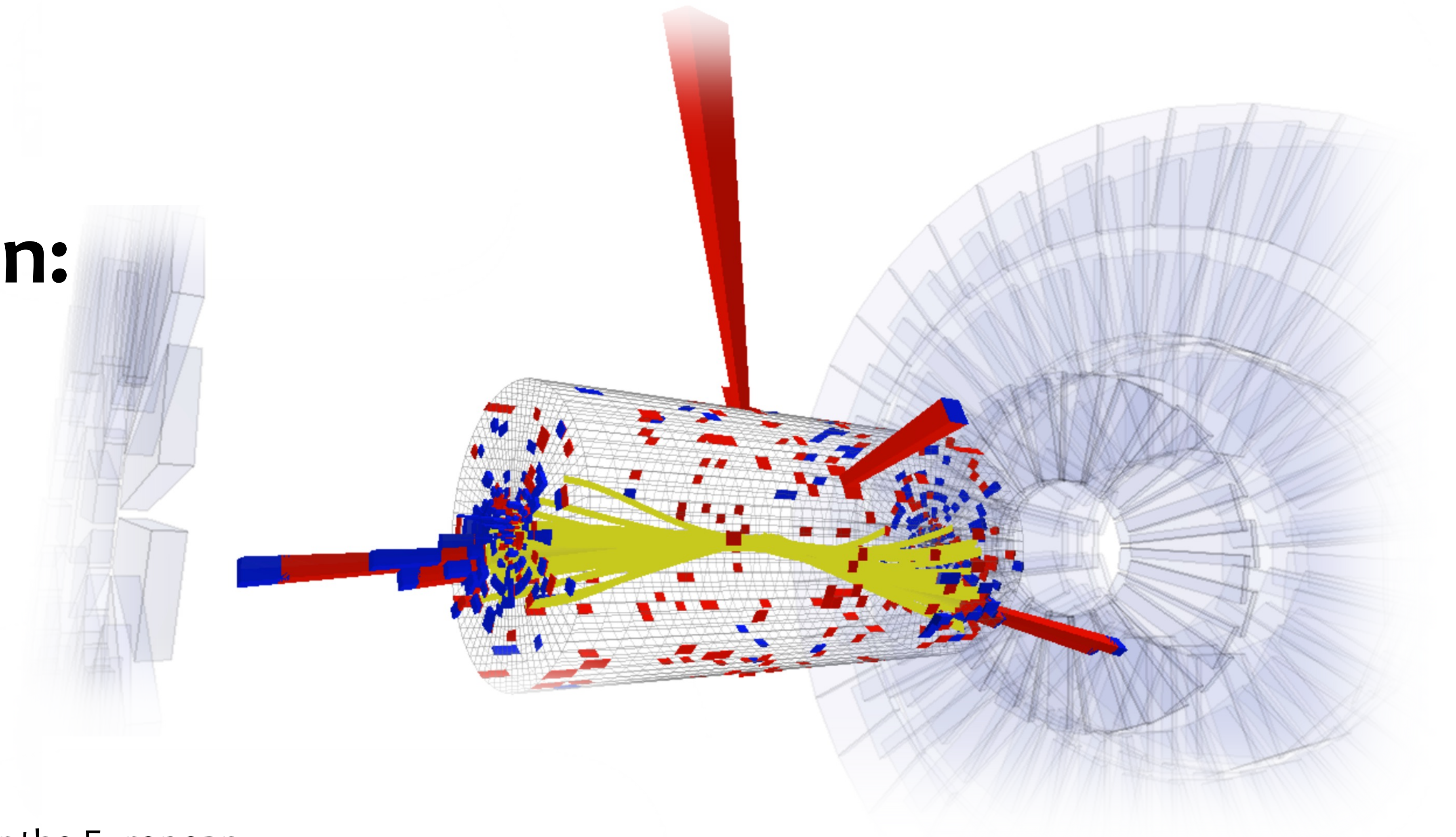
Imperial College London

LHC Exploitation: Higgs Physics

Nicholas Wardle



ECFA-UK Meeting on UK studies for the European Strategy Particle Physics Update

23-26 September 2024

Euro PP strategy - 2020

"The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques.

The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited."

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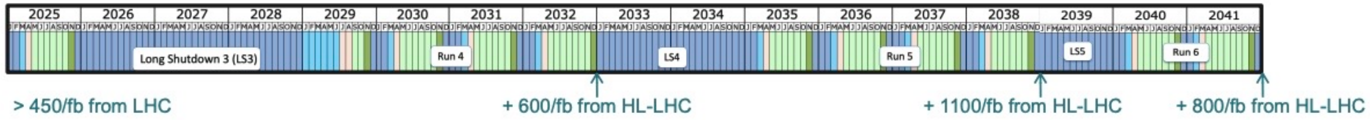
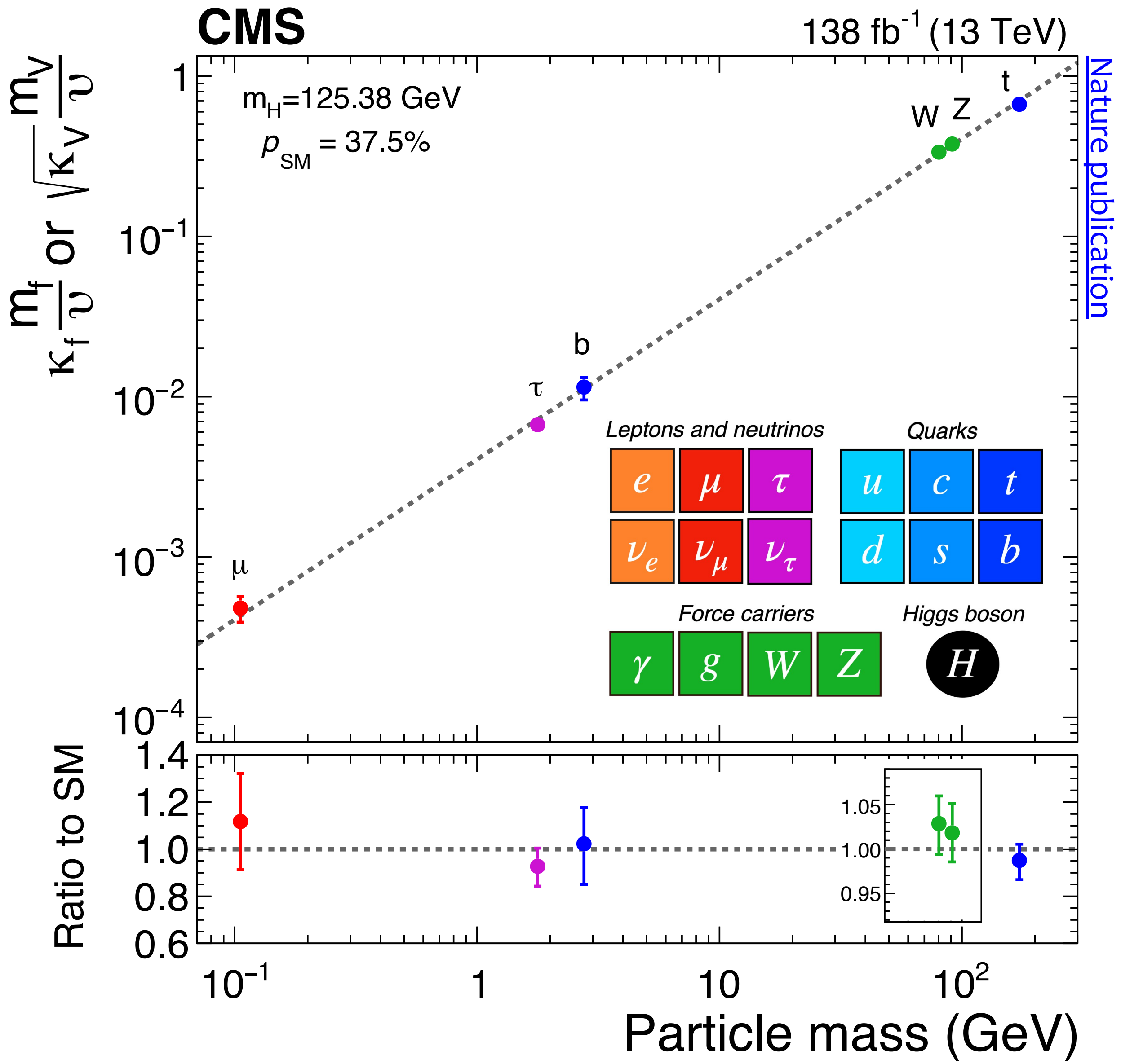


Expect **> 160M H-bosons / 120k HH pairs** per GP experiment by the end of the **HL-LHC** !

Why Higgs @ HL-LHC?

In O(10) years since the discovery, LHC has provided us with a lot of information about the Higgs boson



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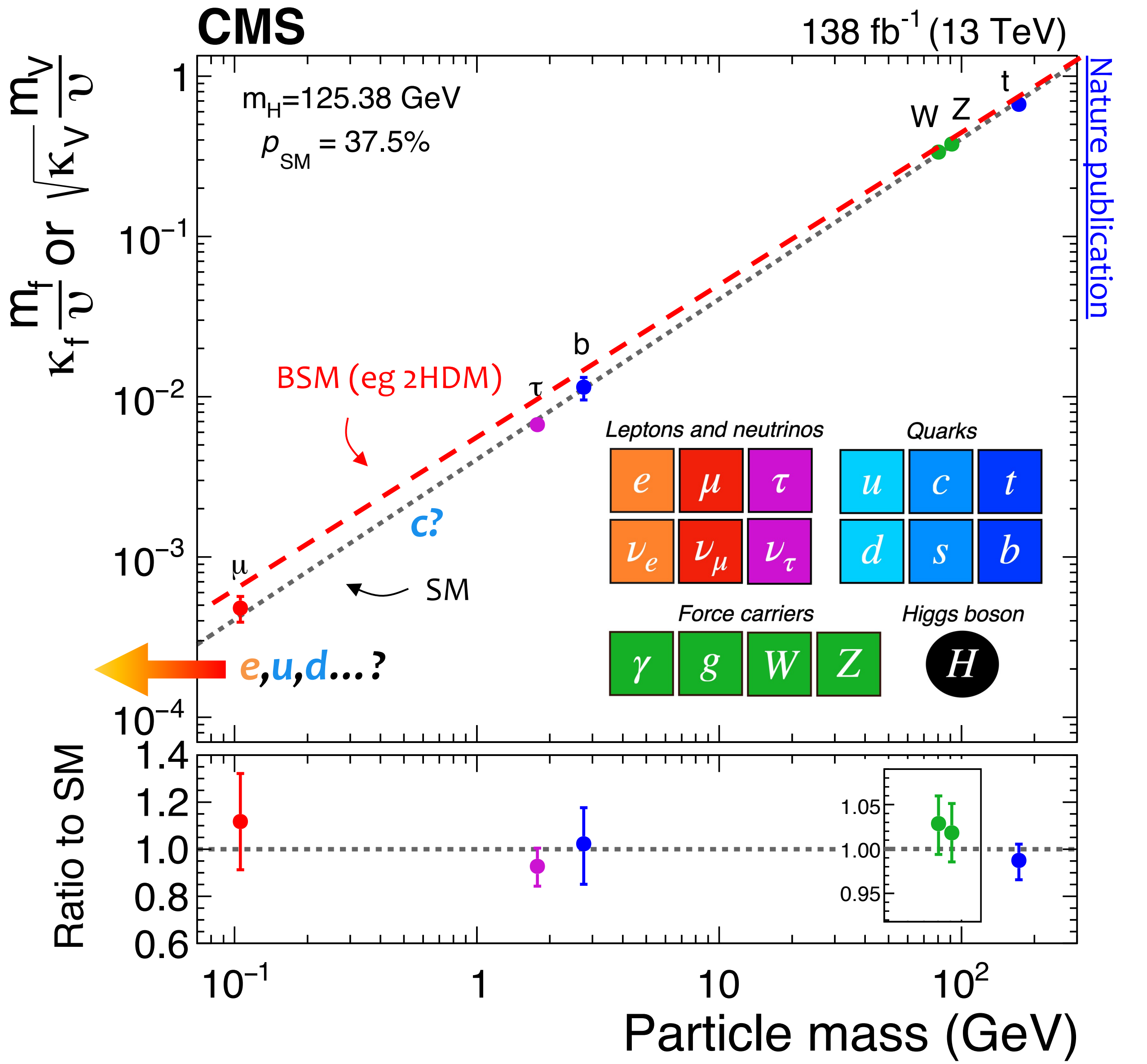
Open questions about the Higgs boson

- **Is the Higgs sector SM-like ? →** Do all the SM particles lie on that line?
- Is the Higgs elementary or composite?



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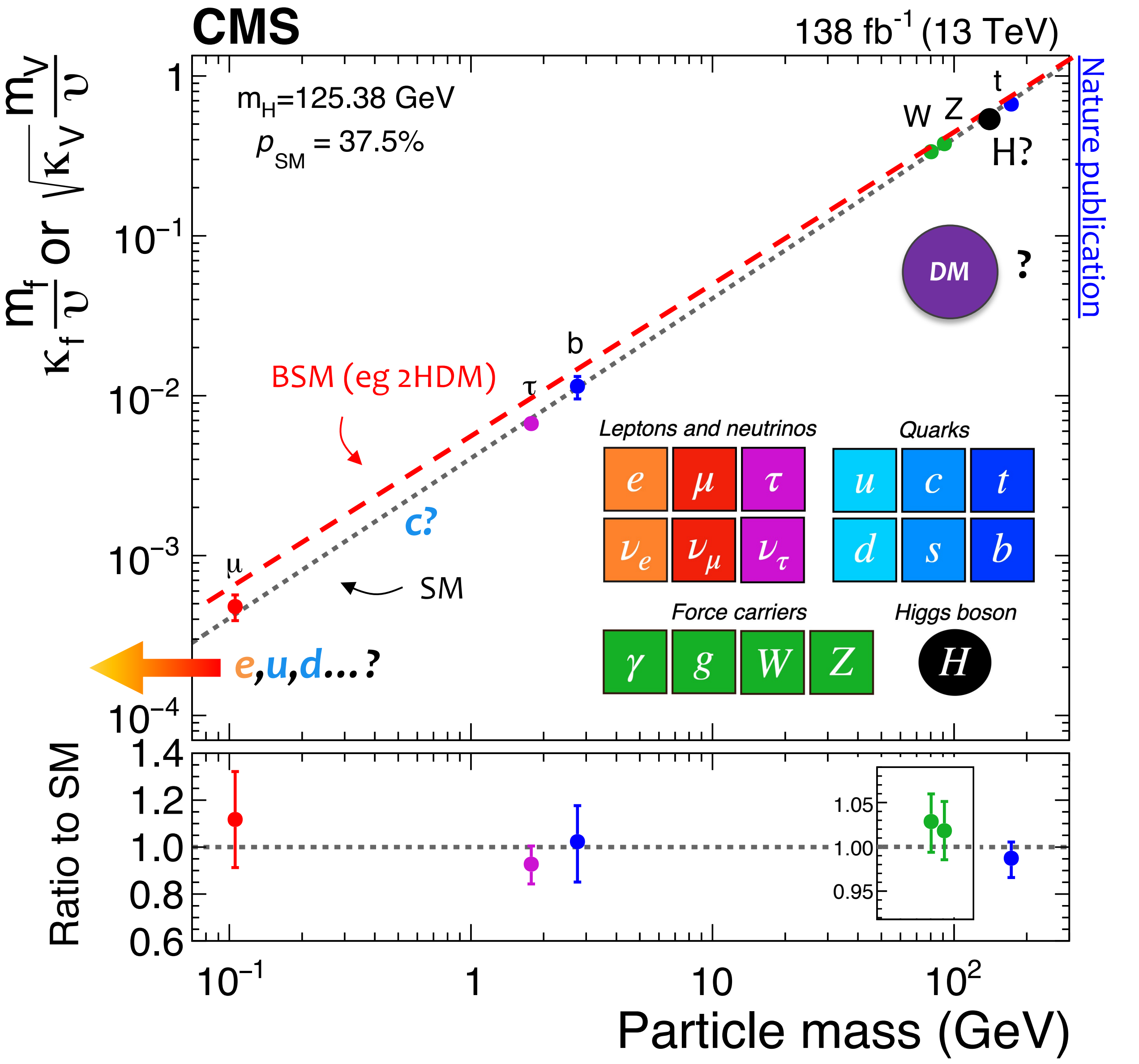
Open questions that the Higgs impacts

- Is the Higgs a portal to a Hidden sector?
- Is electroweak baryogenesis viable (stability?, 1st order PT?)



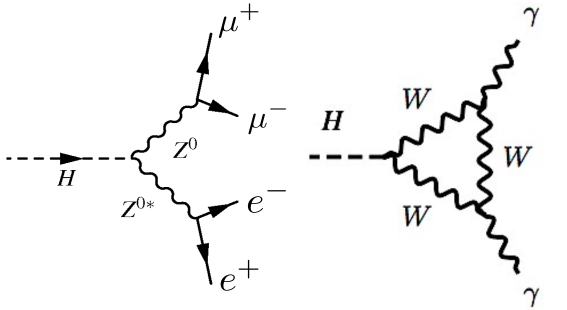
Higgs boson Mass

Higgs boson mass measured in high-resolution final states
H→4l & H→ γγ

Current best measurements

ATLAS (4l+γγ): 125.11 ± 0.11 GeV

CMS (4l): 125.08 ± 0.12 GeV

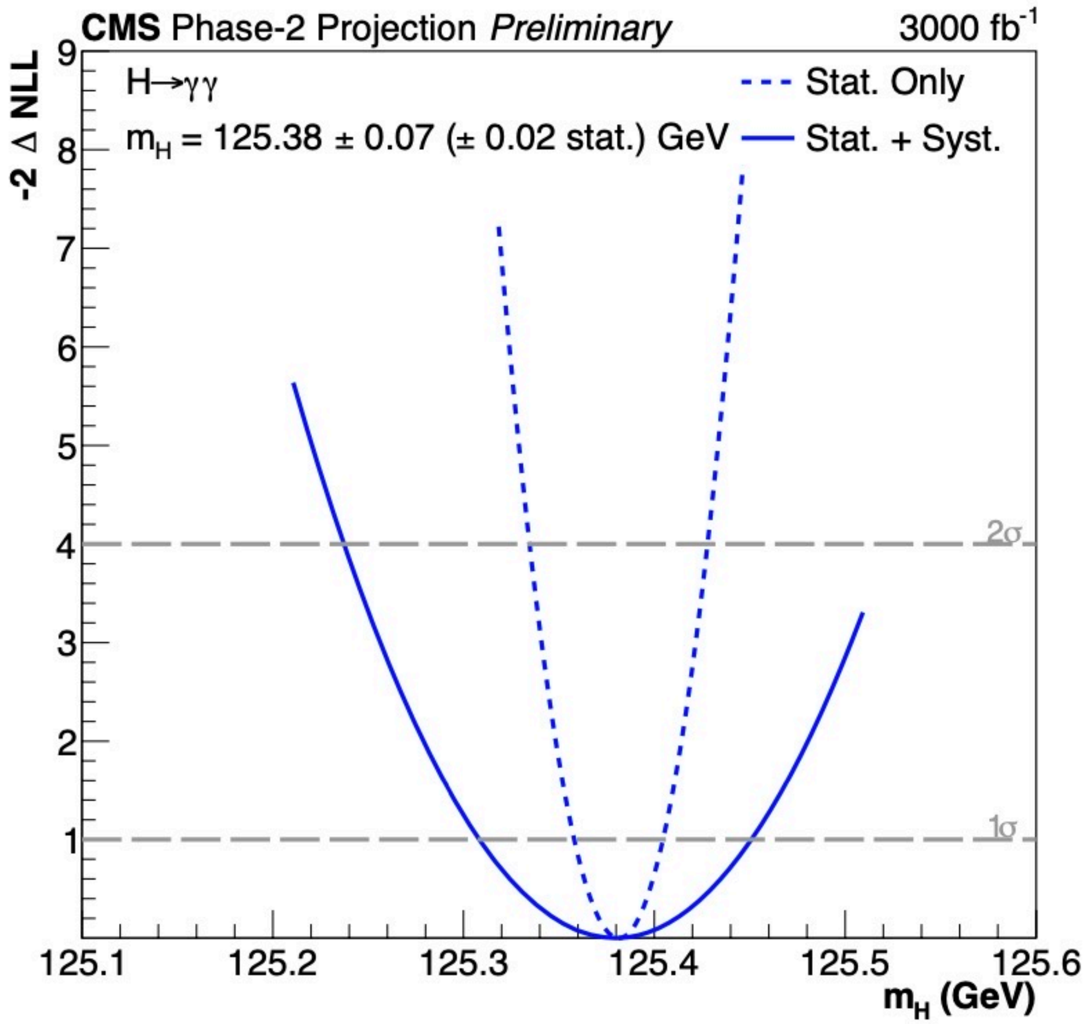


Resolution and scale of lepton/photon momentum measurements will dominate sensitivity to m_H*

ATLAS H→4l

ATL-PHYS-PUB-2018-054

	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14



Combination of H→4l & H→γγ channels with both experiments could yield **δ(M_H) ~ 20 MeV** uncertainty at HL-LHC!

* interference effects can lead to shift of 35 MeV in H→γγ

Higgs boson couplings

Expect to reach O(%)-level precision in many Higgs boson couplings → likely to be the best measurement for many years beyond HL-LHC in some cases

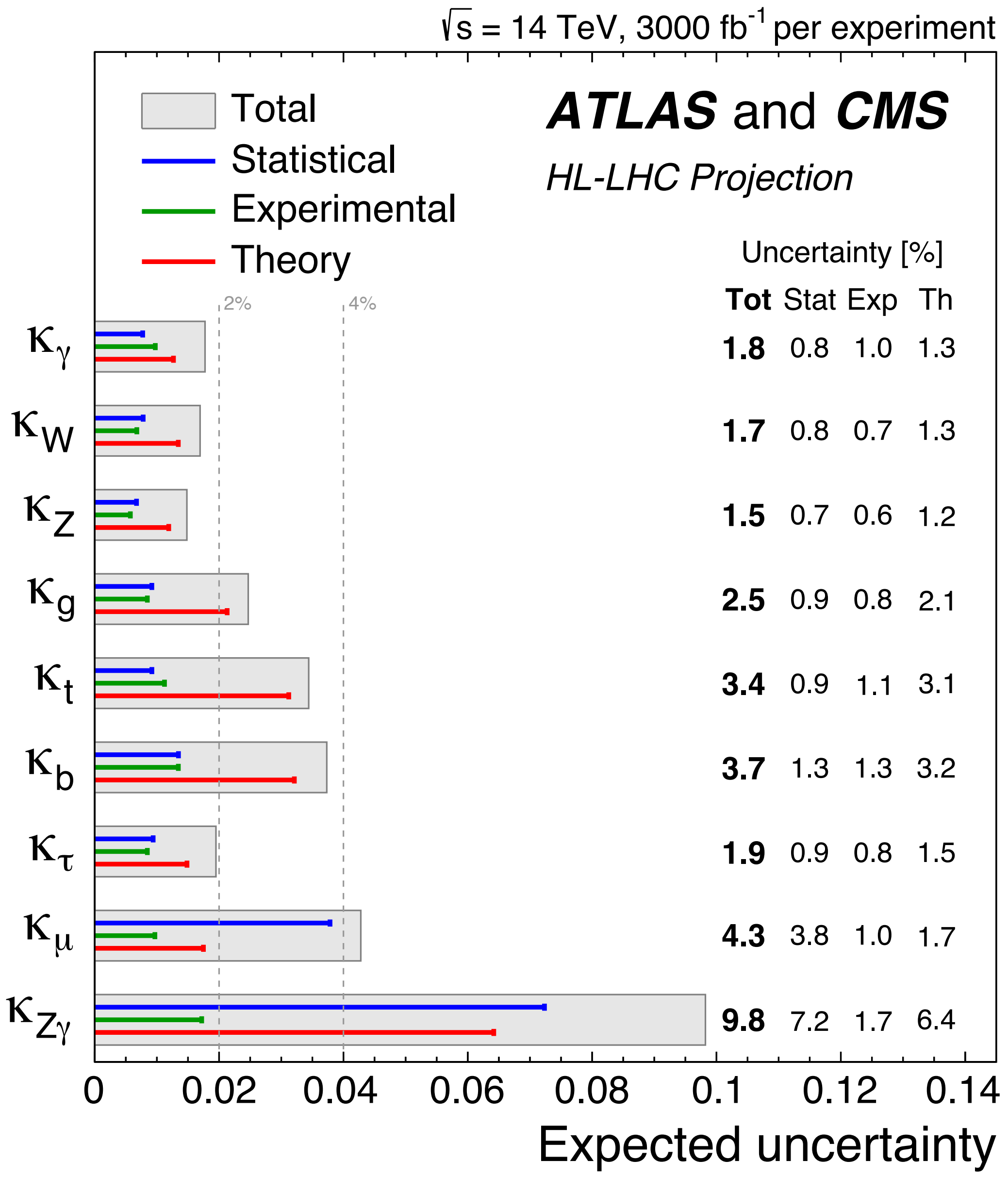
Assumes trigger & detector performance / reconstruction similar to performance of detectors during Run-2

Uncertainty scaling:

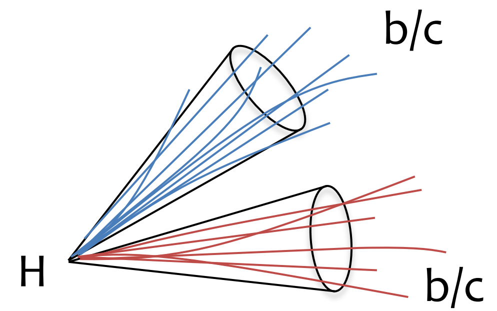
Statistical Uncertainties	$\propto 1/\sqrt{L}$
Experimental Uncertainties	$\propto 1/\sqrt{L}$ Until floor reached
Theoretical Uncertainties	x 0.5

Uncertainty dominated by systematic components in many cases for coupling (inclusive) measurements

