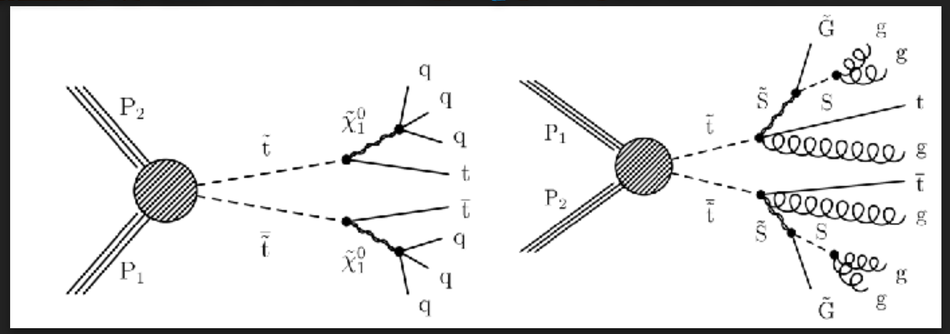




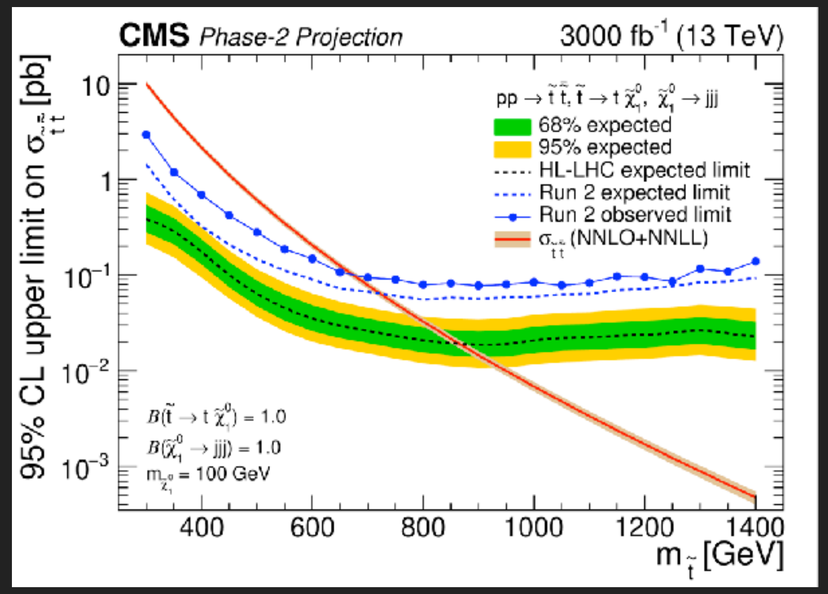
EF08: Stop search with 2 tops + multijets

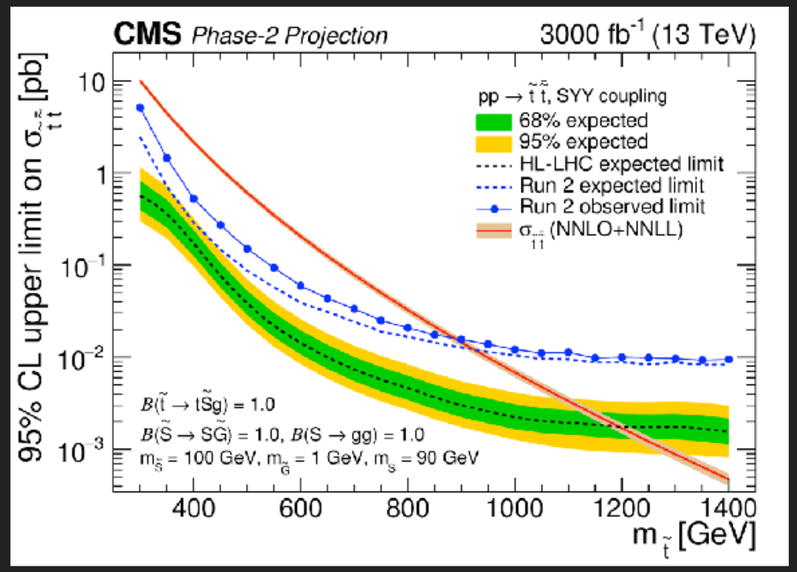
Projection of a search for stop pair production in R-parity violating or Stealth SUSY models:

