Updated expectations of the HL-LHC physics legacy

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be.HEP Solstice Meeting

What is the HL-LHC about?

- who thinks “about our fundamental scalar”?

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- who thinks “about BSM physics”?

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- who thinks “about our fundamental scalar”?
- who thinks “about BSM physics”?
- who thinks “about flavour”?

What is the HL-LHC about?

- who thinks “about our fundamental scalar”?
- who thinks “about BSM physics”?
- who thinks “about flavour”?
- who thinks “about heavy ions”?

What is the HL-LHC about?

about our fundamental scalar

about BSM physics

about flavour

about heavy ions

All of this!

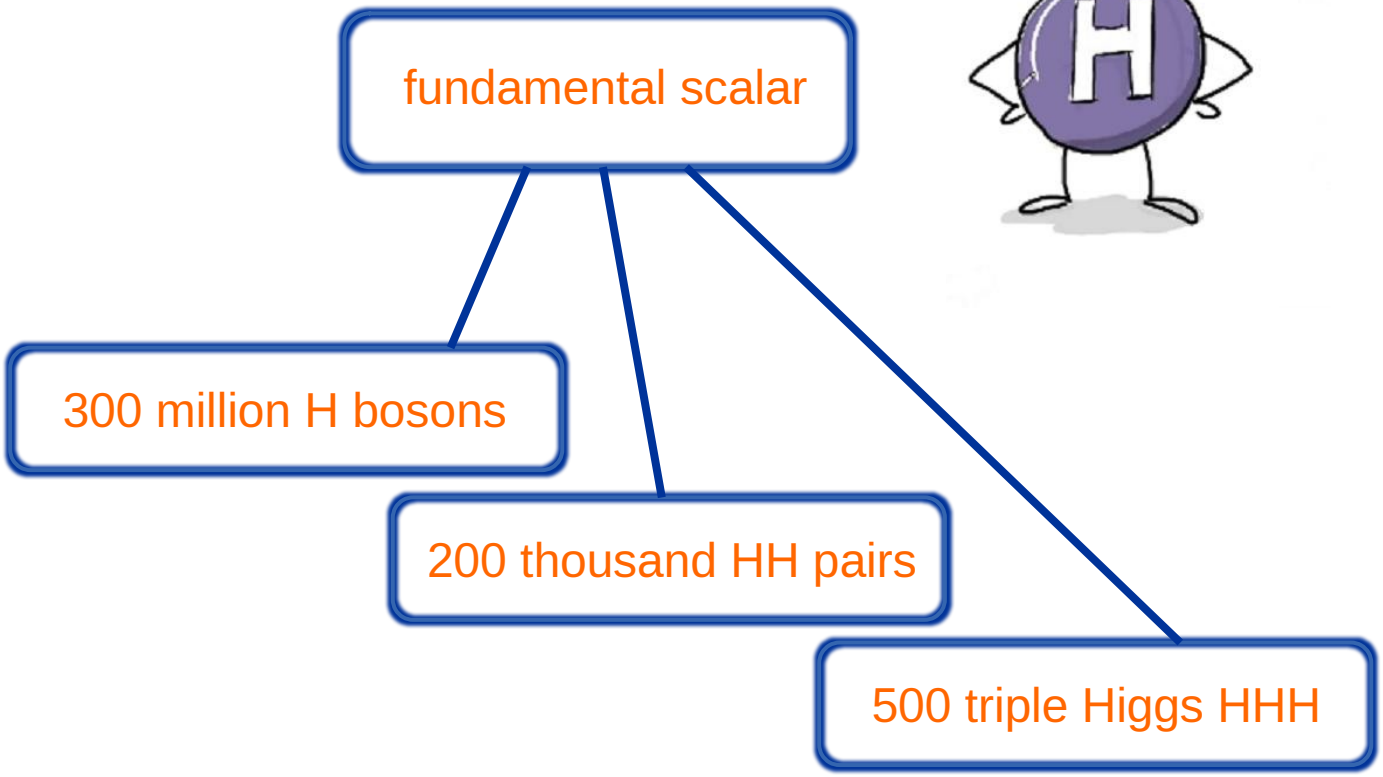
Main parameters:

- L = 3000 fb^{-1} (ATLAS & CMS)
- <pileup> ~ 140 (up to 200, leveled)
- 2030-2041

What is the HL-LHC about?

fundamental scalar

What is the HL-LHC about?



The HL-LHC is a Higgs factory

The ESPP

- European Strategy for Particle Physics is the cornerstone for Europe's long-term decision making process
- last update from 2020, notably:
  - priority on the successful completion of the High-Luminosity LHC over the coming decade
  - Higgs factory as the highest priority to follow the LHC

The ESPP

- European Strategy for Particle Physics is the cornerstone for Europe's long-term decision making process
- last update from 2020, notably:
  - priority on the successful completion of the High-Luminosity LHC over the coming decade
  - Higgs factory as the highest priority to follow the LHC
- CERN council launched in March '24 the process for an update by mid '26
  - submission of written input by March 2025

The HL-LHC is an approved project!

However, input to the EPPS update remains crucial, as it is the starting point for future collider projects

From past to present

(*) HL-LHC as well as HE-LHC

- at the last strategy update...
- 2018-2019: ATLAS+CMS wrote an input (*) based a large joint Yellow Report
  - CMS: “UPSG” group coordinated the work internally
  - 1.5 years available
  - a lot of key physics studies had recently been or were being done in the context of the upgraded detector TDRs
- 2022: ATLAS+CMS Snowmass white paper
  - based on the Yellow Report, with some updates
- 2024-2025: ATLAS+CMS will submit a joint input to the ESPP
  - CMS: no internal HL-LHC physics structure, ~ no ongoing studies
  - much shorter timescale
  - must choose wisely what to update, and what message to bring
- separate document on flavour by LHCb, Belle2, CMS, ATLAS
  - from CMS and ATLAS: $B_{(s)} \to \mu\mu$, CPV in $B_{(s)} \to J/\psi\, \phi$, $B \to K^*(892)\, \mu\mu$ (angular incl. P'_5) , $\tau \to \mu\mu\mu$

Overall vision

- demonstrate the importance of the full 3 ab^{-1} to complete our HL-LHC program
  - the HL-LHC physics program is rich and exciting!
  - deliver on key physics goals
  - channels that are statistically limited
  - analyses that cannot (easily) be improved by next-gen Higgs factory

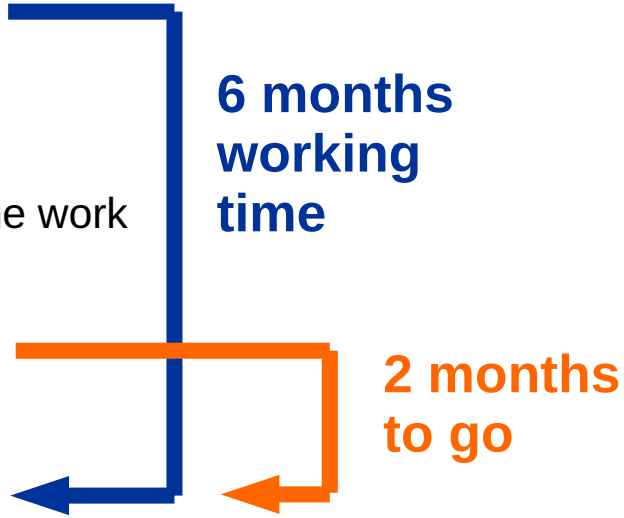
- concentrate the message on precision
  - all lumi is needed, 3 ab^{-1} was and should remain the goal
  - avoid identifying milestones for evidence or observation

    → the goal is to reach the ultimate precision

- engage theorists
  - support in coherently building the physics story
  - Juan Rojo (NIKHEF) and Fabio Maltoni (UCLouvain/UBologna)