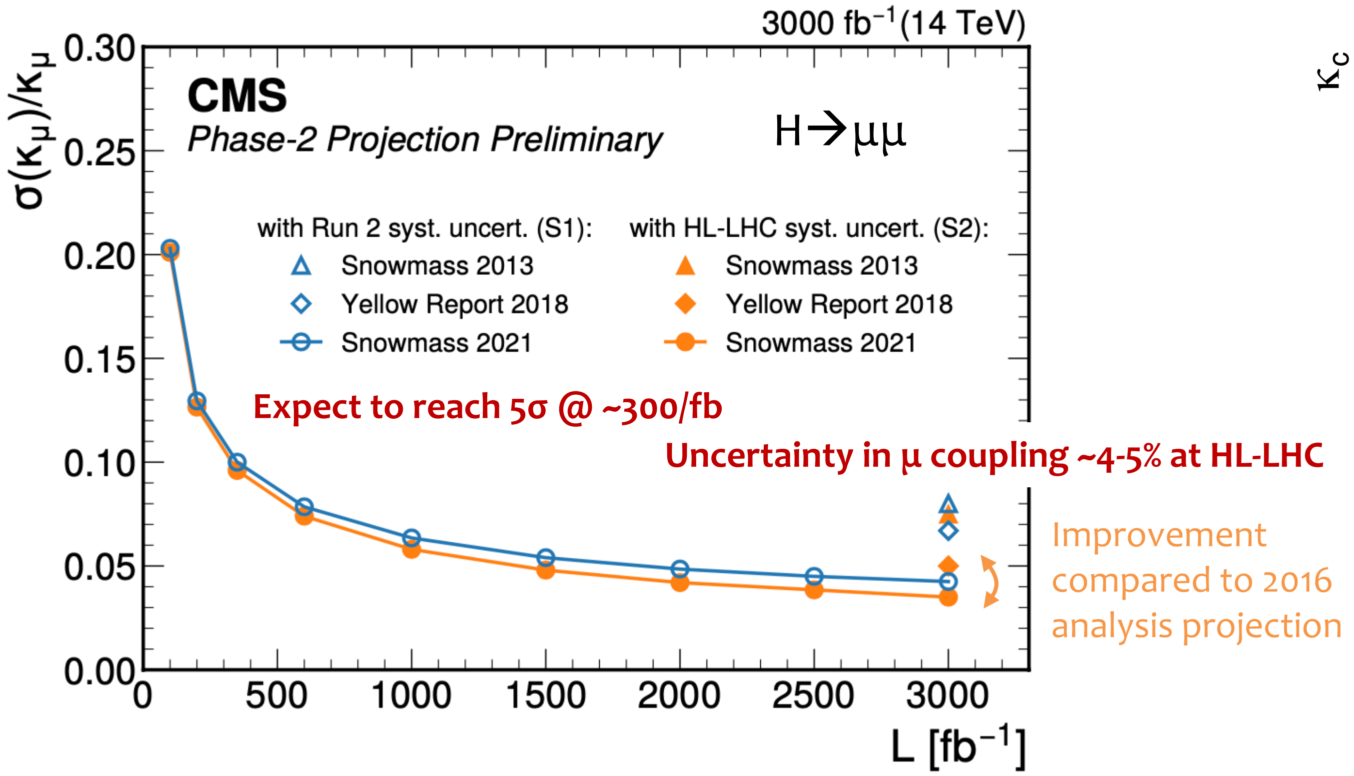
Caveat! Higgs boson couplings based on partial Run-2 data - Represents only ~few % of total expected HL-LHC dataset

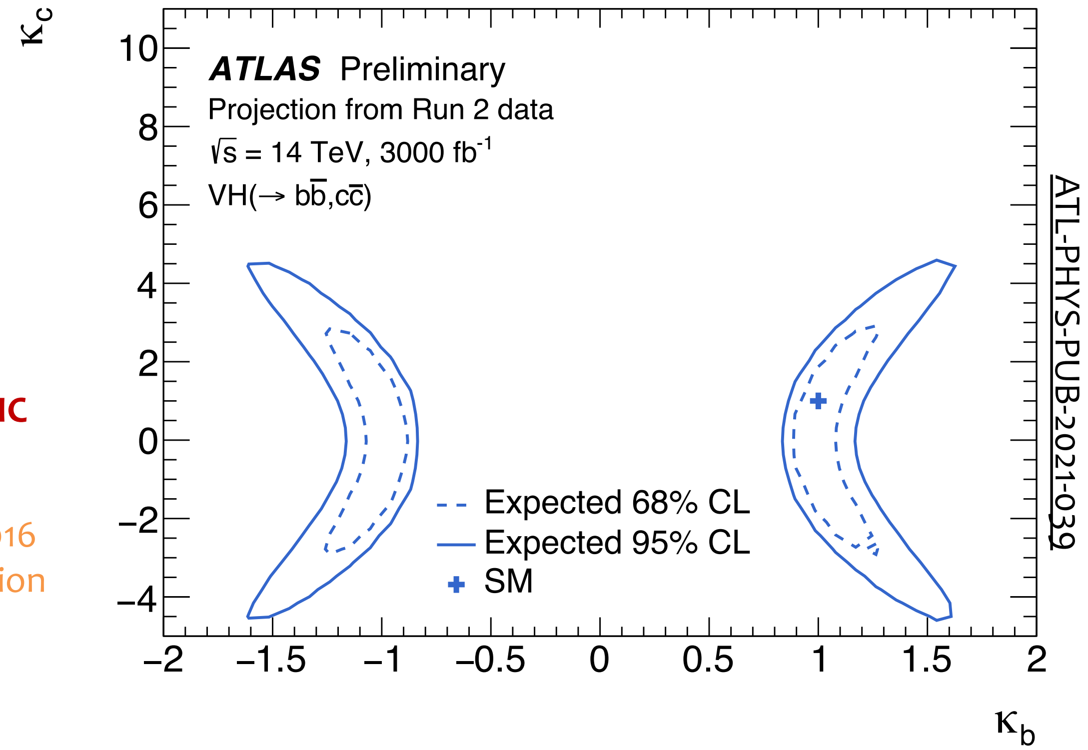


Higgs boson 2nd generation couplings



Updates in 2022 (Snowmass) for key decay channels where projections now use analyses based only **full Run-2 datasets & improved analysis methods**

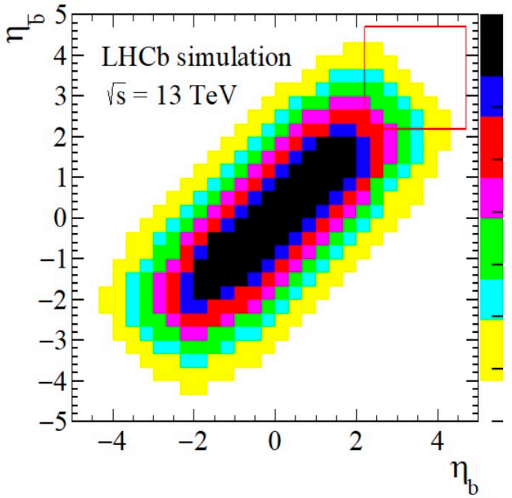


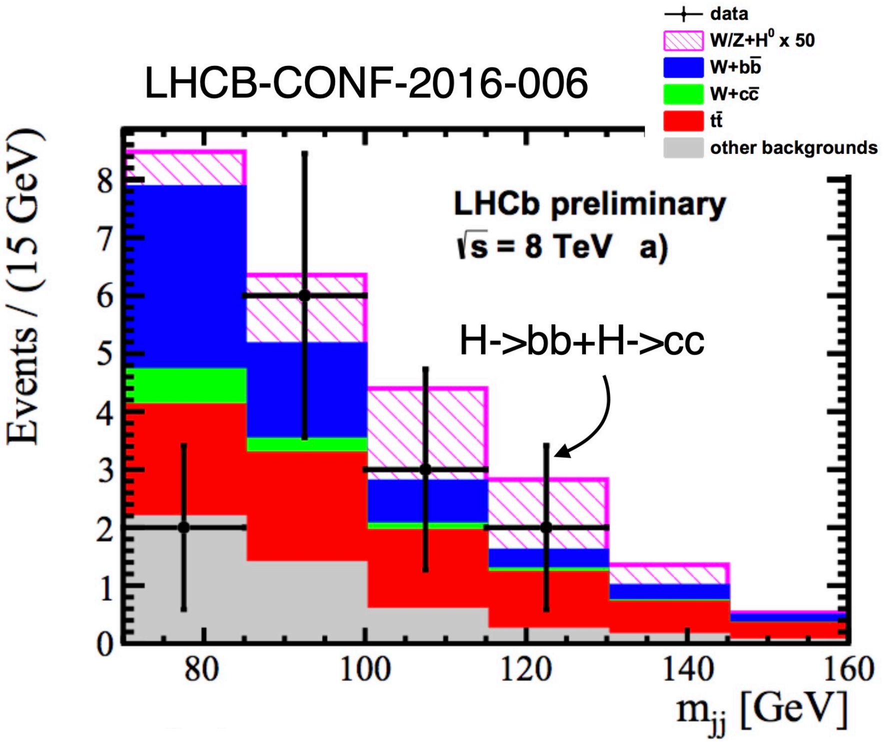


Reminder that projections are often pessimistic as **analysis strategies improve with each iteration**

Higgs boson 2^{nd} generation couplings

LHCb offers unique opportunity to study Higgs decays in forward region





Excellent flavor tagging at LHCb

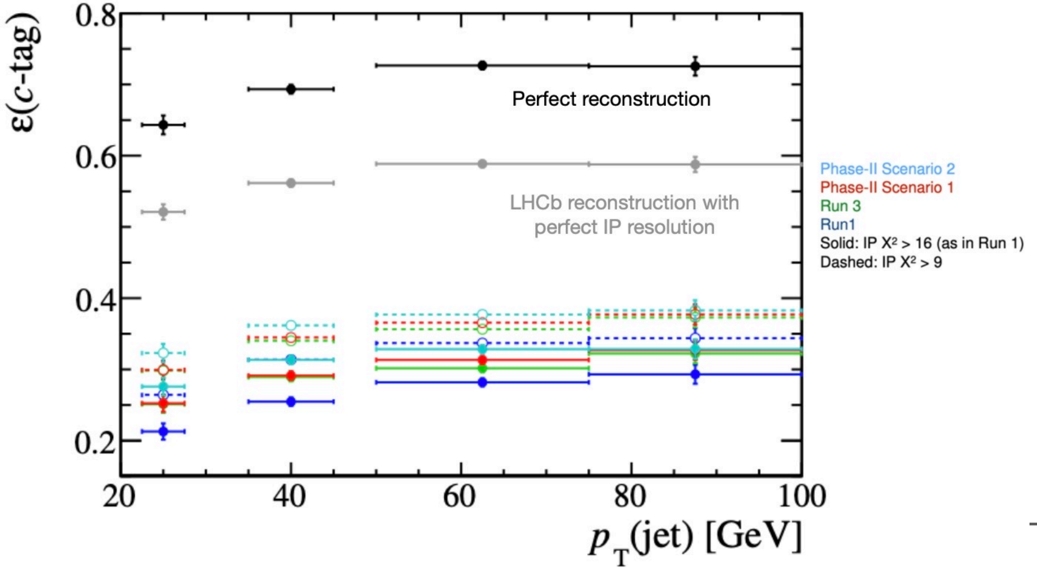
→ Current sensitivity $k_b < 7$, $k_c < 80$ with 2 fb^{-1}

By end of HL-LHC, could expect improvements from

- Luminosity scaling to 300 fb^{-1}
- Improved jet-tagging efficiency
- Improved discrimination between b- & c-quarks with ML (similar to CMS and ATLAS)

→ Expected sensitivity to κ_c ~ 2 at HL-LHC*!

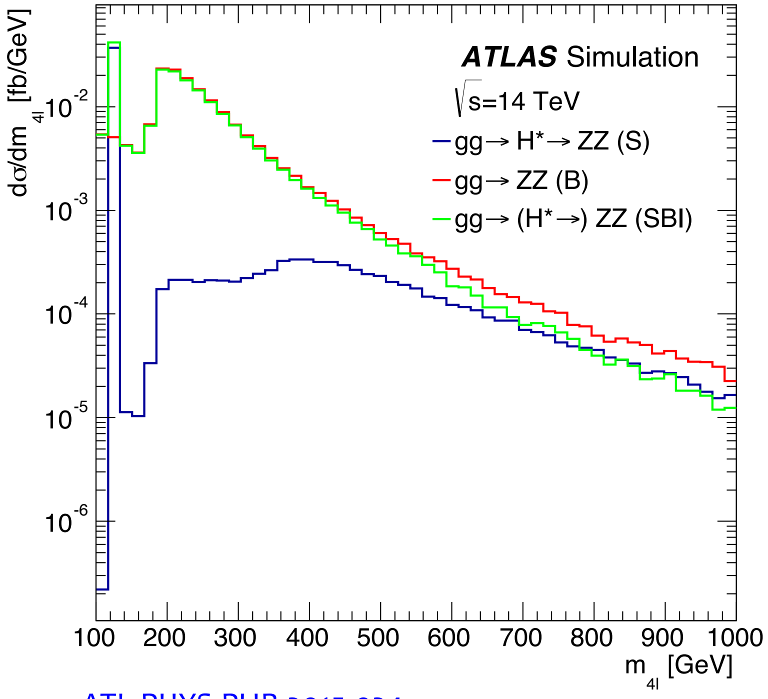
LHCB-PUB-2018-009

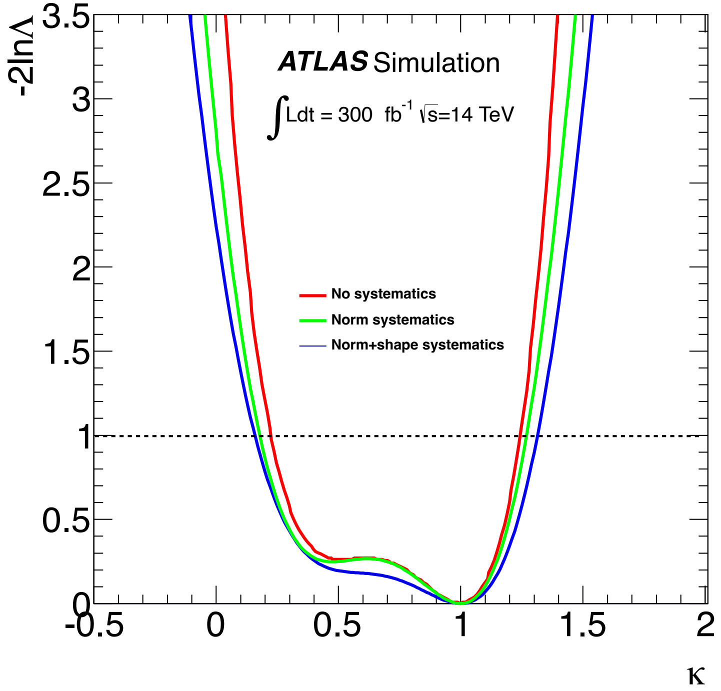


* D. Zuliani @ ICHEP 2024

Off-shell Higgs boson couplings & Width

LHC has access to **off-shell Higgs boson processes**
→ Can measure couplings away from the Higgs pole mass





ATL-PHYS-PUB-2015-024

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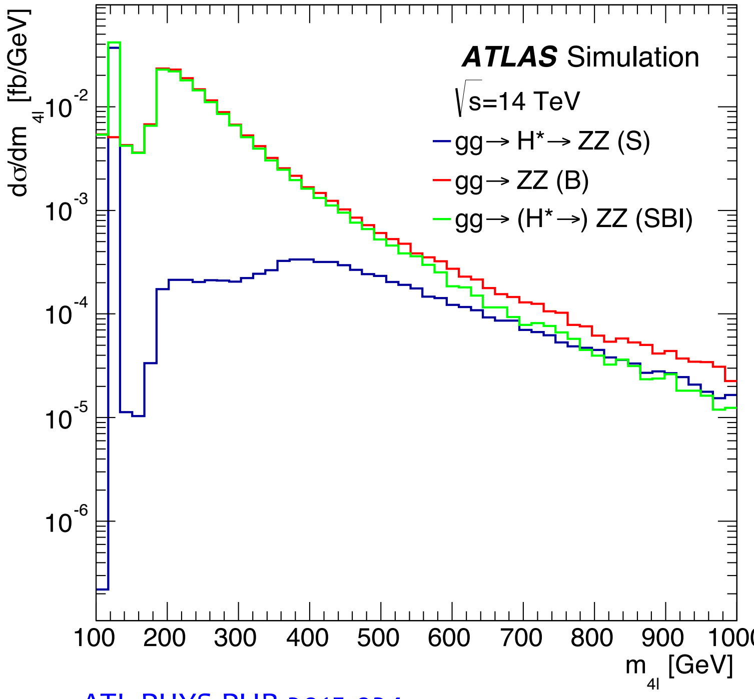
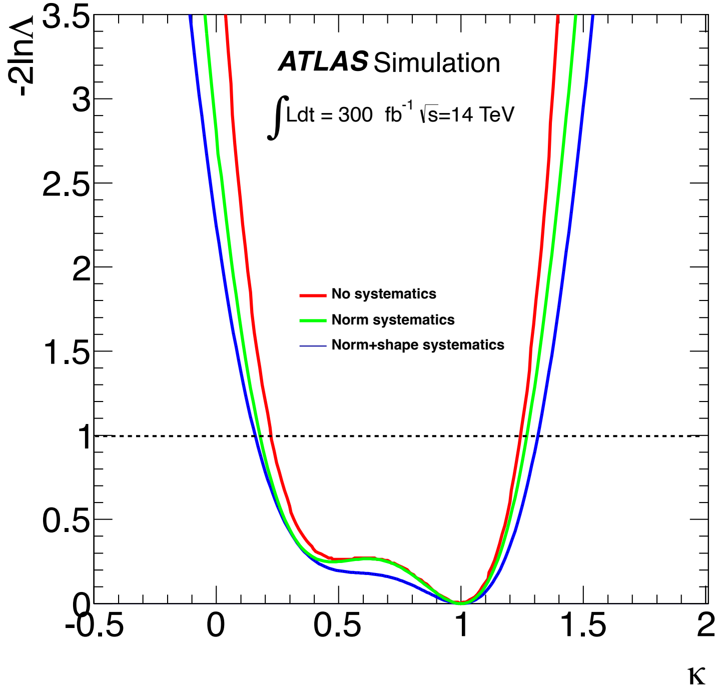
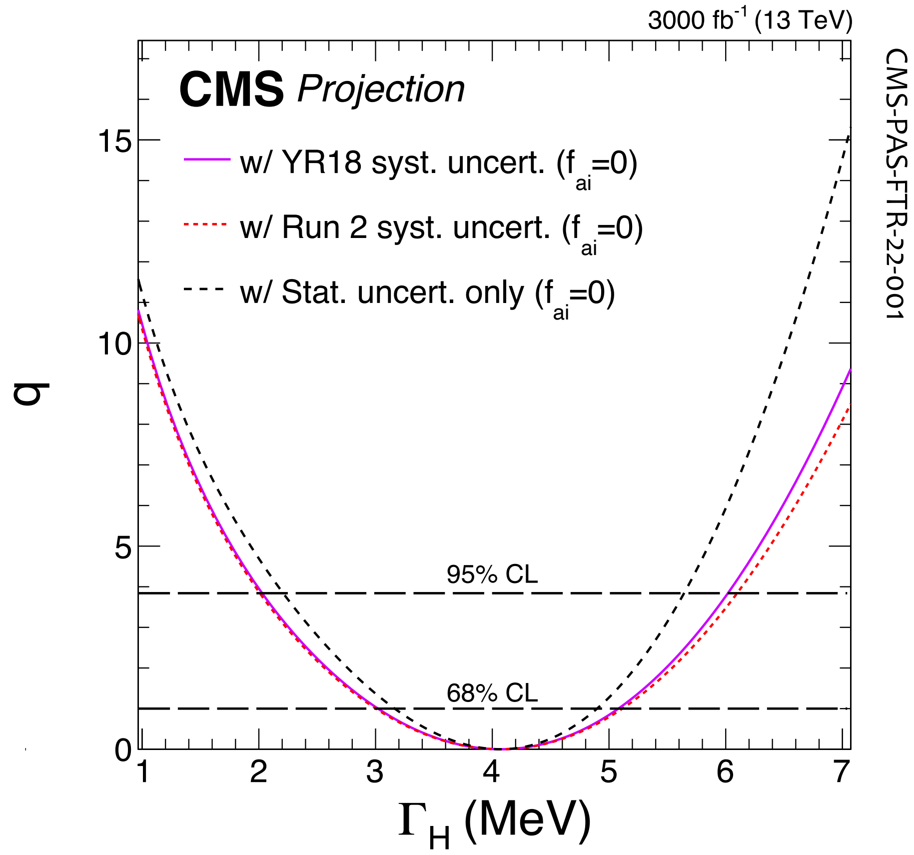




ATL-PHYS-PUB-2015-024

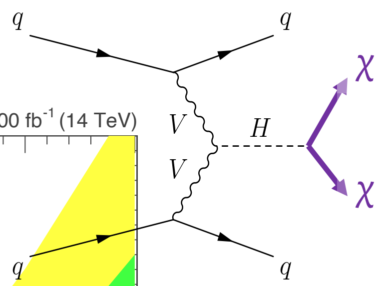


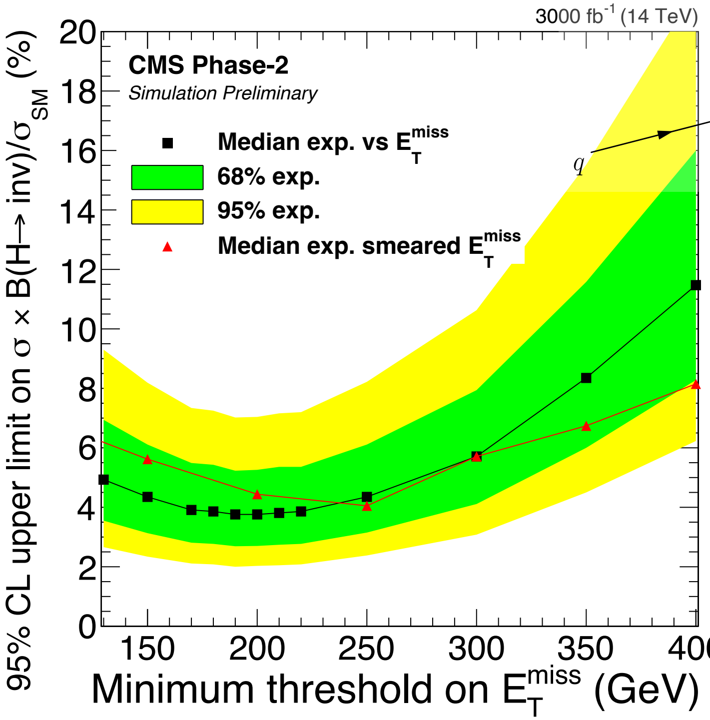
Direct measurement of **Higgs boson width** from line-shape severely limited by peak resolution

Γ_H measurements @ HL-LHC will be driven by **off/on-shell coupling combinations**

H→invisible

Searches for H + p_T^{miss} provide direct constraints on Higgs boson invisible width





SM value ~ 0.1%

Sensitivity dominated by VBF production

→ forward tracking & calorimetry vital @HL-LHC

→ p_T^{miss} needs to be under control (challenge at high PU)

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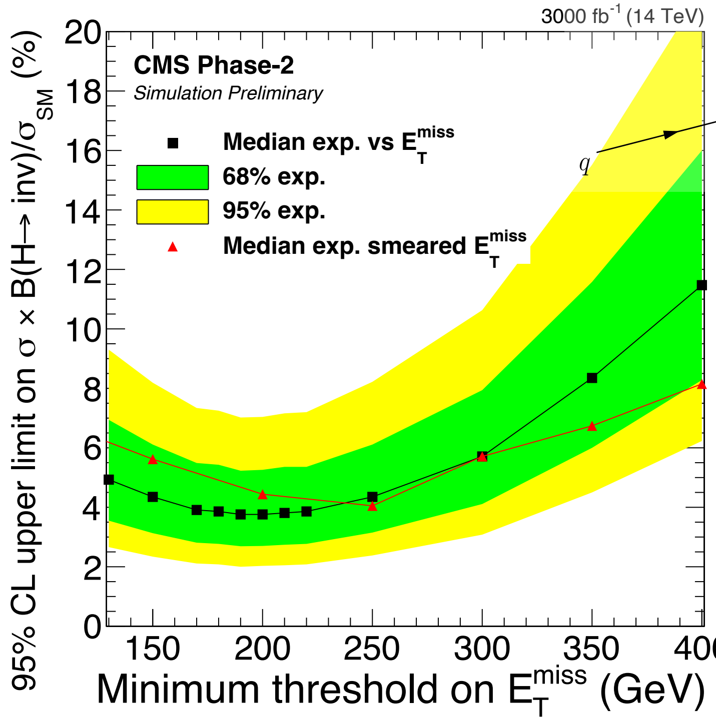

