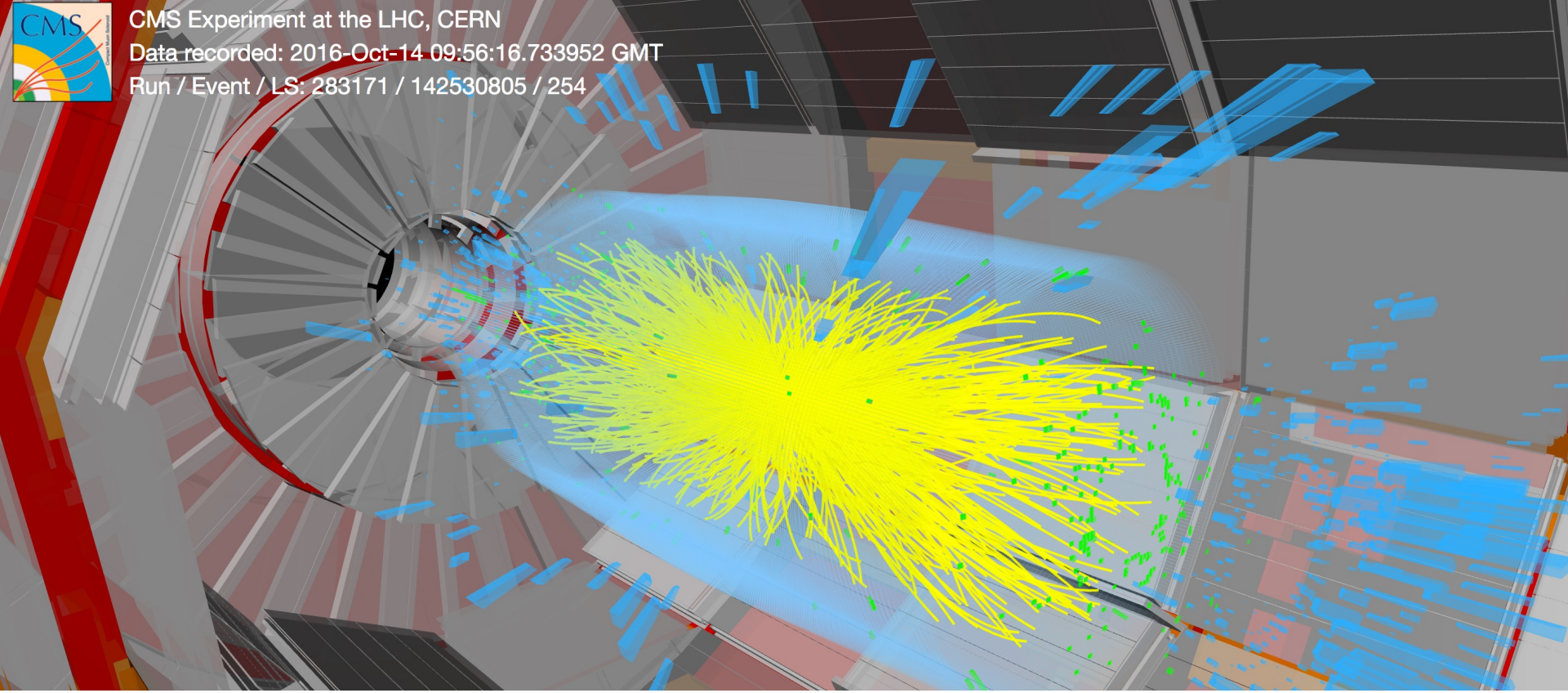


Physics at the High Luminosity LHC with ATLAS and CMS

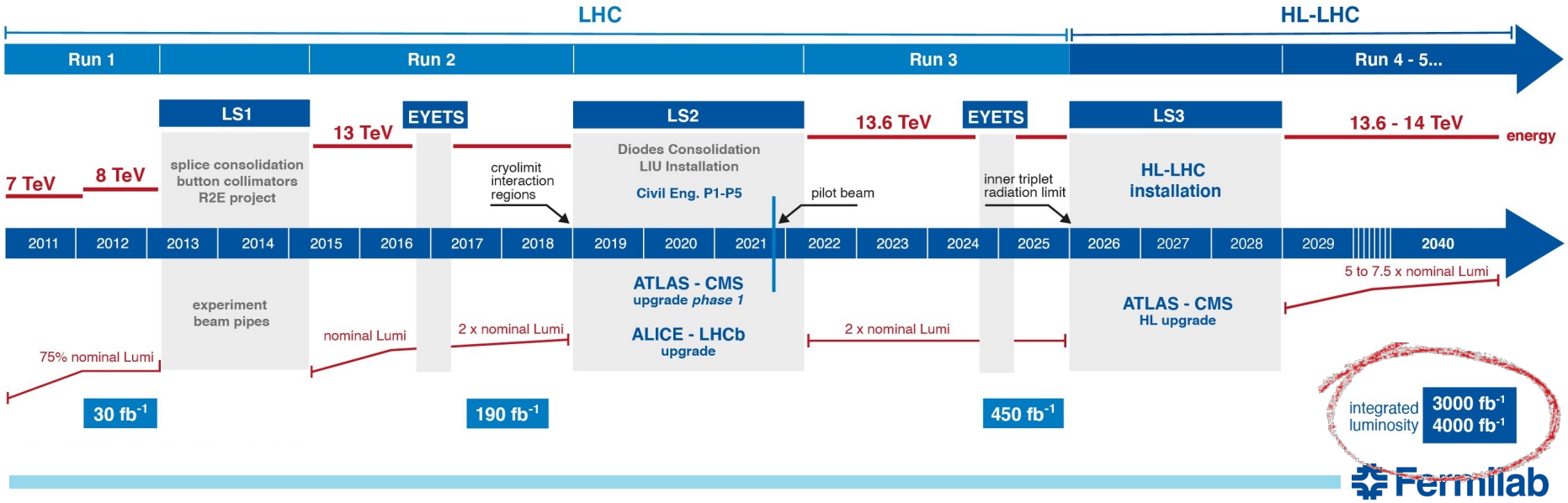
Jennet Dickinson (Fermilab)
on behalf of the ATLAS and CMS collaborations

