Highlights of the HL-LHC Physics Projections by ATLAS and CMS

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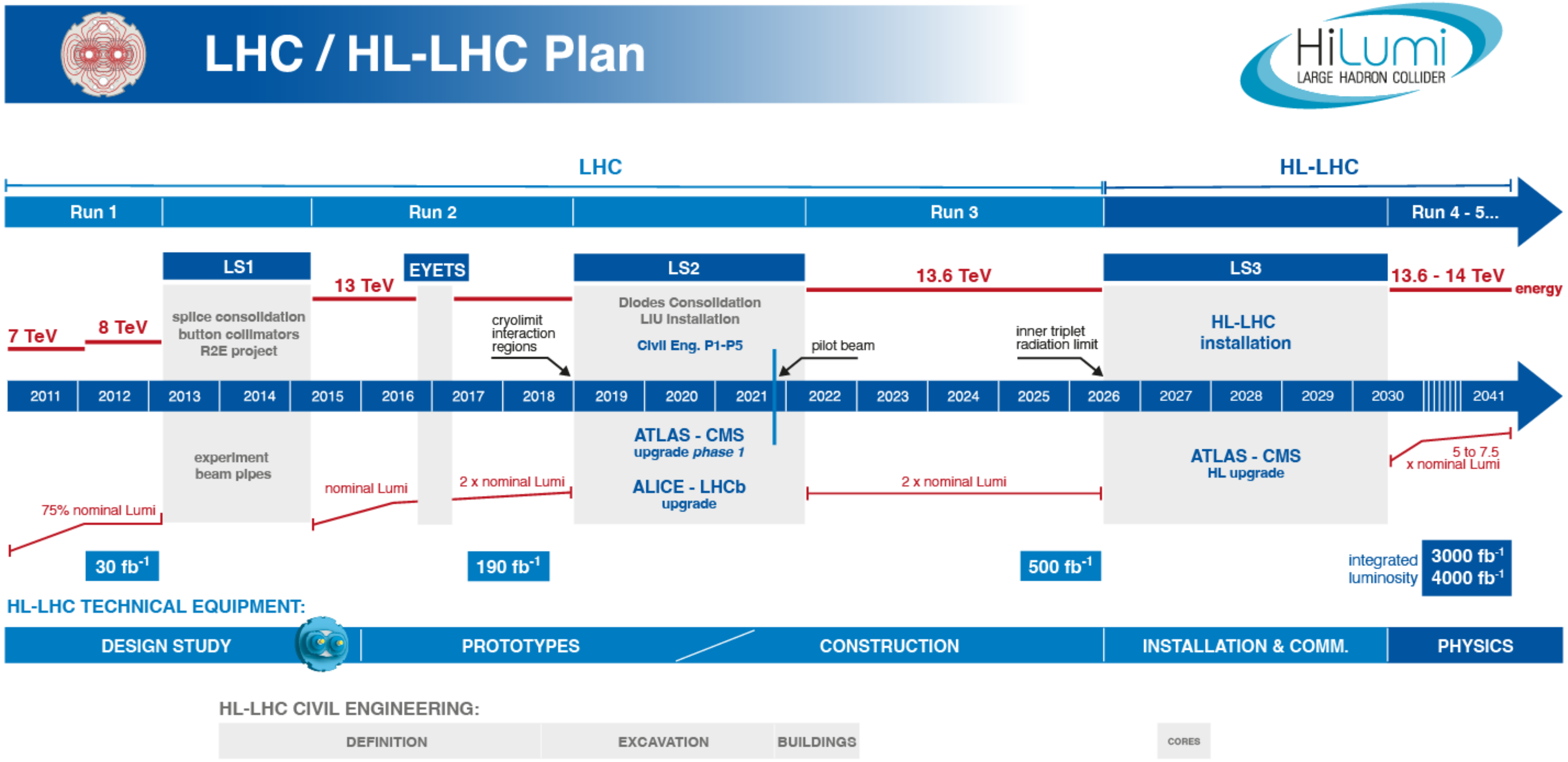
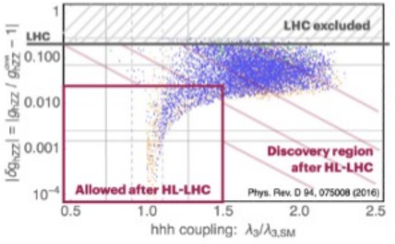
LHC / HL-LHC Schedule



Overview

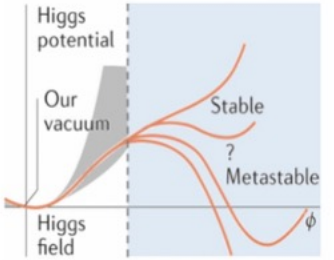
- **European Strategy for Particle Physics is the cornerstone for Europe's long-term decision making process**
- Last update from 2020
  - Priority on the successful completion of HL-LHC
  - Higgs factory as the highest priority to follow LHC
- **Contents of this work**
  - Importance of the full **3 ab^{-1}**
  - Concentrate on the **precision** measurement
  - **EWSB mechanism probed from all angles**
    - H; HH; HHH
    - A heavy scalar
    - BEH potential and a first-order phase transition
    - Interplay between precision Higgs physics and searches for a heavy scalar singlet
    - M_{top} and M_H and their impact on the EW vacuum stability
    - Diboson scattering
    - Rare top quark processes and EFT bounds

precision H



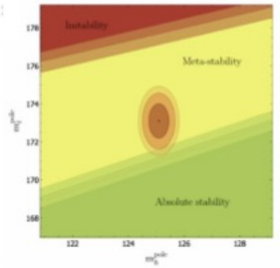
HH - $\kappa_{\lambda 3}$

HHH - $\kappa_{\lambda 4}$



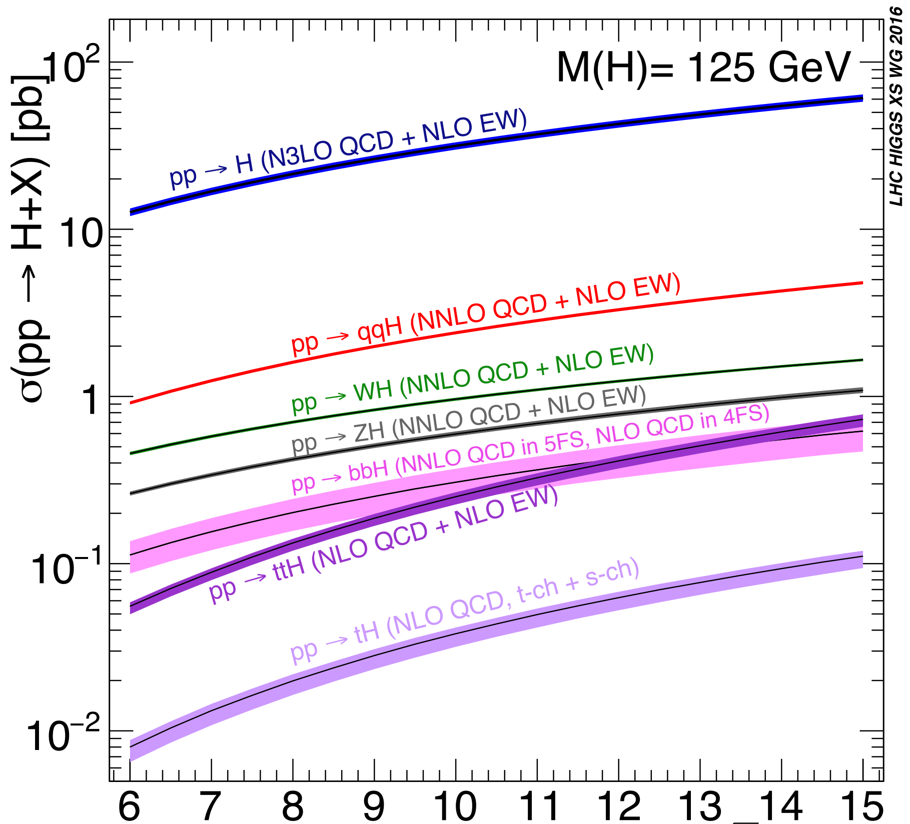
$S \rightarrow HH$ | $S \rightarrow ZZ$ | $t\bar{t}S \rightarrow t\bar{t}t\bar{t}$ | VBS $W_L W_L$