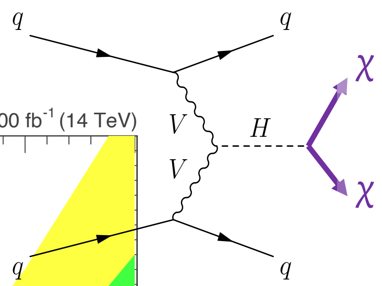

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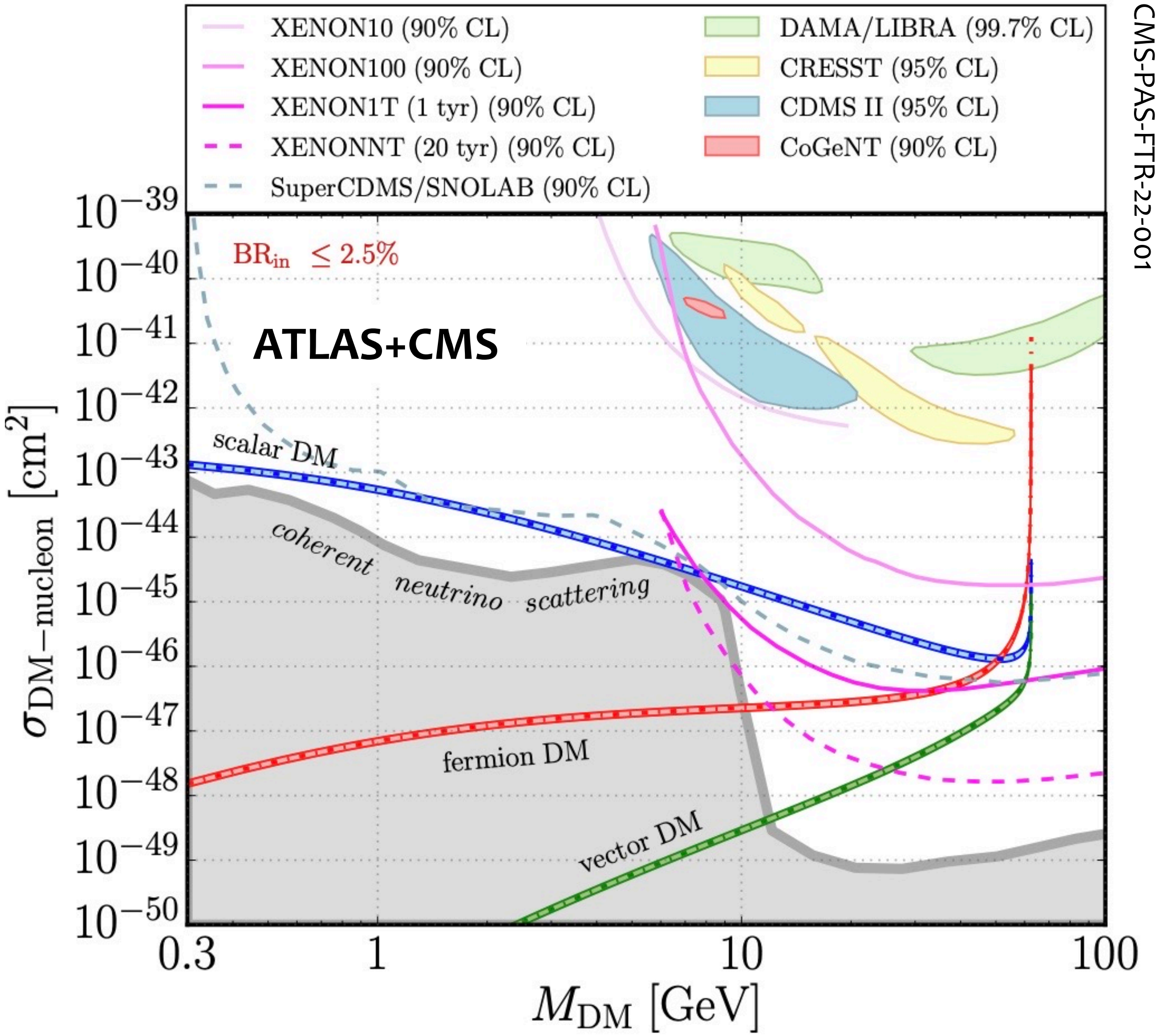


CMS-PAS-FTR-22-001

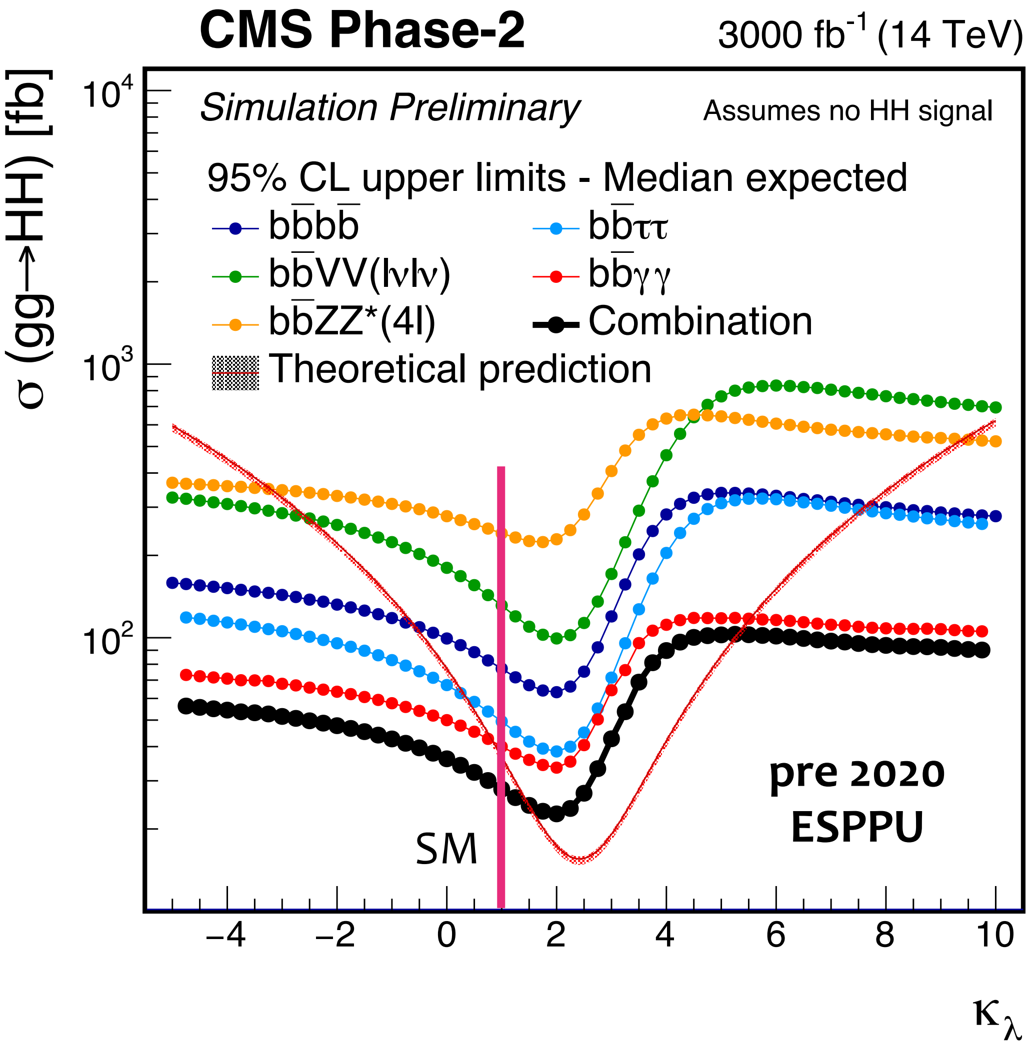
Sensitivity dominated by VBF production

→ forward tracking & calorimetry vital @HL-LHC

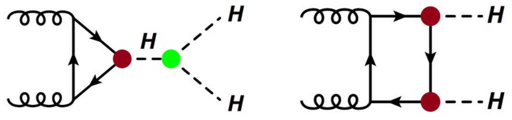
→ p_T^{miss} needs to be under control (challenge at high PU)

Measurements of B(H→inv) provide complementary constrains to direct detectors for DM models

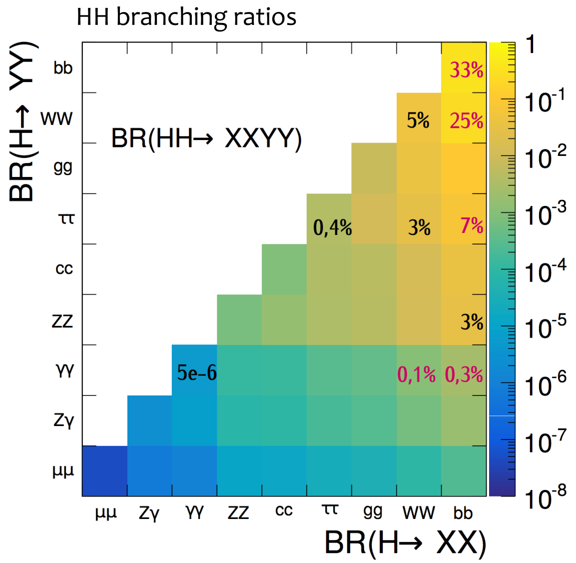
Searches for HH



Double Higgs production extremely rare process in SM due to interference



Sensitivity strongly depends on Higgs boson self-coupling



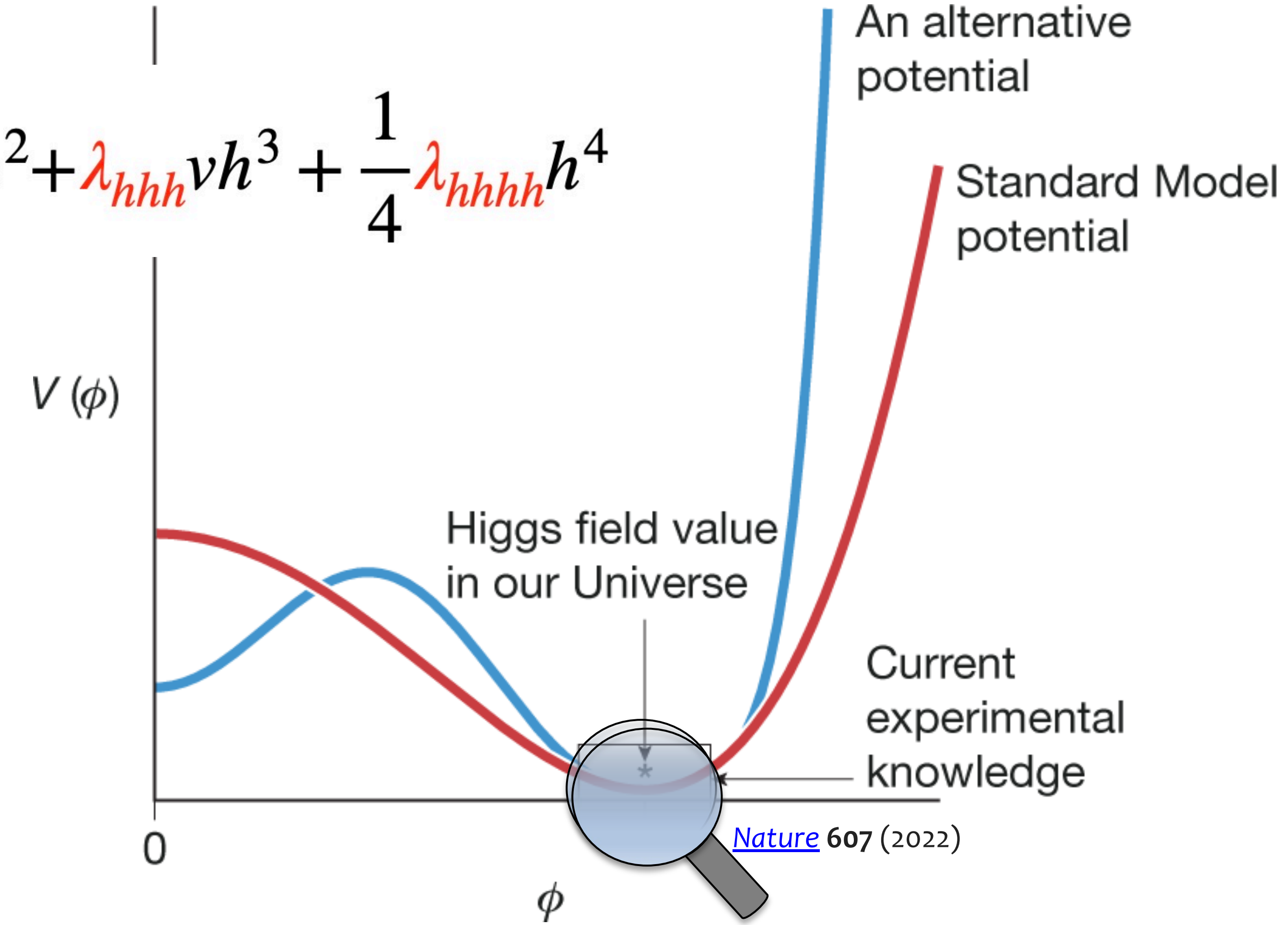
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Combination of 5 channels yields ~2.6σ significance
→ **~4σ with ATLAS combination assuming κ_λ**

Higgs boson self-coupling

Understanding the **Higgs boson potential** a crucial goal of the electroweak physics programme at the LHC

$$V(h) = V_0 + \frac{1}{2}m_H^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4}\lambda_{hhhh} h^4$$



Nature **607** (2022)

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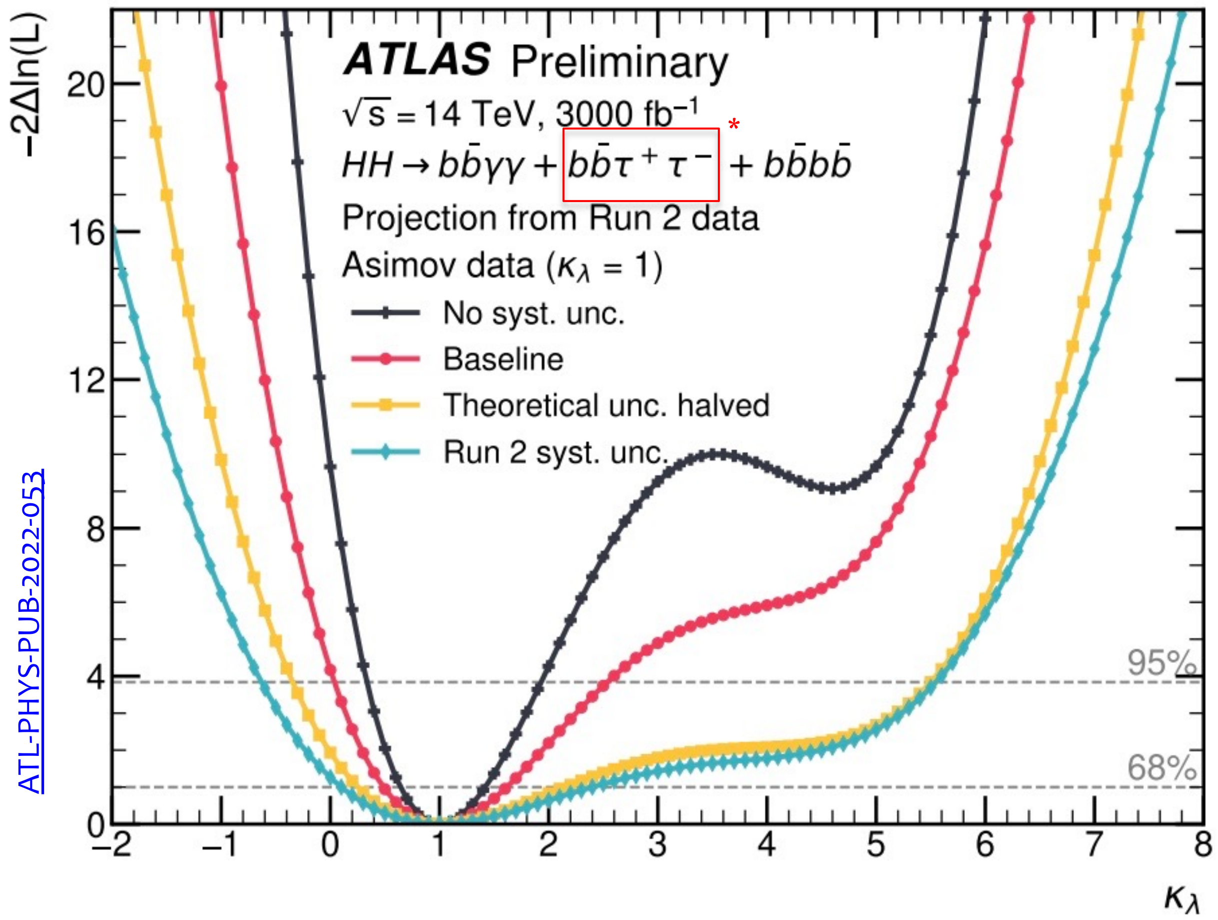

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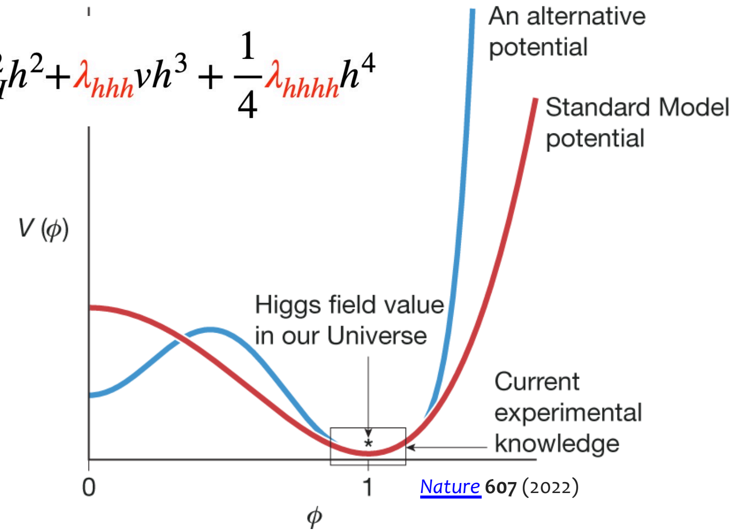


Nature 607 (2022)

New projections from ATLAS much more encouraging
→ Could reach 5σ HH discovery (~3.2σ baseline)

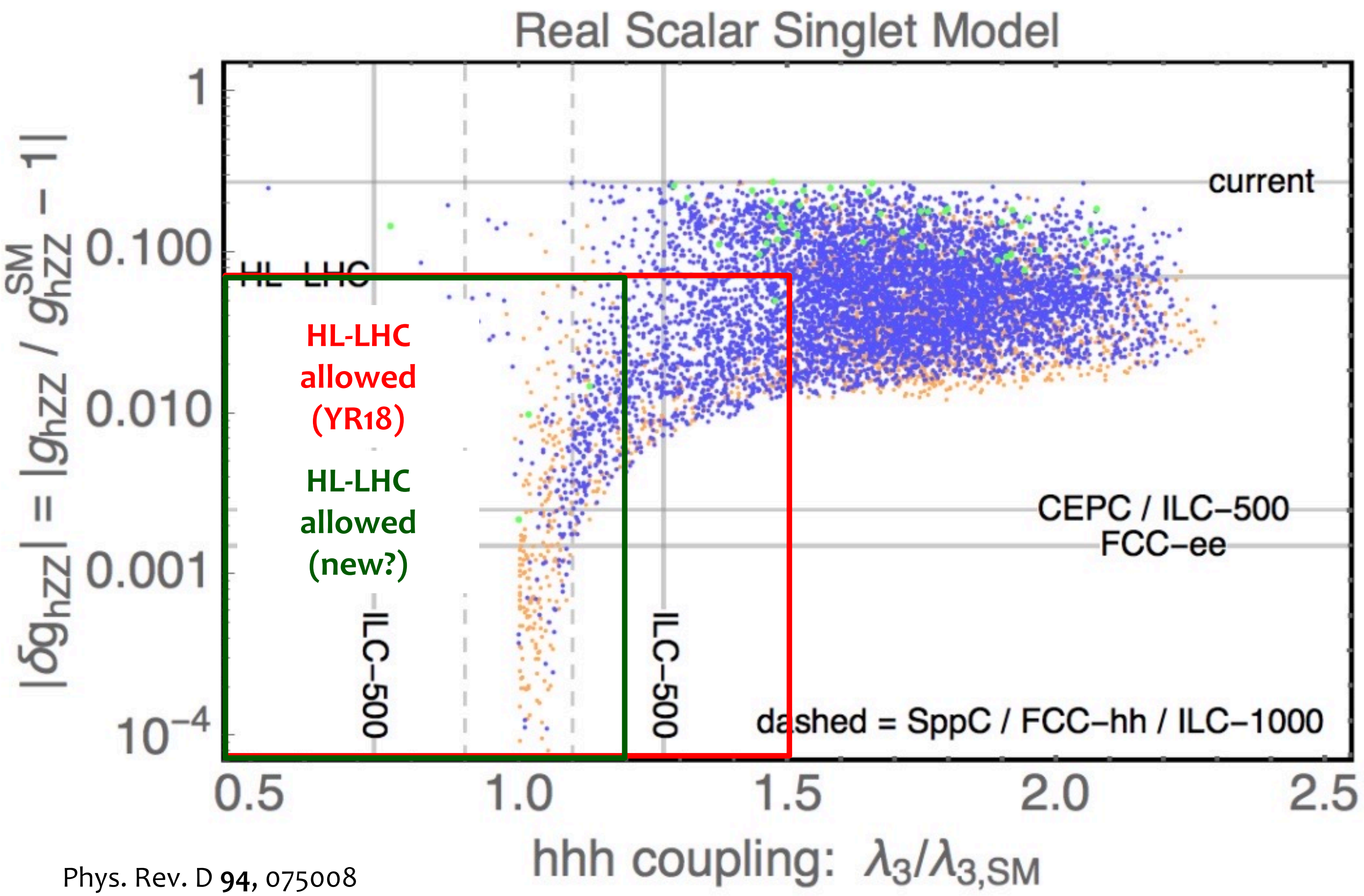
Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

ATLAS 3 ab^{-1}

→ Uncertainty in **κ_λ ~ 20% with LHC combination!**

* *Very recent update from ATLAS in this channel* → similar sensitivity to HH in single channel! ATL-PHYS-PUB-2024-016 + See Jay's talk yesterday

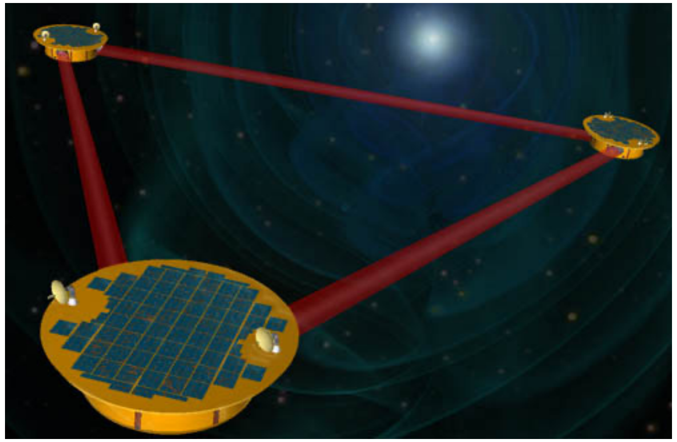
Higgs and the Universe



Phys. Rev. D **94**, 075008

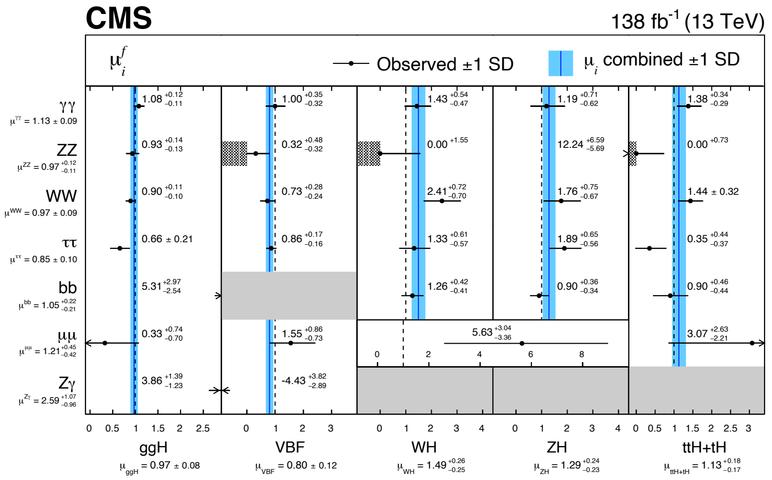
Modified Higgs potentials can result in 1st order electroweak phase transition
→ **required for baryogenesis**

- Strong first order PT (electroweak baryogenesis viable)
- Could be detected at GW detectors (eLISA)



Kinematic distributions

On-shell

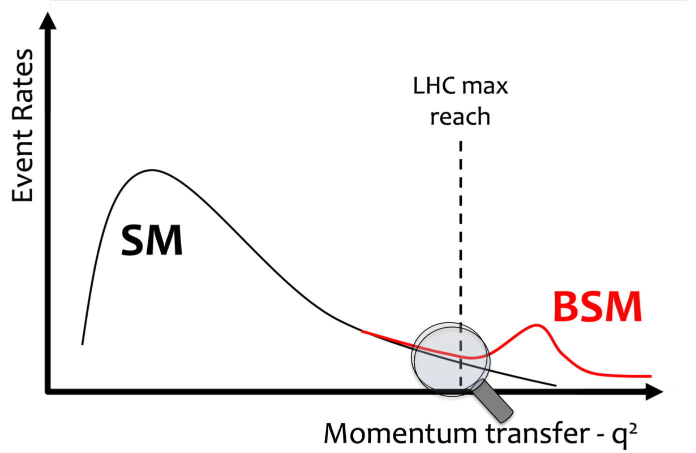


$$\delta \sim \left(\frac{v}{\Lambda}\right)^2$$

Inclusive κ/μ : high-precision yields precision on new physics scale

δ_μ = 1% → Λ ~ 2.5 TeV

Off-shell / large q^2



$$\delta \sim \left(\frac{q}{\Lambda}\right)^2$$

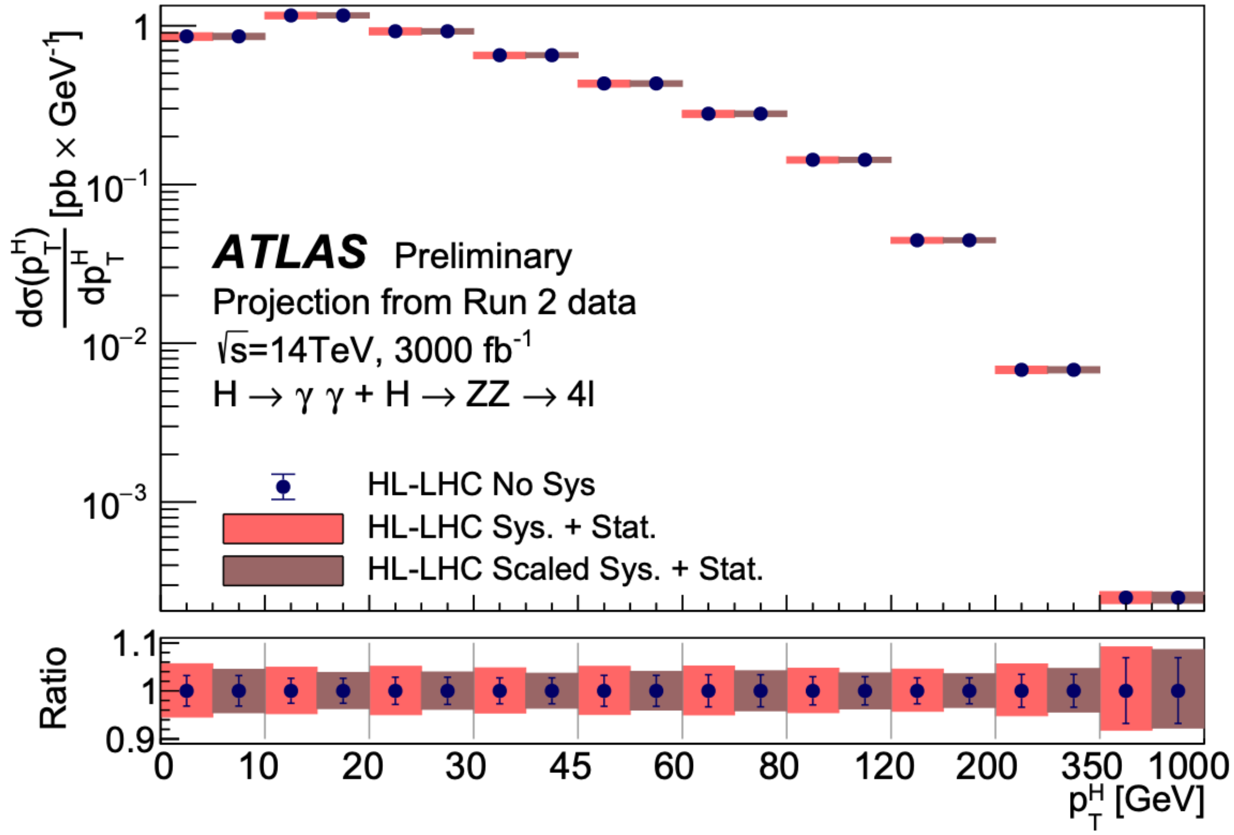
Differential: High momentum production sensitive to new physics