Snowmass Community Summer Study

July 23, 2022

High Luminosity LHC (HL-LHC)

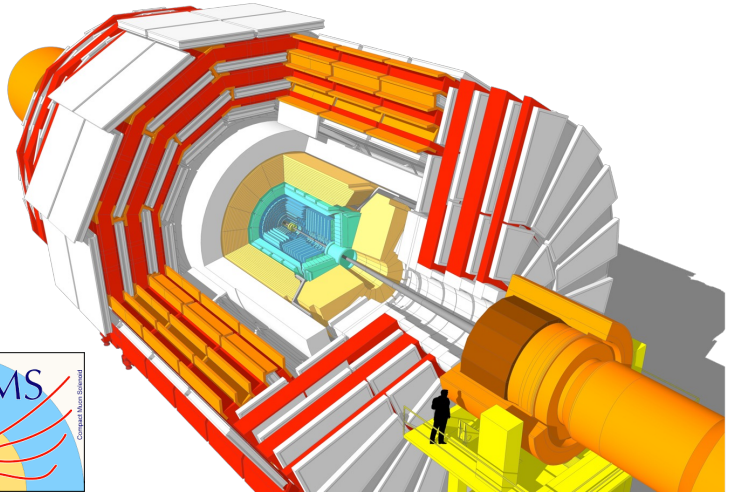
- Broad physics goals
  - Search for **rare processes** and make **more precise** measurements
- **HL-LHC** collider upgrade will provide more data than ever
  - Up to ~20x more integrated luminosity than we have now, ~100x more than we had at the time of the Higgs discovery
  - Associated challenges: complicated environments (**high pileup**), more radiation damage to detectors



HL-LHC detector upgrades

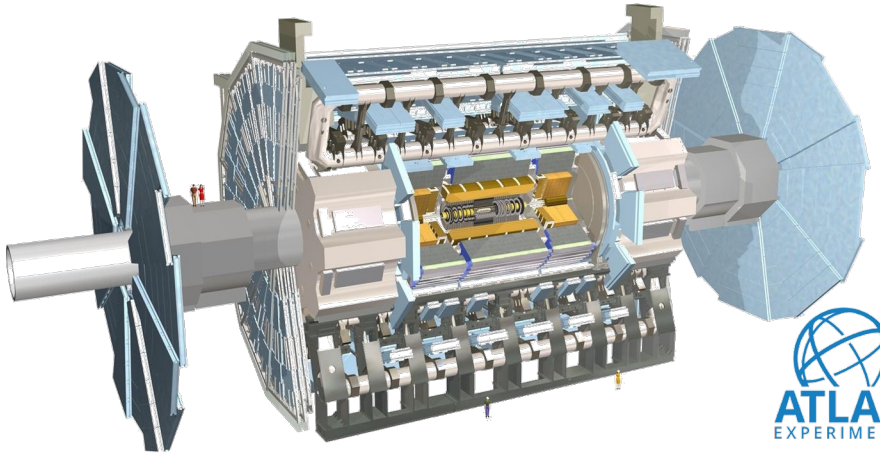
CMS detector

- New: MIP timing detector, additional muon detectors
- Fully replaced: silicon tracker, endcap calorimeters, trigger
- Upgraded: barrel calorimeters, forward calorimeters, muon chambers



ATLAS detector

- New: high granularity timing detector, additional muon detectors
- Fully replaced: silicon tracker, trigger
- Upgraded: liquid argon (EM) and tile (hadron) calorimeters, muon chambers



(Some of the)
Latest HL-LHC projections for Snowmass

☀️ Benefits from **luminosity**

🛠️ Benefits from **detector upgrade**

🧠 Benefits from clever **algorithms**

Physics potential of the HL-LHC

- Overview in ATLAS+CMS Snowmass white paper (2022)
  - Includes results from HL-LHC Yellow Report (2019)
  - +28 **new projections** from the collaborations!
- Assumptions on uncertainties:
  - **Experimental** uncertainties reduced by ~ sqrt(luminosity)
  - **Detector performance** as good or better than now, but with harsher pileup conditions
  - **Theory** uncertainties reduced by a factor of ~ 2