m(H)



m(top) | m(W)? | 4 tops | tt+X

Higgs production at LHC



[LHCHXSWG]

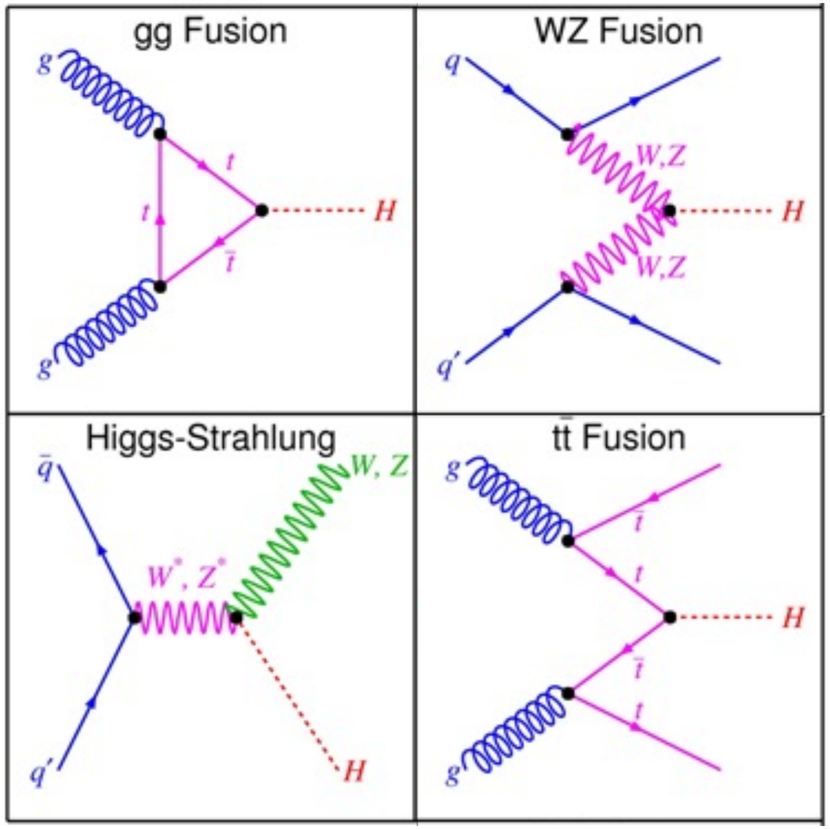
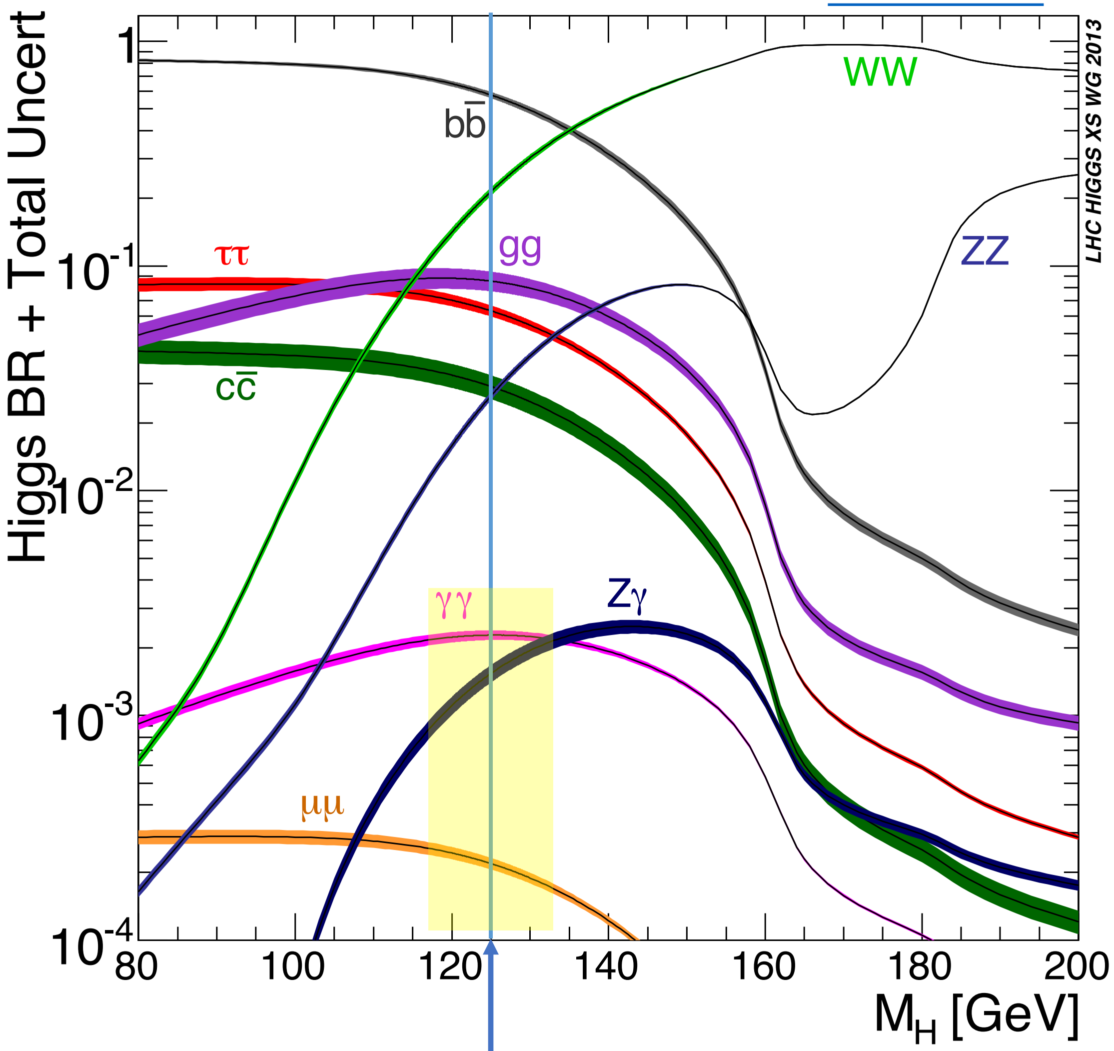