δ_σ = 15% (q=1TeV) → Λ ~ 2.5 TeV

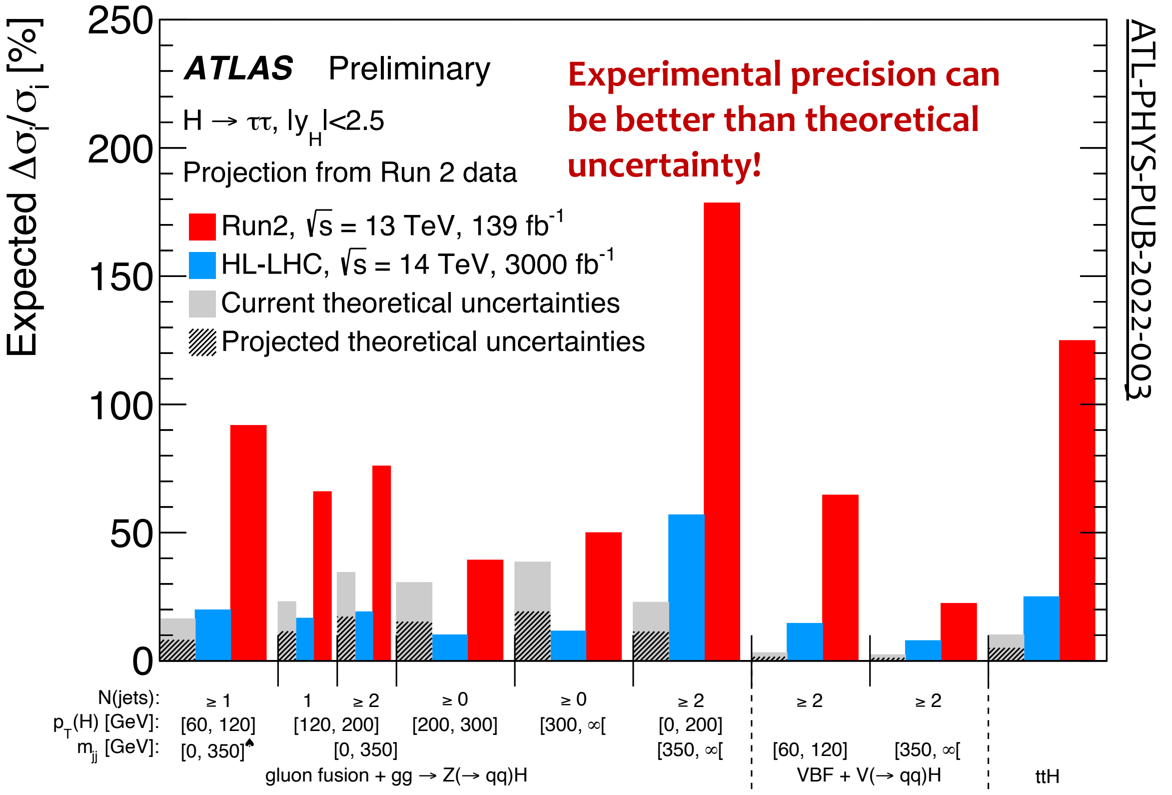
Kinematic distributions

Differential measurements of Higgs boson production provide more granular information as more data available → factorize theory uncertainties and allow to probe scenarios where **BSM physics enhances tails of distributions**

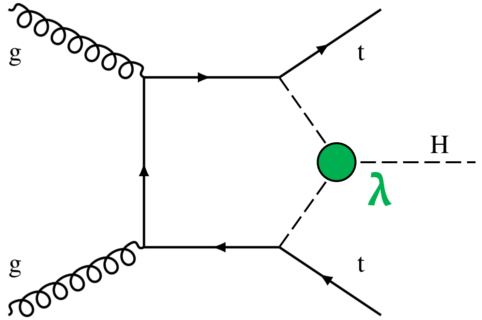
(Fiducial) differential measurements



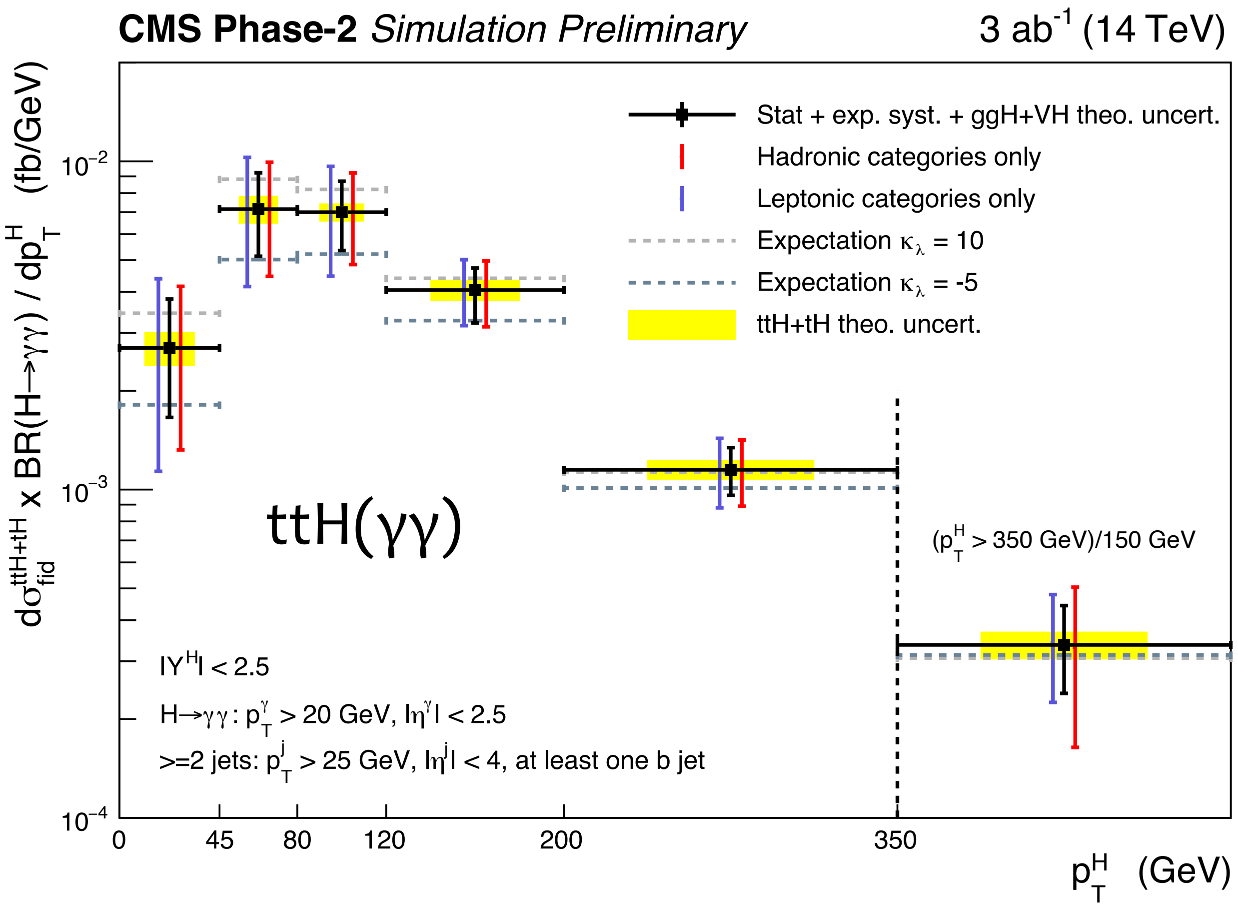
STXS measurements

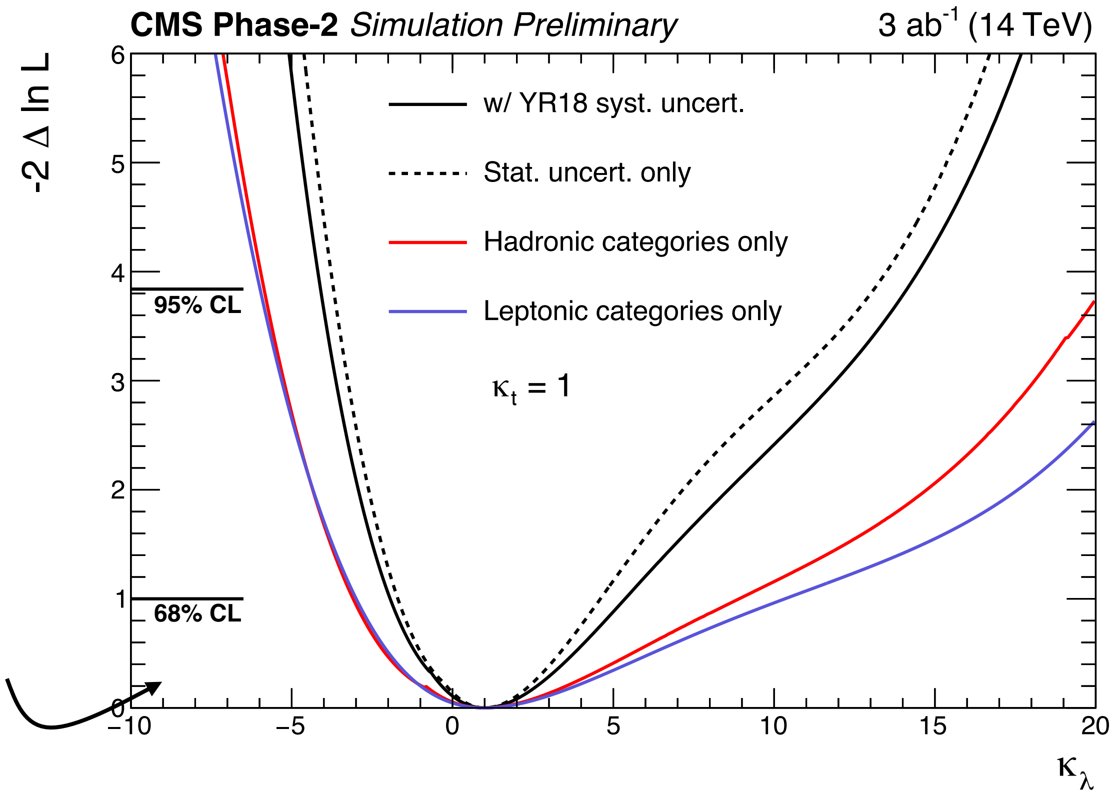


Kinematic distributions



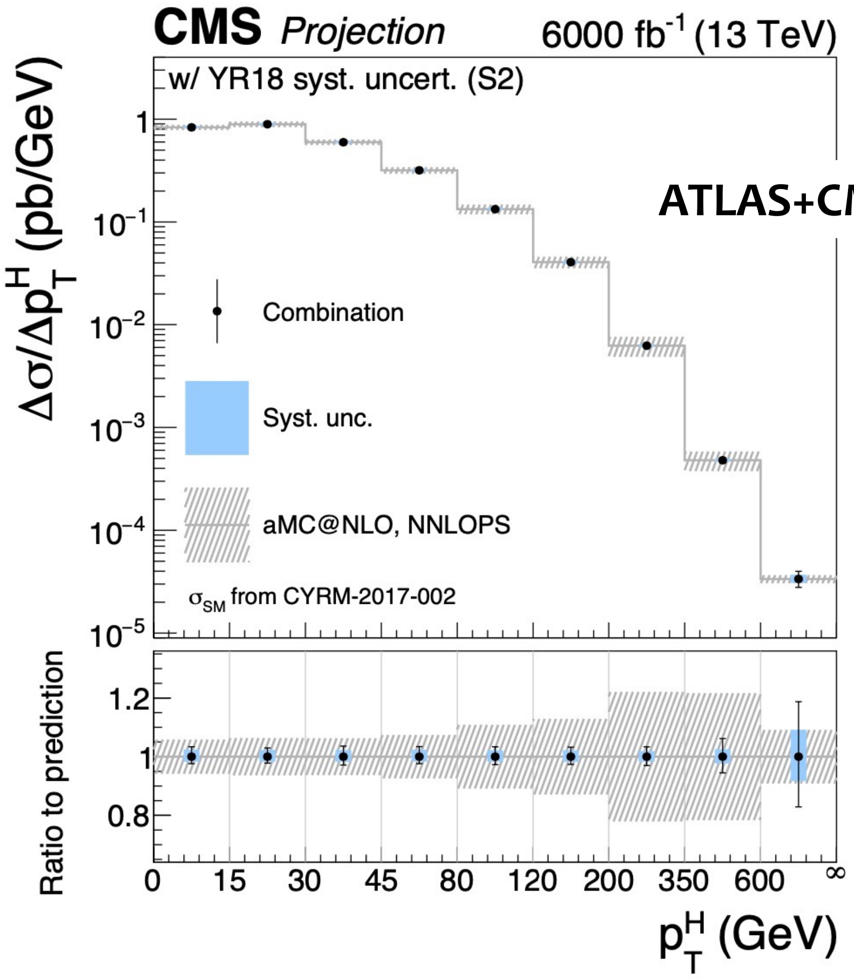
Differential Higgs boson measurements also expected to yield sensitivity to Higgs boson self-coupling → **combine with HH searches for ultimate sensitivity to κ_λ**



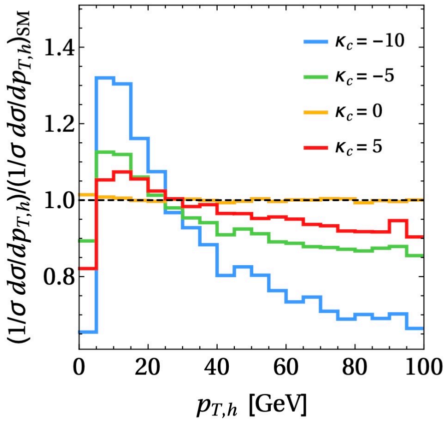


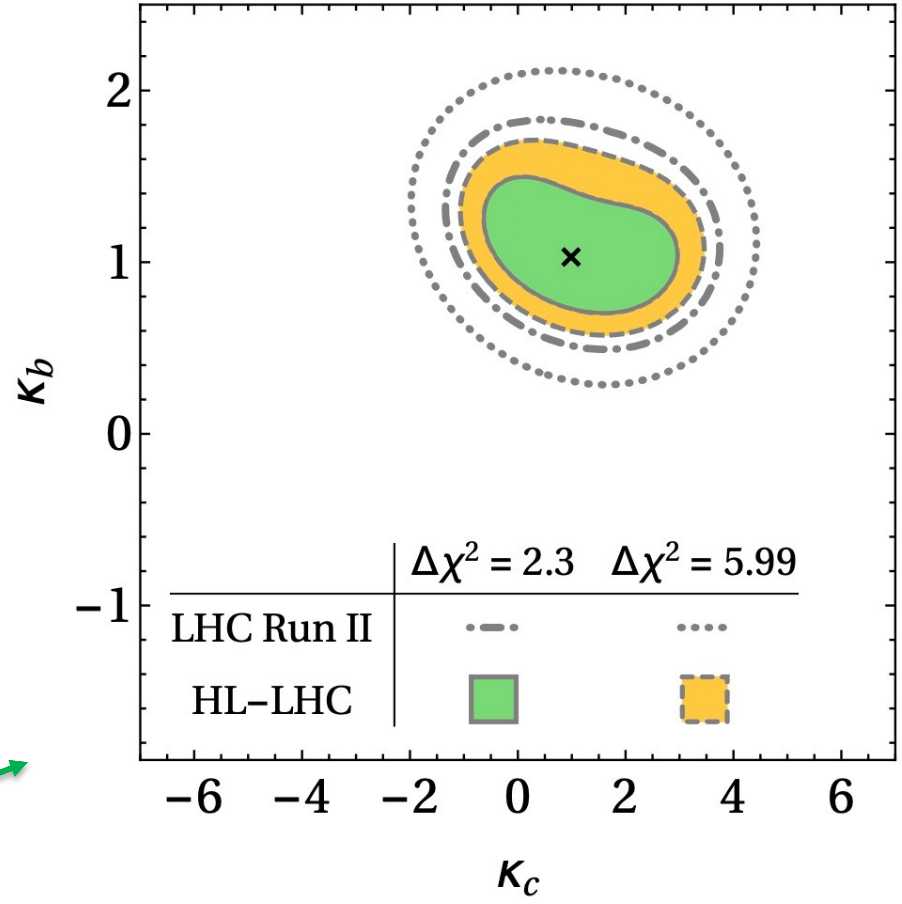
Kinematic distributions

Kinematic measurements provide Additional constraints on b/c-H coupling!



ATLAS+CMS HL-LHC



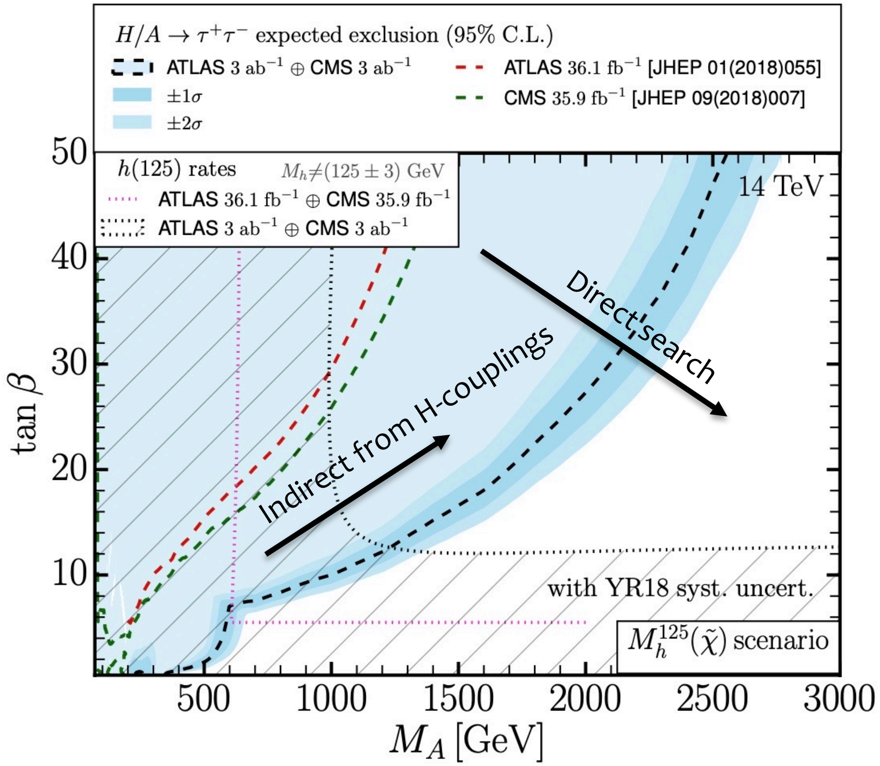


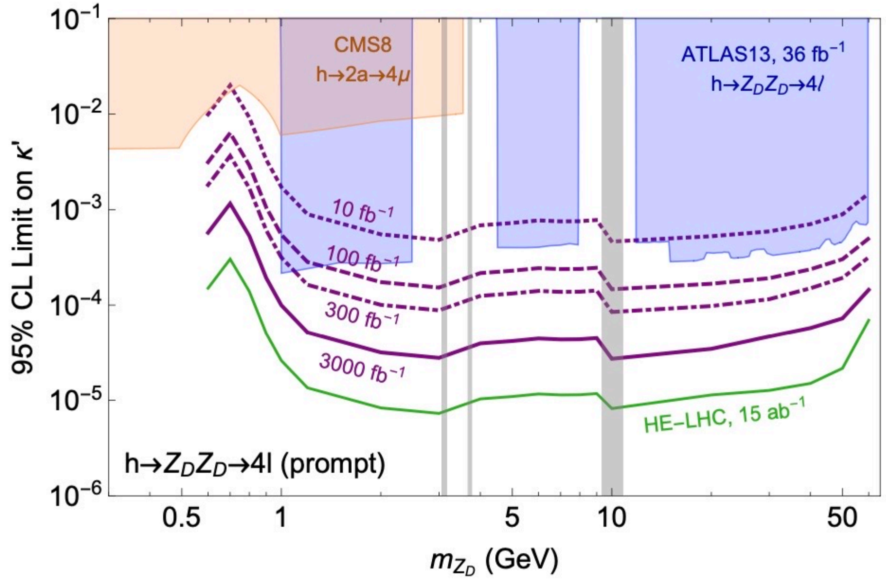
Measurements of differential Higgs boson production now more commonly interpreted under effective field theories (e.g [CMS-PAS-HIG-23-013](), [ATLAS-HIGG-2022-17]()) → **likely to be a legacy of the (HL)LHC**

BSM Higgs

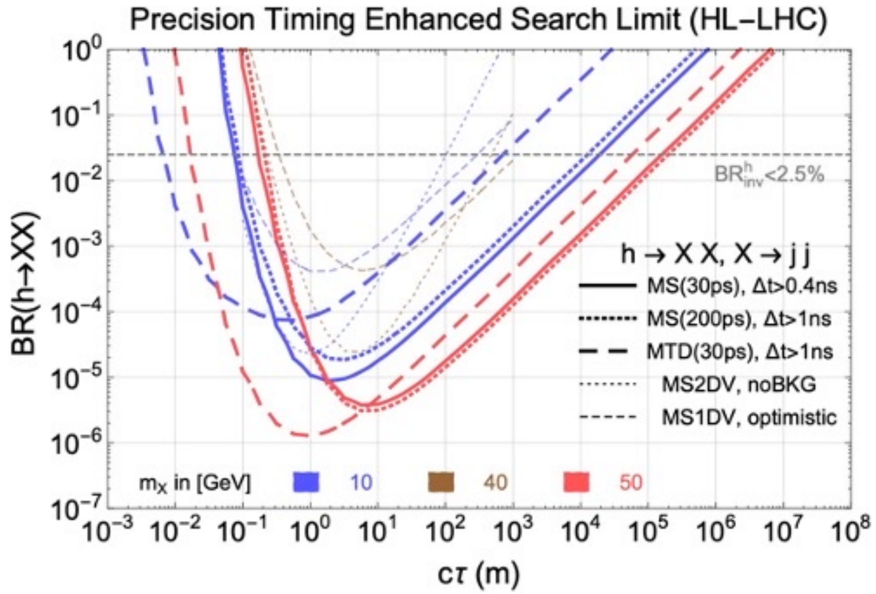
Searches for **extended Higgs sectors and BSM Higgs boson decays** limited at HL-LHC due to

Requirement for statistics (H→BSM rare processes) or energy (BSM Higgs)





Prompt decays



LLPS

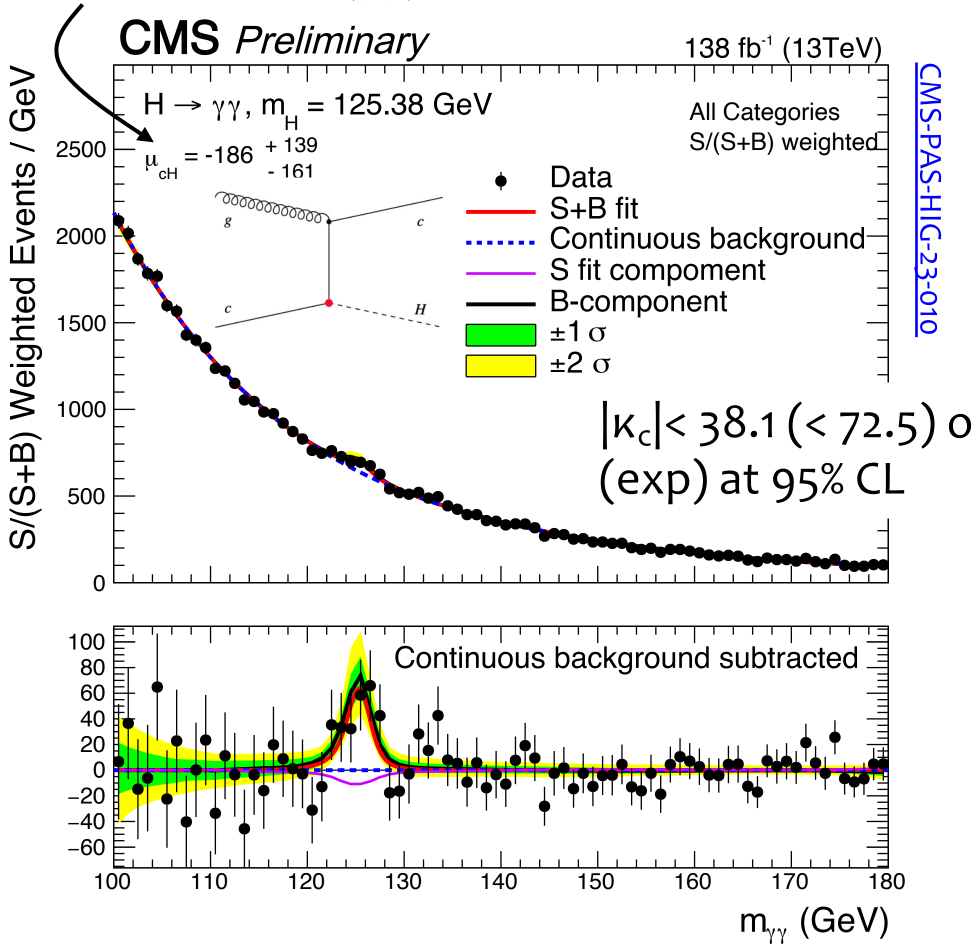
Likely that limits set by HL-LHC will remain **most stringent until future hh** (or other high energy) collider

Exploting all of the data

Current projections don't account for **new methods** to constrain Higgs boson properties
→ More data can bring more than just $\sqrt{L}$ improvements

New ideas even with Run-2 data!