- 2 tops + additional jets —> 1 lepton + ≥7 jets (no E_T^{miss}).
- Bkg:tt-pair + jets production
- Use high jet multiplicity to differentiate sig/bg
  - Binary classifier neural networks.
- Projection at 13 TeV by scaling the luminosity.



RPV Stealth



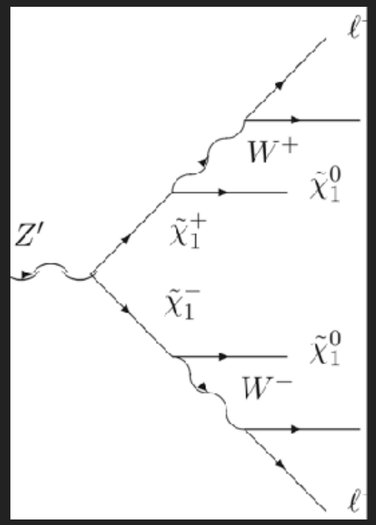


RPV: 670 GeV (Run 2) —> **870 GeV** (Phase-2)

Stealth: 870 GeV (Run 2) —> **1190 GeV** (Phase-2)

CMS-PAS-FTR-21-011 (Dedicated search - studied first time in CMS)

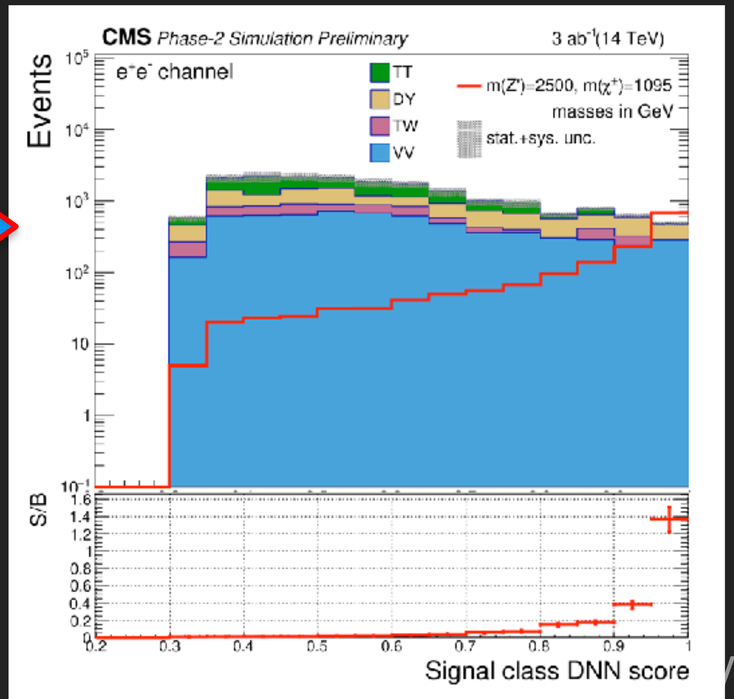
EF08: Leptophobic Z’ to charginos in ll +MET

