Single- and di-Higgs prospects for CMS at HL-LHC

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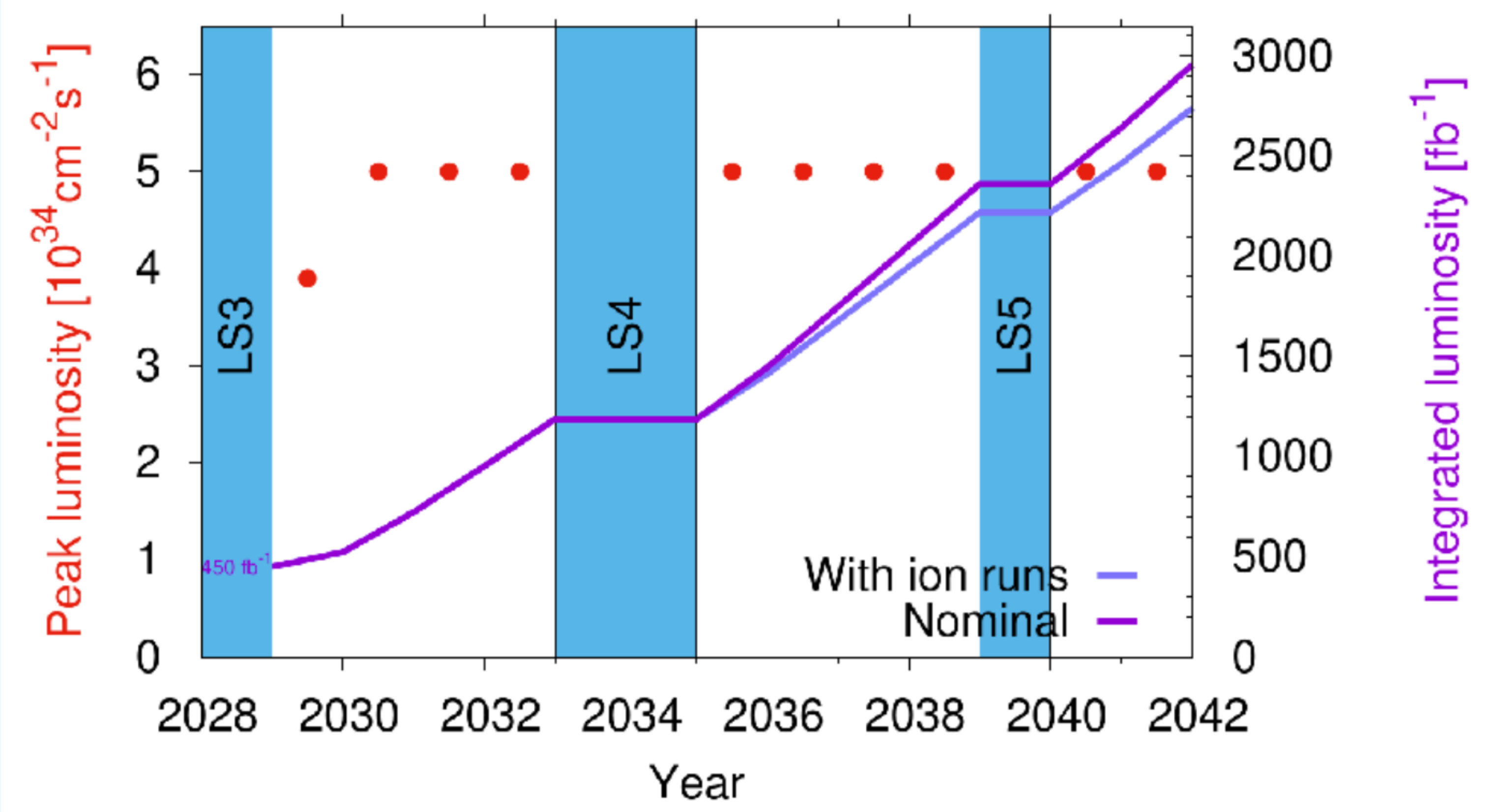
6 Nov 2024

Challenges/opportunity of HL-LHC

- 3x increase of peak luminosity
  - Data equivalent to **3000 fb^{-1} in 10 years of operation**
  - **Upgraded CMS** detector to cope with higher pileup and radiation damage

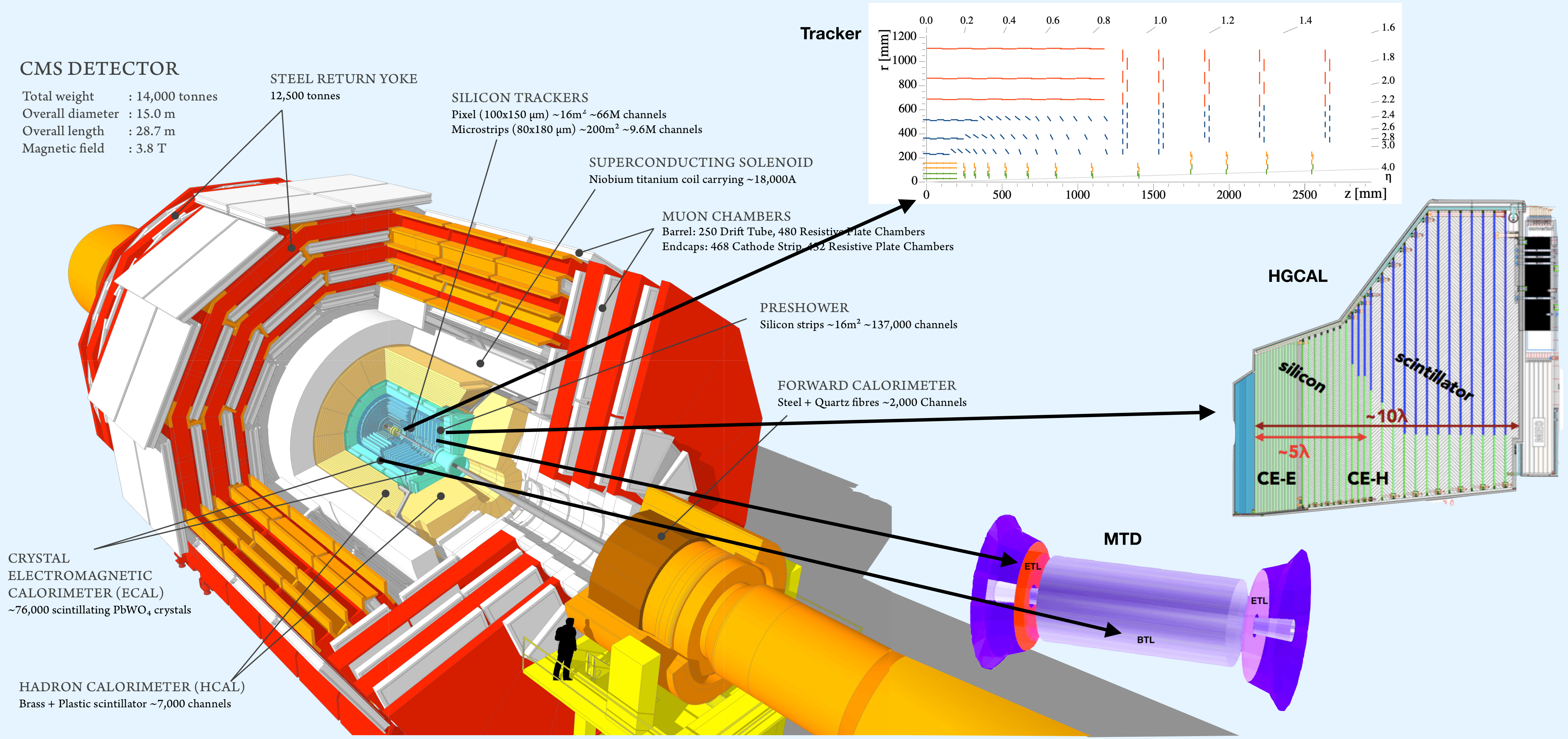


~ 10^5 HH events at 3000 fb^{-1}

~10^7 singleH events at 3000 fb^{-1}

- Lots of statistics → precise measurments

The CMS experiment and the Phase-2 upgrade



Impact of the Mip Timing Detector on HL-LHC physics program

Mip Timing Detector is instrumental in maintaining CMS resolution and reconstruction efficiency thanks to improvements brought to events observables:

- **Rejection of tracks from pile up interactions** by adding requirements on track time
- **Pile-up jet suppression** with the employment of Pile Up per Particle Identification (PUPPI) algorithm
- **Removal of spurious secondary vertices** in heavy-flavour tagging with time information

https://cds.cern.ch/record/2667167/files/CMS-TDR-020.pdf

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Signal	Physics Measurement	MTD Impact
$H \to \gamma\gamma$ $H \to 4$ *leptons*	+15-25% (statistical) precision on the cross section → Couplings	Isolation Vertex identification
VBF→H→ $\tau\tau$	+30% (statistical) precision on cross section → Couplings	Isolation VBF tagging, p_T^{miss}
HH	+ 20% gain in signal yield → Consolidate searches	Isolation b-tagging
EWK SUSY	+40% reducible background reduction → 150 GeV increase in mass reach	Missing E_T b-tagging
Long Lived Particles (LLP)	Peaking mass. reconstruction → unique discovery potential	β_{LLP} from timing of displaced vertices

Improvements on physics objects will bring significant advantages in several searches:

- Higgs boson decays
- Double Higgs boson production
- Supersymmetry
- Long Lived Particles
- Heavy Stable Charged particles
- Quark-Gluon plasma studies with heavy-flavour quarks

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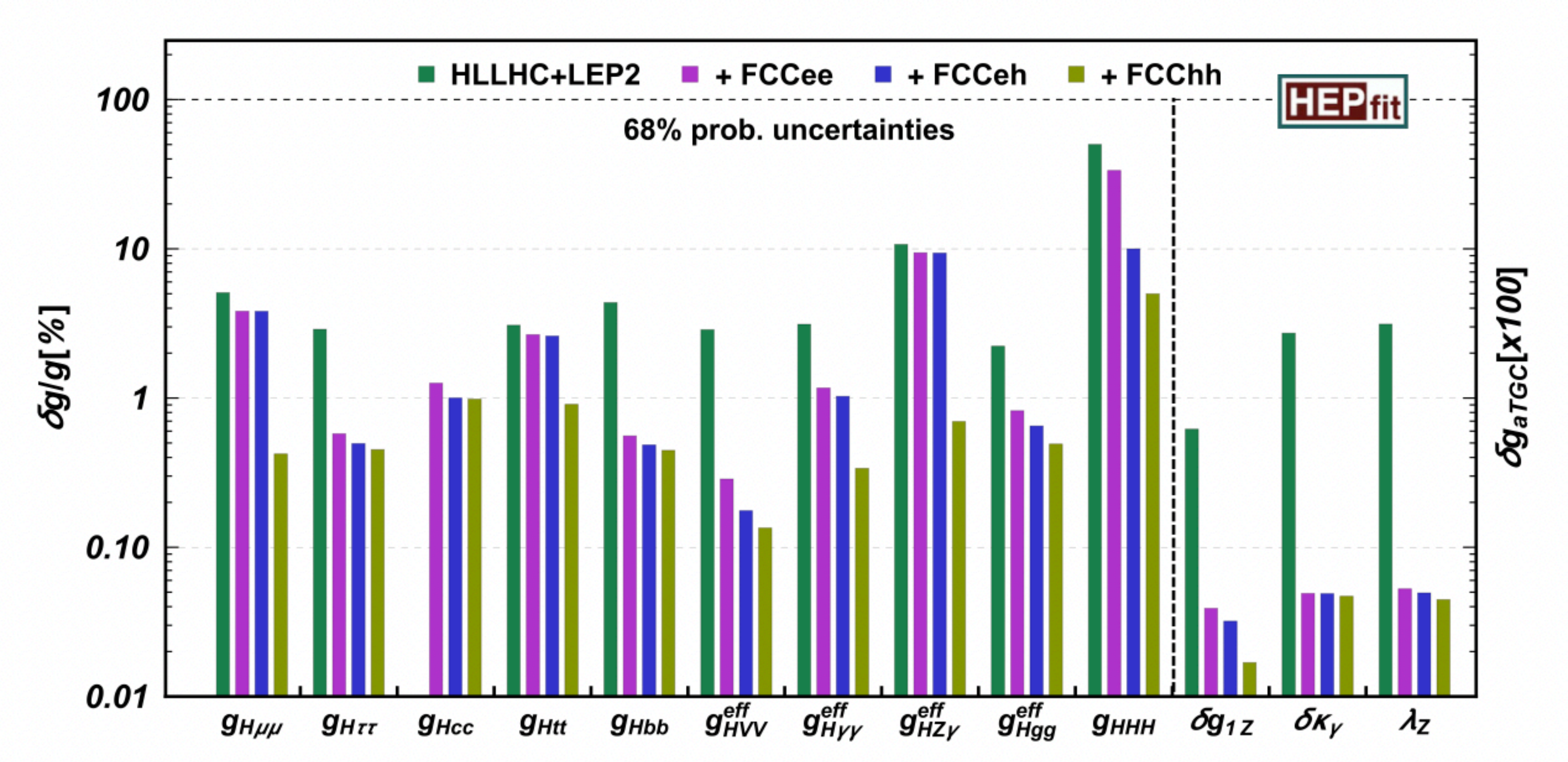
Single H projections

- HL is still going to be the best machine for coupling determination for the next decades years (until FCC-hh)



*Phys. Rev. Lett. 132 (2024) 221802

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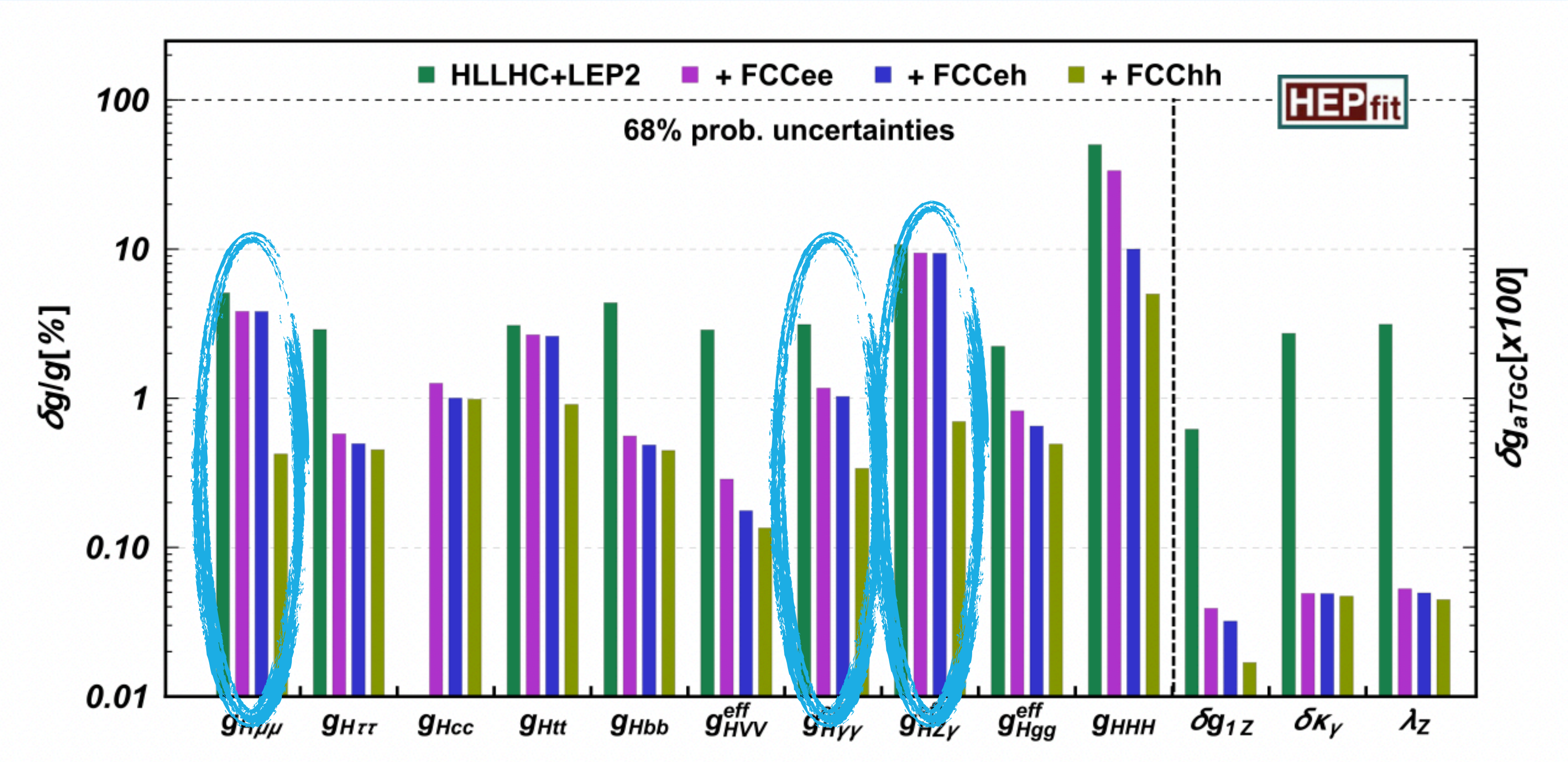

- optimize both the inclusive measurment of the signal strength (especially in the rare channels)
- novel phase space to split finer in differential bins

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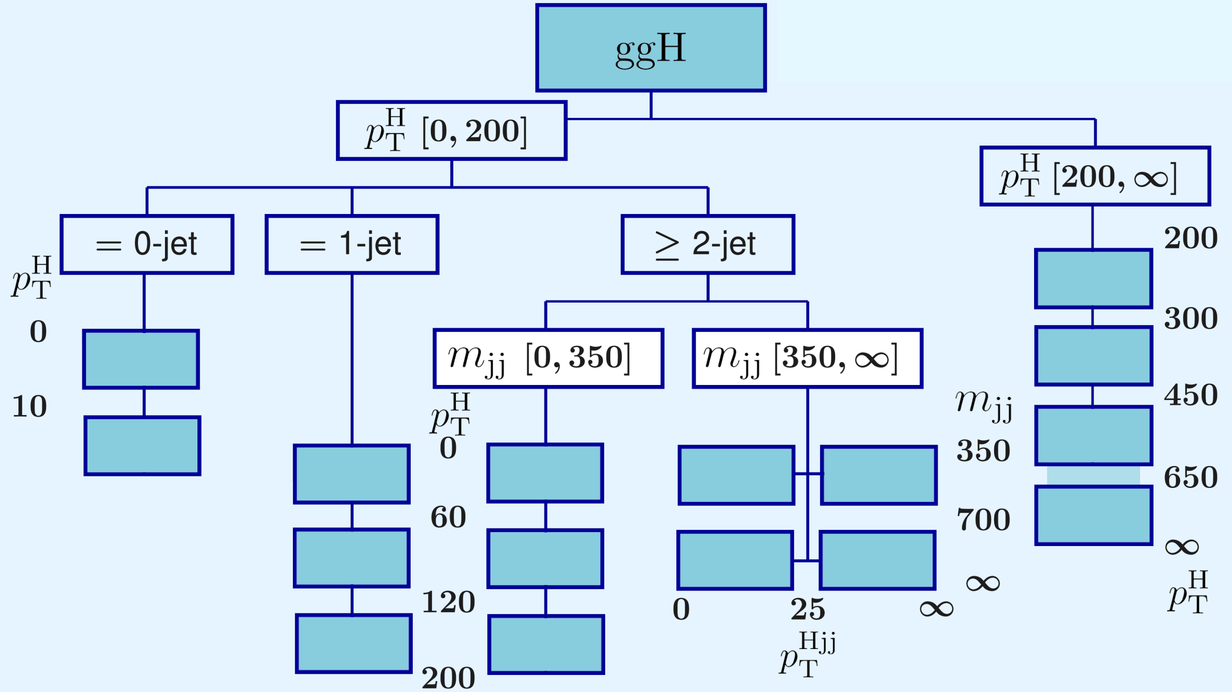
Simplified template cross section (STXS)

- Split production mode cross-sections into various phase-space regions, which are chosen according to sensitivity to beyond Standard Model effects, avoidance of large theory uncertainties, matching to experimental selections

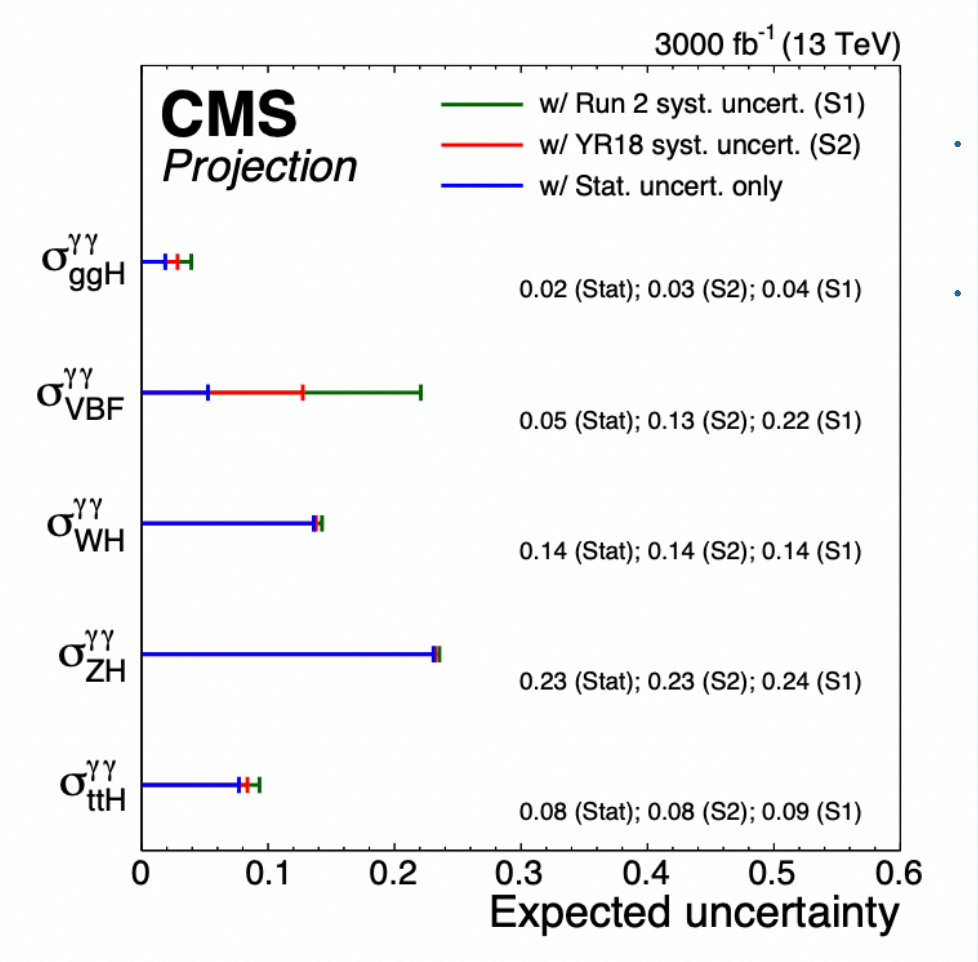
- For each STXS region, use the SM predicted signal templates to fit data



We can understand the expected improvement in different energy ranges

H→γγ STXS analysis (HL-LHC projection)

YR projection with 3000 fb^{-1} based on CMS partial Run-2 analysis (for stage-0 STXS):



- We expect around a ~15% to 25% improvement on the H → γγ channel for detector improvements (slide 4)
- Since then the STXS binning have been optimized, the main aspect to maintain that value of the statistical uncertainty is to keep ECAL noise under a certain value
  - this will be achieved by cooling more the detector in the barrel

More about the H → γγ channel properties in Ruben's talk

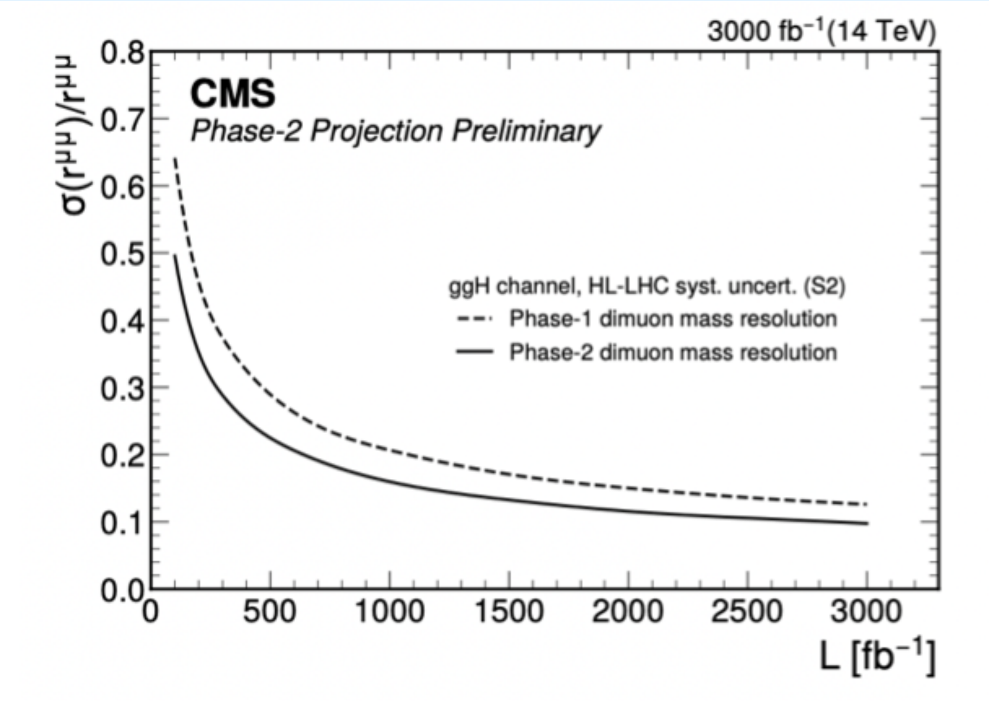
We can arrive at 2% precision on the Higgs production mode!!!

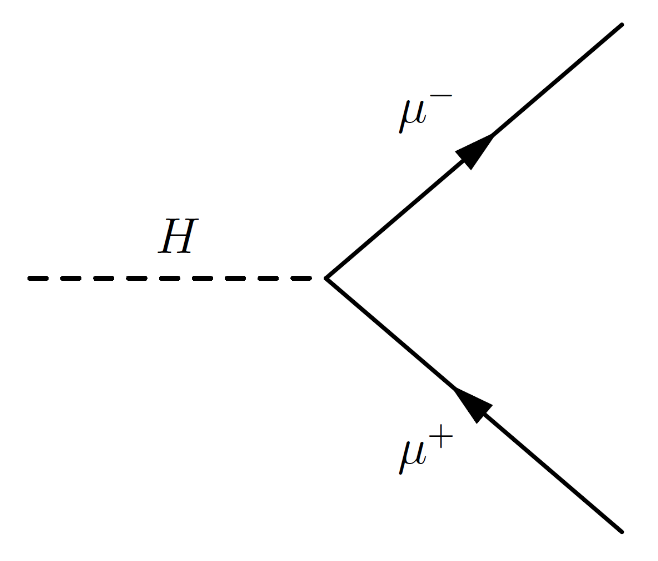
* CMS-PAS-FTR-21-006

H→μμ decay (HL-LHC projection)

The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC

- Small branching ratio in SM (2x10^{-4}), physics beyond the SM could modify it





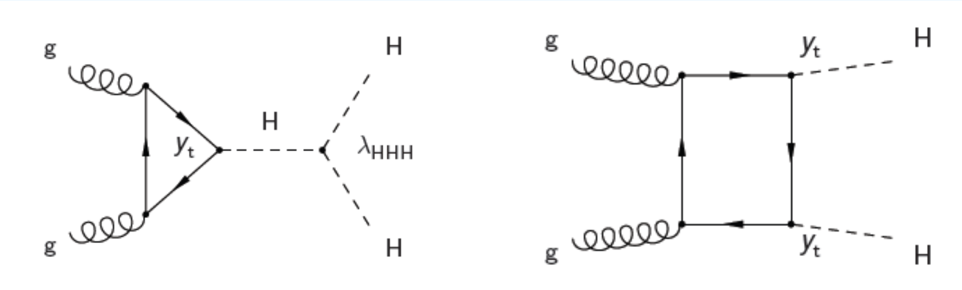
The main factors affecting the analysis is the dimuon mass resolution

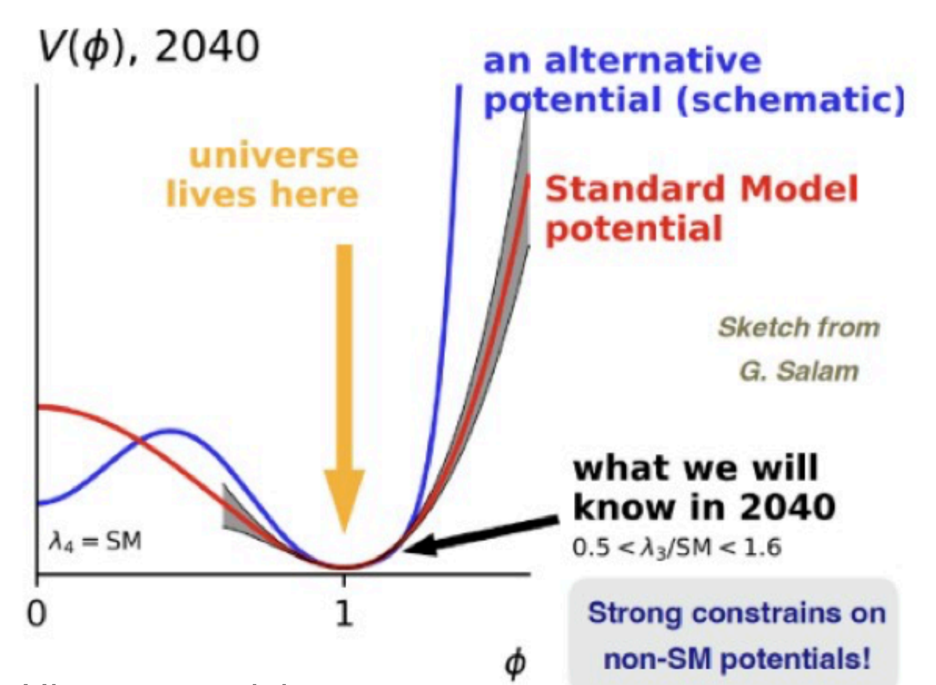
* CMS-PAS-FTR-21-006

Motivation for HH search

- With HL we will have:
  - **Test of the Electroweak Symmetry Breaking (EWSB) mechanism**

LO SM Feynman diagrams





Higgs potential

Motivation for HH search

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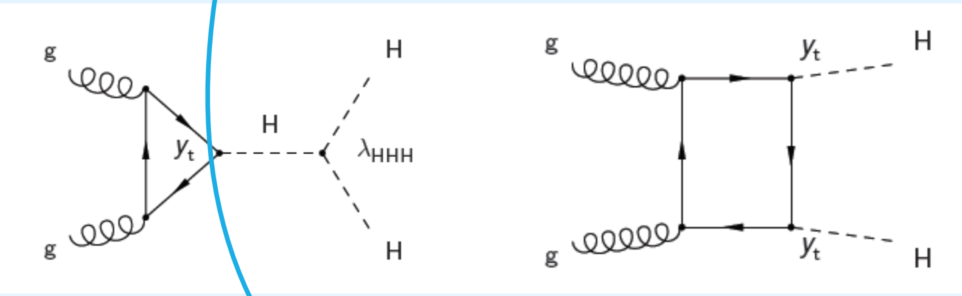
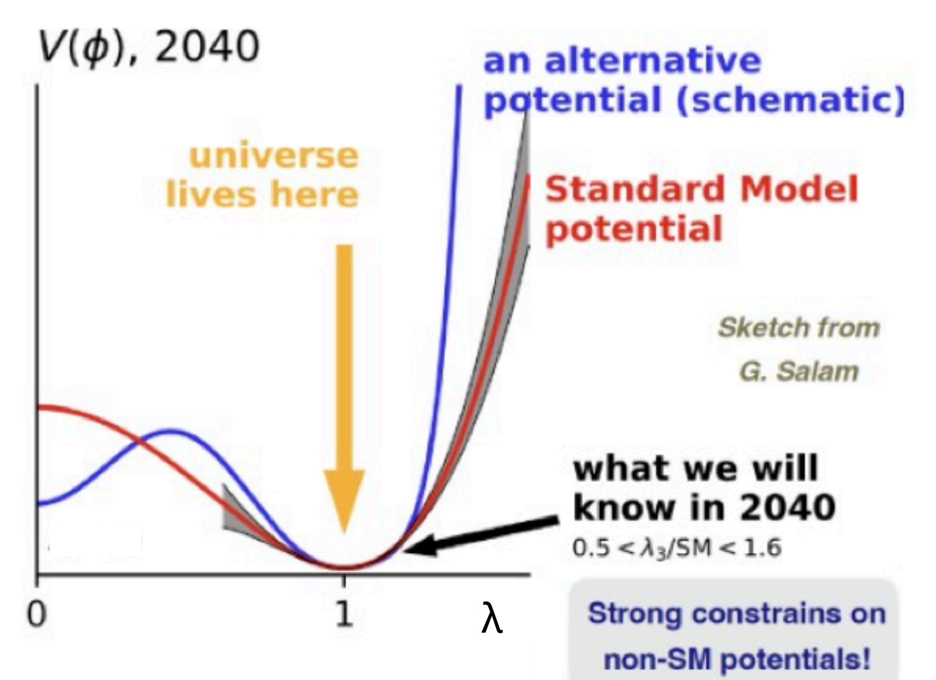
  - **First direct measure of the λ parameter**

LO SM Feynman diagrams





Higgs potential

Deep fundamental questions

- What is the order of the EW phase transition?
- What is the fate of the Universe? Is it stable?

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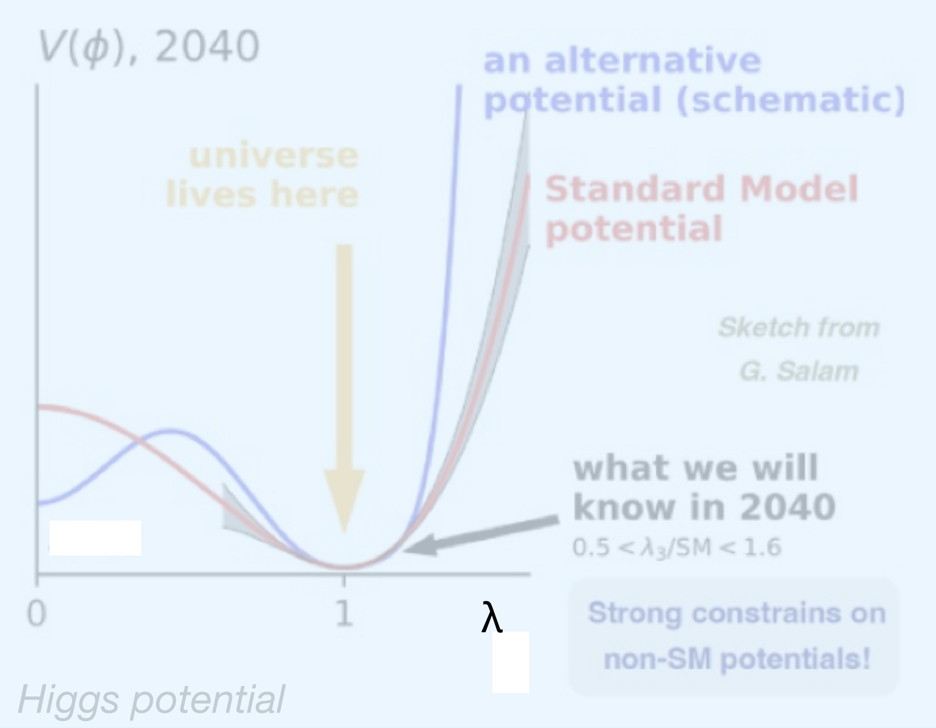

Not possible to answer to this question with HL, we will need more stats

Deep fundamental questions

- What is the order of the EW phase transition?
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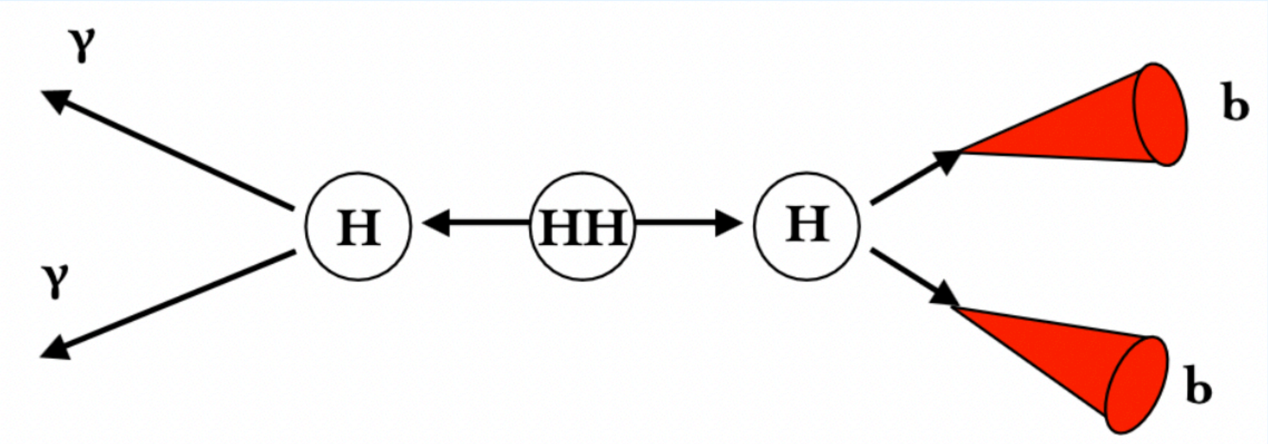
Projection method

- Projections to a integrated luminosity $L \rightarrow$ yields scaled by a factor $k_L = L/L_{Run2}$
- Efficiency of physics object reco, id, misid and resolution are assumed to be same as Run 2
- Projections provided in 3 systematic uncertainties scenarios (same as YR2018):
    - **S1:** same as Run 2
    - **S2:** unc. with stat. origin reduced by $1/\sqrt{k_L}$, theory unc. are halved, MCstat removed
    - **Stat. Only:** unc. frozen in the fit
- Lumi scenarios: 1000, 2000, 3000 fb-1
- Channels: 4b, bbγγ, bbττ, bbWW, multilepton

bbγγ final state

- **Pros:**
  - very clean final state,
  - Very good mass resultion
- **Contros:**
  - Low statistics
- **Main backgrounds:**
  - Non resonant γγ production
  - single H

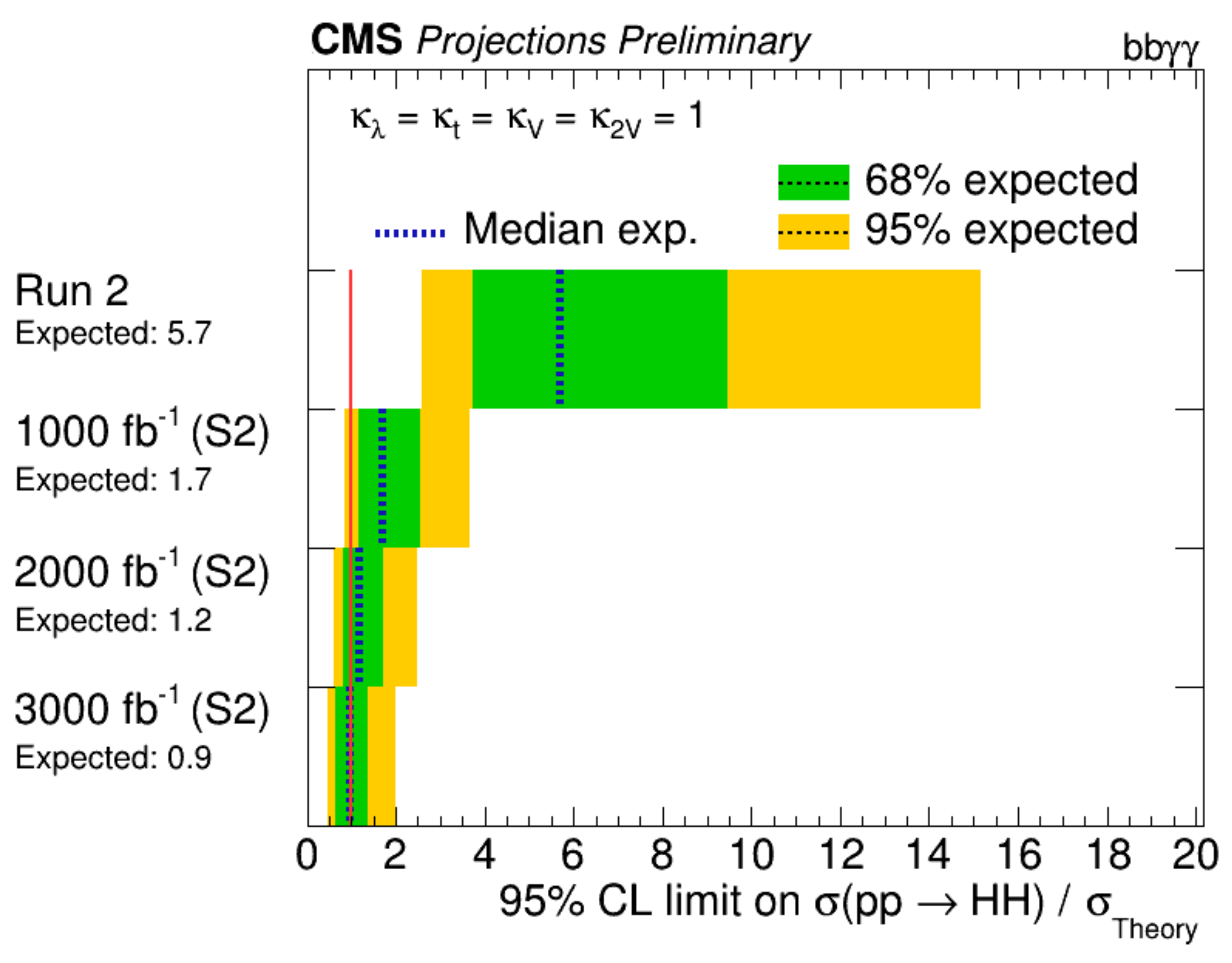


Analysis strategy:

- Select events with 2 photons and 2 bjets and using machine learning to suppres the single H background
- Fit simultaneously the $m_{\gamma\gamma}$ and m_{bb}

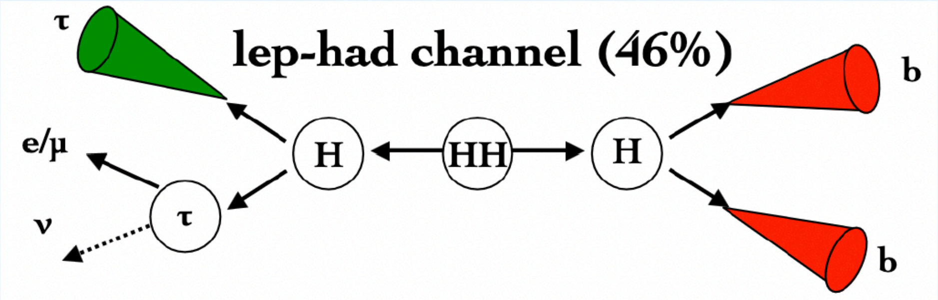
bbγγ final state

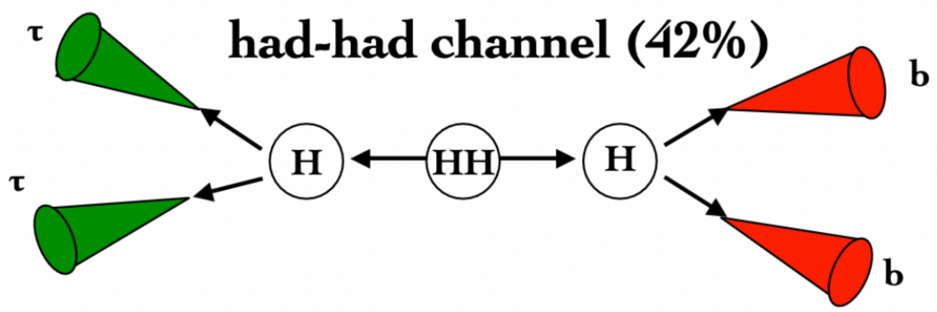
- Photon energy res. unchanged, id eff. scaled by max$(1/\sqrt{k_L}$, 0.5)
- Most impactful syst. are theory unc. and btag efficiency unc.
- Remains dominated by statistical uncertainties
- Improvement of ~30% wrt to YR2018



bbττ final state

- **Pros:**
  - Sizable branching ratio
  - Moderate bkg contamination
- **Contros:**
  - Neutrino in τ decay
  - Challenging τ reconstruction,especially for hadronic tau
- **Main backgrounds:**
  - DY/tt
  - singleH



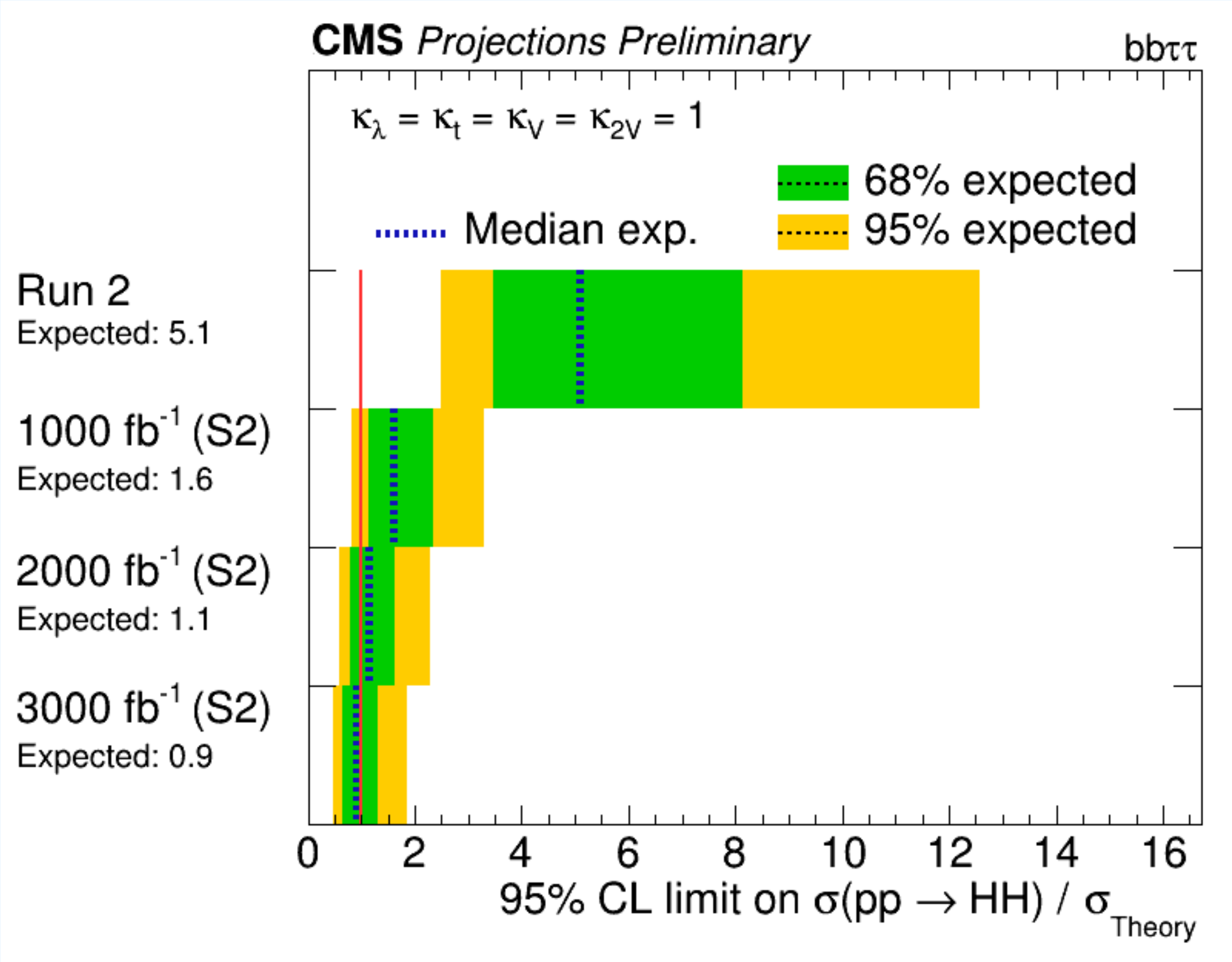


Analysis strategy:

- Events categorised depending on the tau decay mode asking for at least one hadronic tau
- single DNN training to extract signal
- fit the DNN score

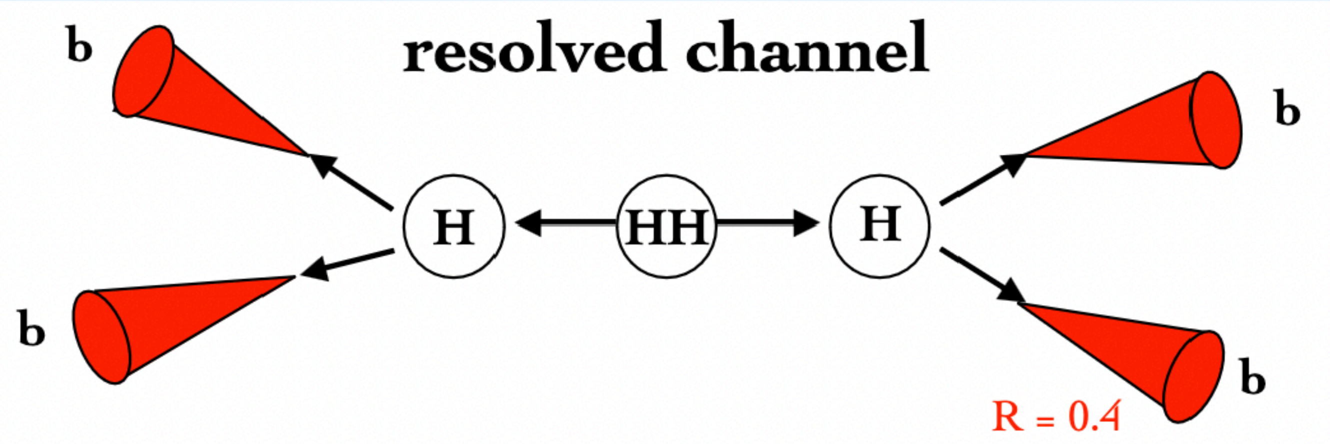
bbττ final state

- Removed unc. in ttbar/DY bkg normalization while QCD reduced by $1/\sqrt{k_L}$
- Remains dominated by statistical uncertainties
- Most impactful syst. are theory unc. and energy scale of jets and taus
- Improvement of ~50% wrt to YR2018



4b resolved final state

- **Pros:**
  - highest branching ratio
- **Contros:**
  - highest multijet background
- **Main backgrounds:**
  - QCD estimated from data

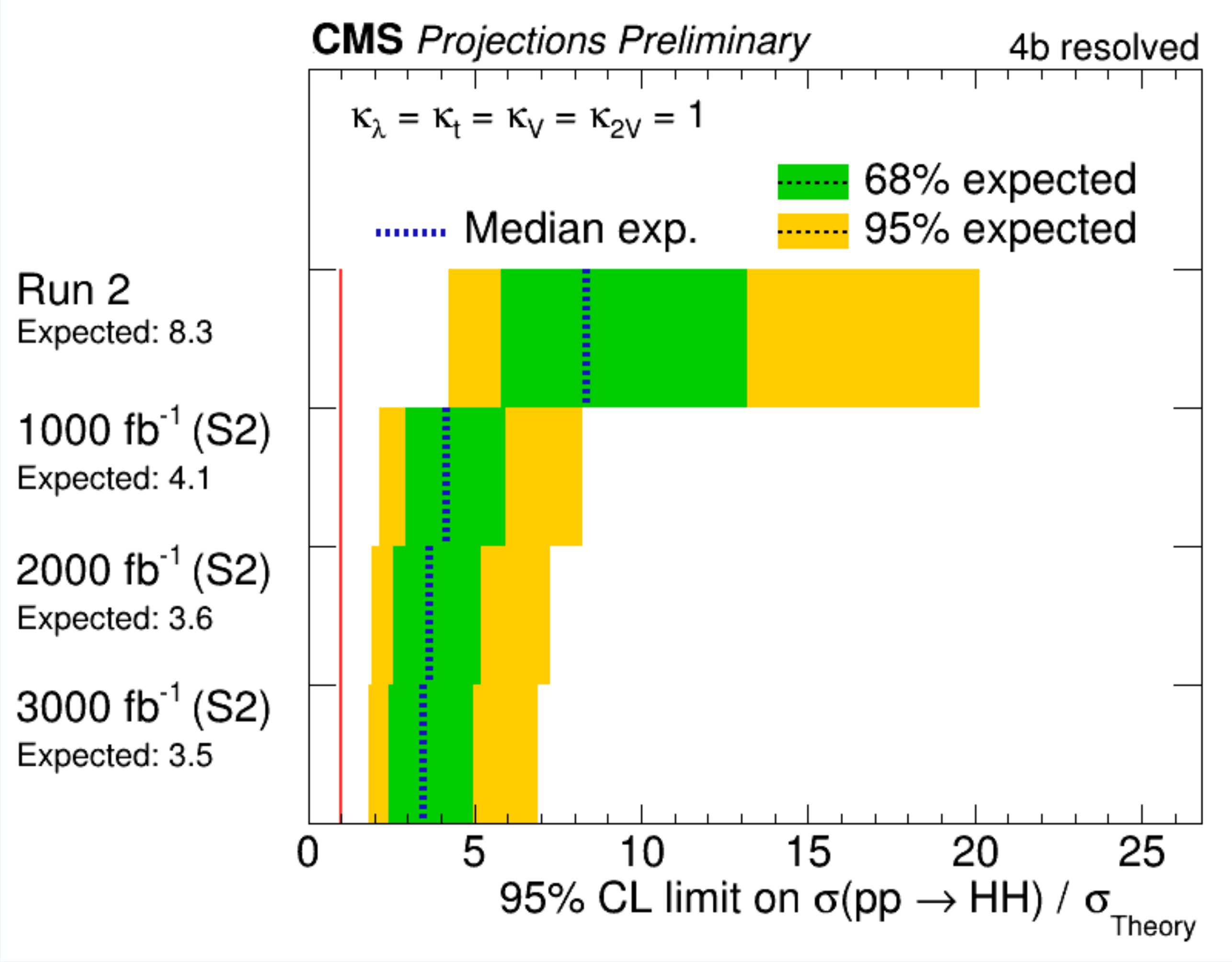


Analysis strategy:

- Select and pair the 4 bjets coming from the Higgses and train a DNN to separe the signal from the QCD background
- Fit the DNN score

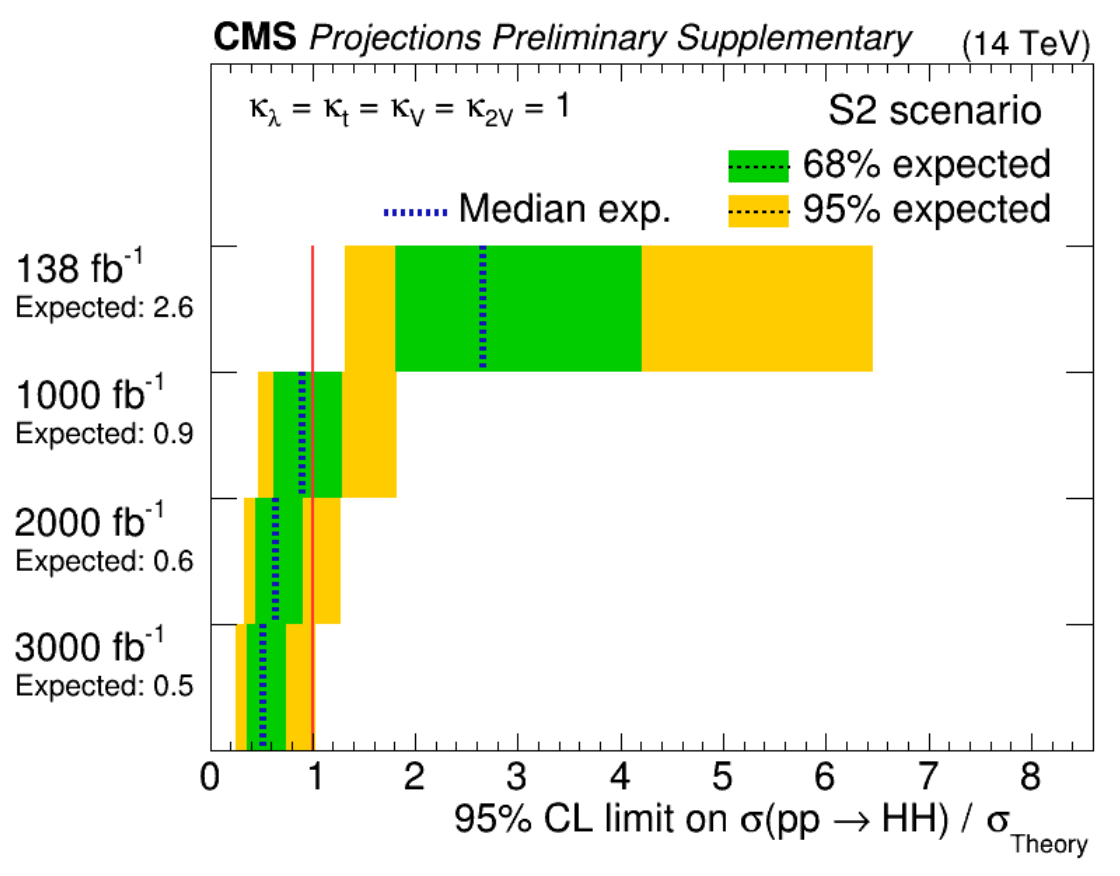
4b resolved final state

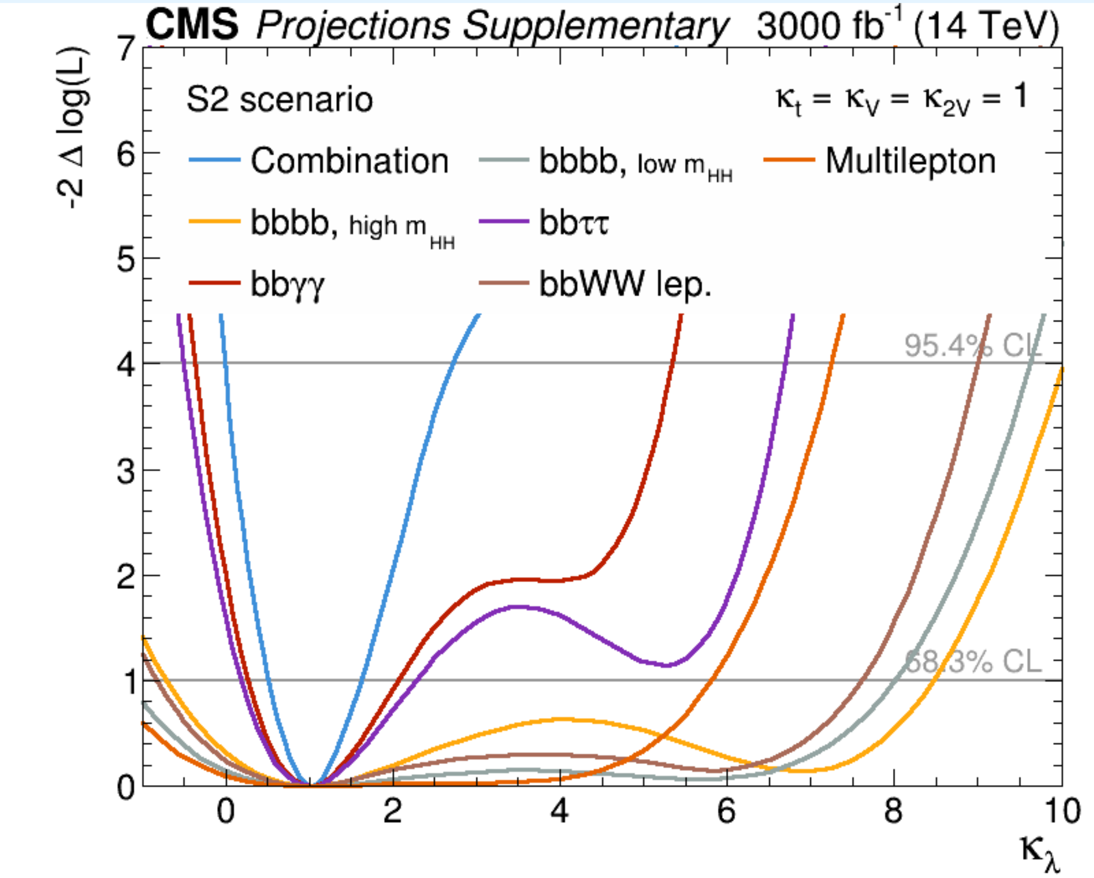
- Leading uncertainty is QCD estimation with data driven method
- Both normalization and shape unc. on data driven bkg are reduced by $1/\sqrt{k_L}$



Combination results

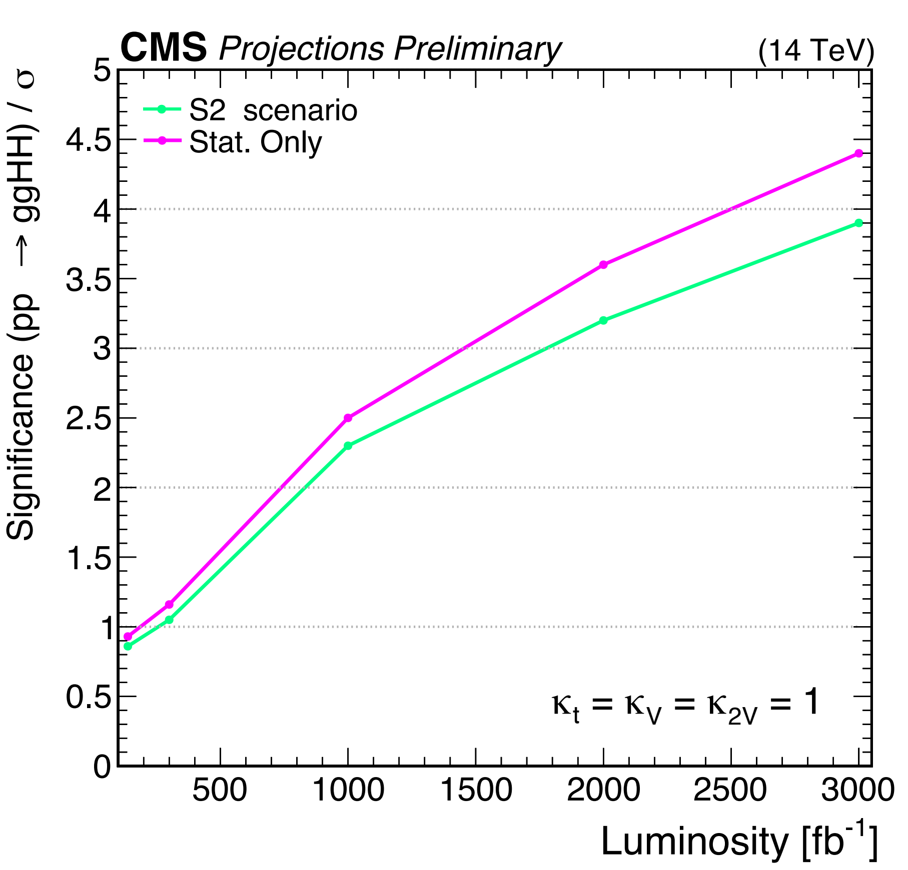
- bbγγ and bbττ lead the combination
- Improvement > 30% wrt YR2018 (upper limit 0.77)





Combination results - significance

- Improvement of ~50% wrt YR2018, mainly driven by bb$\tau\tau$ improvement (same sensitivity as bb$\gamma\gamma$!)
- Expected evidence from ~2000 fb^{-1}
- Combined with ATLAS results (compatible expected significance) → HH observation!



	2000 fb^{-1}		3000 fb^{-1}	
Channel	S2	Stat.Only	S2	Stat.Only
4b resolved	1.0	1.3	1.4	1.6
4b boosted	1.7	1.7	2.0	2.1
bbγγ	1.8	1.9	2.2	2.3
bbWW	0.6	0.8	0.7	0.9
Bbττ	1.8	1.9	2.2	2.3
multilepton	0.4	0.6	0.4	0.7
Comb.	3.2	3.6	3.9	4.4

Conclusions

HL will be a unique opportunity for singleH and HH searches

- High luminosity up to 3000fb^{-1} $\rightarrow$ open new possibilities of studying rare channels as H $\rightarrow$ $\gamma\gamma$ and H $\rightarrow$ $\mu\mu$ and HH

- Update of the detector $\rightarrow$ better object reconstruction

- Best results on the Higgs sector for the next decades

With the new HH projections we will be able to observe the HH process:

- Strong proof of the SM stability
- Precision on λ will give us informations on the EW phase transition of the universe

Looking forward to it!!!!