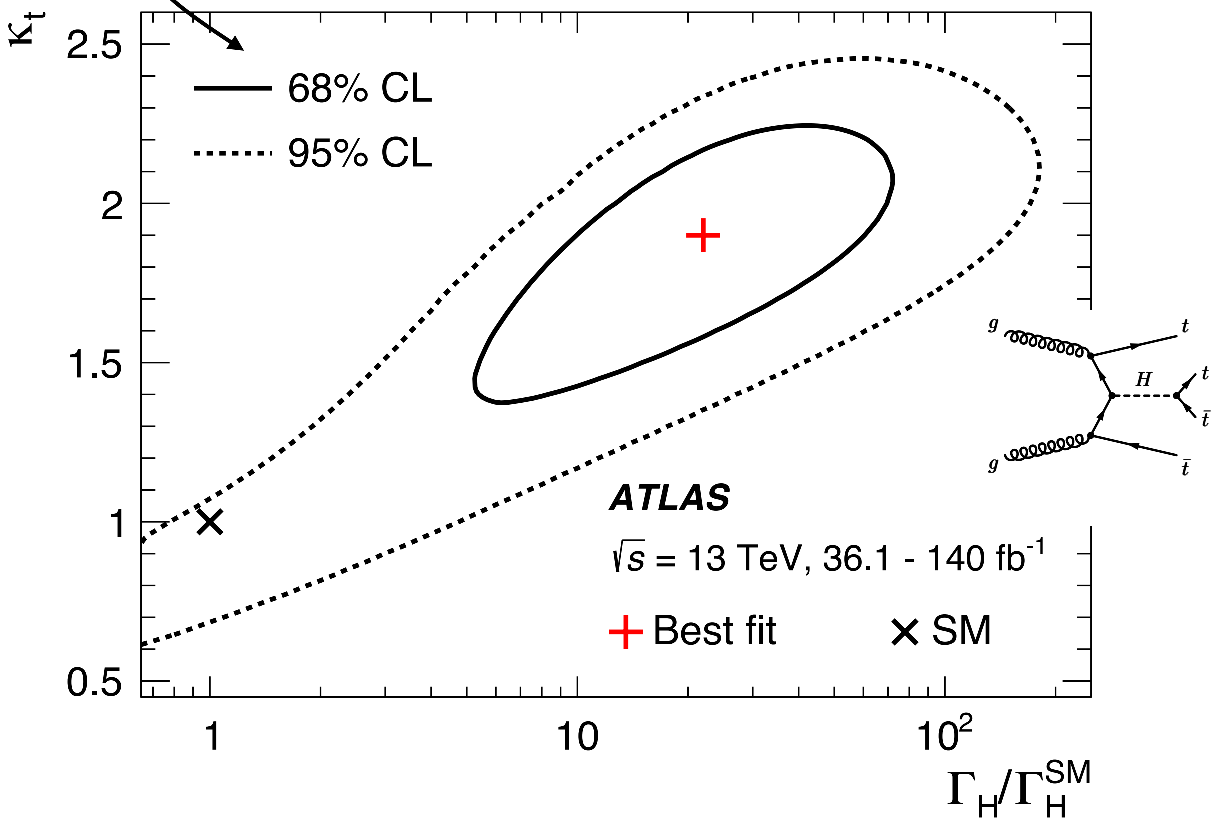
Constraint on κ_c from H(γγ)+c search



$|\kappa_c| < 38.1$ (< 72.5) obs (exp) at 95% CL

Higgs boson width from couplings and pp→4top

ATLAS-TOPQ-2023-22

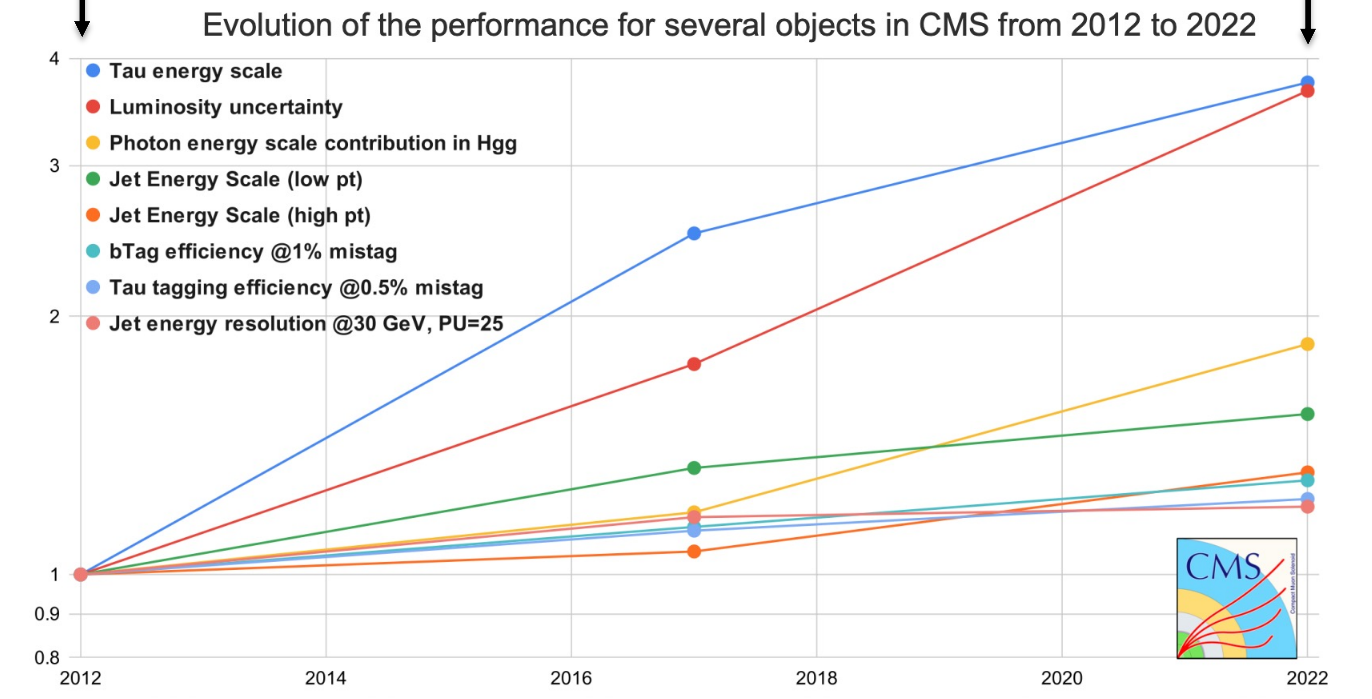


Understanding our data

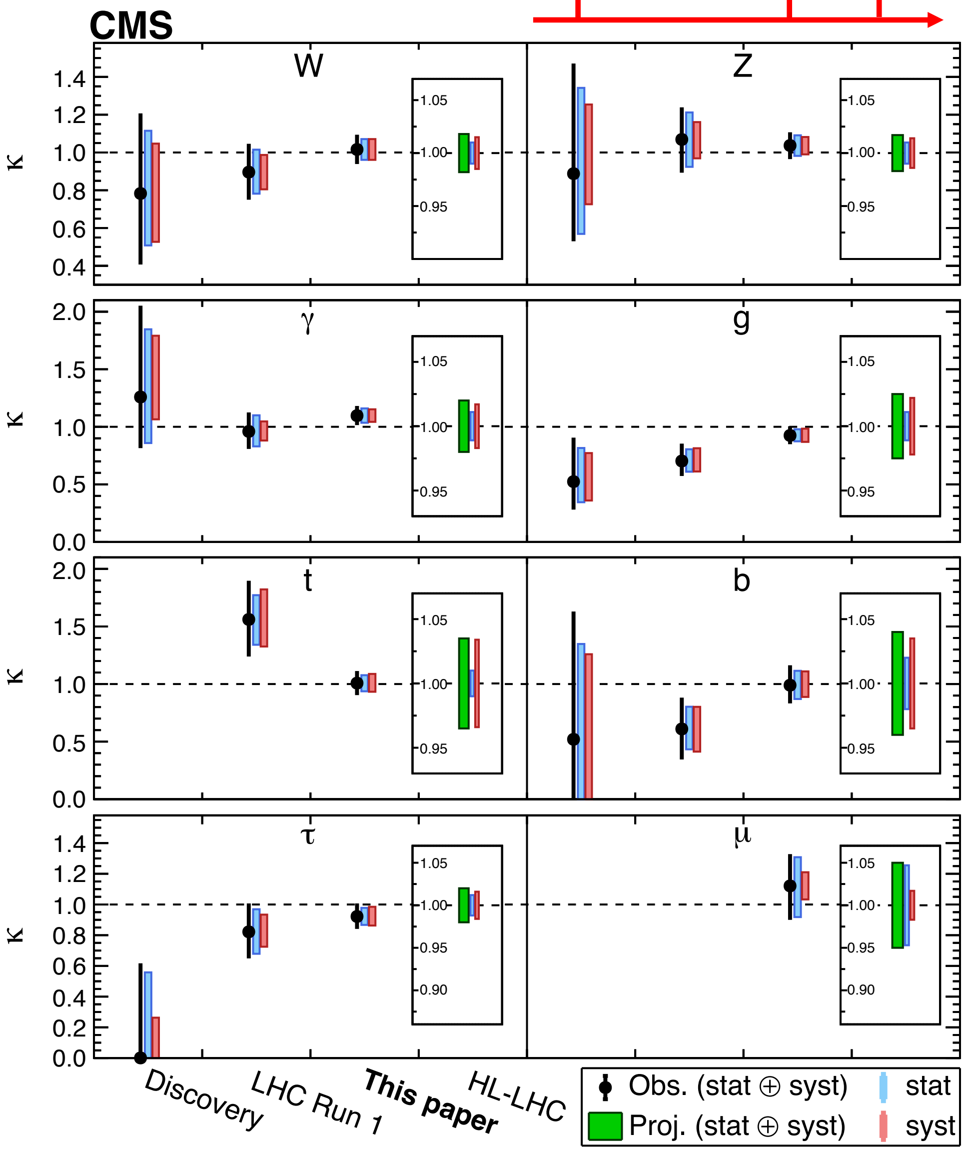
Precision measurements require more than just more data
→ Improvements in reconstruction techniques & calibrations will be needed for few % precision couplings @HL-LHC

Discovery

Today



10 yrs
0 yrs
~ 25yrs?

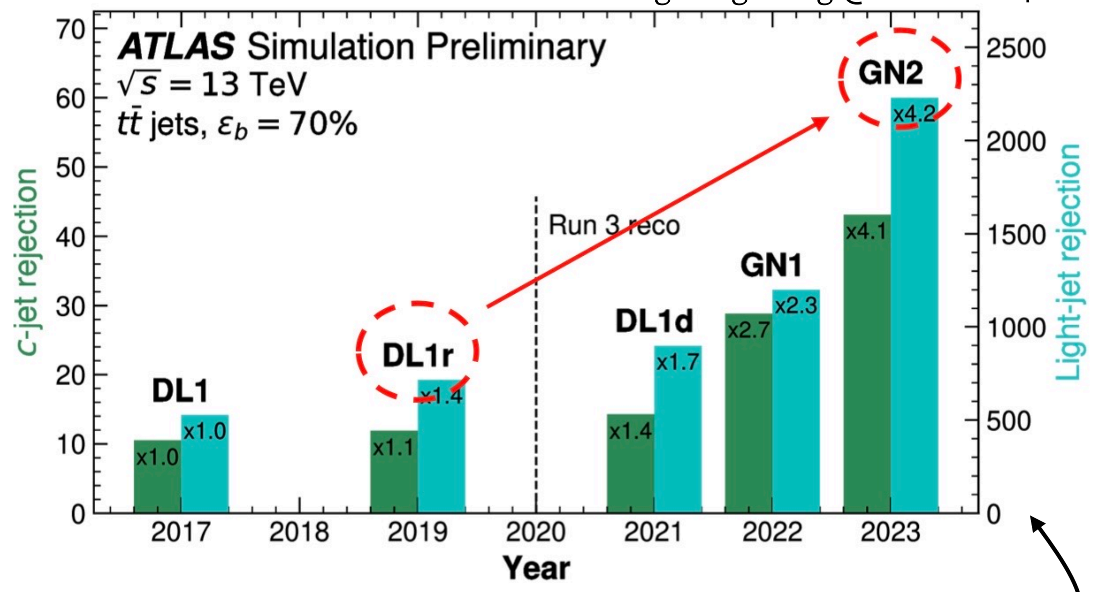


Nature publication

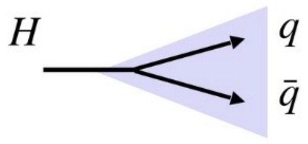
Exploiting new ideas

(FTAG-2023-01)

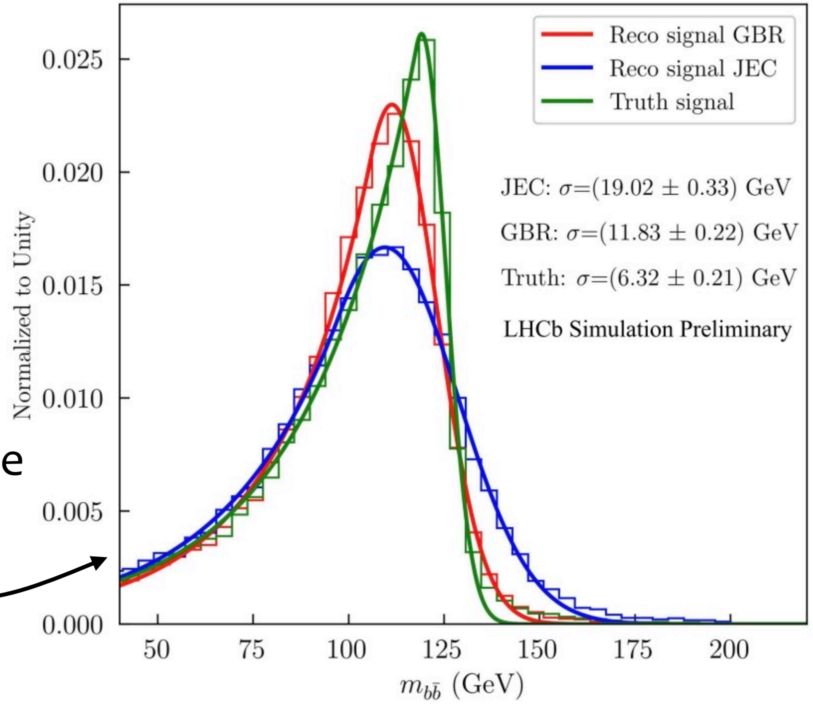
Song-Ming Wang @ ICHEP 2024



Smarter algorithms (enhanced with Graph-based ML) to identify jet-flavor → **VH(bb), HH→4b**

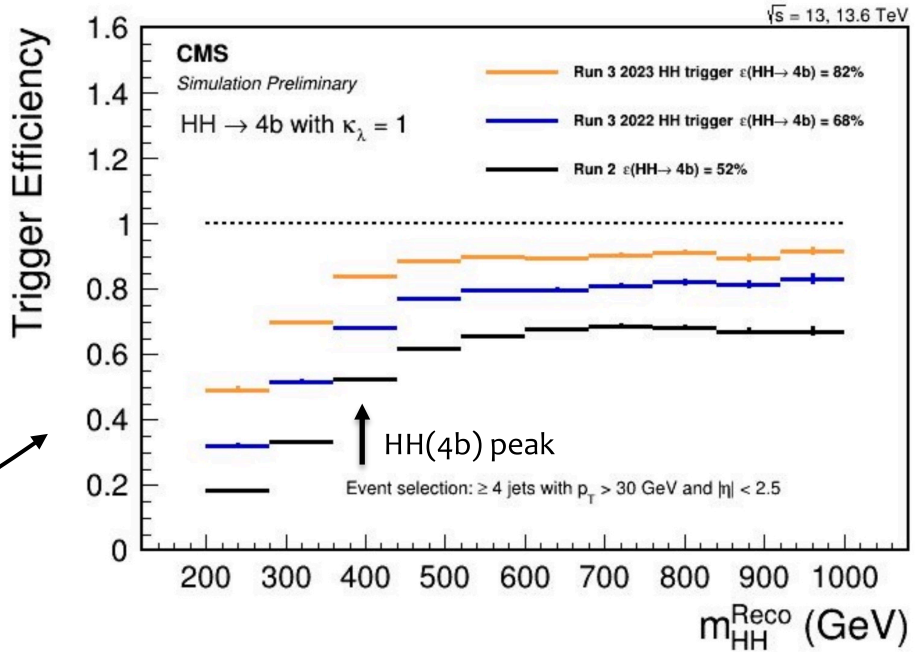


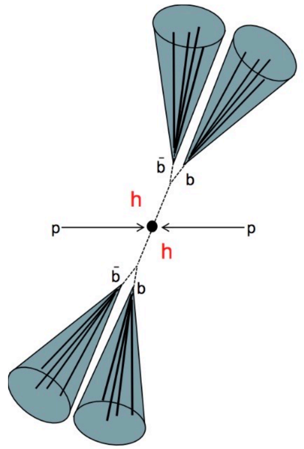
Gradient boosted regressor to improve $m_{bb/cc}$ resolution for **H→bb/cc**



LHCB-FIGURE-2023-029

New dedicated triggers for **HH searches** (both for 4b and 2b2τ final states) to improve signal efficiency in Run-3!





Summary

We are still early (in terms of data taken) of the LHC era

- Expect **> 160M H-bosons / 120k HH pairs** at CMS by the end of the **HL-LHC** !

Extremely broad programme for Higgs physics explored during Run-1/2 and now ongoing in Run-3

- Since discovery, Higgs boson mass, width, couplings, cross-sections, BSM-Higgs

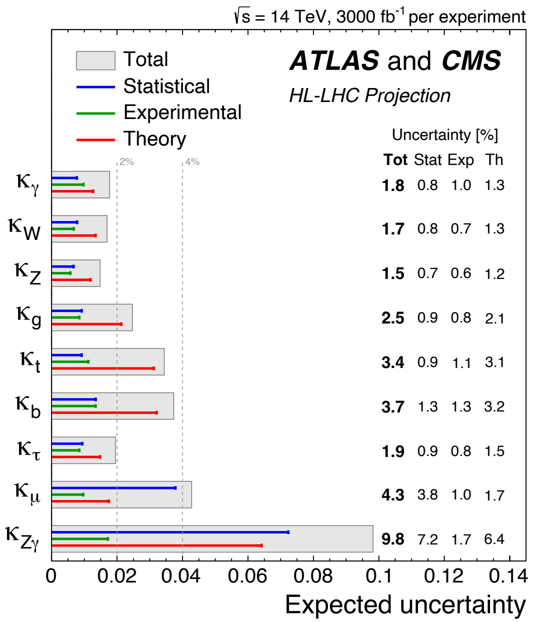
Projections of current analyses show

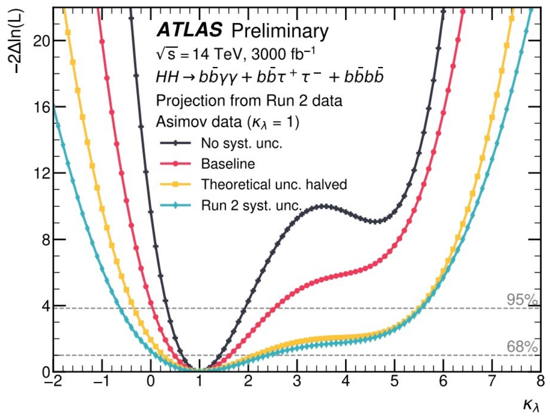
- 20 MeV in m_H and strong constraints on total width
- O(%) uncertainty in many Higgs boson couplings → several will be long-lasting legacy of the (HL-)LHC
- Likely first observation (5σ) of 2^{nd} generation couplings and pushing sensitivity in rare/invisible decays
- Possibility to reach observation of di-Higgs production and < 50% uncertainty in the self-coupling

Projections are always out of date!

- New analyses/methods emerging even now with Run-2/3 data
- We usually get smarter with each iteration of the analyses