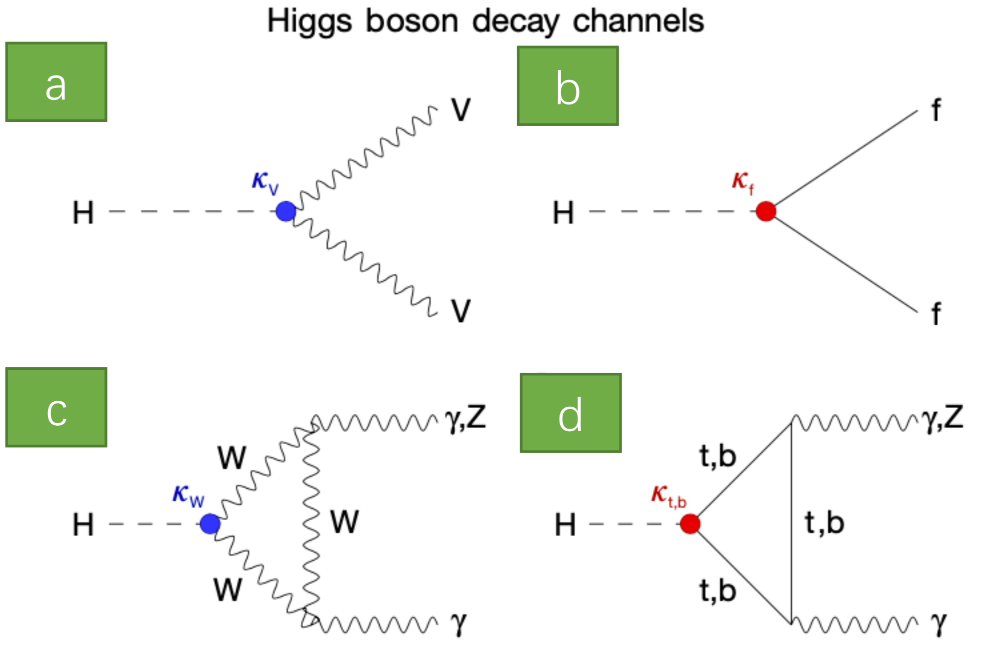
Fig. Feynman diagram of each production model

- Main production model and its cross section at 13TeV and Higgs mass of 125GeV
- Gluon-Gluon Fusion: 48.58 pb
- VBF: 3.782pb
- VH: 1.373pb(WH); 0.8839pb(ZH)
- ttH: 0.5071pb

Higgs decay at LHC

[LHCHXSWG]





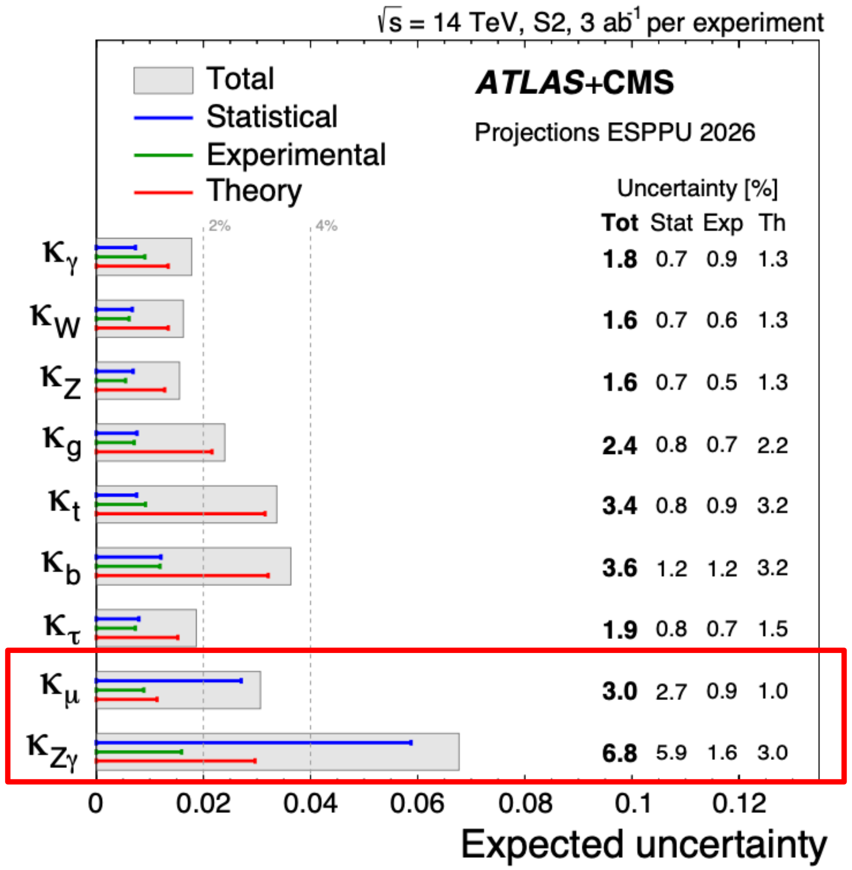
- Higgs boson decays into
  - Heavy vector boson pairs (**a**)
  - Fermion–antifermion pairs (**b**)
  - Photon pairs or Zγ (**c**,**d**)

[Nature 607 (2022) 60–68]

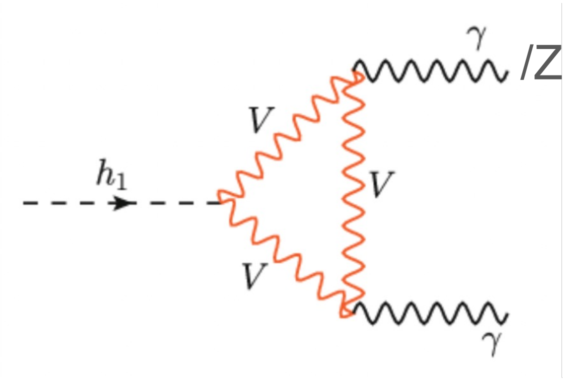
H rare decay channel H→Zγ and H →μμ is our interest in Run III and HL-LHC

Single H precision --- CMS+ATLAS

- Higgs boson coupling modifiers improvement in Higgs rare decay channels
  - $\delta\kappa_{\mu} = 3.0\%$; $\delta\kappa_{Z\gamma} = 6.8\%$ while still dominated by statistical Uncertainty
- Considering the improvements in b, c-jet tagging techniques, a **1.6σ significance** is expected for the **VH → cc** process.
  - $|\kappa_c| < 1.5$ at 95% CL
- Constrains on **Higgs Width** via H → ZZ off-shell cross section Γ_H with an uncertainty of 0.7 MeV



Single H precision - H→Zγ



- Motivation: probe new physics in the quantum loop

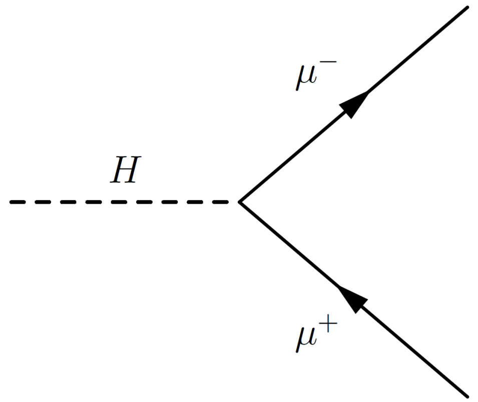
- Small branching ratio in SM (1.6×10^{-3})
  - Measurement driven by statistical uncertainty

$\mathcal{L}$		$\delta\mu$ [%] $H \to Z\gamma$	$H \to \mu\mu$
2 ab^{-1}	ATLAS	21	13
	CMS	23	8.4
	ATLAS+CMS	15	7.1
3 ab^{-1}	ATLAS	17	11
	CMS	19	7.0
	ATLAS+CMS	14	5.9

Single experiment discovery can be reached at the intermediary stages of the HL-LHC

A combination of the run 2 results with ATLAS is published in PRL. 132 (2024) 021803

Single H precision - H→μμ



- Motivation: probe Higgs boson couplings with the 2nd fermion generation

- Small branching ratio in SM (2.2 x 10^{-4})
  - Measurement driven by statistical uncertainty

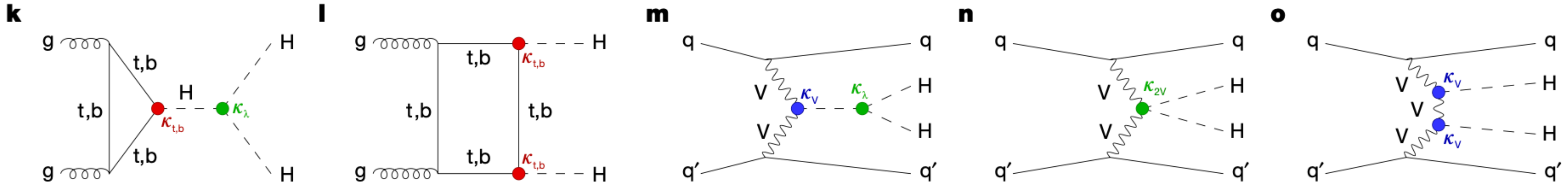
$\mathcal{L}$		$\delta\mu$ [%] $H \to Z\gamma$	$\delta\mu$ [%] $H \to \mu\mu$
2 ab^{-1}	ATLAS	21	13
	CMS	23	8.4
	ATLAS+CMS	15	7.1
3 ab^{-1}	ATLAS	17	11
	CMS	19	7.0
	ATLAS+CMS	14	5.9

Run3 analysis: hopefully observe the H→μμ decay with more than 5σ

Di-Higgs boson physics

- Double H production in ggF is the most direct probe on the H potential
  - Small cross section -> process still undetected
  - Searches provide direct constraints on the H self coupling

Higgs boson pair production



- In S3 scenario, 5% Jet tagging and hadronic tau reconstruction improvements by public material is extrapolated

On the ESU note: Interpretations of these results with direct implications in the determination of the phase transition and baryogenesis are being derived. We can also see the interplay with resonance searches in this context

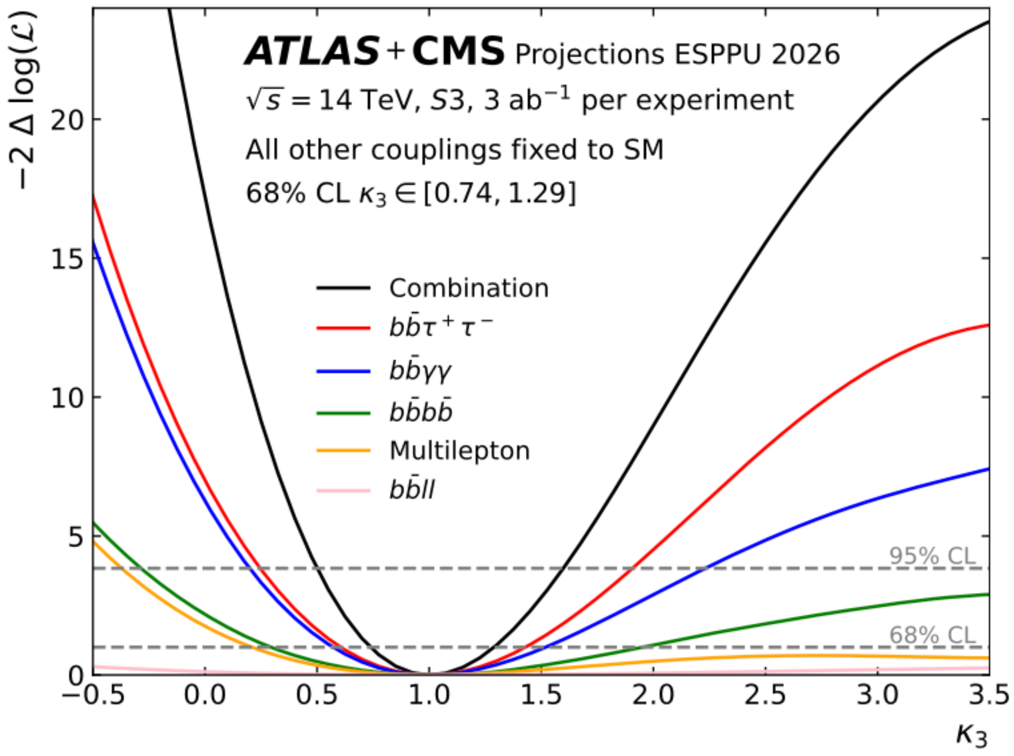
Di-Higgs boson physics

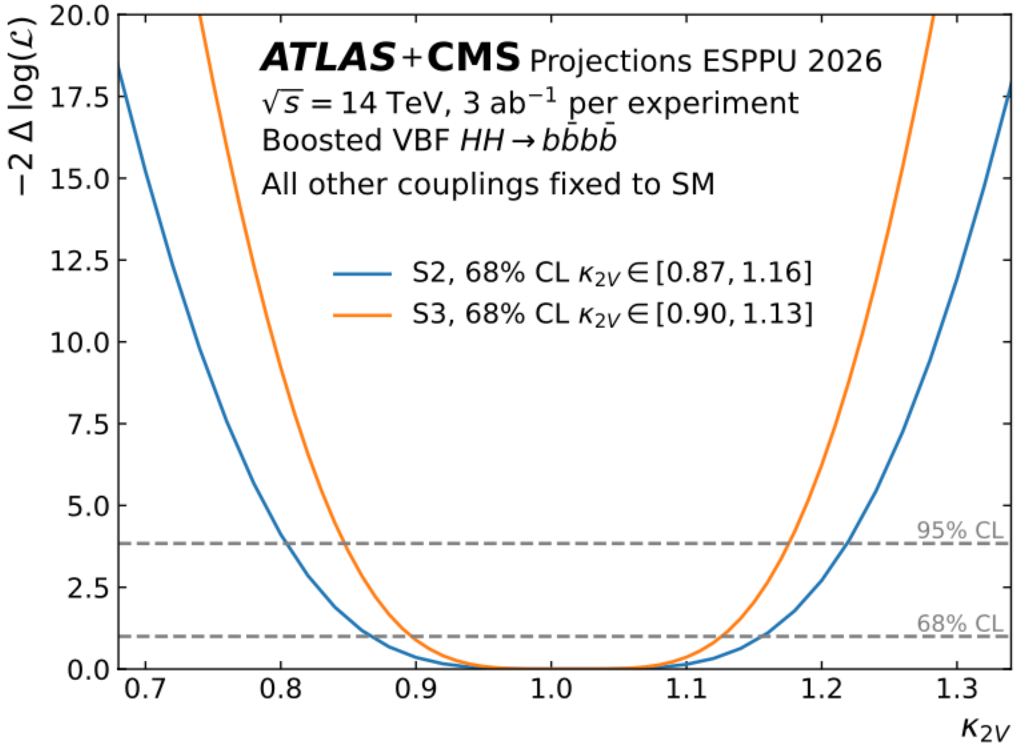
- Expected significance on HH signal yield and at 68% CL on κ_3
- From luminosity **2 to 3 ab^{-1}** brings a gain of **20%** on the signal significance while From **S2 to S3 brings 5%** gain in precision
  - bb$\tau\tau$ channel holds a significant difference compared with CMS and ATLAS.
  - Expected to be recovered with new hadronic tau triggers adoption in CMS

	2 ab^{-1} ($S2$) ATLAS	2 ab^{-1} ($S2$) CMS	3 ab^{-1} ($S2$) ATLAS	3 ab^{-1} ($S2$) CMS	3 ab^{-1} ($S3$) ATLAS	3 ab^{-1} ($S3$) CMS
HH statistical significance						
$b\bar{b}\tau^+\tau^-$	3.0†	1.9	3.5†	2.4	**3.8†**	**2.7**
$b\bar{b}\gamma\gamma$	2.1†	2.0†	2.4†	2.4†	**2.6†**	**2.6†**
$b\bar{b}b\bar{b}$ resolved	0.9	1.0†	1.0	1.2†	**1.0**	**1.3†**
$b\bar{b}b\bar{b}$ boosted	–	1.8†	–	2.2†	–	**2.2†**
Multilepton	0.8†	–	1.0†	–	**1.0†**	–
$b\bar{b}\ell^+\ell^-$	0.4†	–	0.5†	–	**0.5†**	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	
κ_3 68% confidence interval						
$b\bar{b}\tau^+\tau^-$	[0.3, 1.8]†	[0.1, 3.0]	[0.4, 1.7]†	[0.2, 2.2]	**[0.5, 1.6]†**	**[0.3, 2.0]**
$b\bar{b}\gamma\gamma$	[0.3, 2.0]†	[0.2, 2.3]†	[0.4, 1.8]†	[0.3, 2.0]†	**[0.5, 1.7]†**	**[0.4, 1.9]†**
$b\bar{b}b\bar{b}$ resolved	[−0.7, 6.3]	[−0.6, 7.6]†	[−0.5, 6.1]	[−0.3, 7.3]†	**[−0.5, 6.1]**	**[−0.3, 7.2]†**
$b\bar{b}b\bar{b}$ boosted	–	[−0.6, 8.5]†	–	[−0.4, 8.2]†	–	**[−0.4, 8.2]†**
Multilepton	[−0.2, 4.9]†	–	[−0.1, 4.7]†	–	**[−0.1, 4.7]†**	–
$b\bar{b}\ell^+\ell^-$	[−2.4, 9.3]†	–	[−2.2, 9.2]†	–	**[−2.1, 9.1]†**	–
Combination	[0.6, 1.5]	[0.4, 1.7]	[0.6, 1.5]	[0.5, 1.6]	**[0.6, 1.4]**	**[0.6, 1.5]**
ATLAS+CMS uncertainty	−32% / +37%		−27% / +31%		**−26% / +29%**	

† *used in the ATLAS+CMS combination*

Di-Higgs boson physics

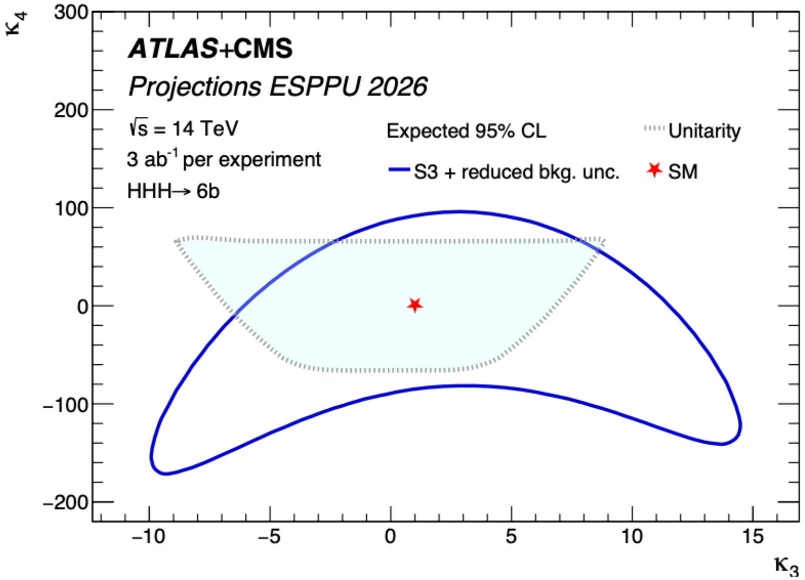




If SM is truth, the HH process will be observed in the HL-LHC
The H self coupling will be measured with ~ 30 % precision

Triple Higgs boson production

Probe quartic Higgs couplings λ_4



- Search for HHH production in the 6b final state
- Expected limit on HHH cross section for S3 scenarios is **86 times** the SM expectation
- With this precision, ATLAS and CMS will start excluding portions of the region bounded by the unitarity limit.

Additional scalar resonances

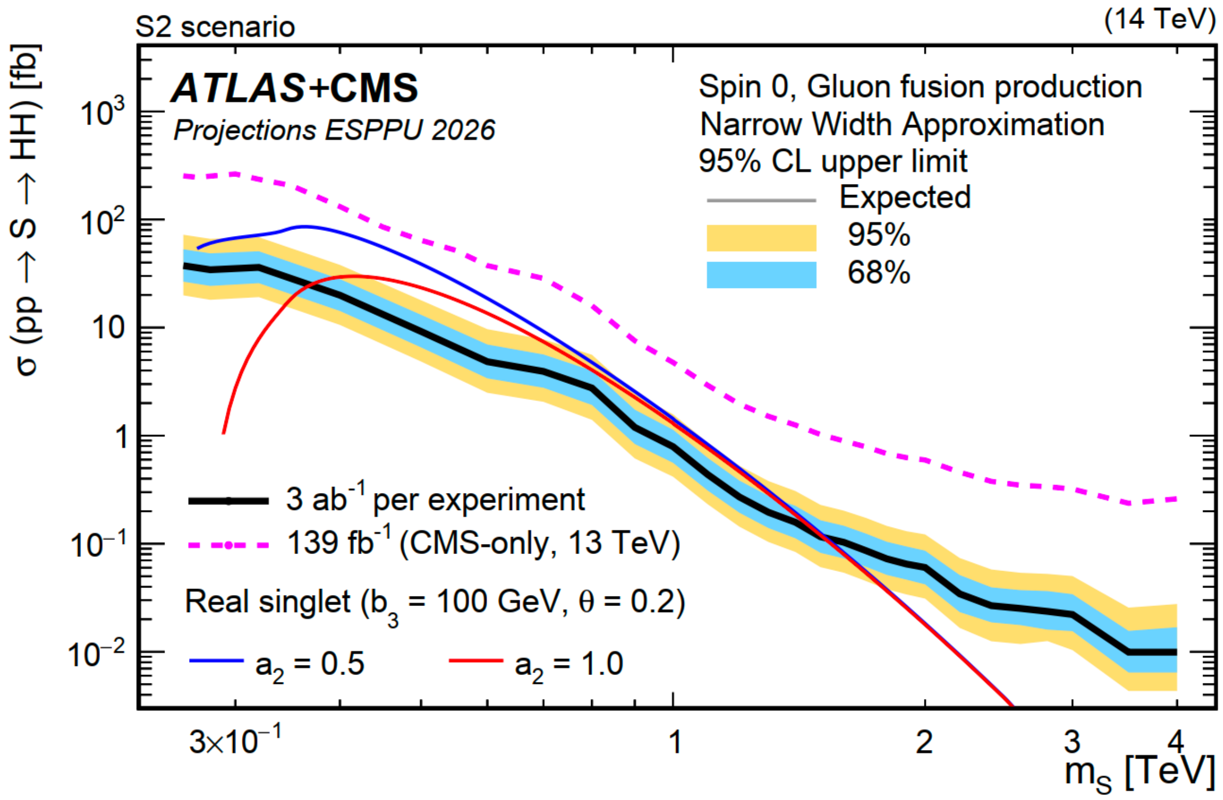
- **Indicate the existence of an extended Higgs sector**
  - Induces modifications in the H potential and couplings
  - As direct interpretation on the ESU note, a model considering one **singlet extension** will connect these searches with the **EWSB mechanism**
    - **In this model**, It is checked by the theorists involved that in most of the non-excluded (by EWPO) parameter space the Narrow Width approximation (NWA) regime is valid

- **Three channels are considered**
  - $S \rightarrow t\bar{t}$: ttbar irreducible BKG large and peak-dip structure of signal more sensitive to interferences arising even with small widths.
  - $S \rightarrow ZZ \rightarrow 4l$
  - $S \rightarrow HH$

The irreducible BKG is not large, and NWA is safely assumed

Together with non-resonant HH production

Additional scalar resonances （ggF Scalar → HH）



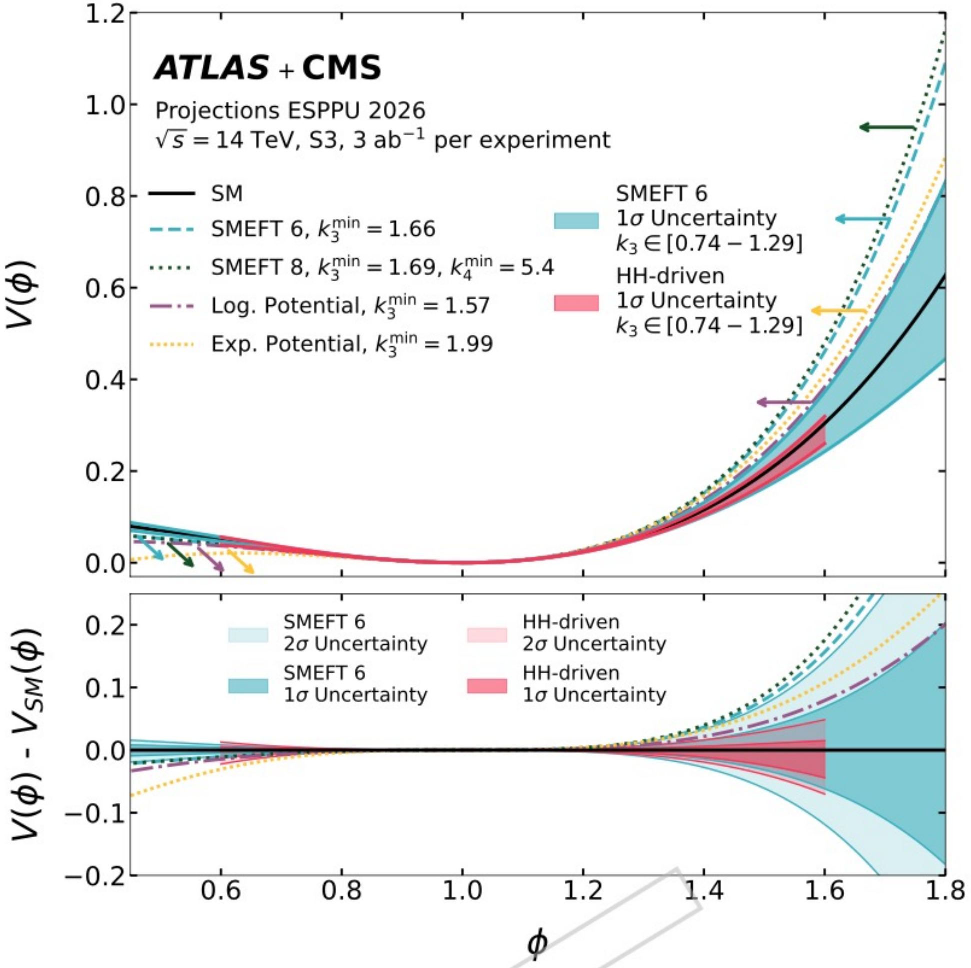
- Projection based on combination of three more sensitive channels $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$ (boosted)
- Expected 95% CL upper limits on the σ(pp → S → HH) cross section as a function of the scalar mass m_S , produced via gluon fusion using the narrow width approximation.
  - It is conservative as other channels are expected to contribute at masses up to ~1TeV

Interpretation

Constraining the shape of the BEH potential

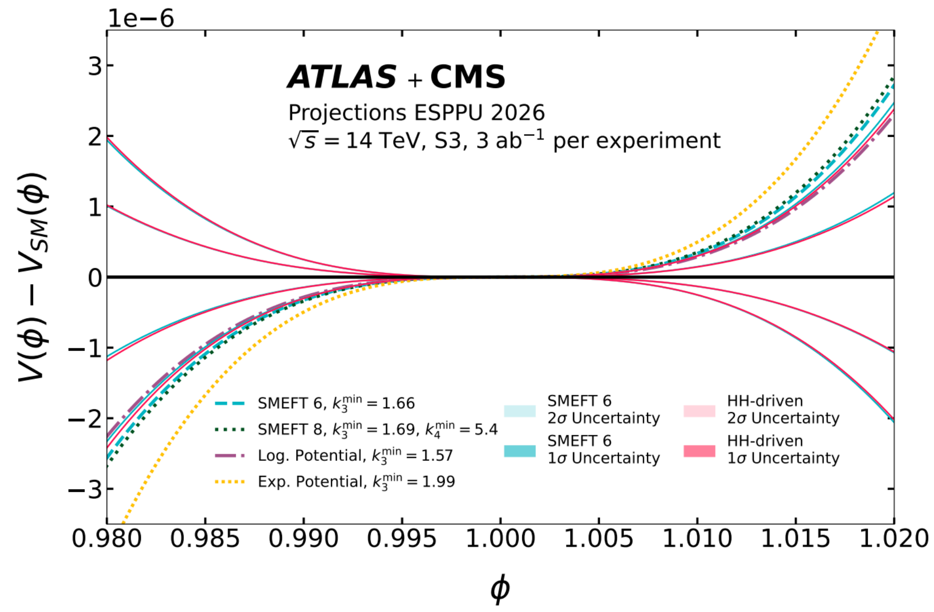
- Tree level, HH is sensitive to κ_3
- Higgs self-coupling alone is **insufficient** to fully determine or constrain the shape of the EWSB potential.
- In order to provide **model-independent** conclusions on fundamental questions, such as **whether** the **EWSB transition is first-order** (a key element for EW baryogenesis) an **assumption about the form of the potential is generally required**.
- Assume that a new heavy particles lie beyond <u>a large energy scale</u> cut-off Λ and hence <u>cannot be produced at the LHC</u>

variations of the shapes could allow a strong FOPT in the early universe



Constraining the shape of the BEH potential

- **HH-driven** and **SMEFT 6** potential are identical around the minimum where the effect of higher-order terms is negligible.