Physics potential of the HL-LHC

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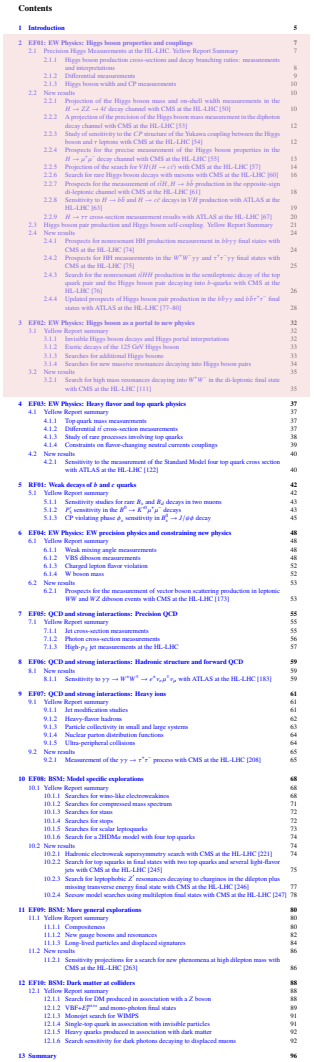
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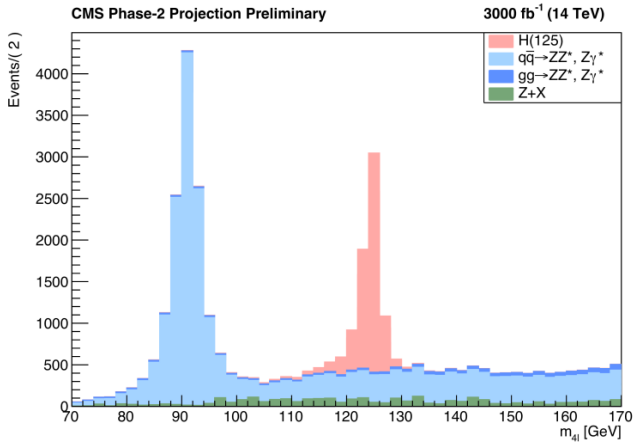
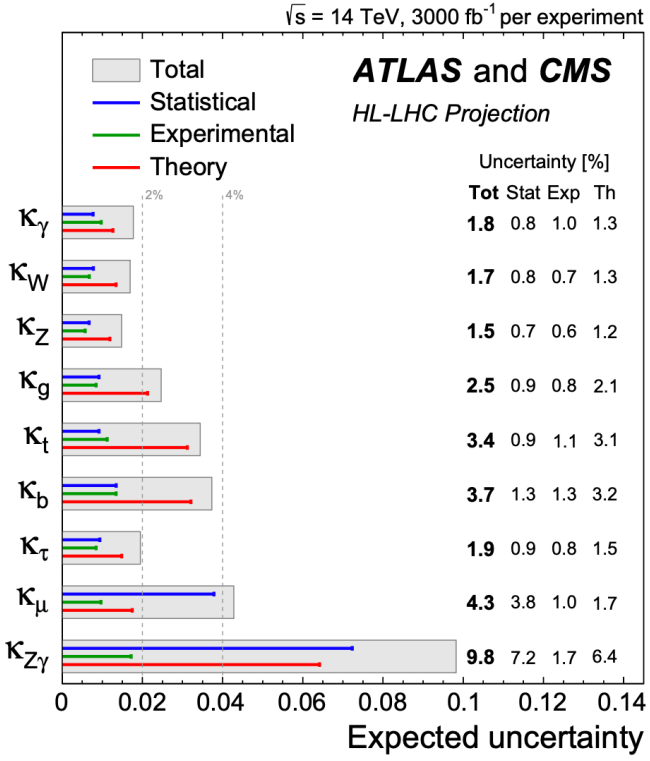
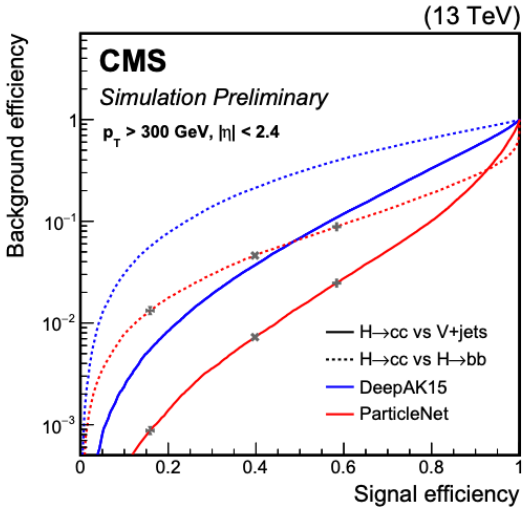
- Precise measurements of **mass and width**
  - H ⟶ ZZ ⟶ 4l and H ⟶ γγ
- Precise measurements of **couplings** to SM particles
  - Increased sensitivity to rare production and decay modes
- Evidence (or more) of **Higgs self-coupling**
- Measurements of **differential distributions**
  - Higgs p_T, Simplified Template Cross Sections, etc.

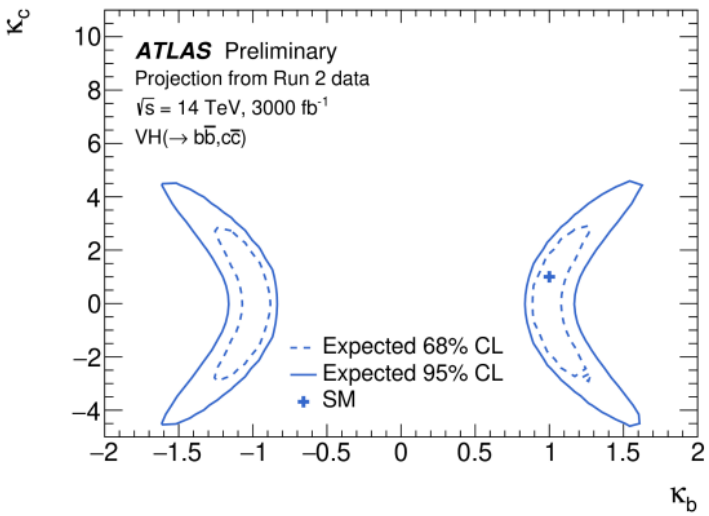




Higgs coupling to second generation fermions

- **H ⟶ *μμ*** in ggF and VBF
  - Evidence in Run 2 at 3σ level. Project 5σ discovery of SM with ~400 fb^{-1}
  - 🧠 New techniques brought us farther in Run 2 than we expected!
  - 🛠️ Big gains from tracking upgrade in $m_{\mu\mu}$ resolution, extended η coverage
- **H ⟶ cc** in high p_T VH
  - Challenging search! rare process, large QCD background, charm tagging
  - Simultaneous measurement of H ⟶ bb and ⟶ cc
  - 🧠🛠️ Gains from boosted jet reco, new charm-tagging algorithms





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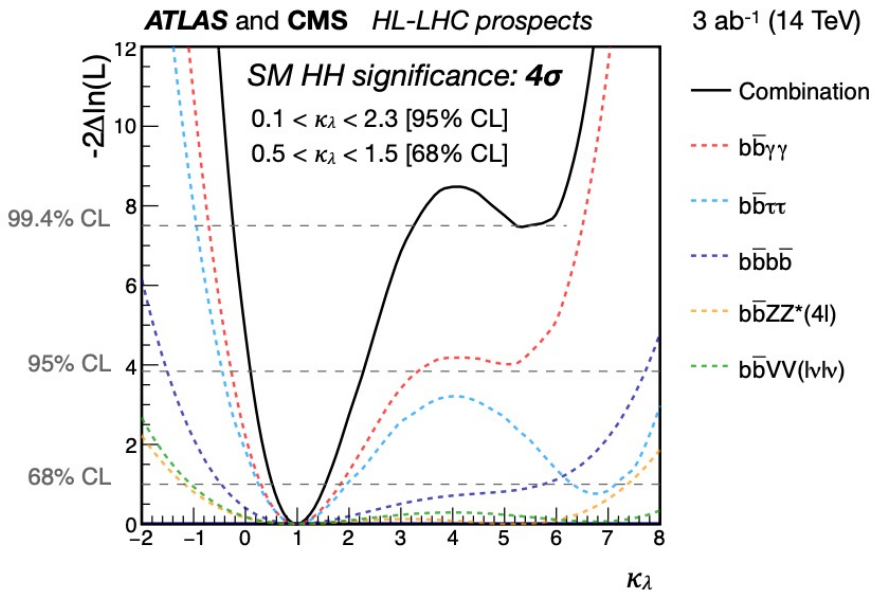
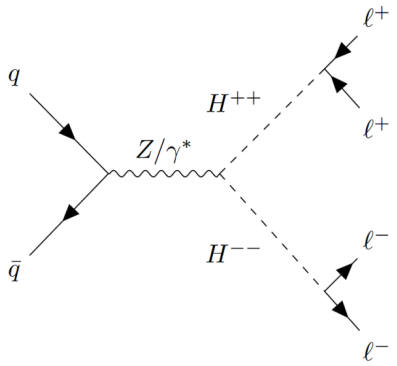
Di-Higgs production ☀️

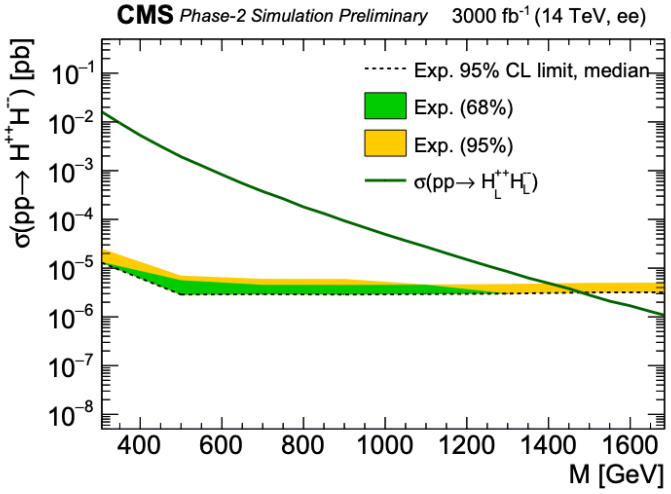
- Current projection: **4σ combined sensitivity** to SM HH
  - 🧠 Constantly improving with analysis of current data
- Number of channels explored is constantly growing
  - New projections for decays HH ⟶ bbγγ, WWγγ, ττγγ, bbττ
  - New projection for ttHH production with semi-leptonic top decay
- Pursuit of the **Higgs boson self-coupling**, κ_λ
  - Combined limits from ATLAS and CMS with full HL-LHC luminosity: $0.5 \leq \kappa_\lambda < 1.5$
  - Expect to exclude $\kappa_\lambda = 0$ at 95% CL

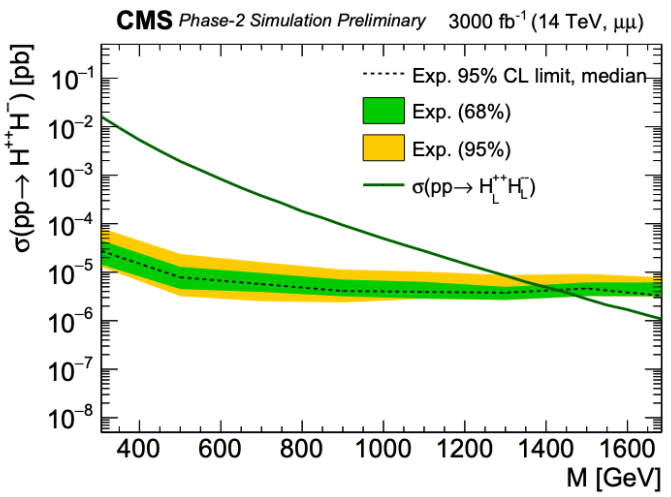


BSM Higgs



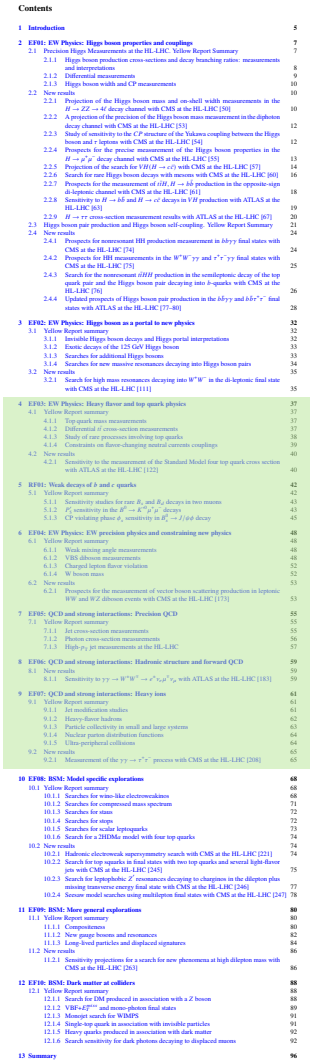
- Search for **doubly charged Higgs** (new)
  - Prediction of type II seesaw mechanism
  - $H^{++} \longrightarrow e^+e^+$ and $H^{++} \longrightarrow \mu^+\mu^+$
  - Nearly background-free search, especially at large H^{++} mass
  - Expected exclusion M < 1400 GeV (compared to 750-870 GeV in Run 2)





- Another study of the seesaw mechanism at the HL-LHC can be found here

Standard Model physics at the HL-LHC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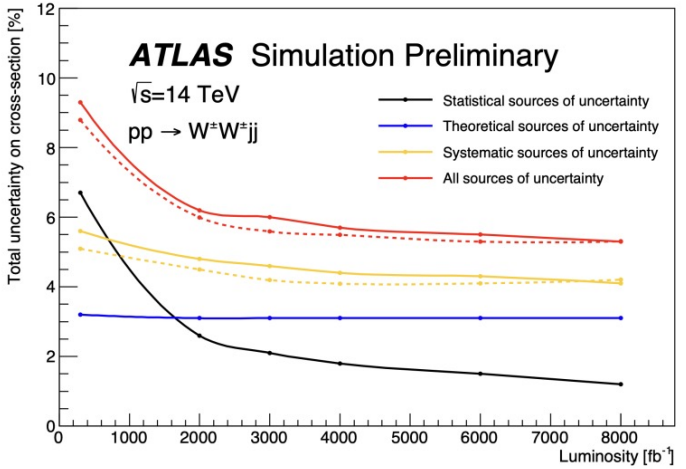
- **Heavy flavor** and top quark physics
  - Particle properties and rare processes
- **Precision electroweak** measurements
  - $\sin^2\theta_{eff}$, m_W
  - Vector boson scattering
- **QCD** measurements
  - Can constrain PDFs and the running of α_S
  - Better understanding of backgrounds for many other analyses
- The HL-LHC as a **photon collider**



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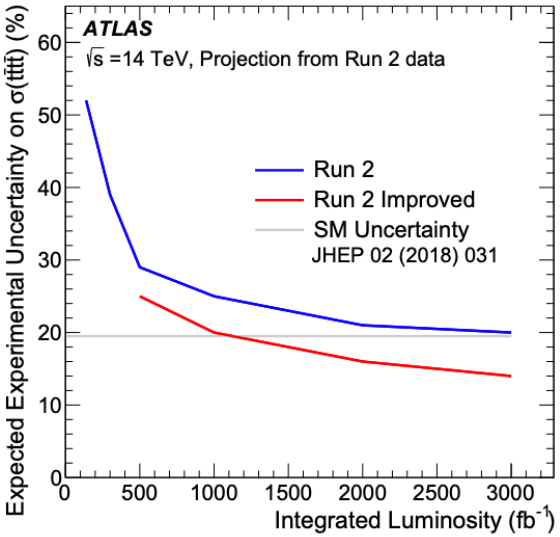
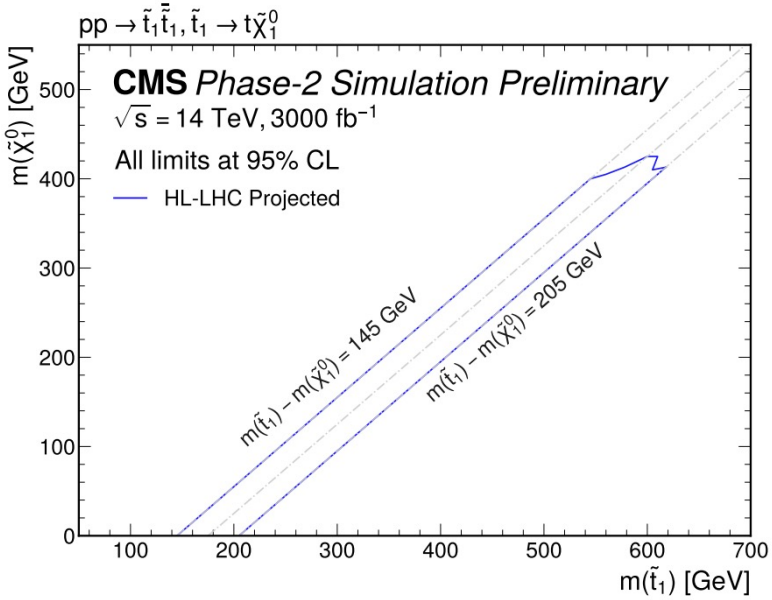
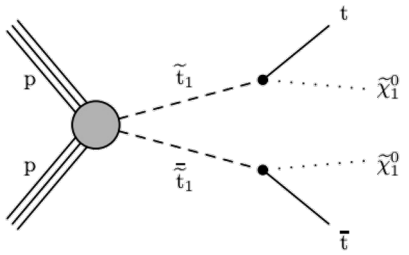
Top quark physics

- Projected measurement of the **four top** cross section
  - SM cross section = 16 fb $^{+18\%}_{-21\%}$
  - Enhancement predicted by many BSM processes (gluinos, scalar gluons, heavy boson + tt)
  - Expect 4-5σ sensitivity to SM process





- Top quark **spin correlations** (new)
  - Opposite sign eμ final state
  - Systematics dominated by theory
  - 🧠 Used in a multivariate search for stop squark pair production where $|m(\text{stop}) - m(\chi_1^0)| \sim m(\text{top})$



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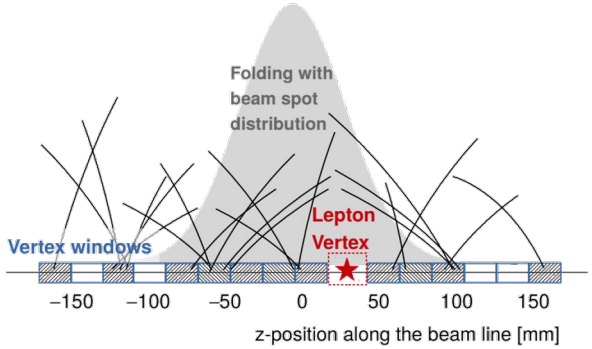
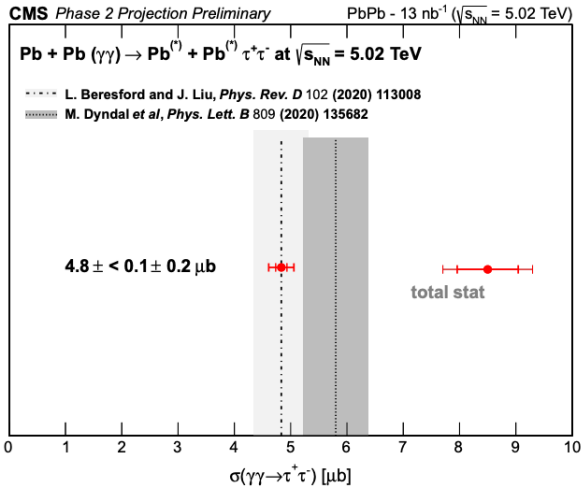
Photon-photon collisions ☀️

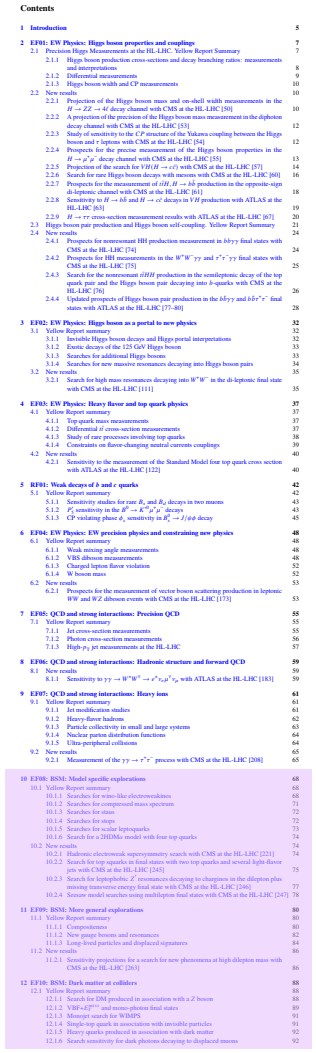


- **Exclusive WW** in pp ($\gamma\gamma \longrightarrow WW \longrightarrow e\nu\,\mu\nu$)
  - Sensitive to anomalous gauge boson couplings
  - Allow no tracks aside from W boson decay. Pileup makes this really hard!
  - 🧠🛠️ Investigation of how to maximize detector upgrades for low p_T tracking, rejection of fake tracks, η coverage
  - Expect total uncertainty reduction of ~50% at high dilepton mass
- Ultra-peripheral collisions of **γγ ⟶ ττ in Pb-Pb**

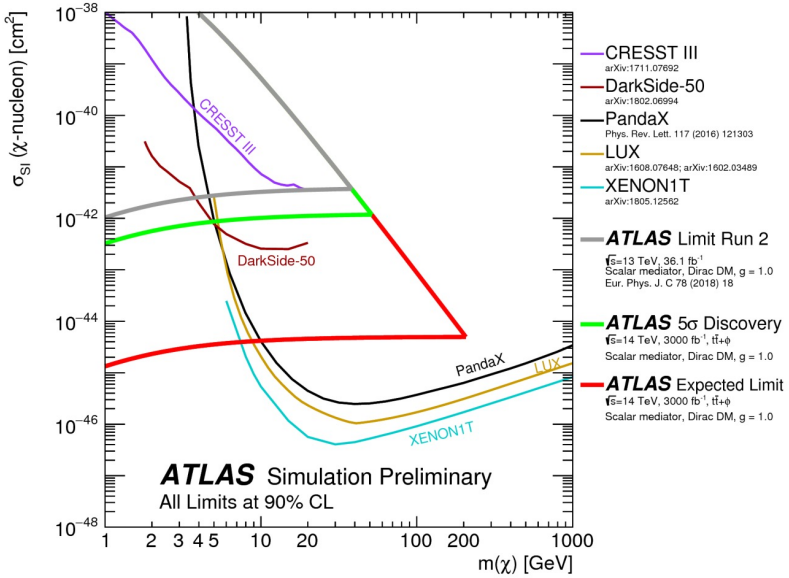


  - Final state with μ + 3 charged particles
  - 4x more precise cross section at HL-LHC vs. Run 2
  - Sensitive to anomalous magnetic moment of the tau $(g-2)_\tau$
  - 🧠 With new analysis ideas & channels, could surpass existing constraints on $(g-2)_\tau$

Physics beyond the SM at the HL-LHC

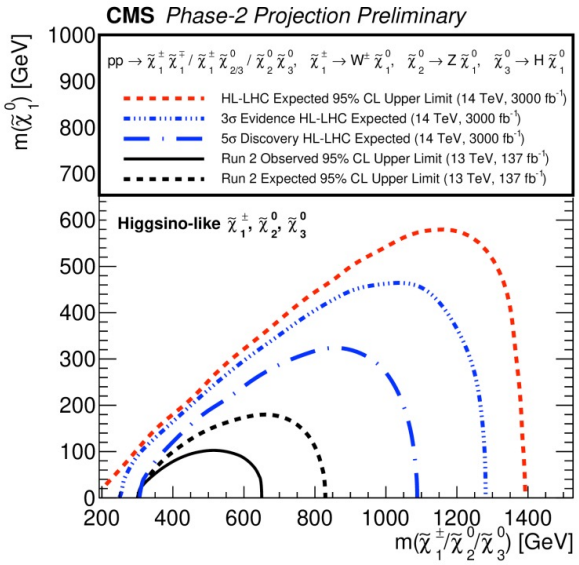

Contents

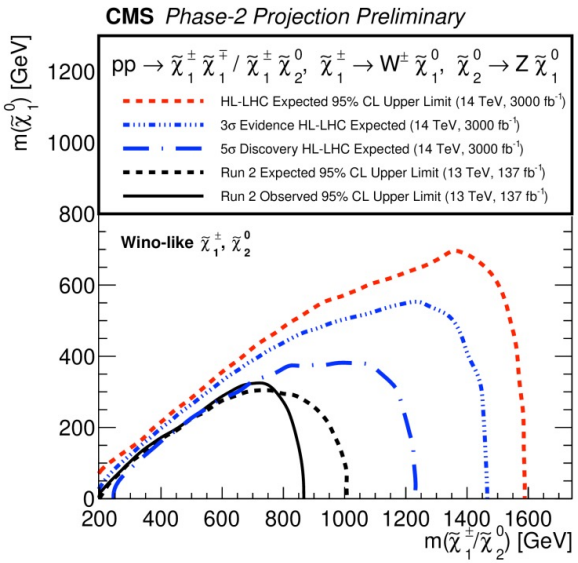
- **Supersymmetry**
  - Strong SUSY is well constrained by the LHC, but HL-LHC probes smaller cross sections, mass splittings
  - Potential increase of 20x in sensitivity to electroweak SUSY
- **Heavy resonances**
- **Long-lived particles**
  - 🧠 Requires dedicated triggers and reconstruction algorithms
- **Dark matter**
  - Searches for DM accompanied by SM particle(s)
  - Complementary to direct detection experiments

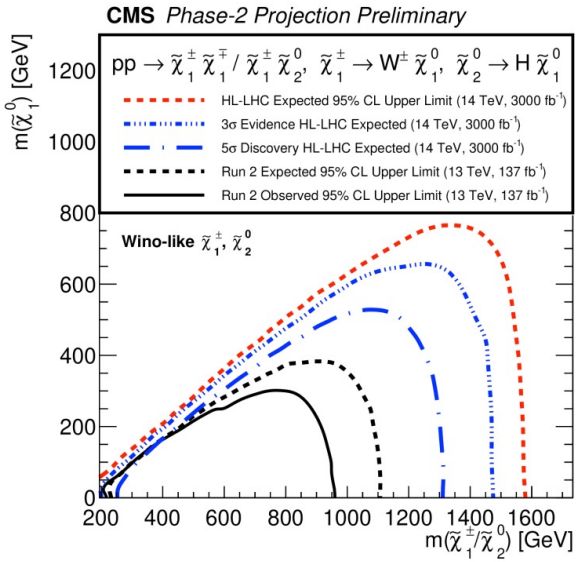


EWK SUSY with hadronic probes ☀️

- Pair production of NLSP: charginos, heavy neutralinos
  - $\chi_1^+ \longrightarrow W^+ \chi_1^0$, $\chi_2^0 \longrightarrow Z \chi_1^0$, $\chi_2^0 \longrightarrow H \chi_1^0$
  - Then hadronic W, Z, H decays (🧠 🛠️ boosted jet reco and flavor tagging)
- Coverage in NLSP mass extended by 600-750 GeV compared to Run 2



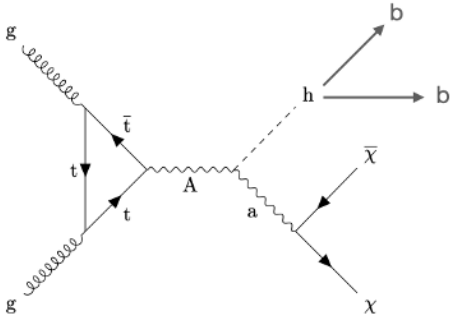


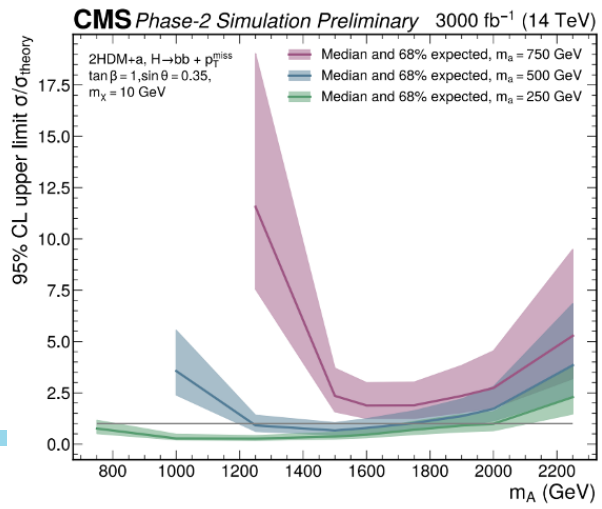


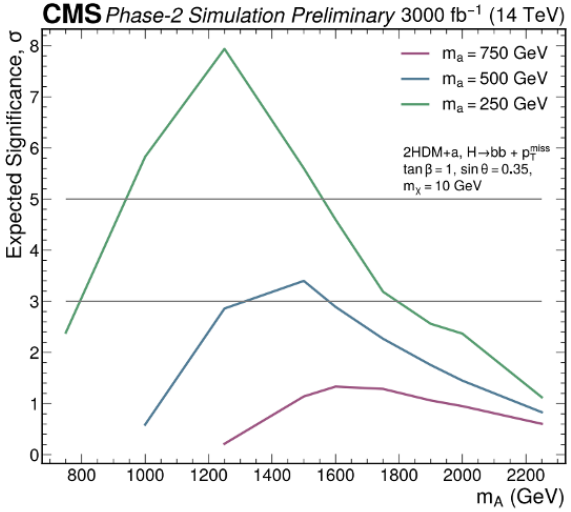
Fermilab

Dark matter with boosted mono-Higgs ☀️

- Boosted H ⟶ bb decay + missing transverse energy (new)
  - 🧠🛠️ Gains from boosted jet tagging, improved vertexing (e.g. tracking, precision timing)
- Interpreted in type II 2HDM + additional light pseudoscalar boson (a)
  - For lighter a, get more boosted H and higher acceptance
  - Projections could exclude 1-2 TeV m_A for $m_a < 500$ GeV
  - 5σ discovery reach: m_A 1-1.6 TeV for $m_a = 250$ GeV







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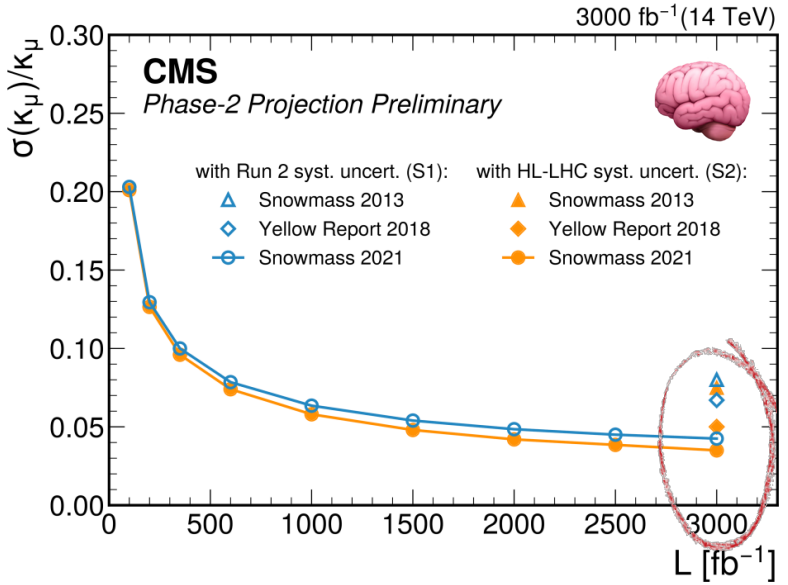
Conclusions

- The HL-LHC is the **immediate future** of physics on the energy frontier
- Along with accompanying upgrades, will be very powerful for physics across **Higgs**, **SM**, and **BSM**
  - Gains from high **luminosity, detector upgrades,** and new clever **algorithms**
- We've barely begun and are always improving!
- HL-LHC will provide a massive amount of new knowledge
  - Legacy will last for decades to come

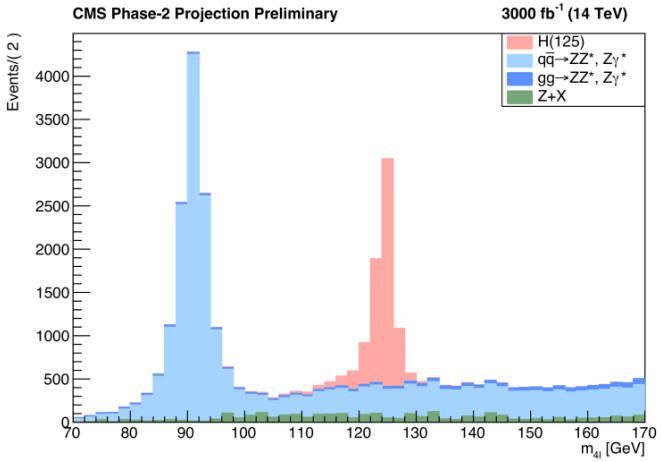


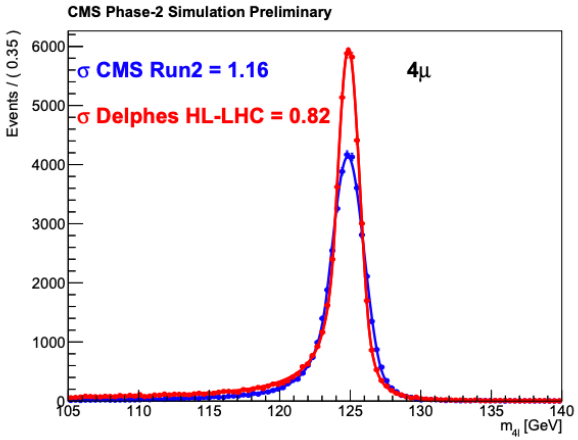
The future is bright!

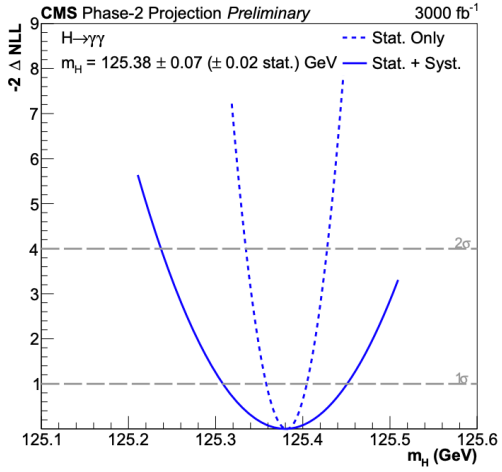
Extras

Higgs mass and width ☀️

- With run 2 data, combined m_H = 125.38 ± 0.14 GeV
- **H ⟶ ZZ ⟶ 4l**
  - Channels: 4e, 4μ, 2e2μ, 2μ2e
  - m_H = 125.38 ± 0.03(stat) ± 0.02(sys) GeV
  - Γ_H < 0.09 (0.18) GeV at 68% (95%) CL
  - 🛠️ Detector upgrades give better mass resolution, especially 4μ







- **H ⟶ γγ**
  - m_H = 125.38 ± 0.02 (stat) ± 0.07 (syst) GeV
  - Benefits from 🛠️ tracker and HGCAL upgrades, 🧠 photon energy calibration
  - Systematics dominated by photon energy scale

BSM Higgs ☀️

- **Heavy Higgs ⟶ WW,** W ⟶ ev, W ⟶ μv
  - 🧠 Multivariate analysis rejects background
  - Interpreted in several BSM scenarios, including MSSM and THDM
  - THDM run 2 limit at $m_H \sim 700$ GeV