  → **Expect HL-LHC Higgs legacy to be better than we expect now!**

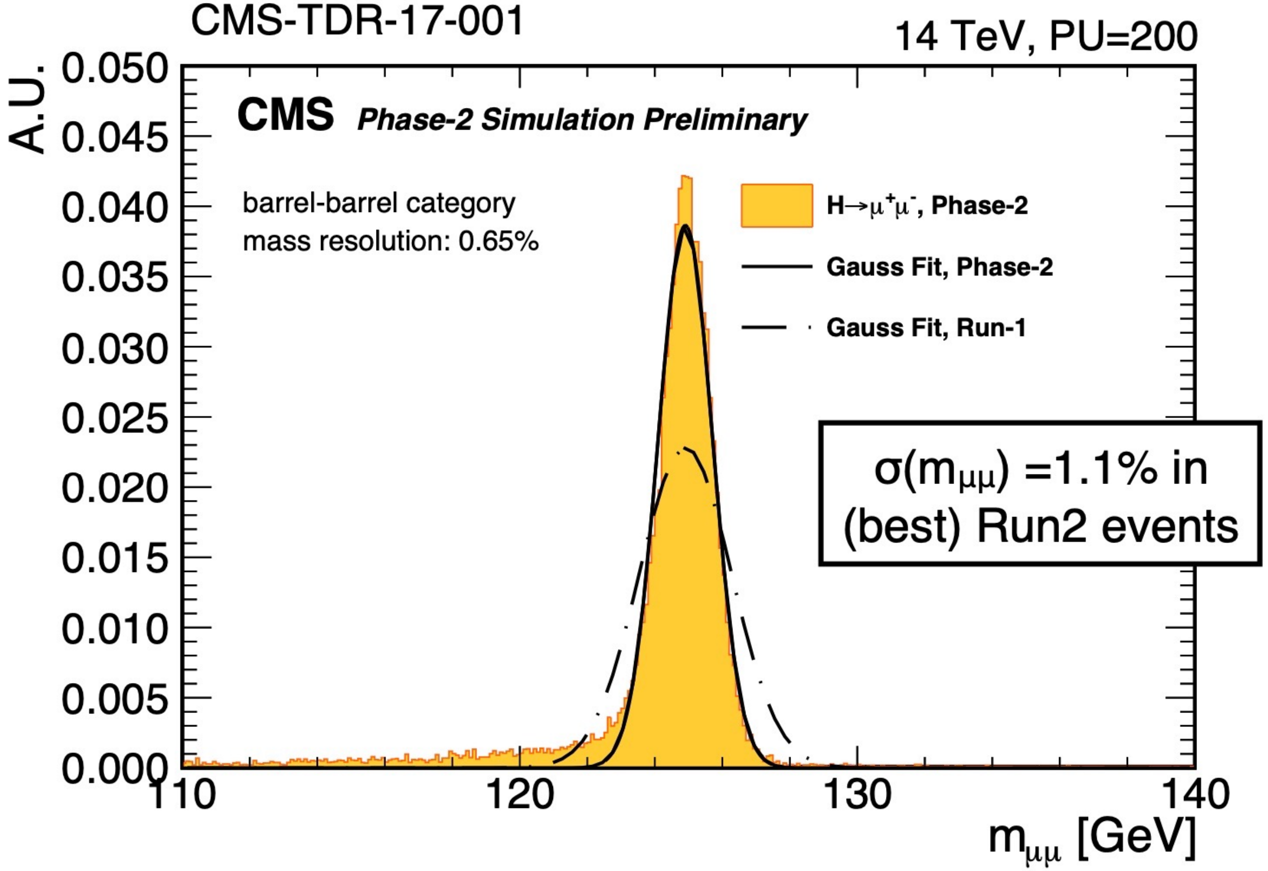




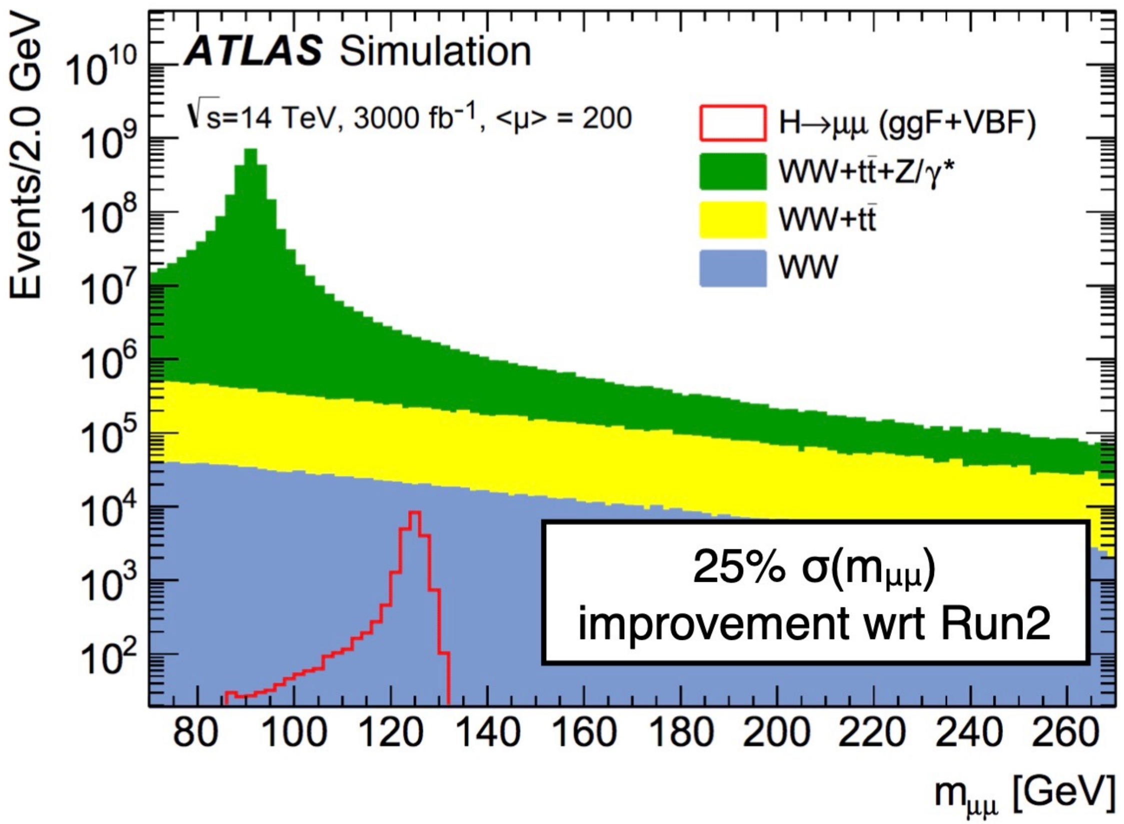
Backup

Muons - Upgrades

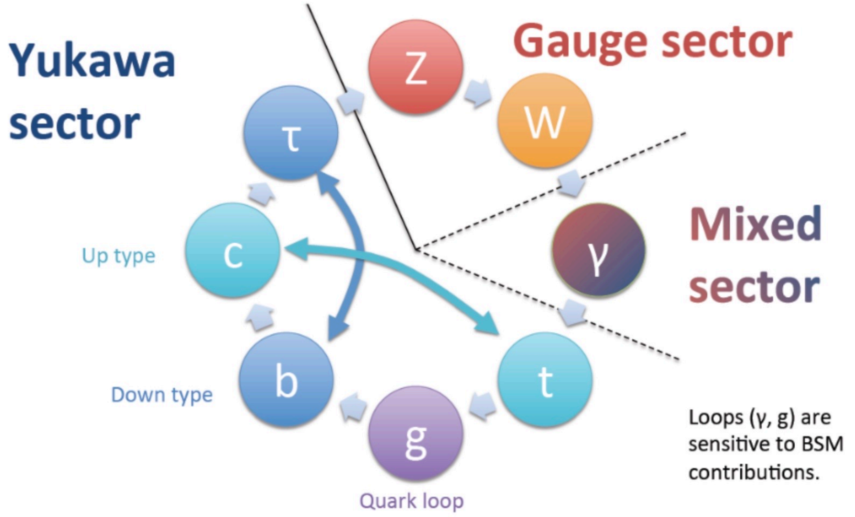
CMS-TDR-17-001



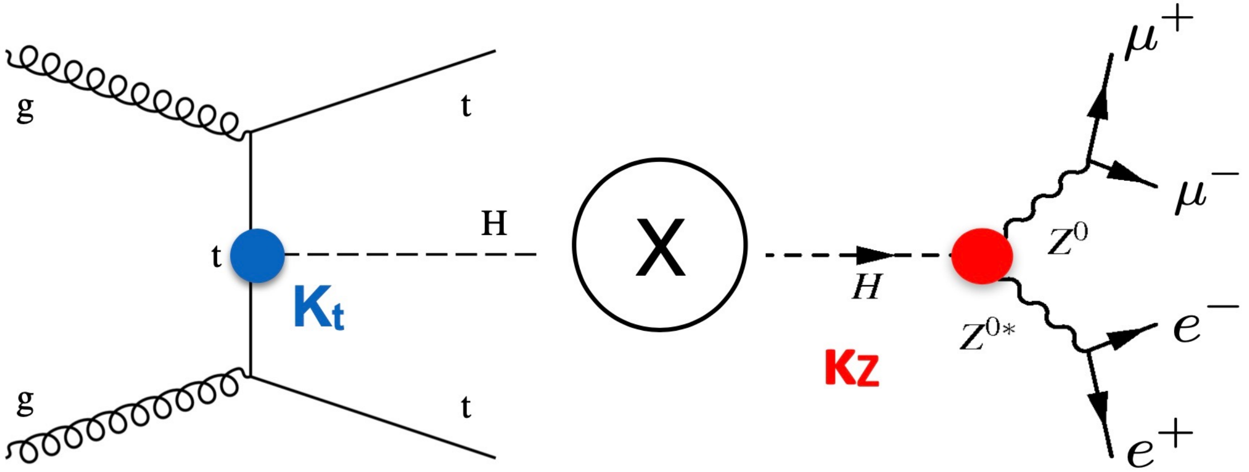
ATLAS-TDR-025



Higgs boson coupling measurements



$$\sigma(i \to H \to f) = \sigma_i(\boldsymbol{\kappa}) \cdot \frac{\Gamma^f(\boldsymbol{\kappa})}{\Gamma_H}$$

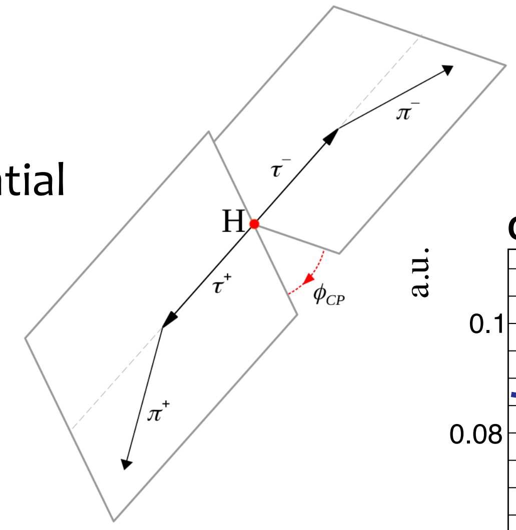


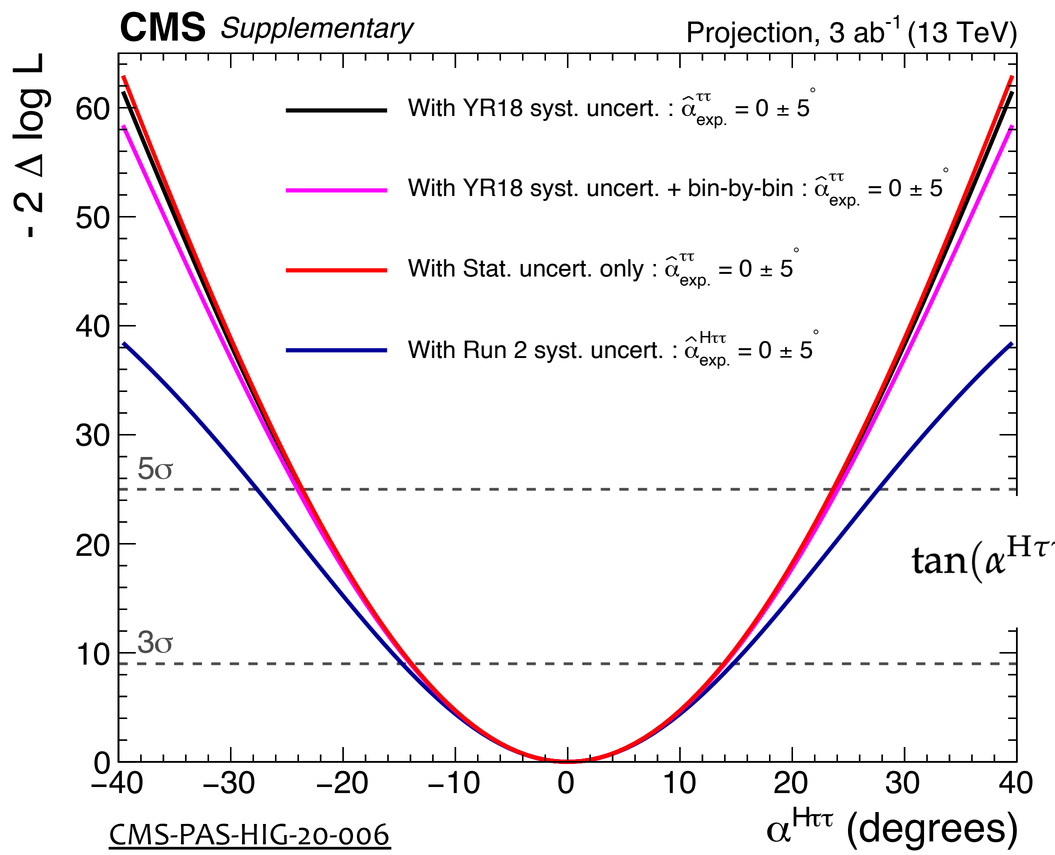
$$= \sigma_{\mathrm{SM}}(\mathrm{tt}H) \cdot B_{\mathrm{SM}}(H \to \mathrm{ZZ}) \cdot \frac{\kappa_{\mathrm{t}}^2 \kappa_{\mathrm{Z}}^2}{\kappa_H^2}$$

$$\Gamma_H(\boldsymbol{\kappa}) = \kappa_H^2(\boldsymbol{\kappa}) \cdot \Gamma_H^{SM}$$

CP in H→ττ

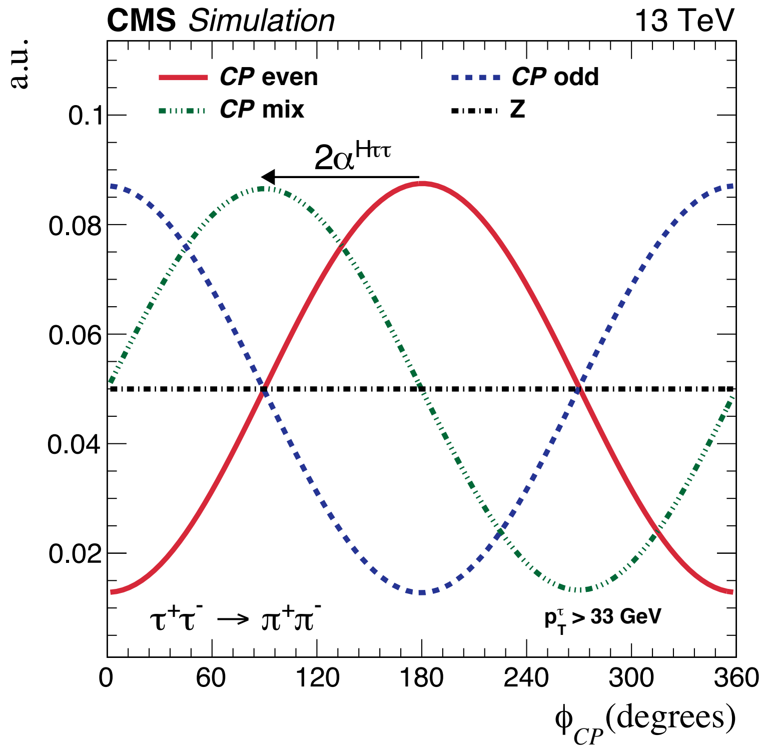
Measure H→ττ decays differentially in Φ_{CP} to access potential CP-odd contributions to H-τ coupling





CMS-PAS-HIG-20-006

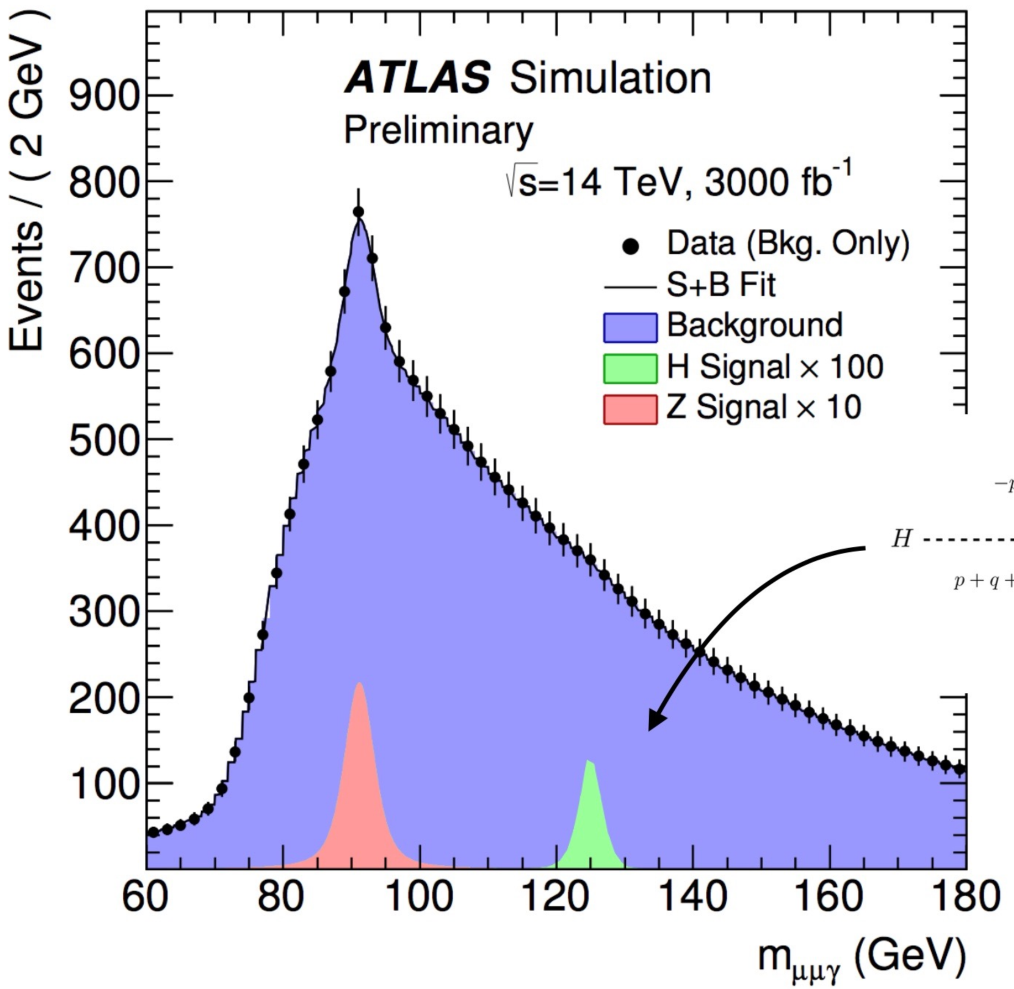
$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



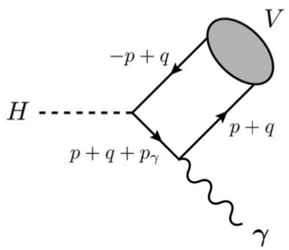
Projection of Run-2 analysis at CMS
→ Expect to constrain CP-mixing angle ($\alpha^{H\tau\tau}$) to ~5 degrees at HL-LHC!

Rare decays

ATL-PHYS-PUB-2015-043



	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$
	Standard Model expectation		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	2.9 ± 0.2		0.80 ± 0.05



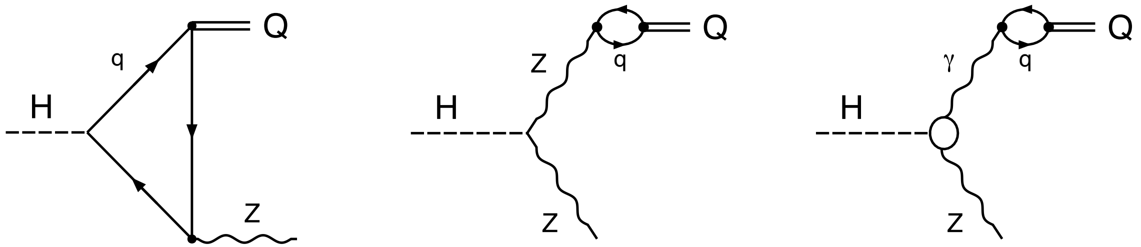
Projection assumes

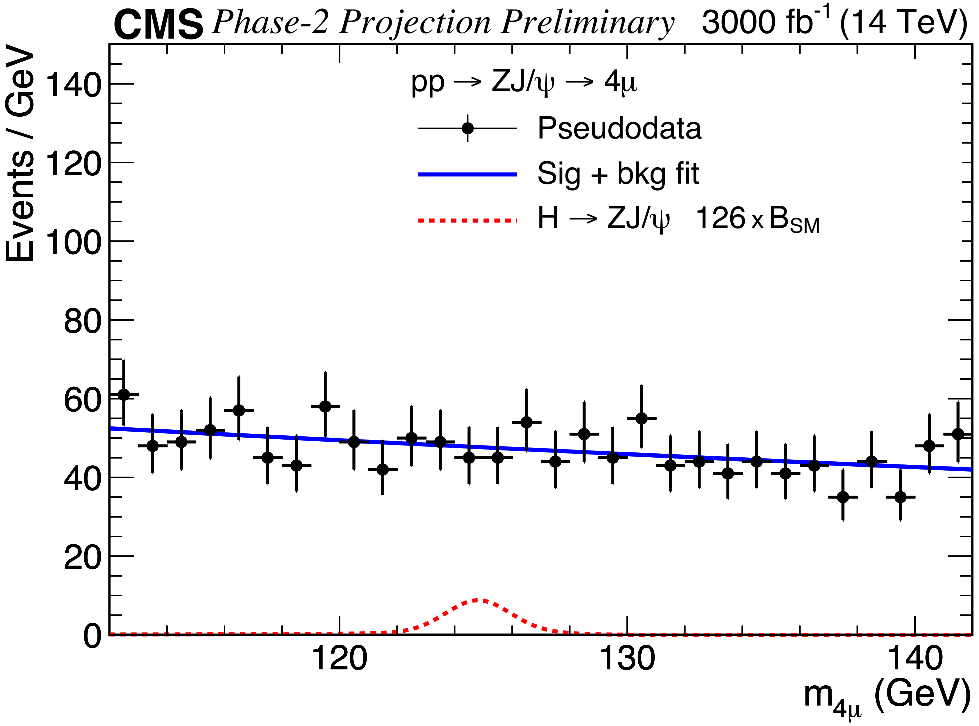
- Similar lepton and the photon reconstruction as in Run1
- Background distribution understood at ~5% level

Rare decays

CMS-PAS-FTR-21-008

Beyond SM physics can lead to large modifications of 1st generation quark Yukawas → possible enhancement in H→ZQ/QQ compared to SM





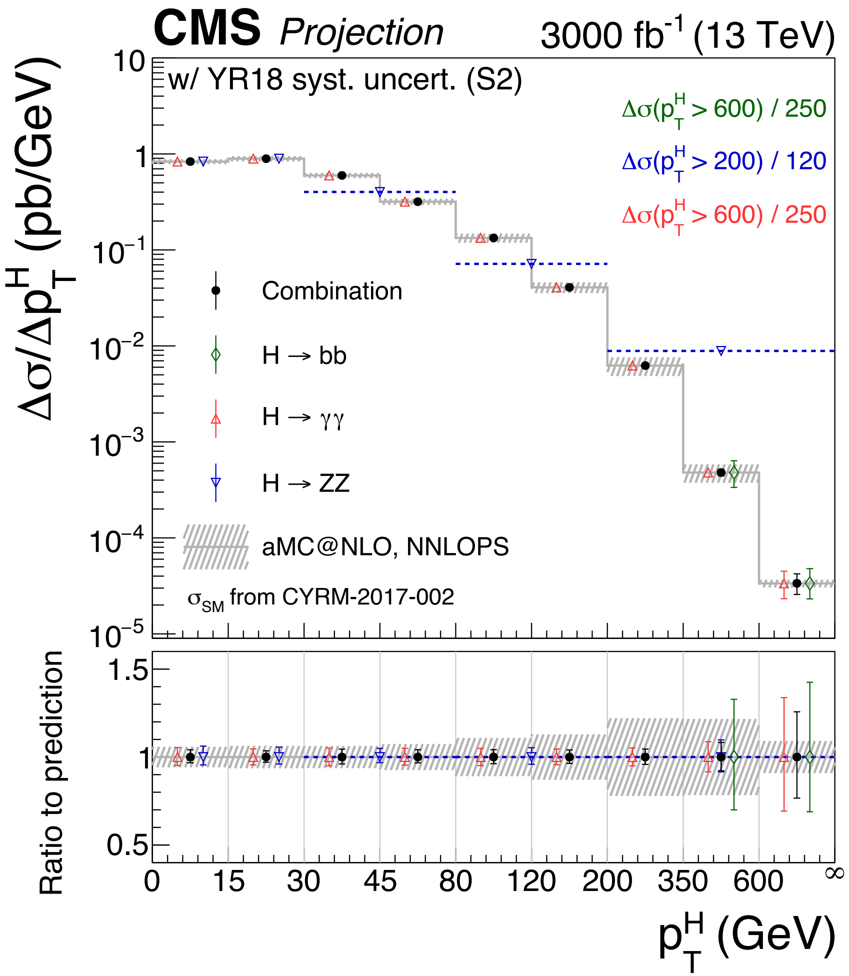
Projection of Run-2 search for H→Z J/ψ → 4μ and H→ ΥΥ → 4μ

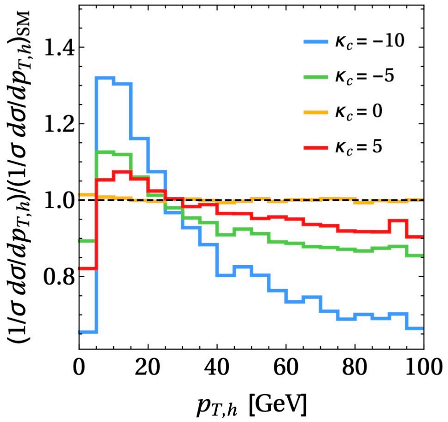
Analysis still very statistics limited at HL-LHC → 3 events in H→ΥΥ Higgs peak would constitute discovery!

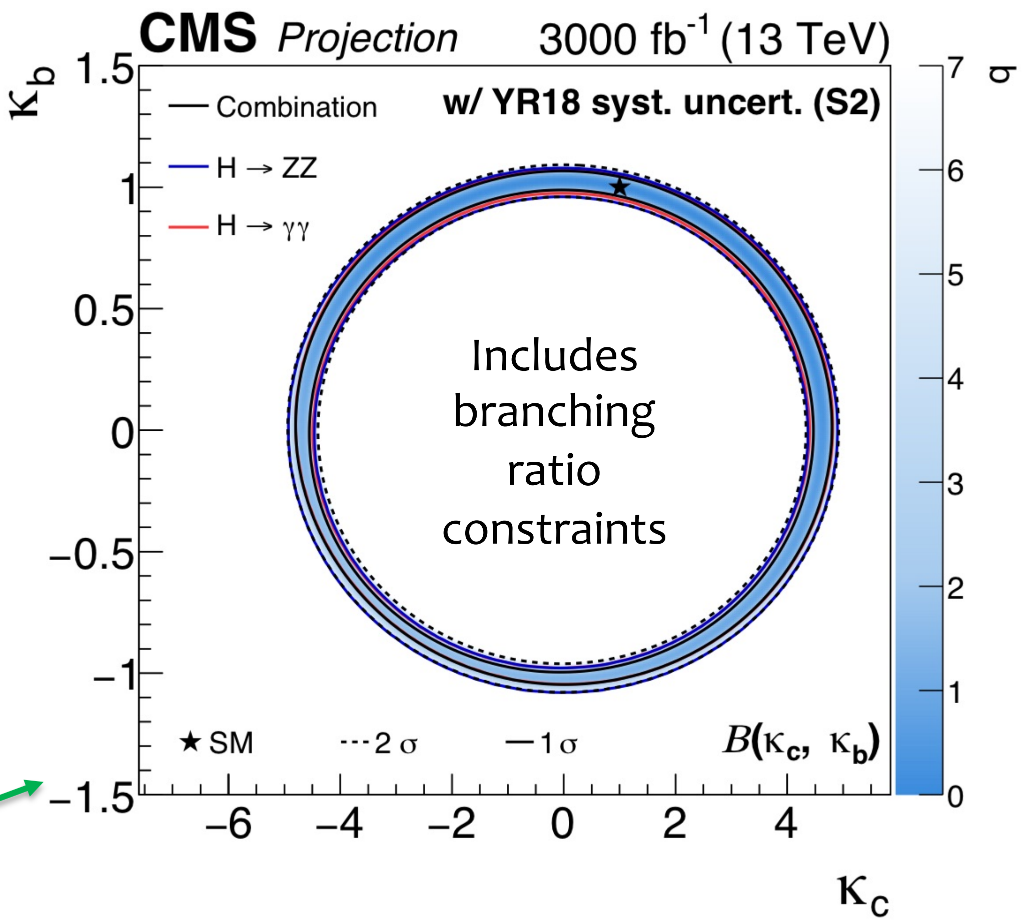
Channel	3000 fb^{-1}	(×SM)	4500 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)

Kinematic distributions

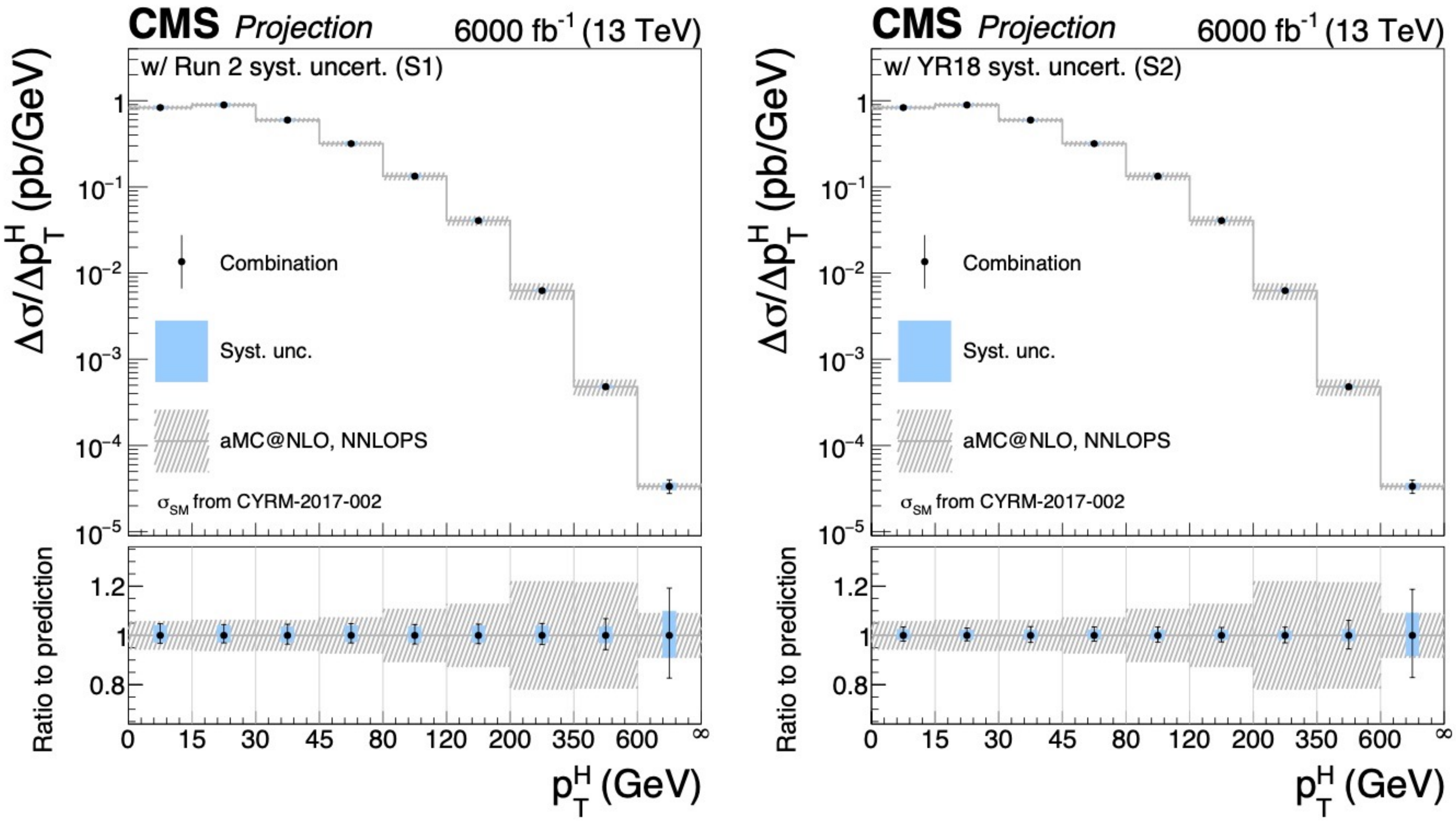
Kinematic measurements provide Additional constraints on b/c-H coupling!