Timeline

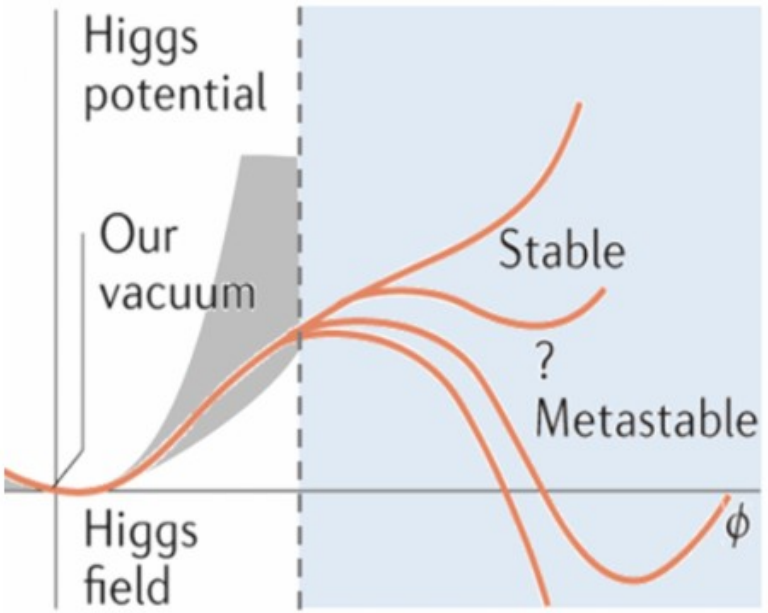
- very compressed timeline
  - June: coordinators appointed
  - July: CMS + ATLAS coordinators and PCs strategy meeting
  - August: meet with theorists and analyzers to define storyline
  - September: detailed meetings with the different groups, define work
  - End October: progress checkpoint with all teams
  - Fall: start writing, converge early next year
  - February: present to collaborations
  - Before end of March: submit to ESU



- no time for brand new studies
  - base ourselves off of extrapolations from latest Run2
- go with best performance @6 ab^{-1}
  - unless we know fundamental differences detectors

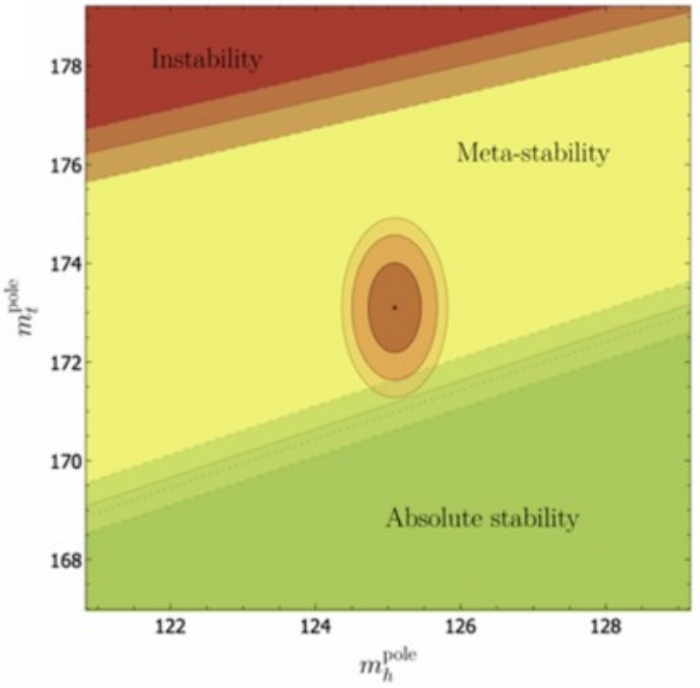
The physics storyline

- prominent role for di-Higgs and Higgs potential



JHEP 08 (2012) 098

1,762 citations



shape of the Higgs potential

→ at EW scale

→ update with latest extrapolations for H and HH measurements

stability of the Higgs potential

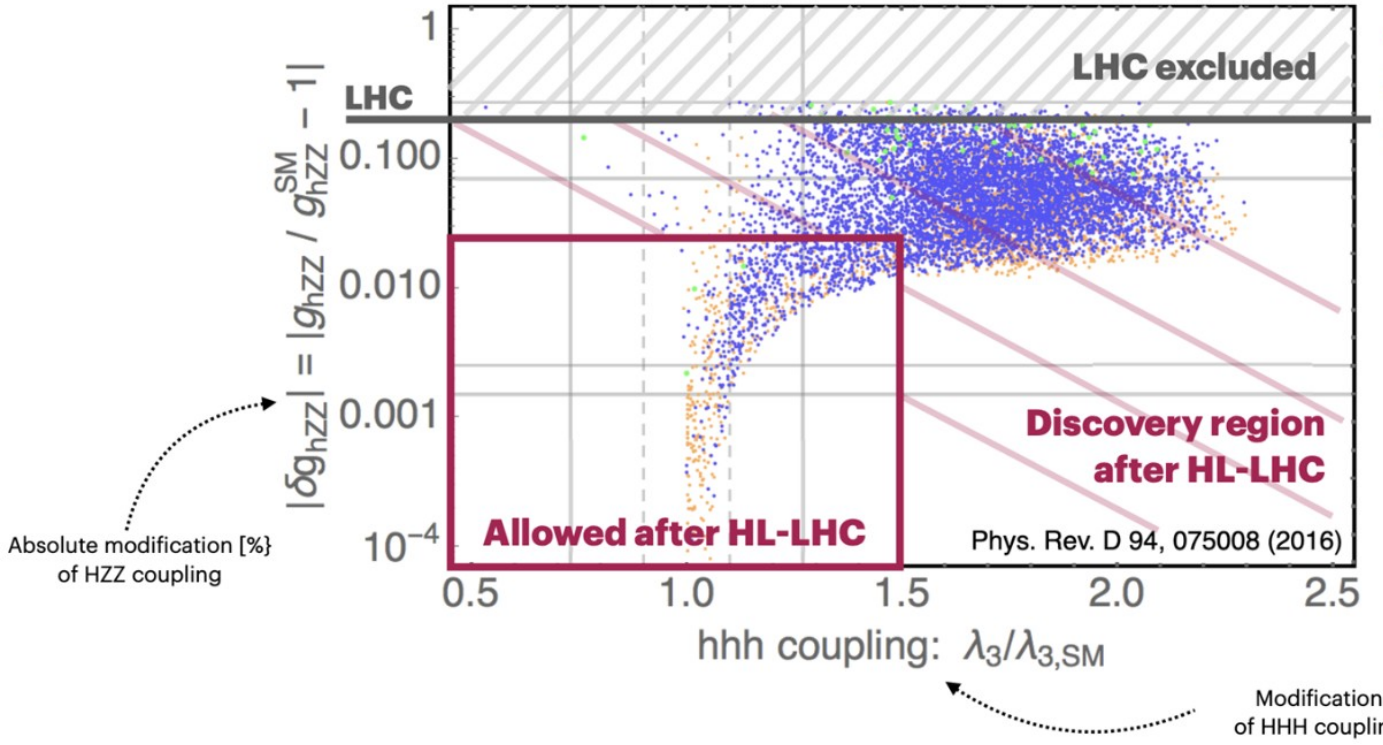
→ at Planck scale, assumes SM

→ update with best expectation H and top pole masses

The physics storyline

- electroweak baryogenesis
  - SM + real scalar singlet
  - Higgs mixing modifies hZZ and hhh couplings

$$V(\phi, S) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4 + \frac{1}{2}a_1 S\phi^\dagger\phi + \frac{1}{2}a_2 S^2\phi^\dagger\phi$$



- first order phase transition
- strong first order phase transition
- very-strong first order phase transition

LHC start to exclude a part of the phase space

After **HL-LHC** a large discovery region will be probed and still an allow region will remain

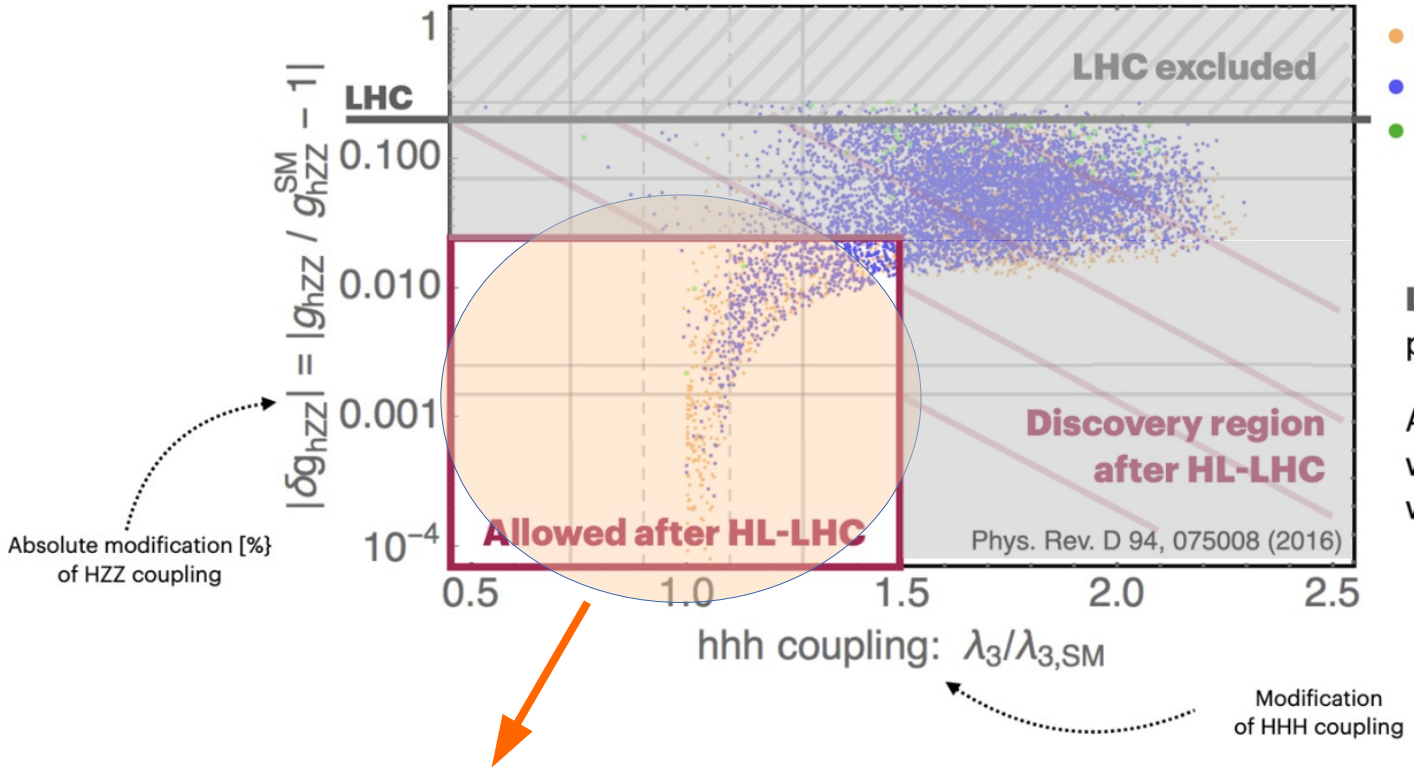
R. Salerno

- bottomline: the HL-LHC will leave a strong legacy here

The physics storyline

- electroweak baryogenesis
  - SM + real scalar singlet
  - Higgs mixing modifies hZZ and hhh couplings

$$V(\phi, S) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4 + \frac{1}{2} a_1 S \phi^\dagger \phi + \frac{1}{2} a_2 S^2 \phi^\dagger \phi$$



- first order phase transition
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LHC start to exclude a part of the phase space

After **HL-LHC** a large discovery region will be probed and still an allow region will remain

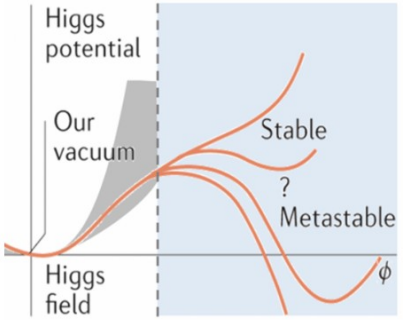
R. Salerno

- further constraints from scalar searches in tt / hh / WW ?
  - theoretical exploration

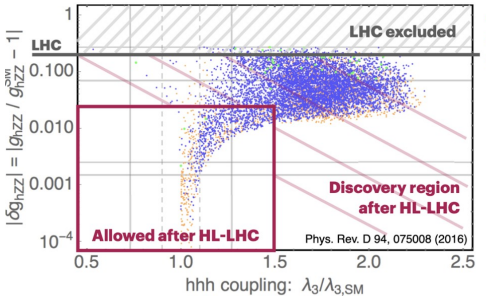
The broader HL-LHC picture

HHH - $\kappa_{\lambda 4}$

precision H



HH - $\kappa_{\lambda 3}$



VBS $W_L W_L$

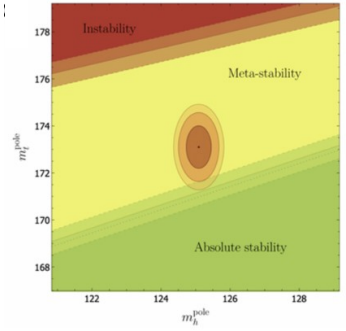
m(H)

$\phi \rightarrow ZZ$

$\phi \rightarrow tt$

$tt\,\phi \rightarrow tttt$

$\phi \rightarrow HH$



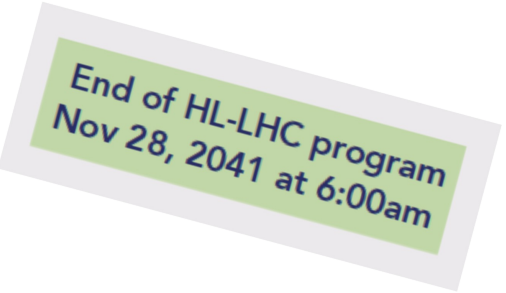
m(top)

4 tops

tt+X

Scenarios

- we assume 3 ab^{-1} per experiment
  - comparison to 2 ab^{-1}, to show the importance of running HL-LHC till the end
- no specific model of detector upgrade
  - timeline is too tight for detailed studies
- no special assumption for pileup
  - upgraded detectors will make HL-LHC PU look like our pileup now
- extrapolate from Run2, folding in Run3 improvements when possible

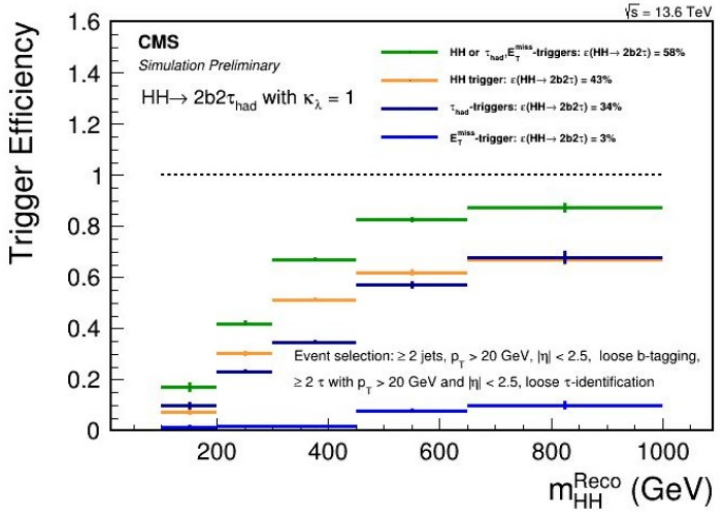


- 3 extrapolation scenarios:
  1) conservative: standard legacy Run2 systematics, plus stat error scaled with sqrt(L)
  2) minimally realistic: as first scenario, but with relevant experimental systematics also scaled with sqrt(L), with some agreed on floor.
     halved theory uncertainties
     MCstat = 0
  3) for di-Higgs only: add latest b-tagging, tauID, trigger

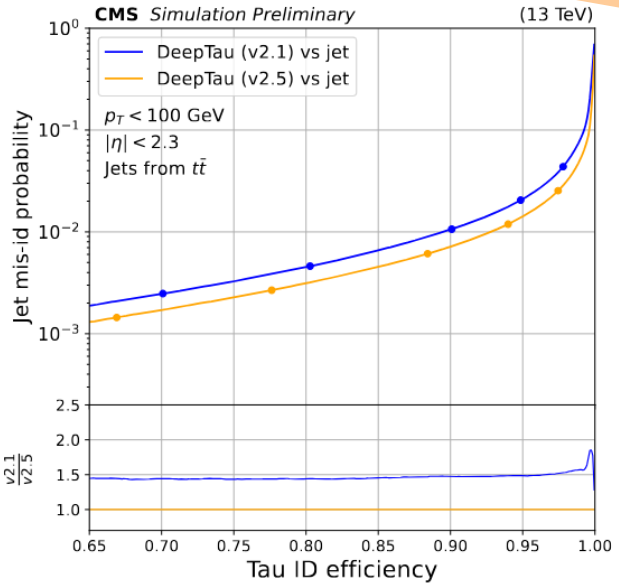
- these are almost certainly underestimates wrt capabilities by 2040
  - new detectors, with some amazing capabilities
  - >15y of technical development ahead

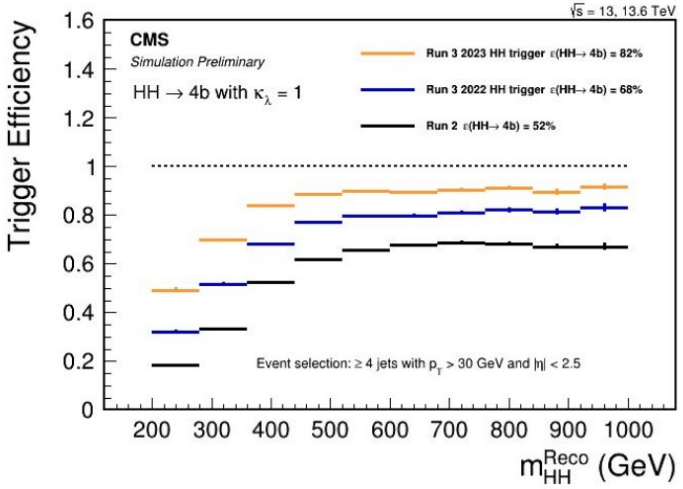
CMS improvement snapshots

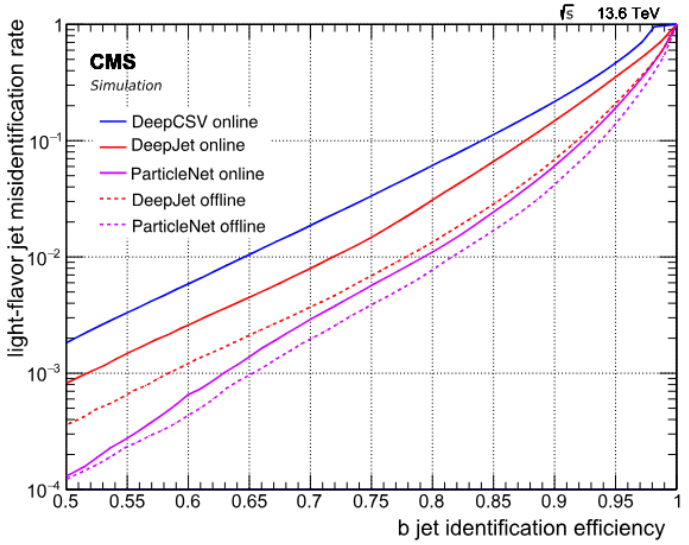
CMS-DP-2023/050



CMS-DP-2024-063







JINST 19 (2024) P05064

HH: observation

- both experiments will report
  - including the S3 scenario: includes recent improvements on b- and tau-tagging
  - assumptions aligned: sqrt(s), simplify sys. scaling,...
- naive ATLAS – CMS combination: quadratic sum significance and sum κ_λ likelihood
- recent HL-LHC projections of Run-2 HH searches (much) better than the 2019 Yellow Report
  - expectation of discovery with CMS+ATLAS

2019 Yellow Report

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
Combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

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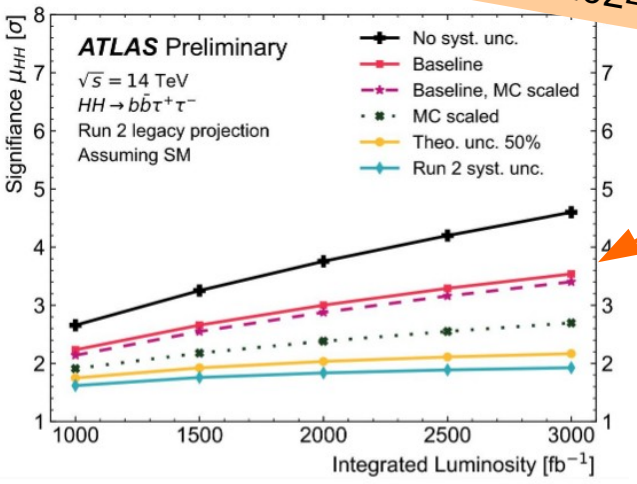
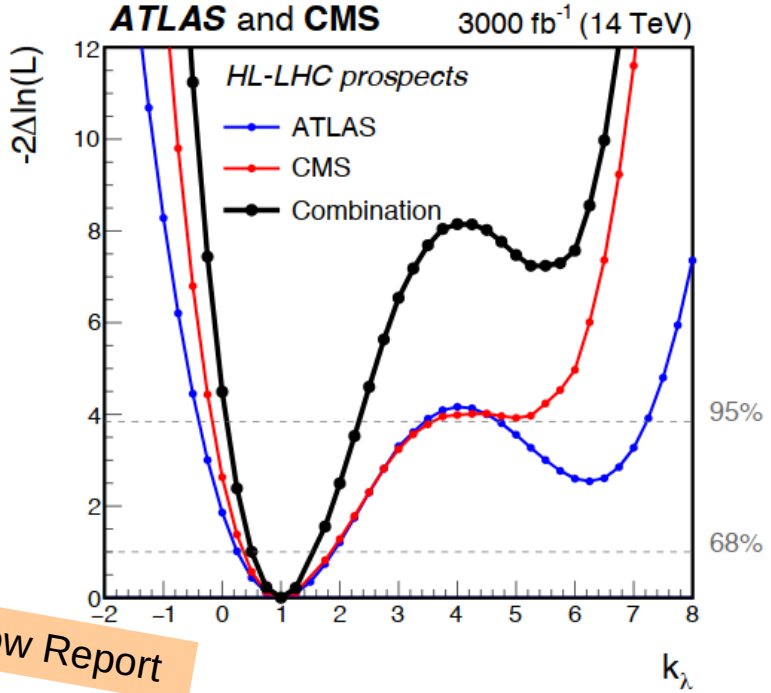


CMS-PAS-HIG-20-011

	Significance (σ) at 2000 fb^{-1}		Significance (σ) at 3000 fb^{-1}	
	S2	Stat. only	S2	Stat. only
$b\bar{b}b\bar{b}$ resolved jets	1.0	1.3	1.4	1.6
$b\bar{b}b\bar{b}$ merged jets	1.7	1.7	2.0	2.1
$b\bar{b}\tau\tau$	1.7	1.9	2.1	2.3
$b\bar{b}$WW	0.6	0.8	0.7	0.9
$b\bar{b}\gamma\gamma$	1.8	1.9	2.2	2.3
Combination	3.2	3.6	3.8	4.3

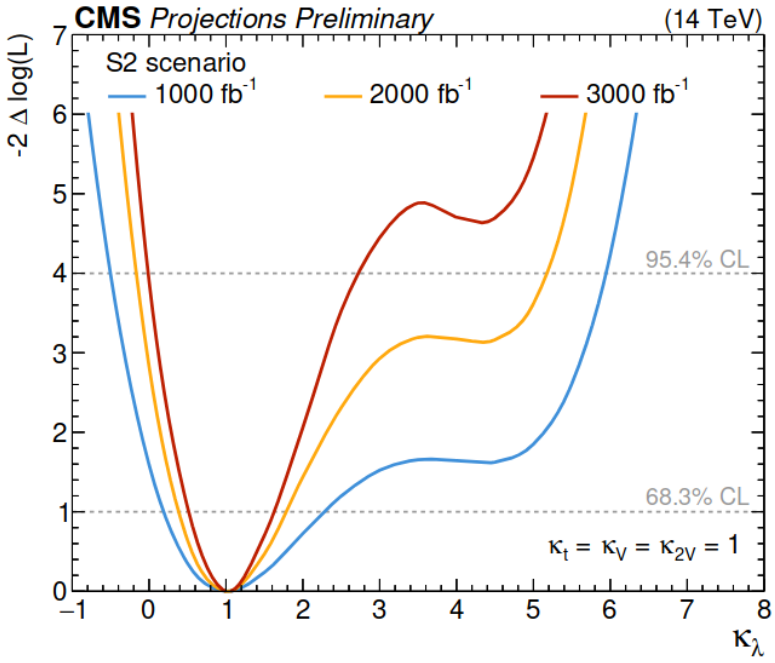
HH: $\kappa_{\lambda 3}$

- both experiments will report
  - including the S3 scenario: includes recent improvements on b- and tau-tagging
  - assumptions aligned: sqrt(s), simplify sys. scaling,...
- naive ATLAS – CMS combination: quadratic sum significance and sum κ_λ likelihood
- recent HL-LHC projections of Run-2 HH searches (much) better than the 2019 Yellow Report
  - $\kappa_{\lambda 3}$ < well below 1.5 combined



2019 Yellow Report

CMS-PAS-HIG-20-011



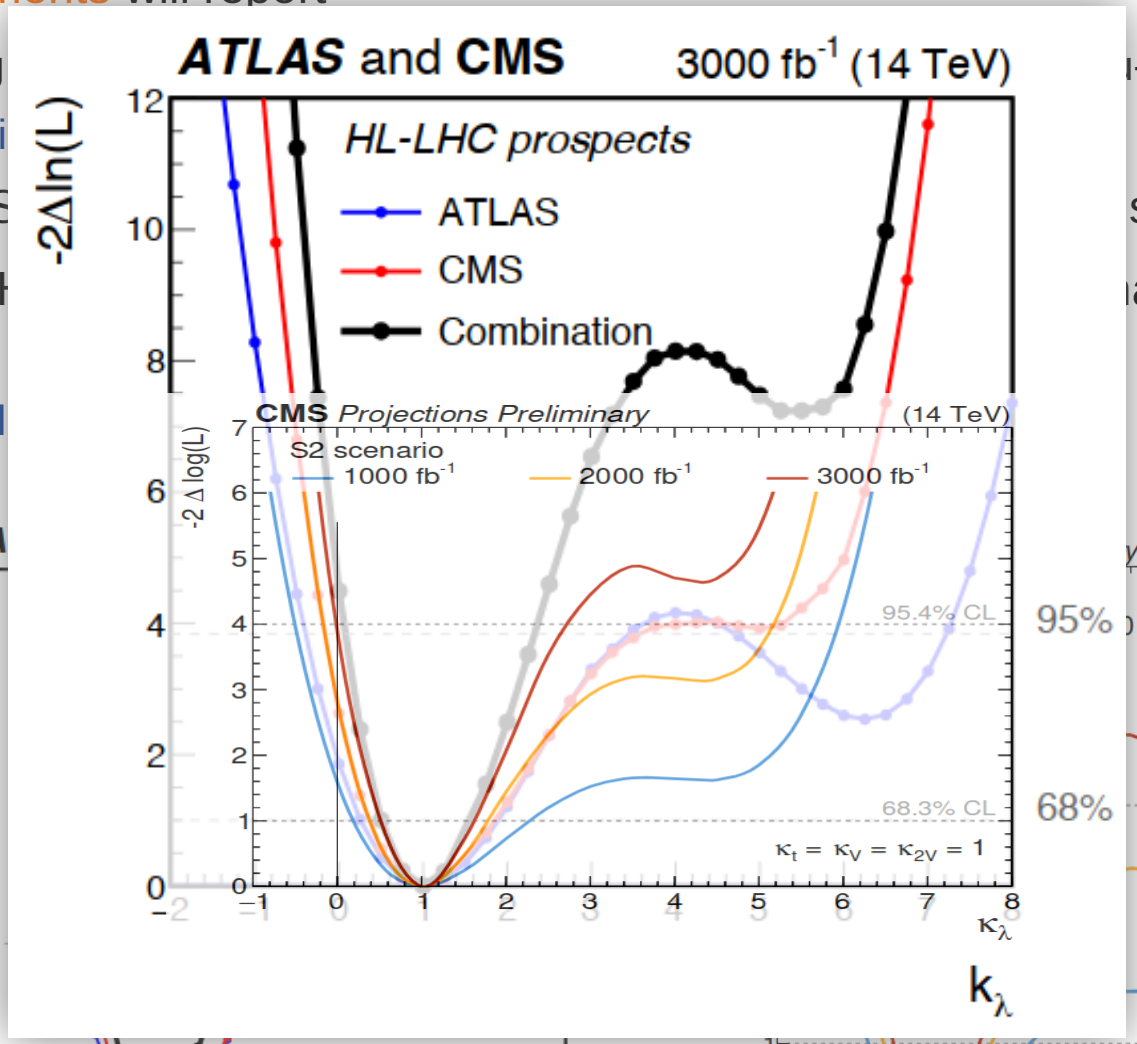
HH: $\kappa_{\lambda 3}$

- both experiments will report
  - including
  - assumpti
- naive ATLAS
- recent HL-LH Report
  - $\kappa_{\lambda 3}$ < well

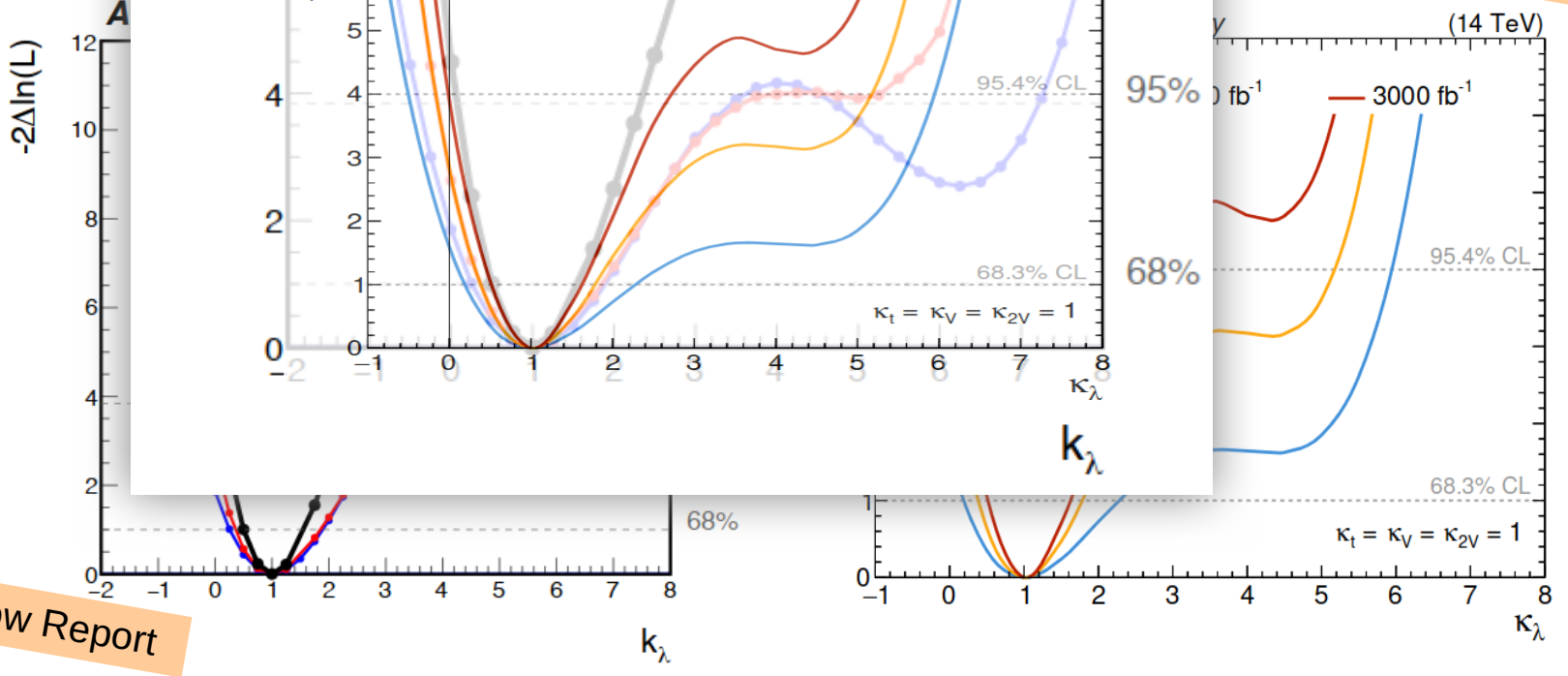
-tagging

sum κ_λ likelihood

an the 2019 Yellow



CMS-PAS-HIG-20-011

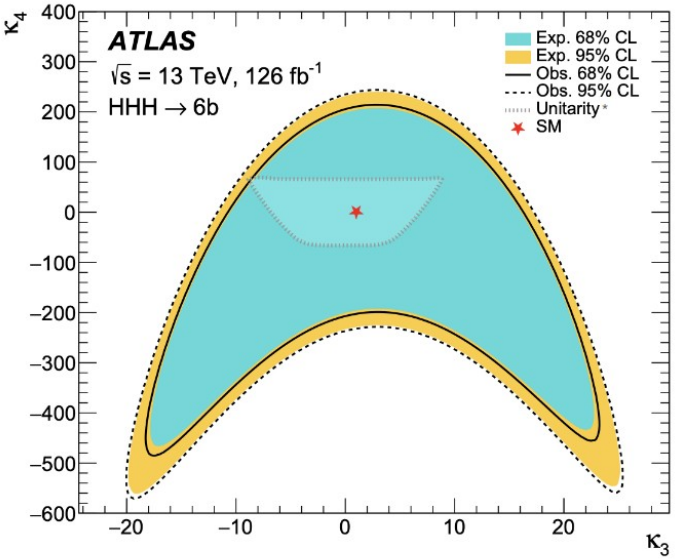


2019 Yellow Report

New: HHH

- HHH → 6b final state
  - recent ATLAS result: arXiv:2411.02040
- constraints are weak,
  but HL-LHC has unique sensitivity
  - on quartic coupling
  - linking $\kappa_{\lambda 3}$ and $\kappa_{\lambda 4}$

(k_3, k_4) 2-dimensional likelihood scan



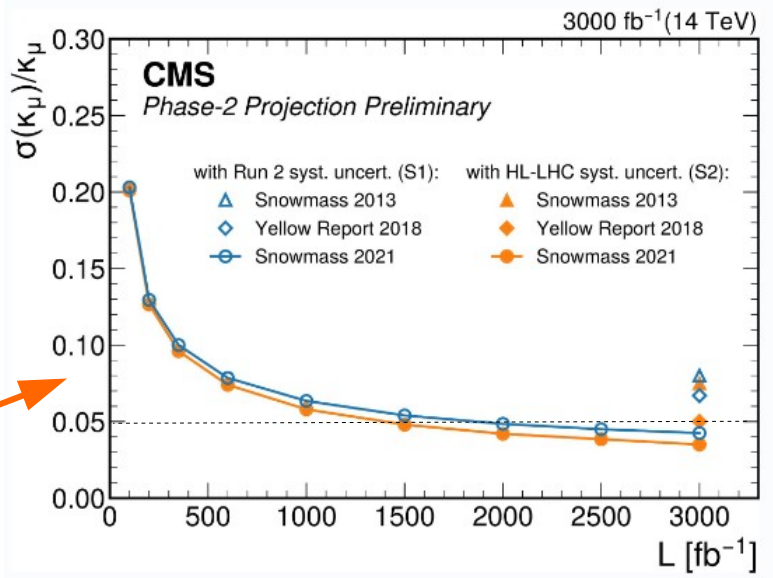
*unitarity bounds from Eur. Phys. J. C 84 (2024) 366

- easy to extrapolate, since fully statistically driven
  - extrapolation ready for 3+3 ab^{-1}
  - will reach first constraint on unitarity bounds
- a first view only
  - significant improvements ahead, other decay channels

Precision H

- H → Zγ :
  - nearly ready from both sides, combination exercised
- H → μμ :
  - ATLAS nearly ready, combination exercised
  - dominated by CMS; includes extended acceptance and improved resolution

CMS-PAS-FTR-21-006



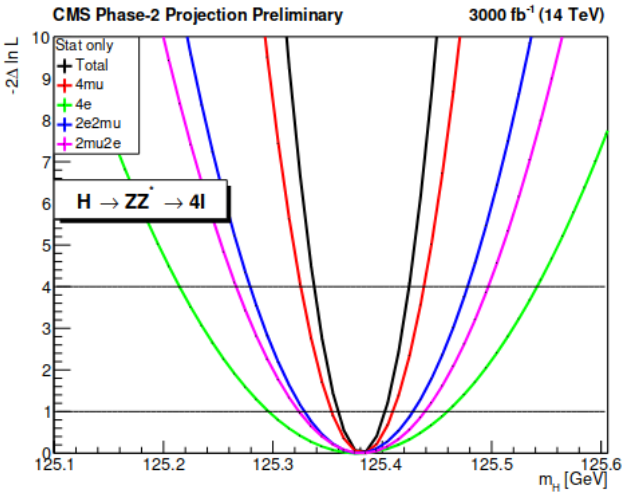
- H → γγ :
  - work ongoing to split merged STXS highest p_T^H bin: 450+ GeV → 450-650 and 650+ GeV
- H → ZZ :
  - based on previous projections
- κ_t from ttH and tH :
  - ATLAS @ 6 ab^{-1}

Higgs and top mass

CMS-PAS-FTR-21-007

- Higgs mass
  - CMS has mass $H \rightarrow ZZ^* \rightarrow 4l$ already projected
  - projection 0.02% (!) : $m_H = 125.38 \pm 0.03$ GeV

    optimistically even 20MeV



- top pole mass
  - direct measurements come with interpretation uncertainty
  - for pole mass, we have two extrapolations of 2016 tt+jet analysis: one too conservative, one too aggressive...

    strategy under discussion
  - quickly systematically limited

    essentially no improvement between 4 ab^{-1} and 6 ab^{-1}

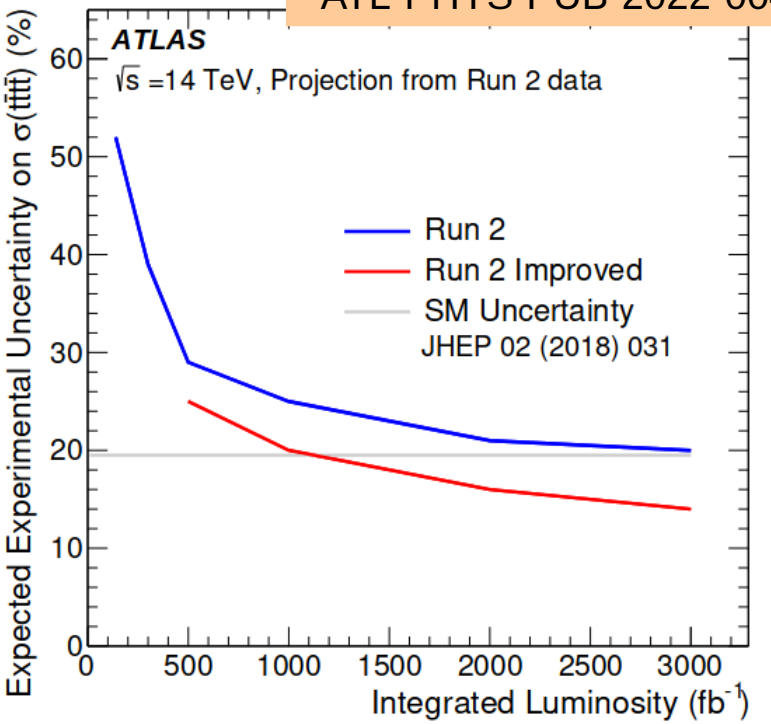
4 tops and tt+X

- 4 tops
  - updated ATLAS projections bring us below 10% cross section uncertainty

    systematics start to dominate > 500 fb^{-1}
  - not impactful for κ_t constraints when coupled with ttH
  - working to add EFT

    4-top H_T with 4 b-jets

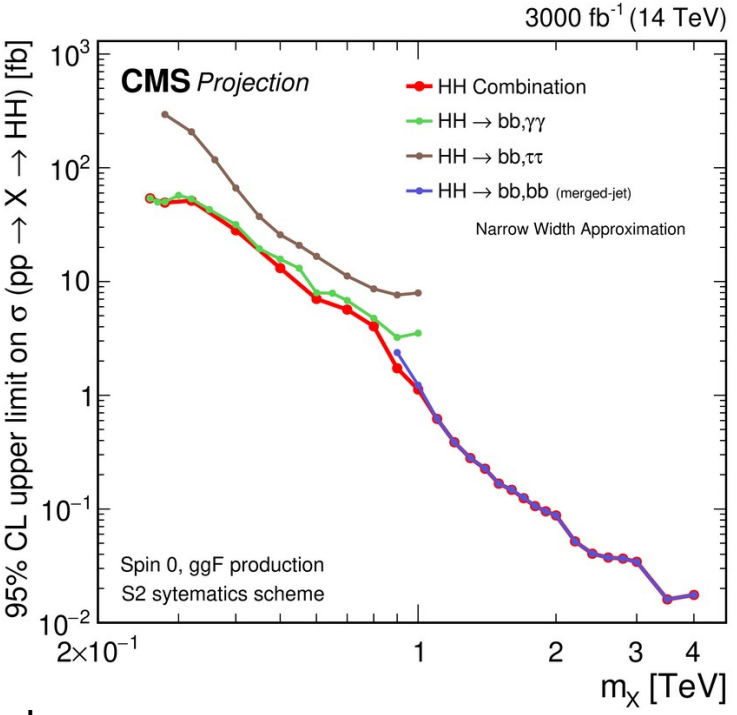
ATL-PHYS-PUB-2022-004



- tty / ttZ
  - extrapolating ATLAS EFT interpretations from differential cross sections
  - considering a few relevant SMEFT operators

Searches

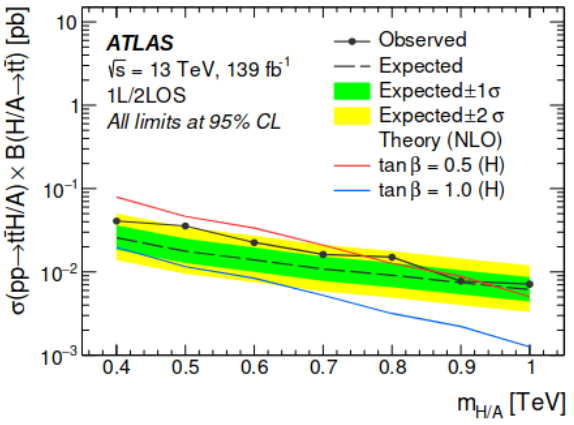
- X → HH
  - CMS extrapolation public: arXiv:2403.16926
  - ready to confront scalar singlet model and recently proposed TRSM (2 scalars)



- A/H → tt
  - extrapolate ATLAS result: JHEP 08 (2024) 013
  - proper treatment of the interference with SM background

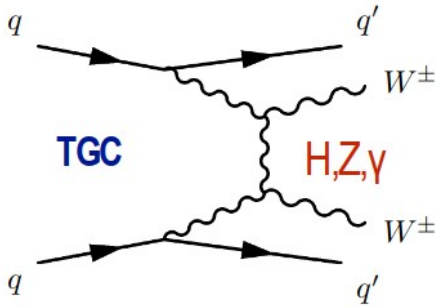
- tt A/H → tttt
  - extrapolating ATLAS analysis: arXiv:2408.17164
  - marginal improvement 4→6ab^{-1}

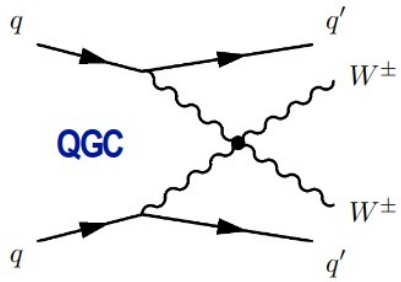
    not tuned towards high lumi
  - scalar singlet model interpretation in progress



- X → ZZ: to revisit?

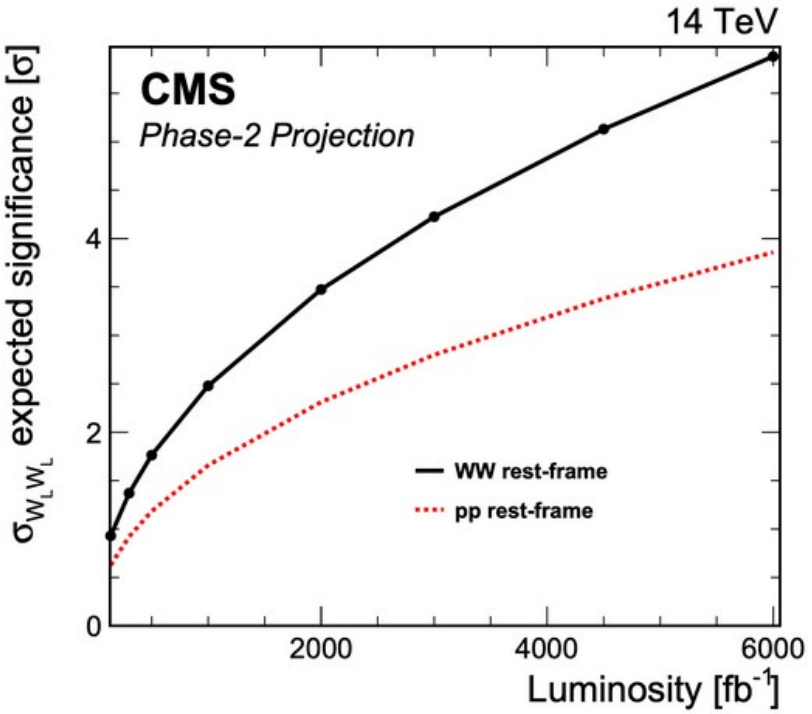
VBS: $W^{\pm}W^{\pm}$





- longitudinal polarization remains stat limited
  - essential component of SM
  - crucial test of BEH mechanism
  - key target for HL-LHC

- CMS projection public and ready: CMS-PAS-FTR-21-001
  - 10% of W_LW_L fraction, at best
  - conservative: no MTD or HGCAL, but same effect from pileup
  - increased cross sections QCD+EW corrections as function of m(jj) theory errors halved



Practical steps

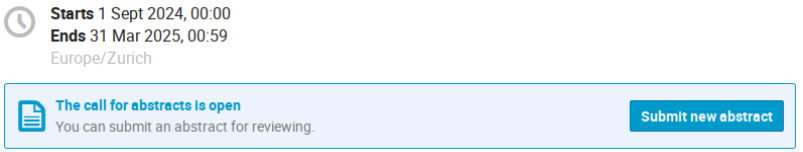
- what we are preparing:
  - CMS Notes and ATLAS Pub Notes on individual studies → expect public during February
  - ATLAS+CMS common document

    roughly 5 pages per subject

    contains also the combination material
  - 10 page submission document (editors P/M/S)

    will be submitted to the ESPP update
    with broader common document as appendix

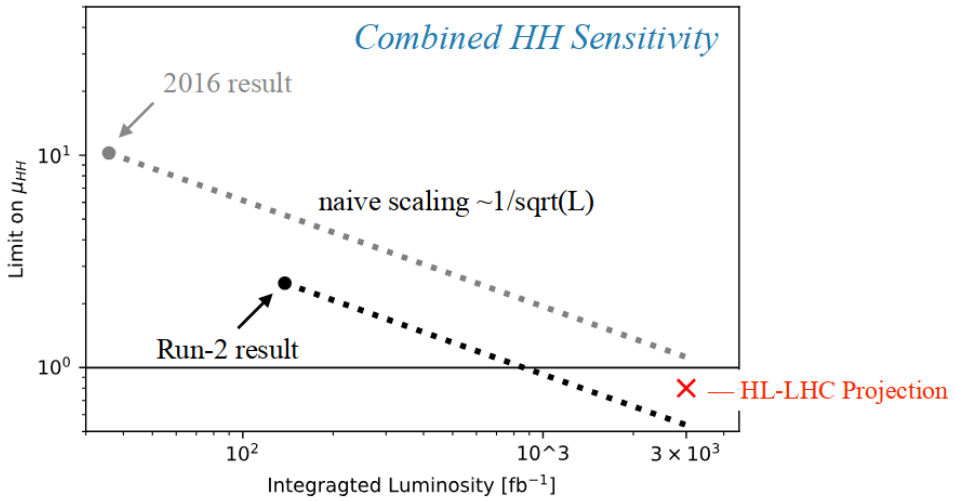
- dense timeline
  - This week: first drafts
  - Early Jan: 10p skeleton, notes taking shape, studies rounding up
  - End of Jan: internal approvals individual studies and combinations
  - Early Feb: common document presented to collaborations
  - 2nd half Feb: collaboration-wide internal reviews
  - End of March: submit 10p + appendix

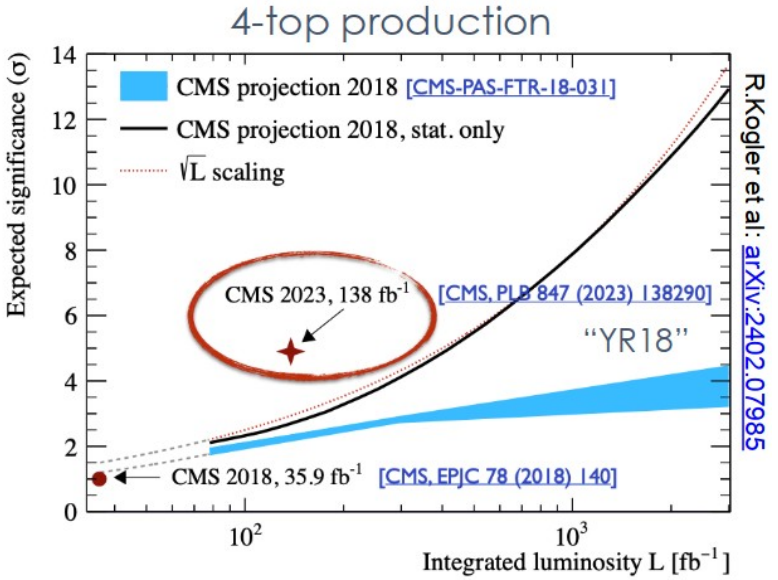


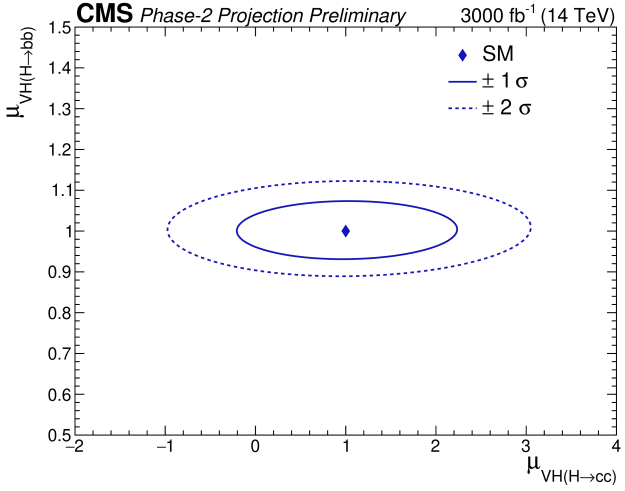
What's beyond?

- "Prediction is very difficult, especially if it's about the future." (N. Bohr)

John Alison, LHCP2024







Additional material of
PRL 131 (2023) 061801

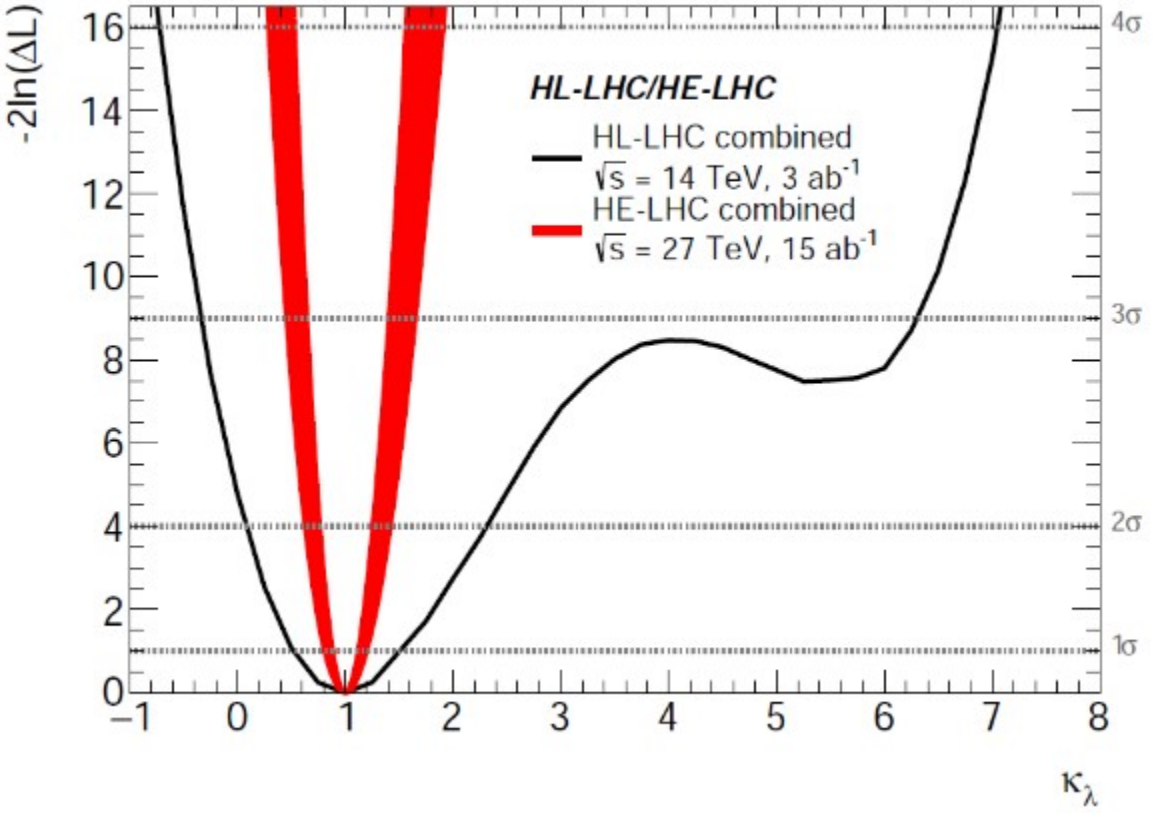
Summary

- working towards CMS+ATLAS input to European Strategy Update
  - demonstrates exciting program of HL-LHC physics
  - starting point for any next collider

- timeline is short
  - robust extrapolations from Run2 legacy (+ some improvements)
  - pragmatic and fruitful synergy between ATLAS and CMS
  - work is in full swing!

Backup

Backup


-2ln(ΔL)
16
14
12
10
8
6
4
2
0
−1
0
1
2
3
4
5
6
7
8
4σ
3σ
2σ
1σ
HL-LHC/HE-LHC
HL-LHC combined
√s = 14 TeV, 3 ab-1
HE-LHC combined
√s = 27 TeV, 15 ab-1
κλ