Exclude as good as all possible strong-FOPT scenarios across the four alternative hypotheses with 3 ab^{-1} at 95% CL

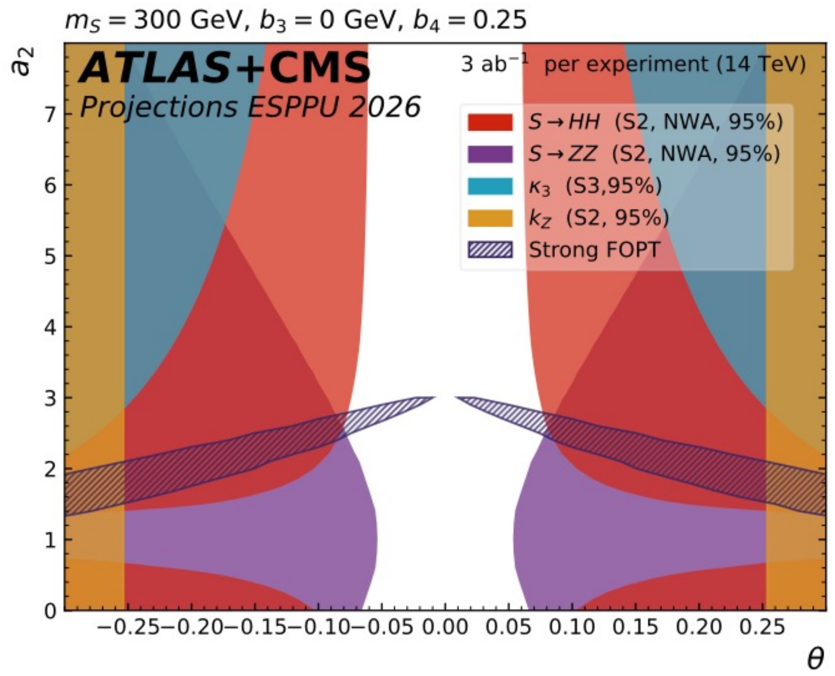
At the end of the HL-LHC operation it would be of extreme importance to our understanding of the origin of the universe and would be a unique result for decades to come.

Interplay between precision Higgs physics and searches for a heavy scalar singlet

$$V(\Phi, S) = -\mu_H^2|\Phi|^2 + \lambda_H|\Phi|^4 + b_1 S - \frac{\mu_S^2}{2}S^2 + \frac{b_4}{4}S^4 + \frac{a_2}{2}|\Phi|^2 S^2 + \frac{b_3}{3}S^3 + \frac{a_1}{2}|\Phi|^2 S.$$

A minimal extension of the SM involve a new real scalar singlet S

- Modifications of the H couplings to SM particles
- Additional heavy scalar can decay into a pair of Higgs bosons, and modify three- and four-point Higgs self-interactions.
- The enriched scalar potential dynamics enable the possibility of a strong FOPT
- This phase transition could also be probed in a complementary way through gravitational wave observations
- Additionally, stability of vacuum for large field configurations can be affected



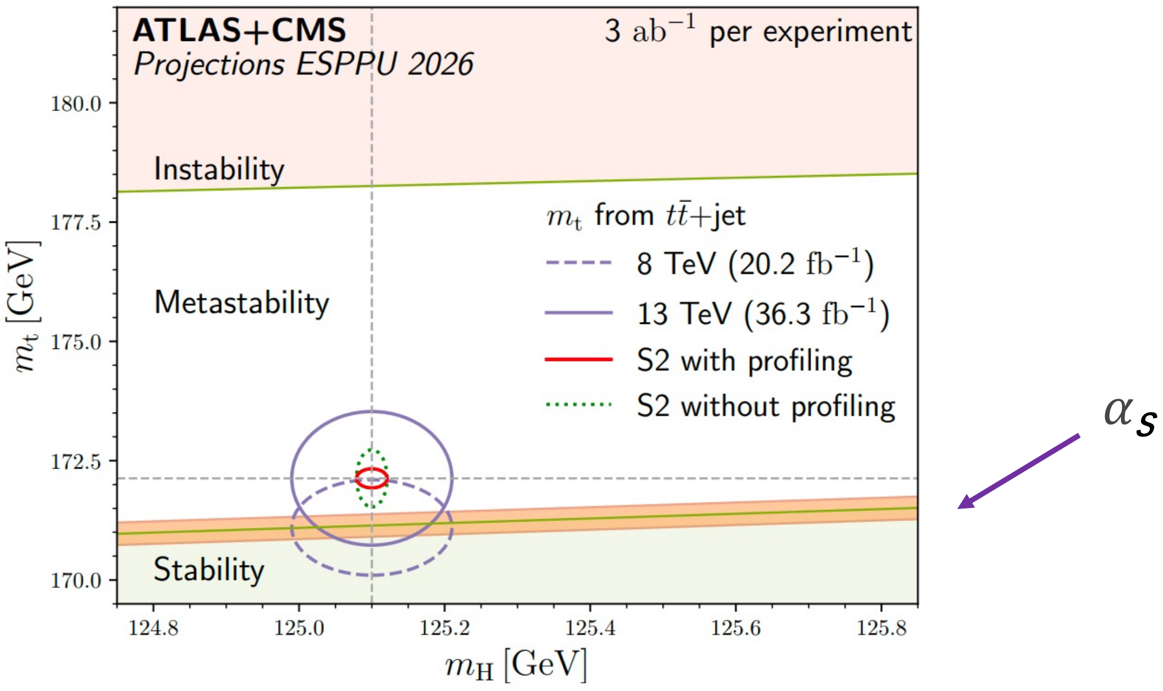
Exclusion of a large portion of the phase space with a strong FOPT is achieved in scenario *S3* with 3 ab^{-1}

Back to measurements

Top quark mass and Higgs mass

- **The top mass is a major source of uncertainty in key theory predictions on SM**
  - Together with the H mass and the H potential it determines the state of (meta)stability of universe

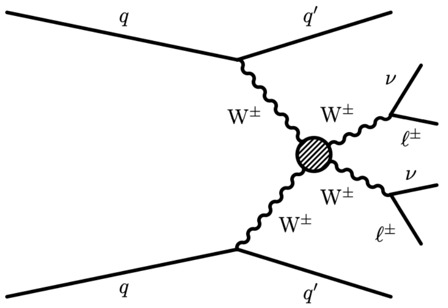
- Results on the pole top mass from naive combination of the extrapolations from both experiments
- Optimistically we achieve an uncertainty of 200 MeV on the pole top mass with profiling method
- Higgs mass precision: 21 MeV



Assuming the central values of the masses the same as measured at present, and assuming the value of α_s as the current world average

Even in the most conservative scenario (unprofiled combination) the meta-stability of the universe will be determined by the end of HL-LHC

Vector Boson Scattering

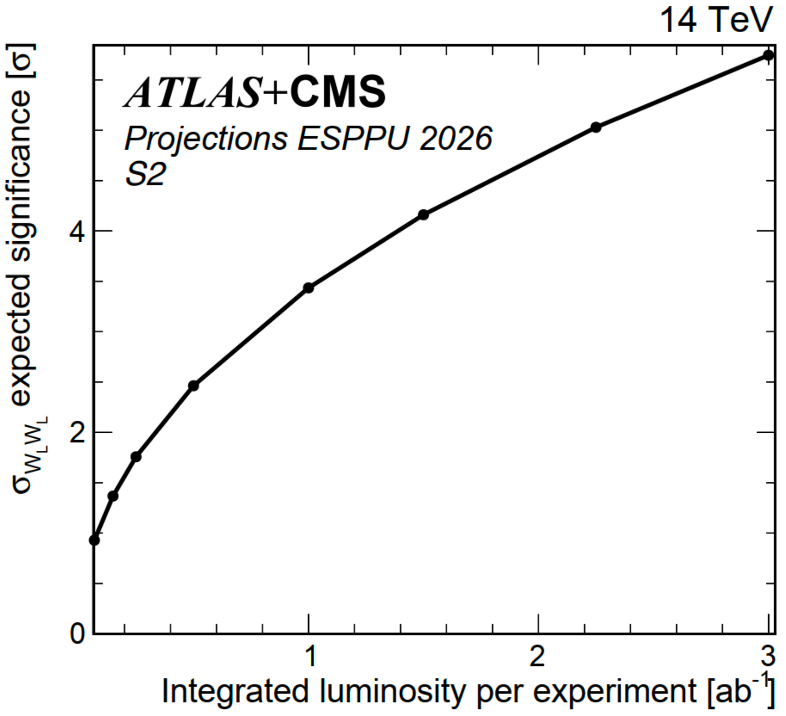


- **Test of unitarity of the SM by measuring longitudinally polarized V bosons**
  - Complementarity probe of EWSB mechanism with respect to Higgs physics

ATLAS+CMS combined uncertainty			
Scenario	$W^{\pm}W^{\pm}$	$W_L^{\pm}W_L^{\pm}$	$W^{\pm}Z$
S2	2.9%	17.5%	5.9%

Extrapolation of the ATLAS+CMS combined uncertainty in 3 ab^{-1} on production cross section of gauge bosons by VBS

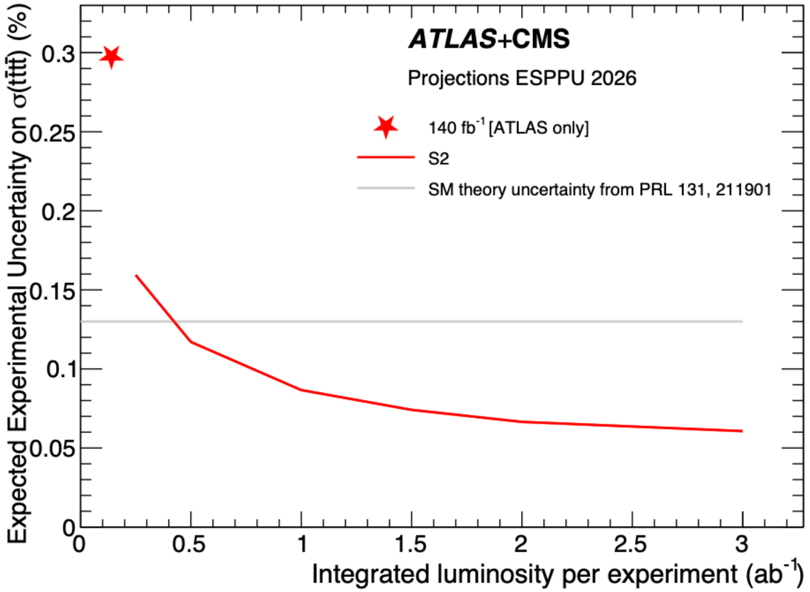
Total cross section measurement is greatly improved with better control of systematics,
The longitudinal part is statistically dominated

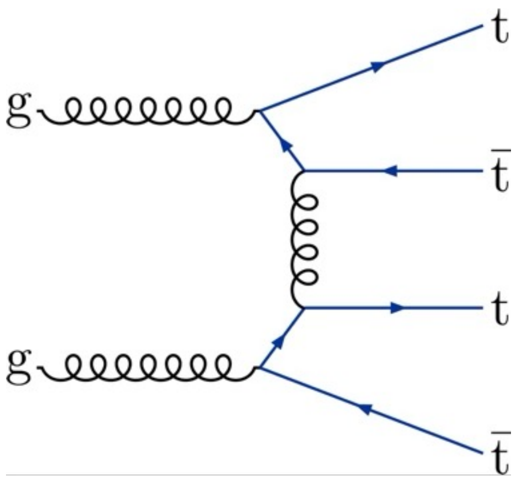


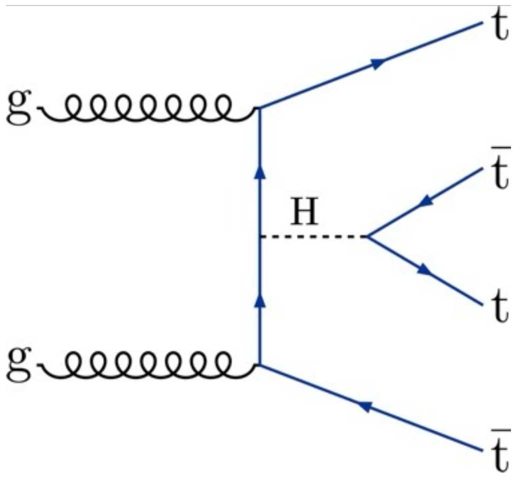
Observation of longitudinal VV production in VBS by the middle of the HL-LHC program !!!

Four Top Production

- **Provides sensitivity to new physics and Higgs-top Yukawa coupling**







With 3 ab^{-1}, the expected uncertainty in the four top quark production cross-section is 6%, and a 95% CL limit on yt $\lesssim$ 1.5 is obtained

HL-LHC will achieve long-term world's best sensitivity

HL-LHC Physics Prospects

- **HL-LHC serving as unique drivers of fundamental understanding of nature**
  - Aiming for an integrated luminosity of 3 ab^{-1}
- Precision Higgs measurements ($\boldsymbol{\delta\kappa_{\mu}}$~3%; $\boldsymbol{\delta\kappa_{Z\gamma}}$~6.8%)
- Di-Higgs (**HH**) production: significance >7σ with CMS+ATLAS; trilinear coupling $\boldsymbol{\kappa_3}$ precision ~30%
- Strong constraints on **Beyond Standard Model** scenarios, probing first-order phase transitions (matter-antimatter asymmetry)
- Precise measurement of **Top quark mass** (Unc. ~200-400 MeV) and **Higgs mass** (Unc. ~21 MeV), unveiling the **stability of the universe**
- Crucial to reduce **theoretical uncertainties** to fully utilize the HL-LHC potential
- Providing a more **realistic assessment** of the HL-LHC physics reach, as input to the discussion on the choice of a **future collider**

Thanks for Listening!