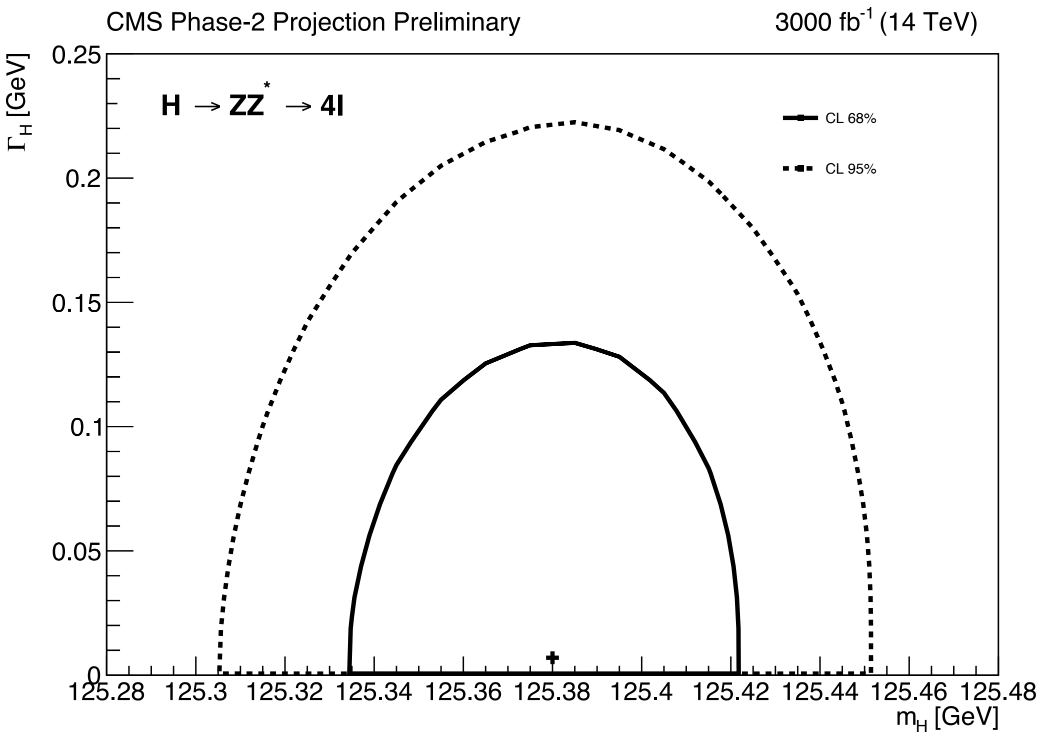


ATLAS+CMS differential combination



CMS H→4l mass measurement

CMS H→4l	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu 2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177



Direct measurement of Higgs boson width from line-shape severely limited by peak resolution

Γ_H measurements @ HL-LHC will be driven by off/on-shell coupling measurements

Legacy of the HL-LHC - couplings

Factors of improvement (reduction in uncertainty) when combining different options with the HL-LHC

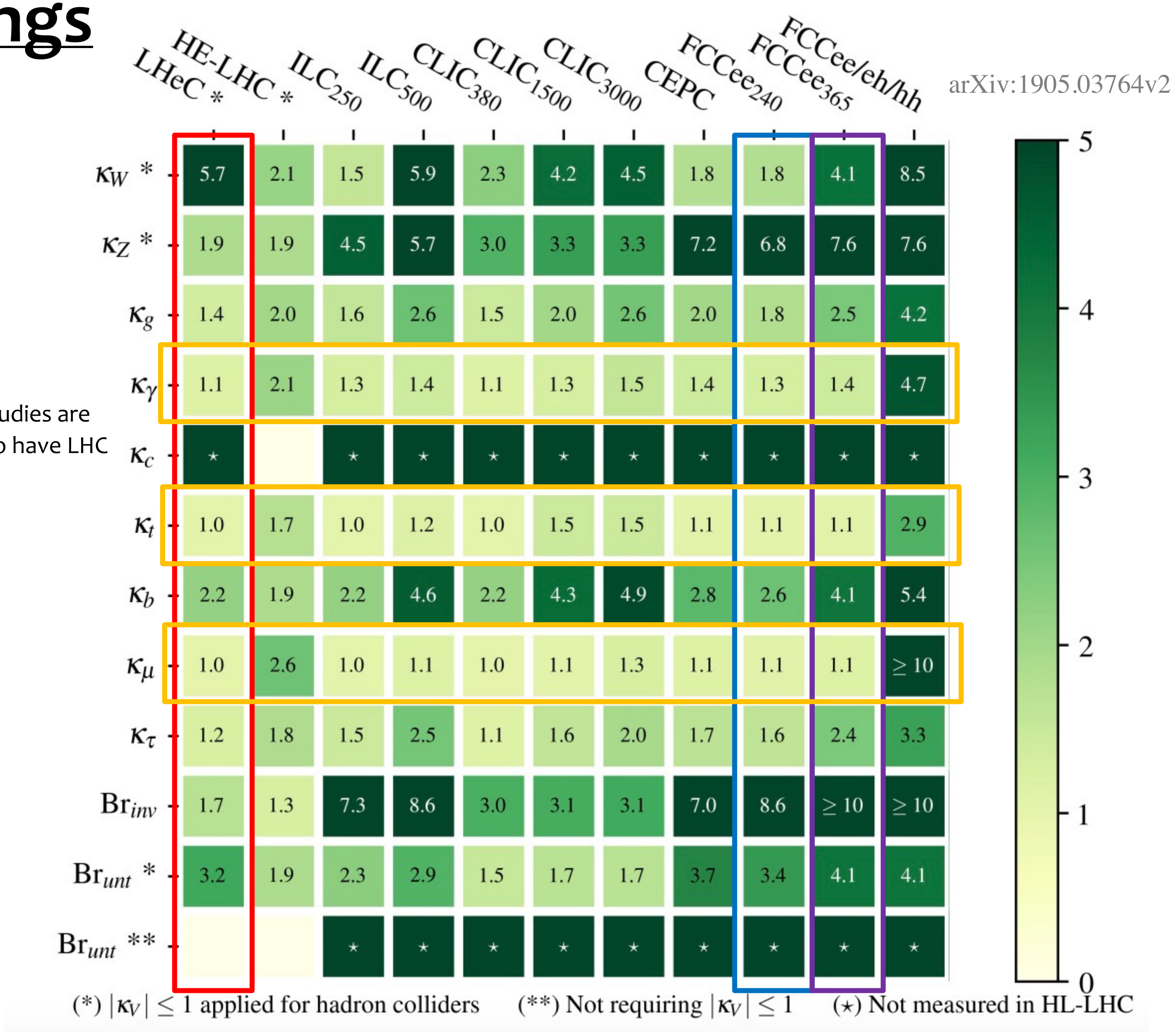
LHeC brings most improvement in κ_W but comparable to **$FCC_{240+365}$**

Remember, main gain in **FCC_{240}** run is through direct interpretation of couplings

Factors of 10 improvement not seen in many cases until full FCC programme

HL-LHC will remain dominant in some cases throughout (low-energy) lepton collider era

Remember these studies are out of date as we do have LHC constraints on κ_c

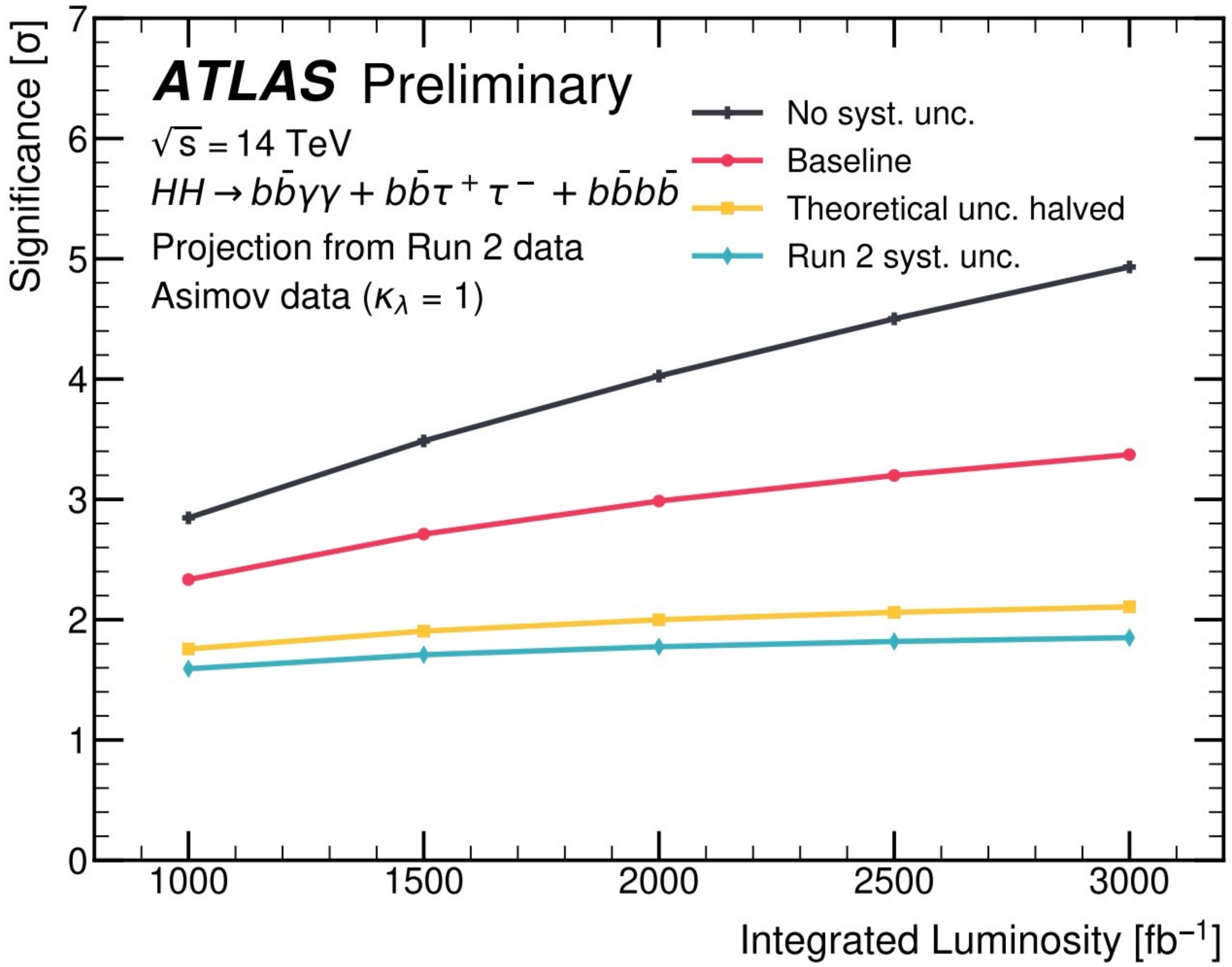


	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

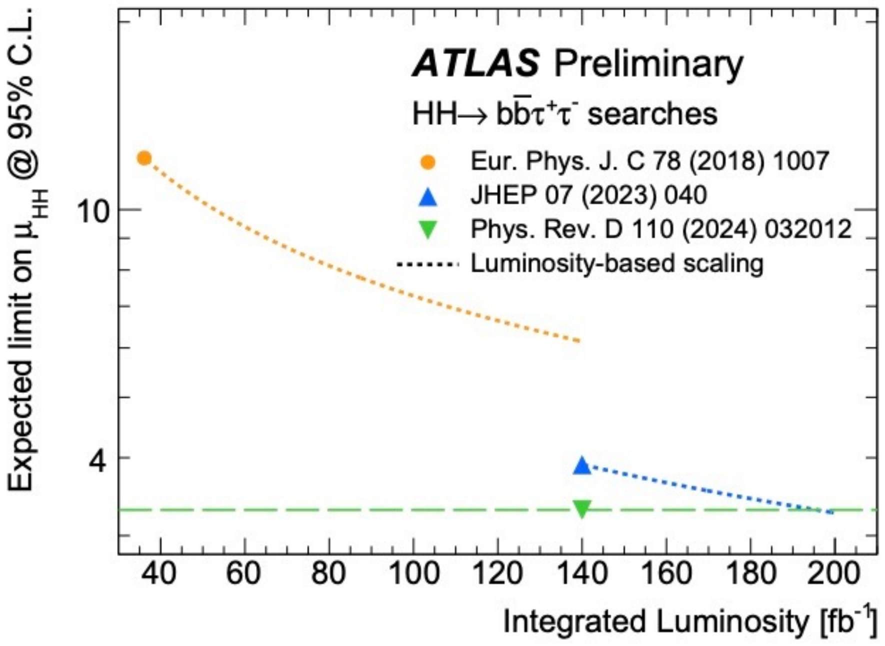
ATLAS HH discovery potential

ATL-PHYS-PUB-2022-053



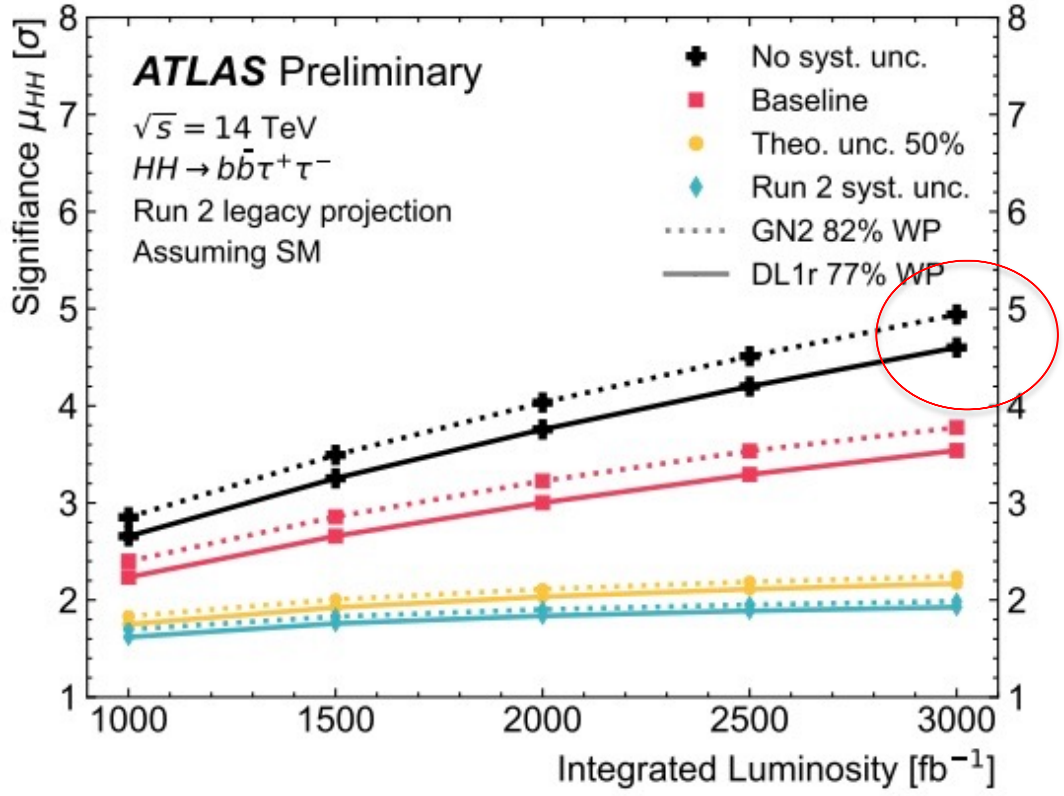
Updated HH→bbττ

ATL-PHYS-PUB-2024-016



Improvements on previous analysis → step function in projections

Impact of smarter flavor tagging →



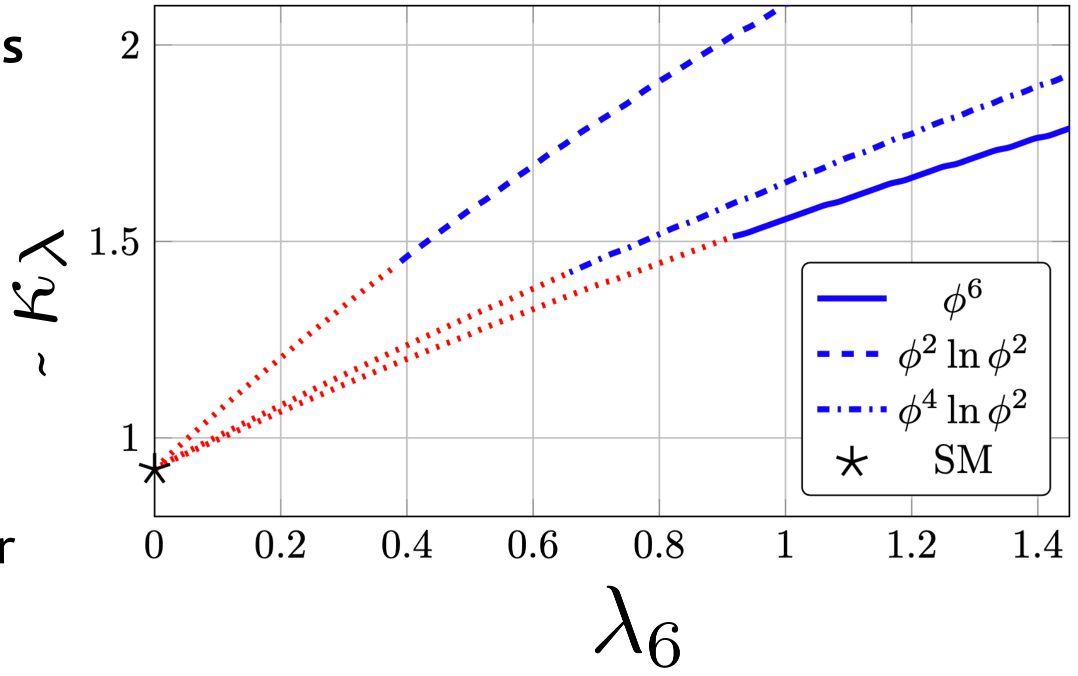
Higgs potential and electroweak baryogenesis

Perhaps one interesting coupling already has a sensible goal post

$$V(H) = \underbrace{\frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4}_{\text{SM}} + \underbrace{\frac{\lambda_6}{\Lambda}(v+H)^6}_{\text{BSM}}$$

Inclusion of **Dimension-6 (BSM)** term in potential **changes the relationships between** the fundamental Higgs **parameters**

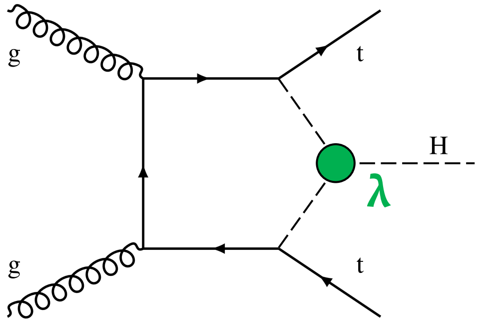
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}$$



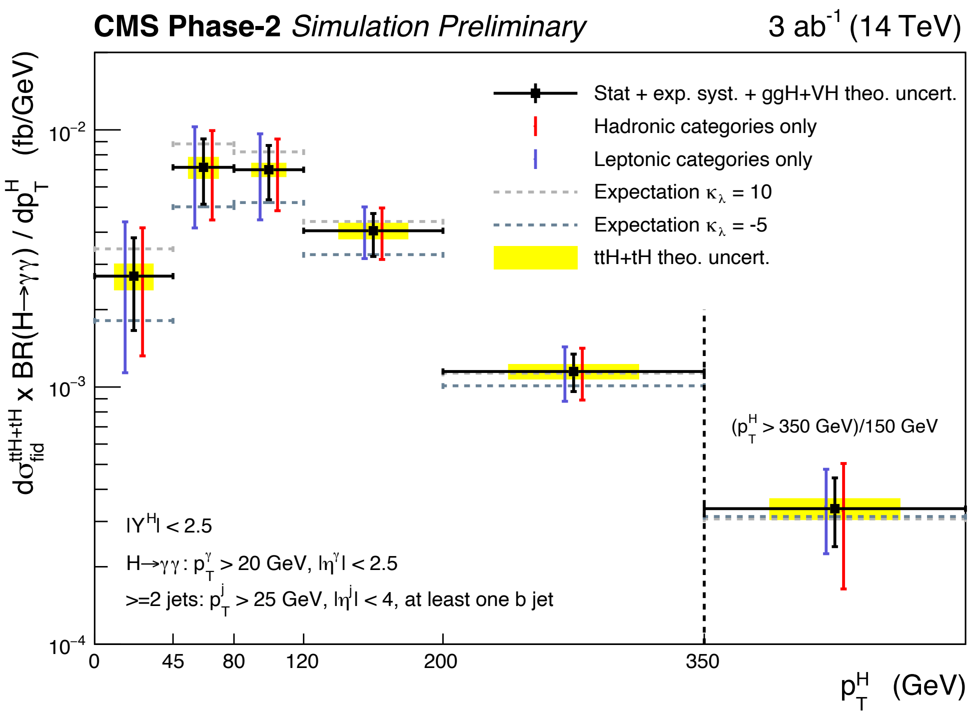
Phys. Rev. D 97, 075008 (2018)

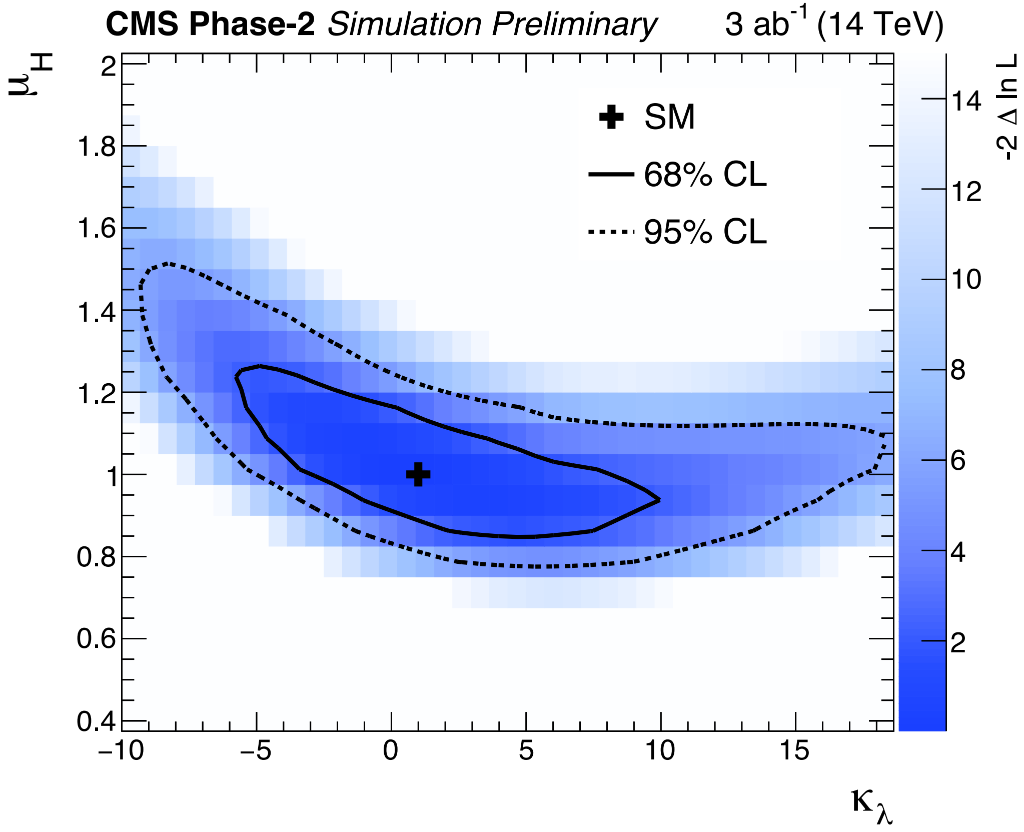
50% increase in self-coupling could hint at mechanism for 1st order EWK phase-transition accuracy

Self-coupling from single-H differential



Allow overall rate to float freely → still constrain self-coupling through shape information only

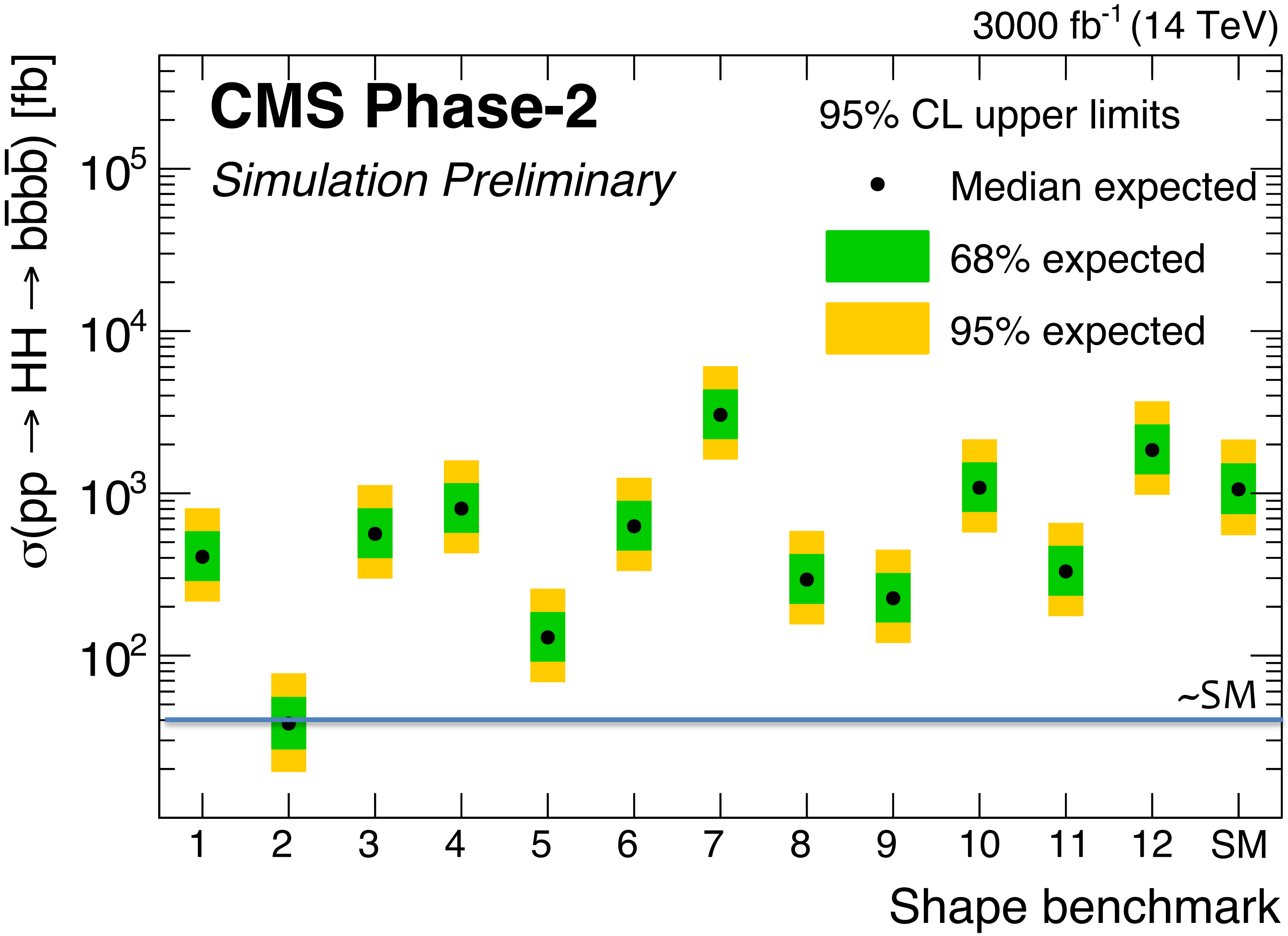




Non-SM sensitivity to HH

Sensitivity to HH dramatically varies depending on what we assume about the SM-like and BSM couplings!