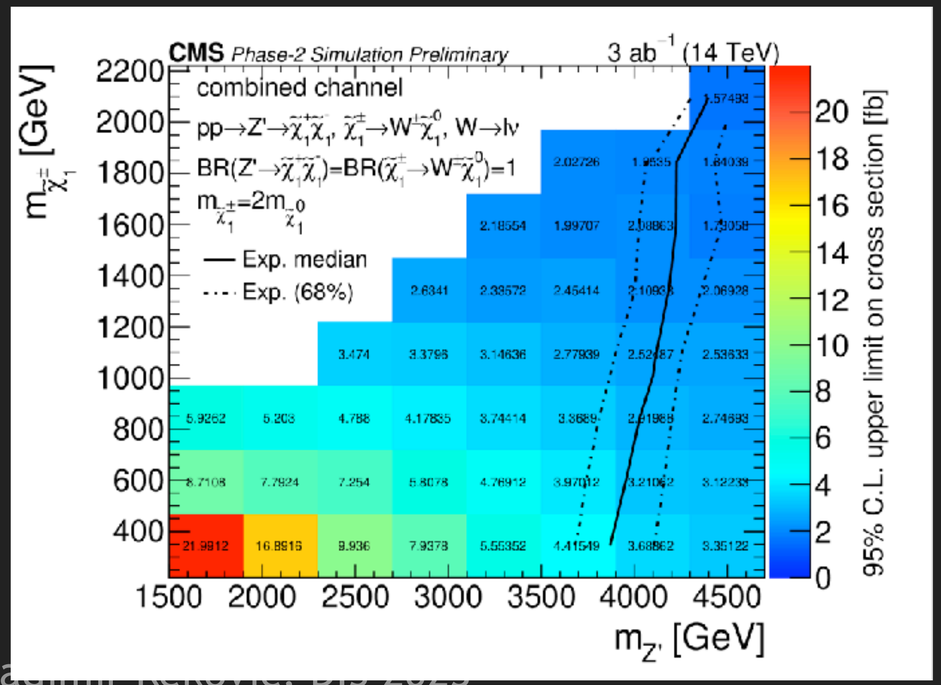


Search for leptophobic Z’ decaying to two charginos, which subsequently decay to leptonically decaying Ws and neutralinos using Delphes.

- Bkg; dileptonic decays of $t\bar{t}$+jets , Drell-Yan+jets with m_{ll}>100GeV, ….
- Select events with ee, μμ, eμ (high p_T, opposite-charged) and E_T^{miss} > 80 GeV.
- Signal extraction via DNNs per each signal point.
  - Input variables exploiting the resonance nature of the Z’.

DNN score trained for
$m_{Z'}$ = 2.5 TeV
m_{CH1} =1.095 TeV





Phase-2 exclusion for Z’ xsec:

Can exclude $m_{Z'}$ up to **4.5 TeV**.

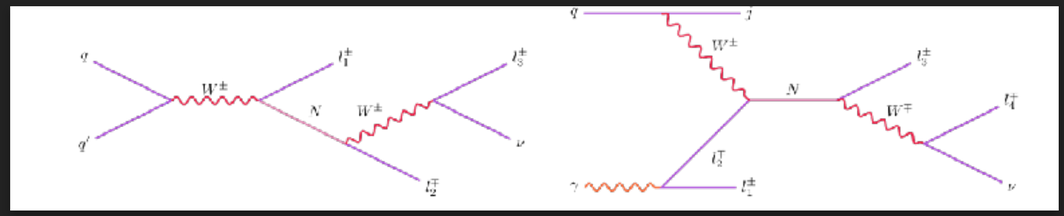
CMS-PAS-FTR-22-003 (Dedicated search)

EF08: Seesaw model searches with multipleptons

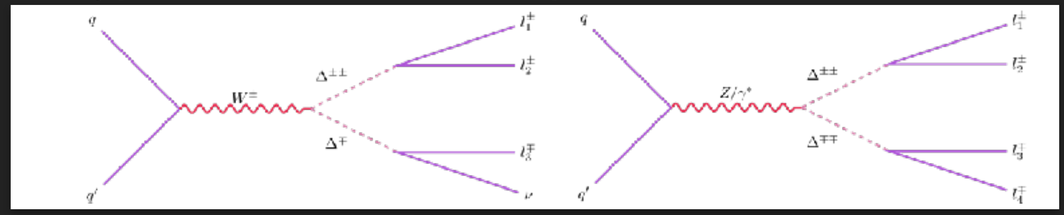
Search for Type-I and Type-II seesaw models (explaining neutrino masses) using Delphes.

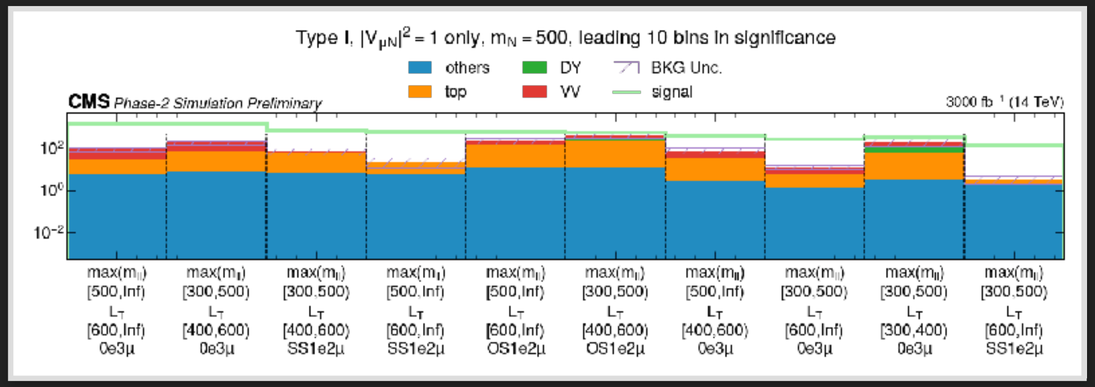
- Final states with exactly 3 or 4 leptons, $p_T > 40$ GeV
- Discriminating variables: L_T = sum(p_T leptons), min(m_{ll})
- 87 bins of lepton flavor, L_T, max(m_{ll}).

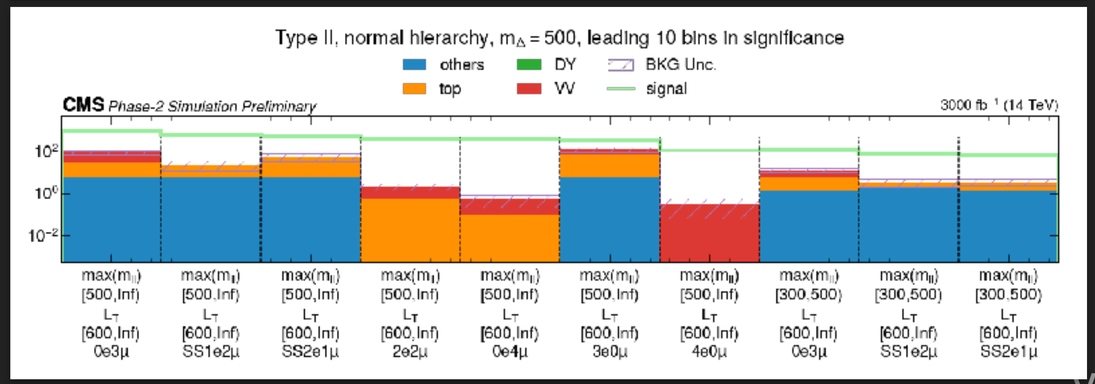
Type-I seesaw with singlet N:

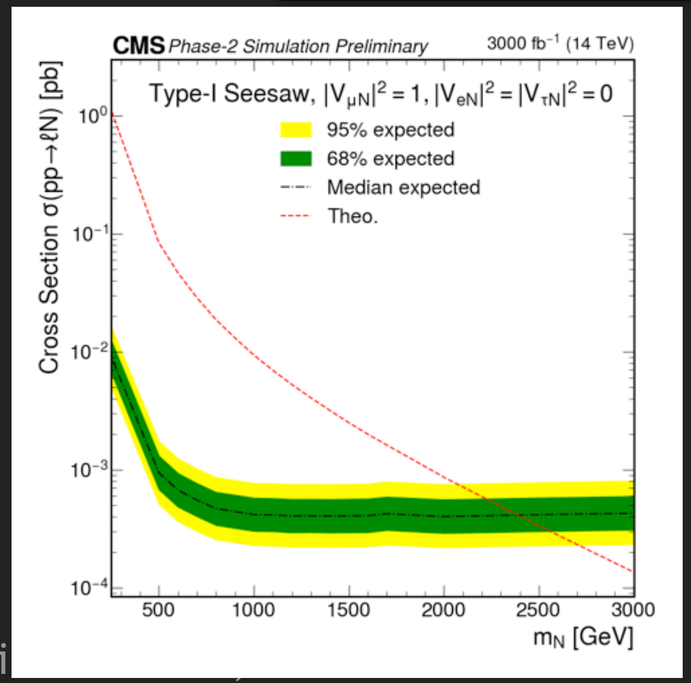


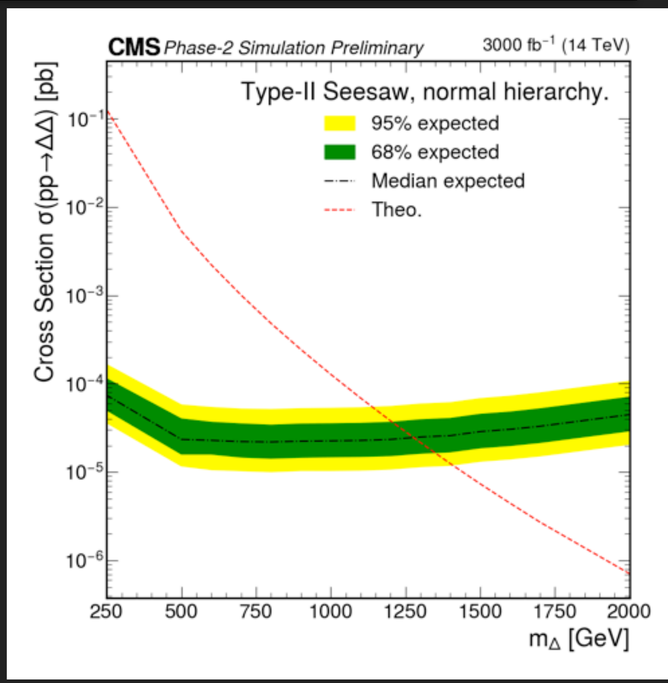
Type-II seesaw with triplet Δ:











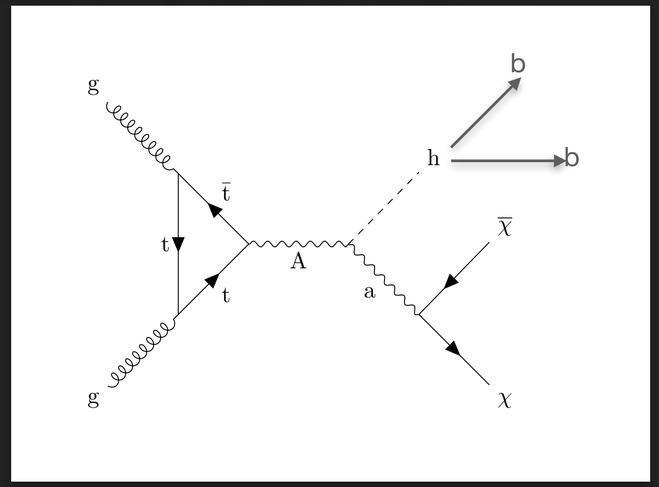
CMS-PAS-FTR-22-005 (Dedicated search based on CMS-EXO-16-050)

EF10: H -> bb + MET

Not in WP, approved.

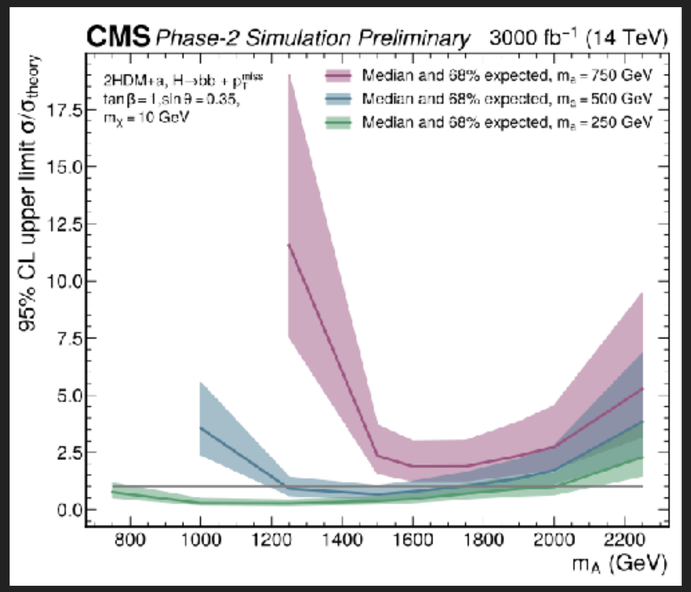
Search for boosted mono Higgs, with h → bb + dark matter using Delphes:

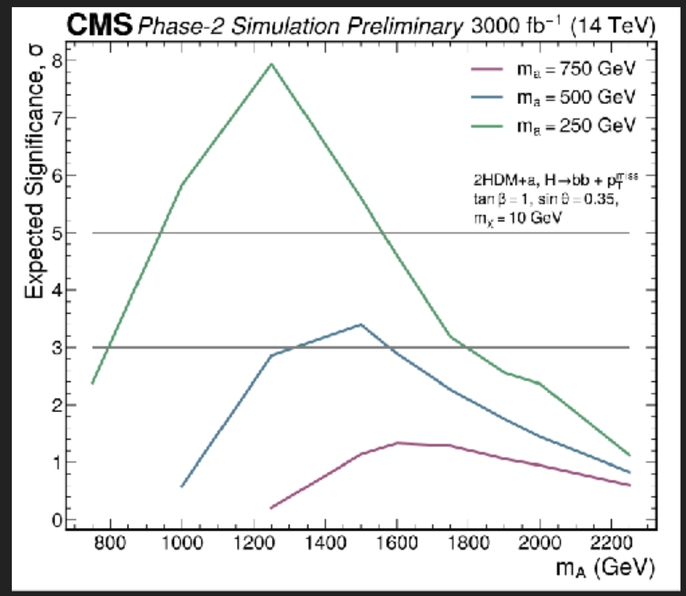
- ML-based boosted Higgs tagging on AK8 jets ; $E_T^{miss} > 200$ GeV.
- Upgraded detector + improved timing + improved heavy particle taggers + ML methods will enhance Phase-2 sensitivity.
- Interpretation in terms of a Type-II 2HDM+a model: tanβ = 1, sinθ = 0.35, mχ = 10 GeV.



Phase-2 limit on signal strength:

Exclude masses **$1 < m_A < 2$ TeV** for $m_a < 500$ GeV.





Phase-2 significance:

5σ disc. for

CP-even pseudoscalars heavy **m_A ~1-1.6 TeV**, light **m_a = 250 GeV**.

The future of future physics

- Studies for the Yellow Report and White Paper covered a substantial part of the HL-LHC physics phase space.
- Exploring new ideas is encouraged, in particular final states only accessible at HL-LHC and studies exploiting Phase-2 detector features.
  - di-Higgs and long-lived particles are obvious examples.
  - Wherever new physics reach available with Phase-2 Upgraded Detectors
    - e.g. CMS Phase2 Level-1 Trigger (CMS-TDR-021)
      - Track Trigger
      - Particle Flow

Extra slides

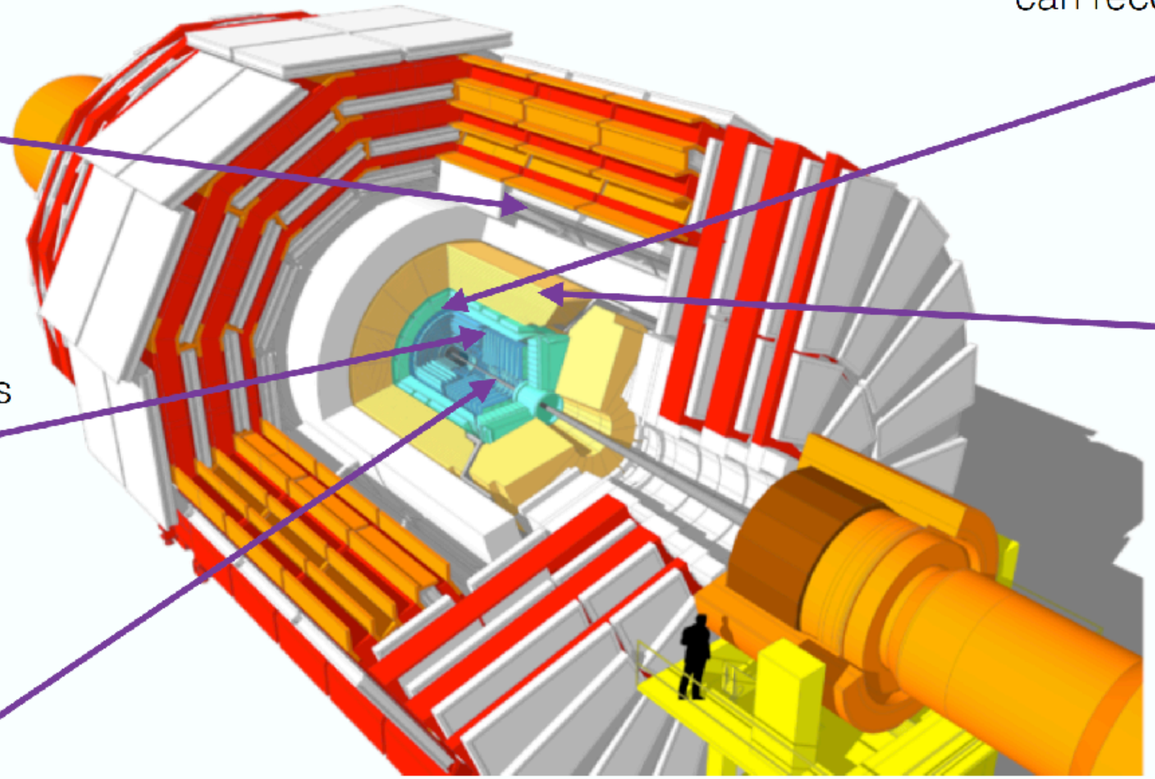
Phase-2 upgrade for the CMS detector

Improved muon coverage and trigger
increased RPC coverage ($1.5 < |\eta| < 2.4$)
new electronics

CMS-TDR-016

New endcap calorimeters
high granularity
can reconstruct showers in 3D

CMS-TDR-019



New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of $|\eta| < 3.0$

CMS-TDR-020

Updates to calorimeter and trigger
higher granularity
electronics for trigger

CMS-TDR-015

New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to $|\eta| < 4$

CMS-TDR-014

L1: CMS-TDR-021
DAQ/HLT: CMS-TDR-022

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

Beam Radiation Instrumentation and Luminosity Detectors

CMS-TDR-023