Extractions on sensitivity to HH (and self-coupling) @HL-LHC should be studied also ***not*** assuming SM



cc and bb differential cross-sections

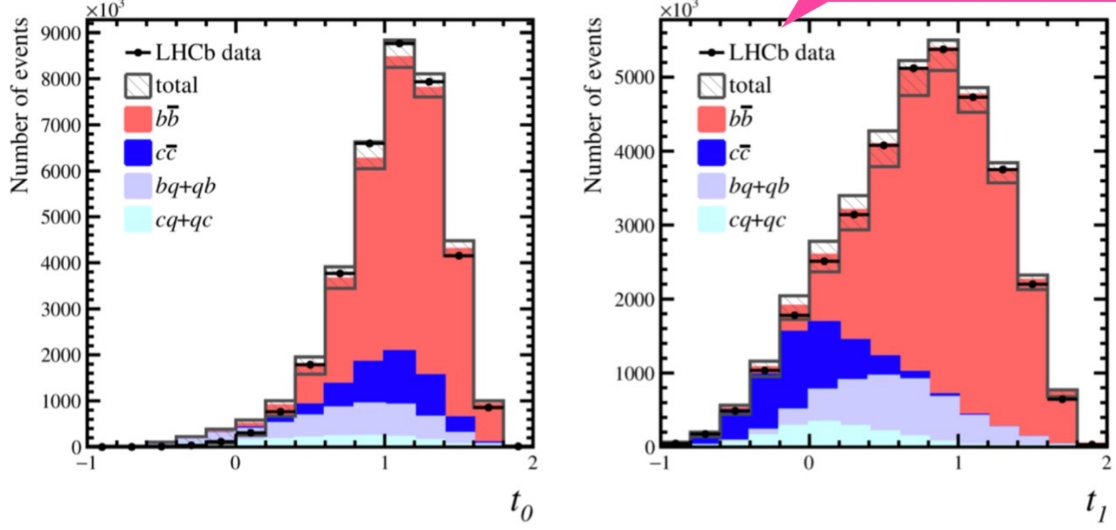
D. Zuliani @ ICHEP 2024

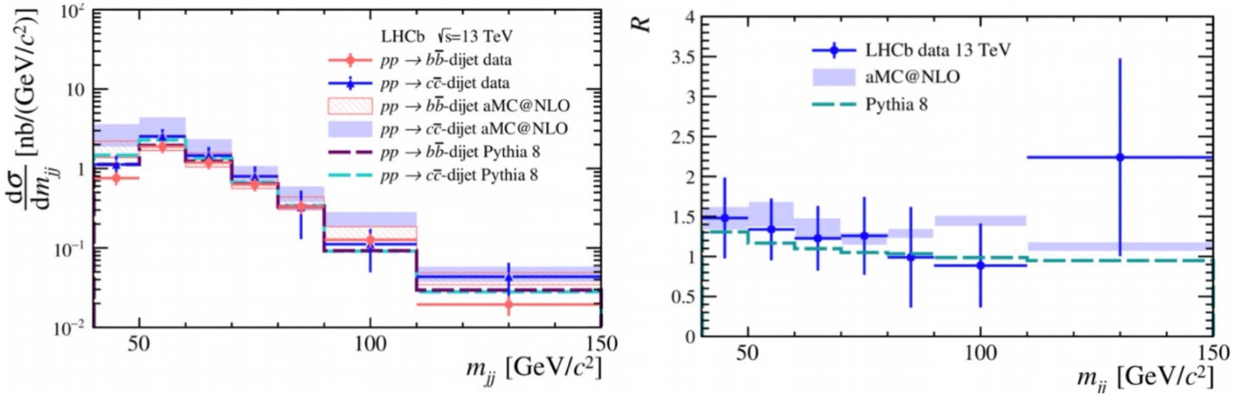
JHEP 02 (2021) 023

- The main idea is to study the inclusive decay of high mass resonances decaying to $b\bar{b}$ and $c\bar{c}$ di-jets
- It is possible to study lower invariant masses with respect to ATLAS/CMS
- **A first study has been performed to measure $b\bar{b}$ and $c\bar{c}$ differential cross sections with 2016 data**
- Fit to combination of two MVA discriminators t_0 and t_1 to get flavour composition:

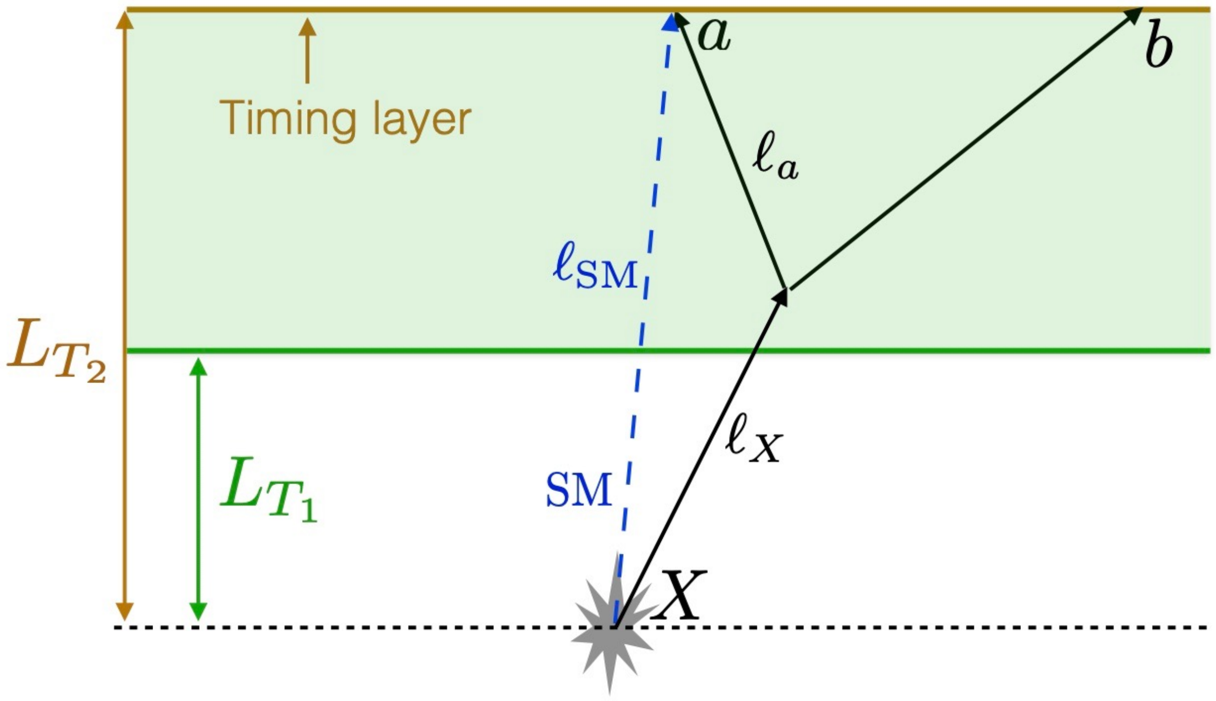
$$t_0 = \mathrm{BDT}_{bc|q}(j_0) + \mathrm{BDT}_{bc|q}(j_1)$$
$$t_1 = \mathrm{BDT}_{b|c}(j_0) + \mathrm{BDT}_{b|c}(j_1)$$

- The cross section ratios $R = \sigma_{b\bar{b}}/\sigma_{c\bar{c}}$ are also computed as functions of kinematic variables
- Results are compatible with expectations
- **First measurement of $c\bar{c}$ di-jet differential cross section at a hadron collider**

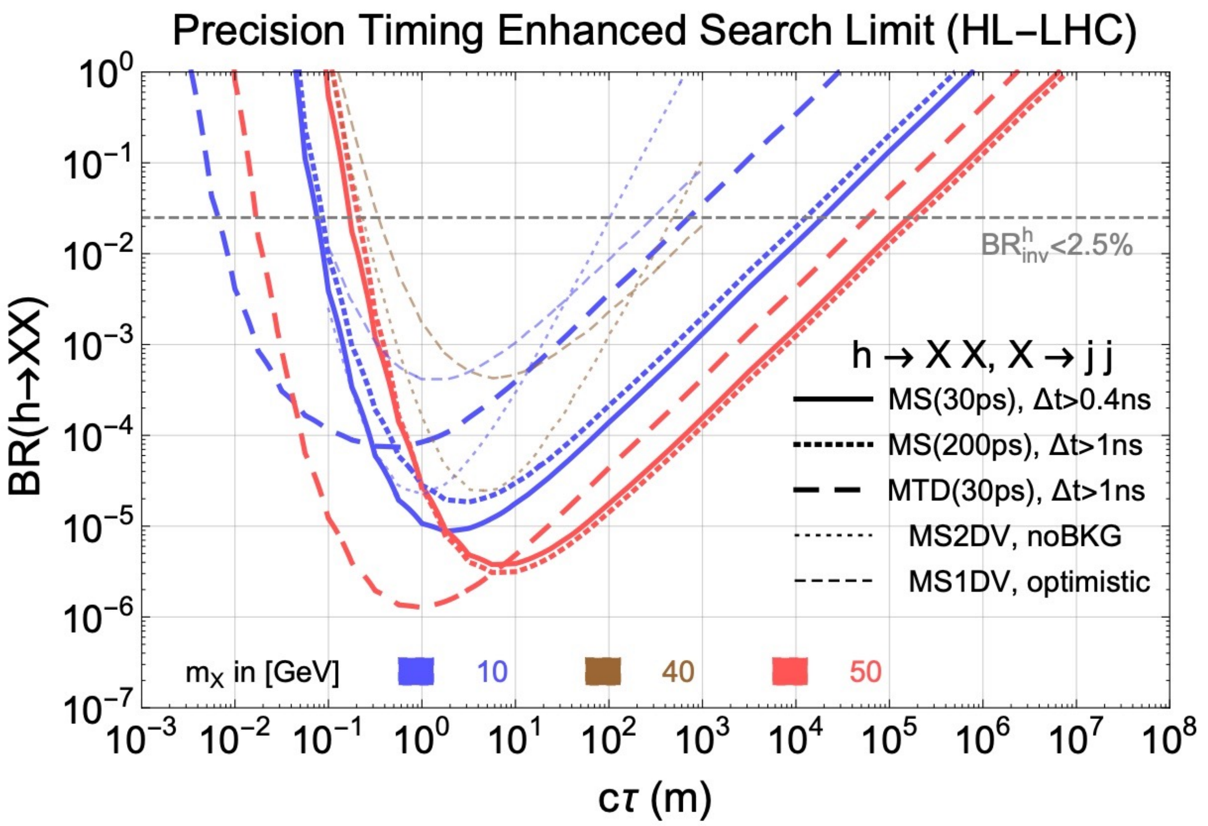




HL-LHC H→LLPs



Timing layer
a
b
ℓ_a
ℓ_{SM}
ℓ_X
SM
X
L_{T_2}
L_{T_1}



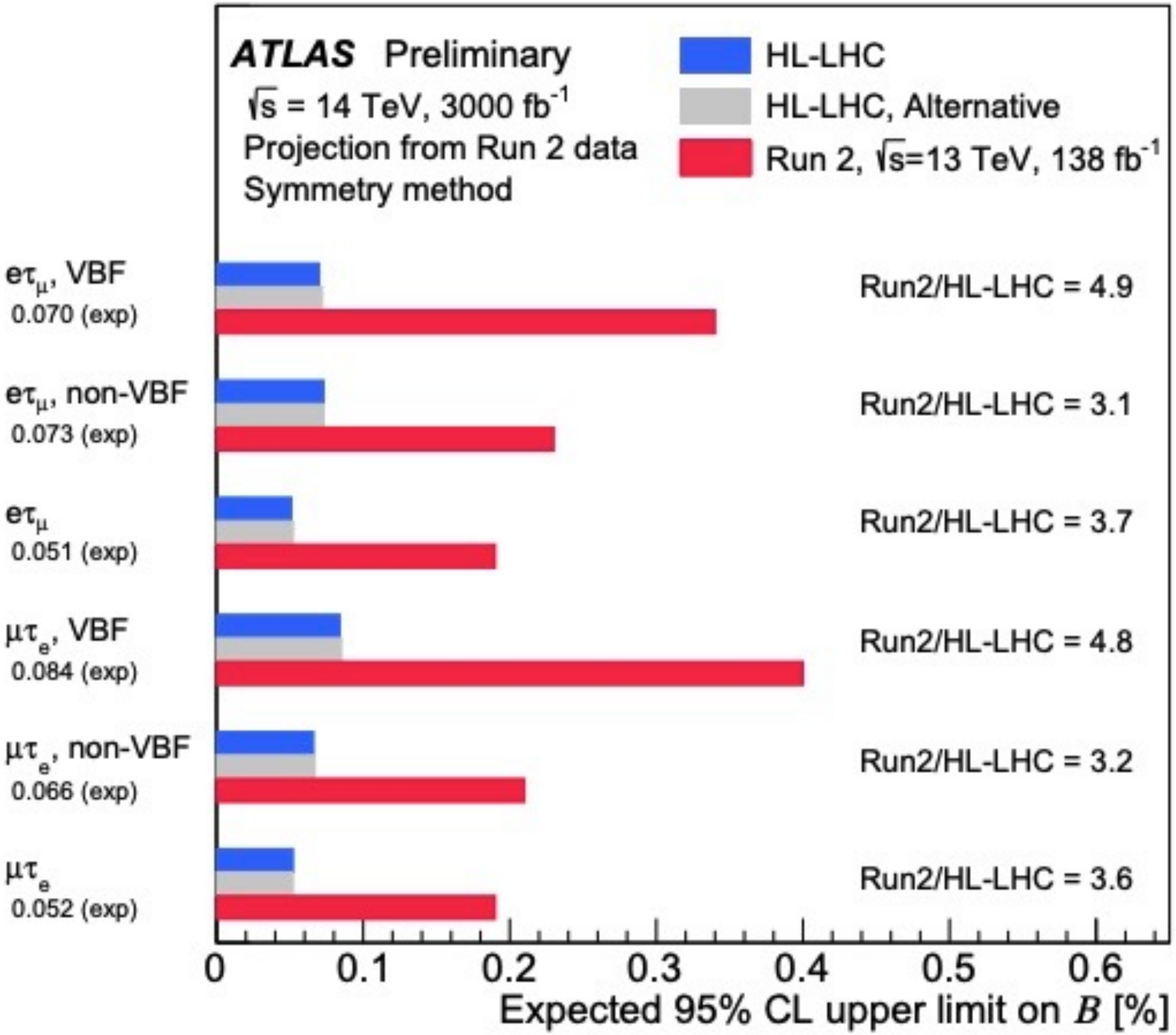
Precision Timing Enhanced Search Limit (HL−LHC)
BR(h→XX)
cτ (m)
BR^h_{inv}<2.5%
h → X X, X → j j
MS(30ps), Δt>0.4ns
MS(200ps), Δt>1ns
MTD(30ps), Δt>1ns
MS2DV, noBKG
MS1DV, optimistic
m_X in [GeV]
10
40
50

H→LFV @ HL-LHC

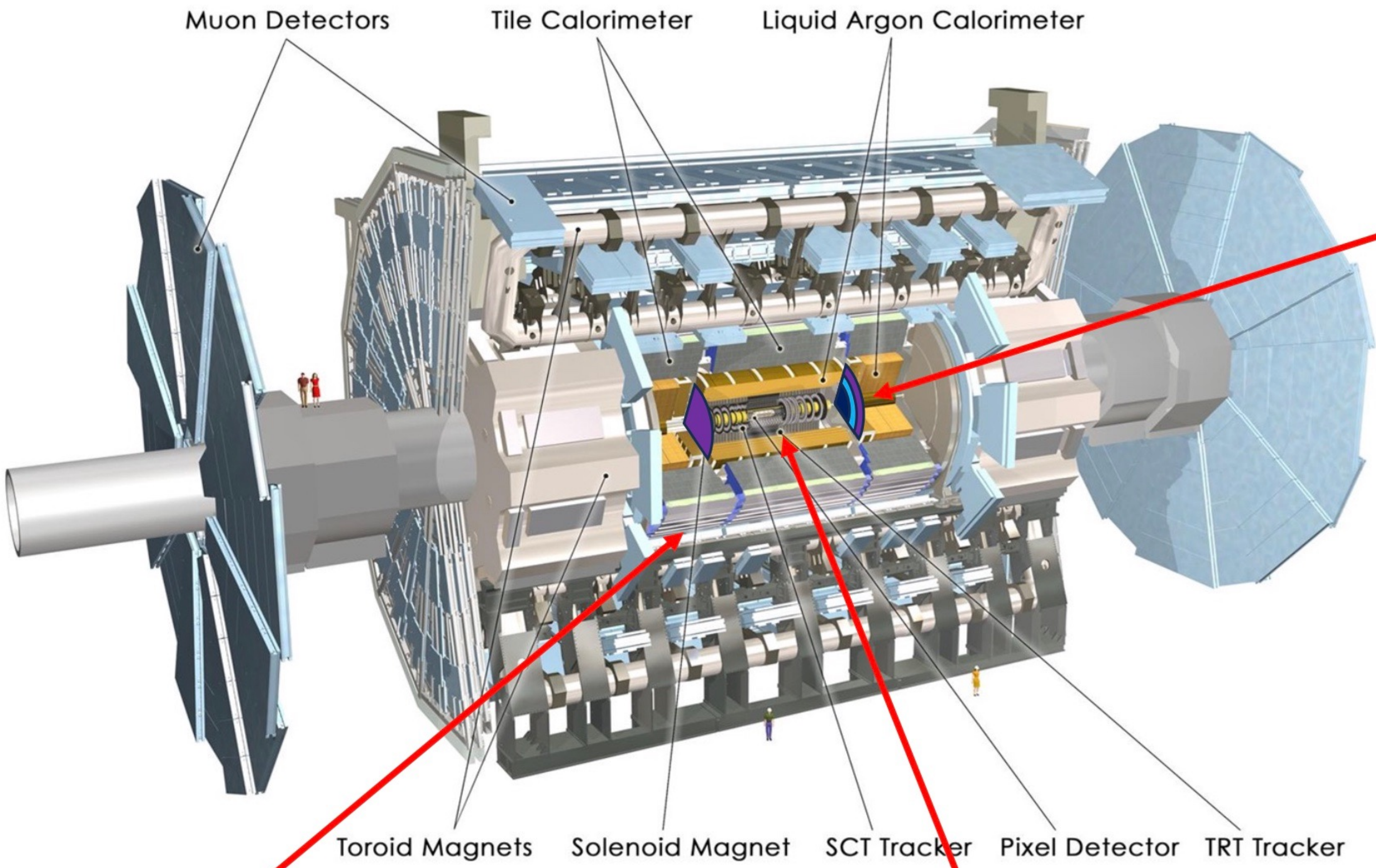
ATL-PHYS-PUB-2022-054

Projections of searches for lepton-flavour violating Higgs boson decays at ATLAS

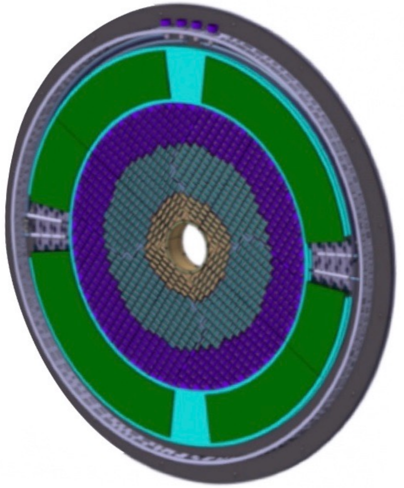
Alternative assumption how MC statistical uncertainties are expected to scale is shown



ATLAS Upgrade for HL-LHC



High Granularity Timing Detector (HGTD)
Forward region (2.4<|η|<4.0)
Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

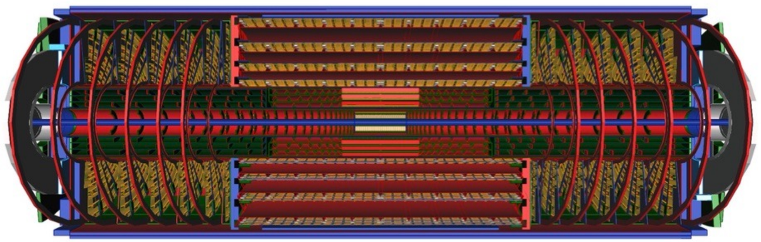


Song-Ming Wang @ ICHEP 2024

Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz
Improved High-Level Trigger
(150 kHz full scan tracking)

New Muon Chambers
Inner barrel region with new RPC and sMDT detectors

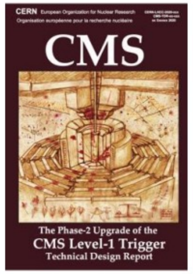
New Inner Tracking Detector (ITK)
All silicon, up to |η|=4

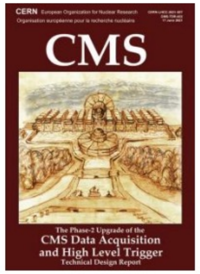


Additional small upgrades
Luminosity detectors (1% precision goal)
HL-ZDC

Electronics Upgrades
LAr Calorimeter,
Tile Calorimeter, Muon System

CMS Upgrades

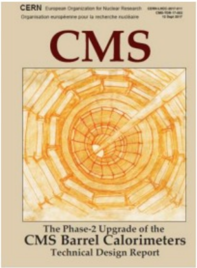




L1-Trigger HLT/DAQ

https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072

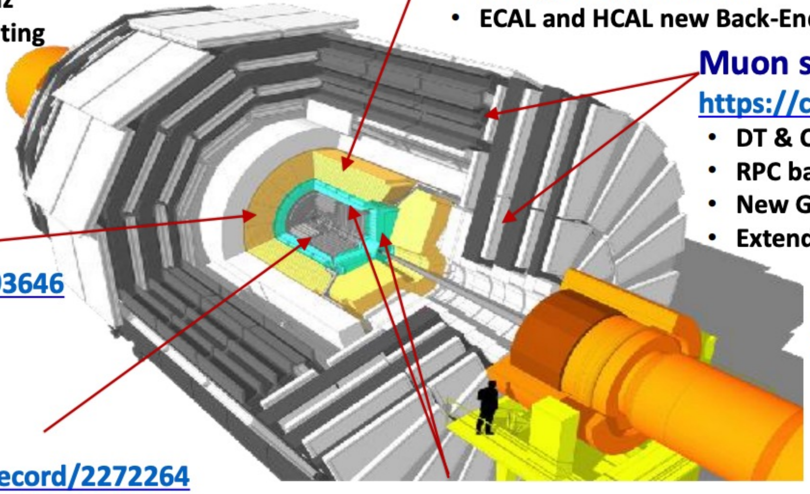
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



Barrel Calorimeters

https://cds.cern.ch/record/2283187

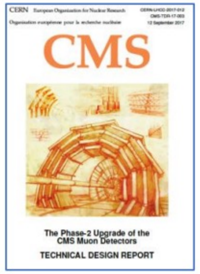
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

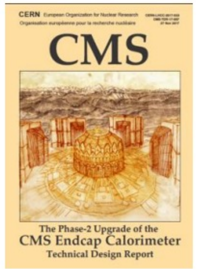


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$





Calorimeter Endcap

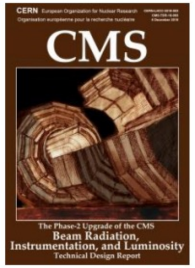
https://cds.cern.ch/record/2293646

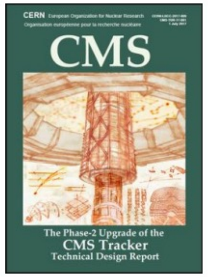
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online





Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes