Higgs prospects at the HL-LHC

corrinne mills

University of Illinois at Chicago and Fermilab

On behalf of the ATLAS and CMS collaborations

DIS conference

April 16, 2021

The promise of the HL-LHC

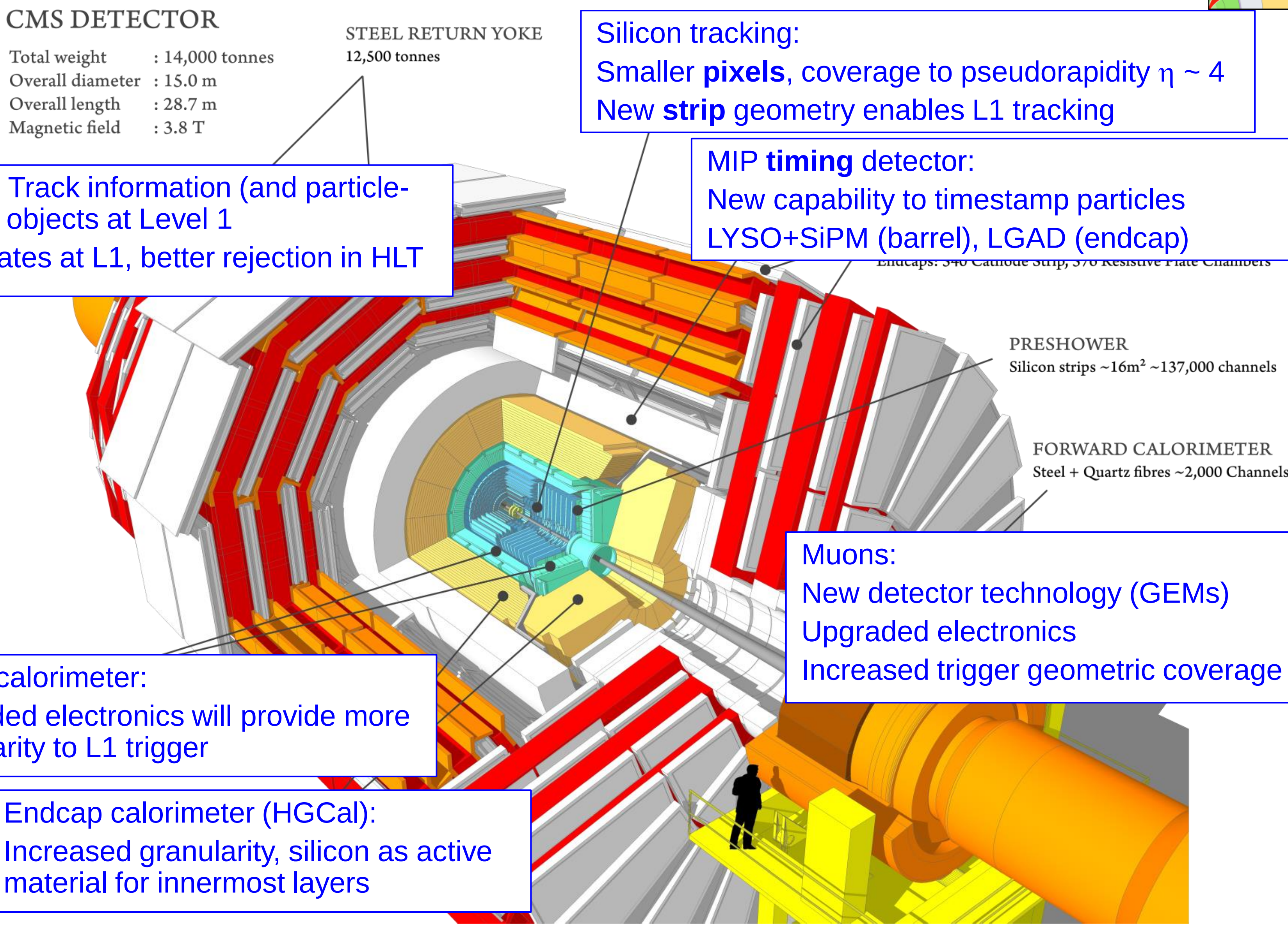
- *Compelling physics case with Higgs boson studies at the center*
  → *Relevant context in S. Dawson's talk on Tuesday morning:* *https://indico.bnl.gov/event/9726/contributions/47610/attachments/33601/54068/dis_2021_dawson.pdf*
    - Scalar sector a very likely place for new physics to appear, directly or indirectly
    - "Just getting to the interesting regime" in Higgs couplings

- Both ATLAS and CMS have invested in **detector upgrades** that will bring **qualitatively new capabilities** to the experiments
  → *and allow us to cope with the large amount of "pileup" resulting from up to 200 simultaneous proton-proton collisions*

- **Order of magnitude more integrated luminosity** will illuminate key measurements that have been limited by statistical uncertainties

- In this talk, I try to connect improvements to the detector upgrades, and highlight the different experimental factors still limiting measurements

CMS Phase 2 upgrade highlights



Silicon tracking:
Smaller **pixels**, coverage to pseudorapidity $\eta \sim 4$
New **strip** geometry enables L1 tracking

MIP **timing** detector:
New capability to timestamp particles
LYSO+SiPM (barrel), LGAD (endcap)

Trigger: Track information (and particle-flow-like objects at Level 1
Higher rates at L1, better rejection in HLT

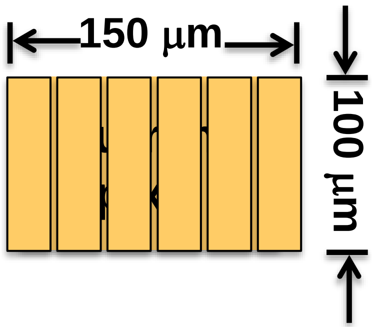
Muons:
New detector technology (GEMs)
Upgraded electronics
Increased trigger geometric coverage

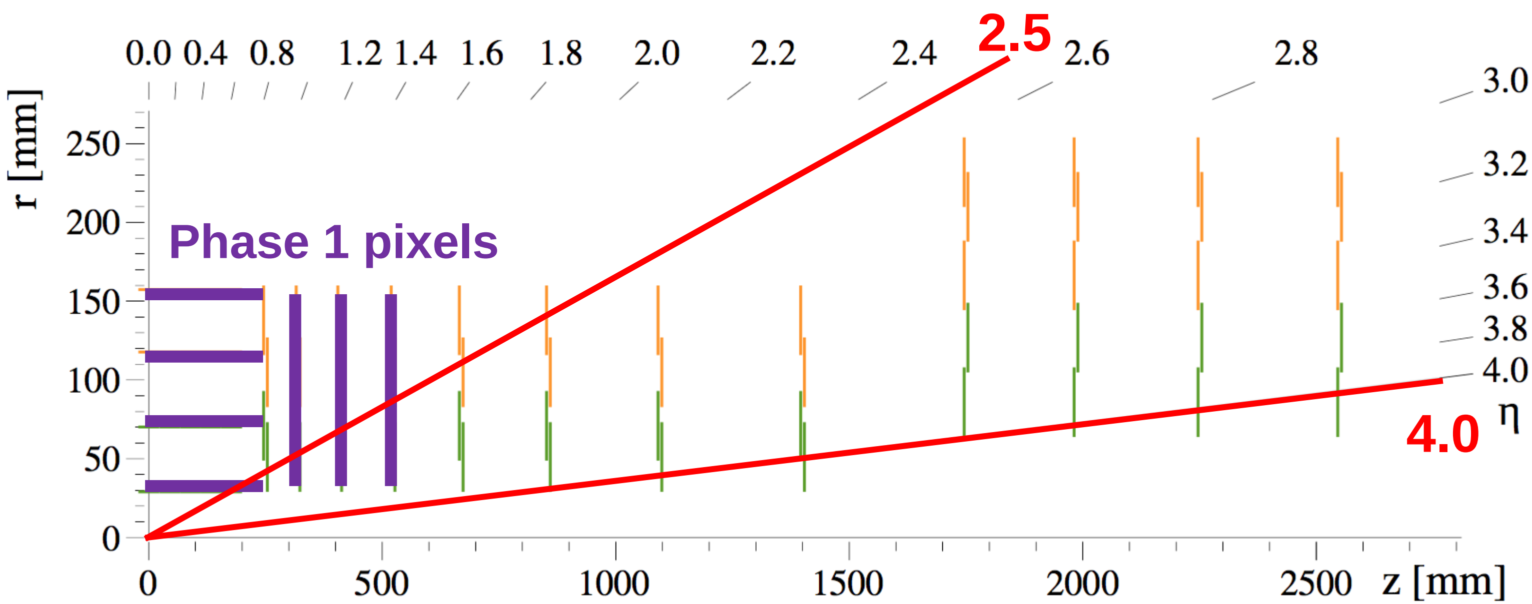
Barrel calorimeter:
Upgraded electronics will provide more granularity to L1 trigger

Endcap calorimeter (HGCal):
Increased granularity, silicon as active material for innermost layers

CMS Pixels for the HL-LHC

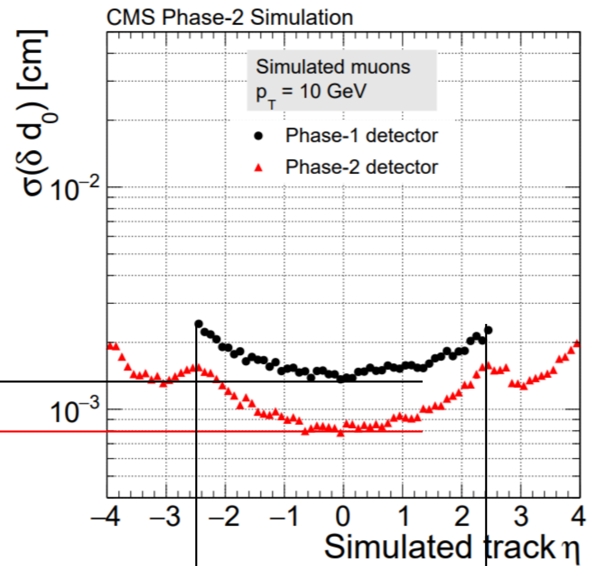
- Focus on improved radiation tolerance
  - → *New "RD53"-based chip common to ATLAS and CMS*
  - → *Sensor design improved*
    - n+-in-n to n-in-p planar
    - "3D" under consideration
    - Thinner sensor material
- More layers, more granularity



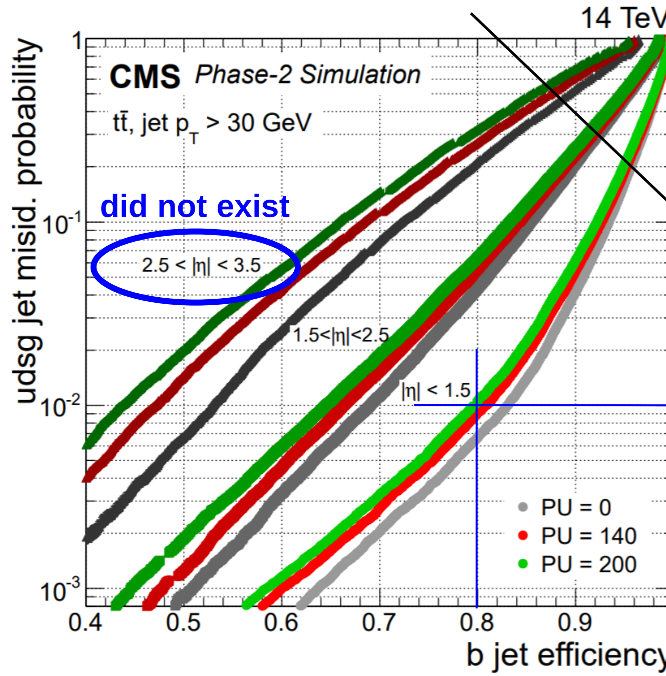


b-tagging and the new trackers

improved resolution

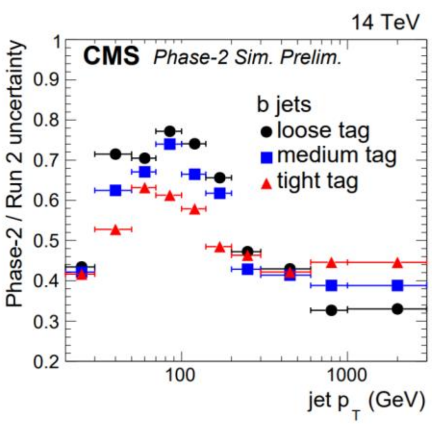


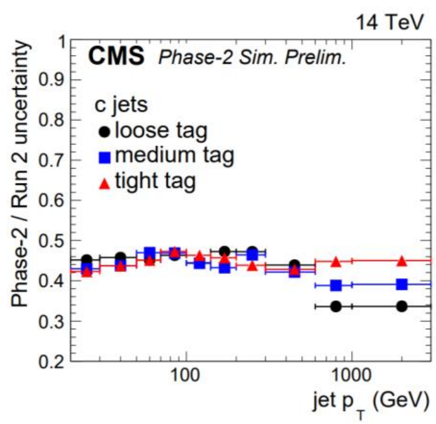
improved acceptance



better

approximate current deepCSV medium (from CMS-DP-2021-004)





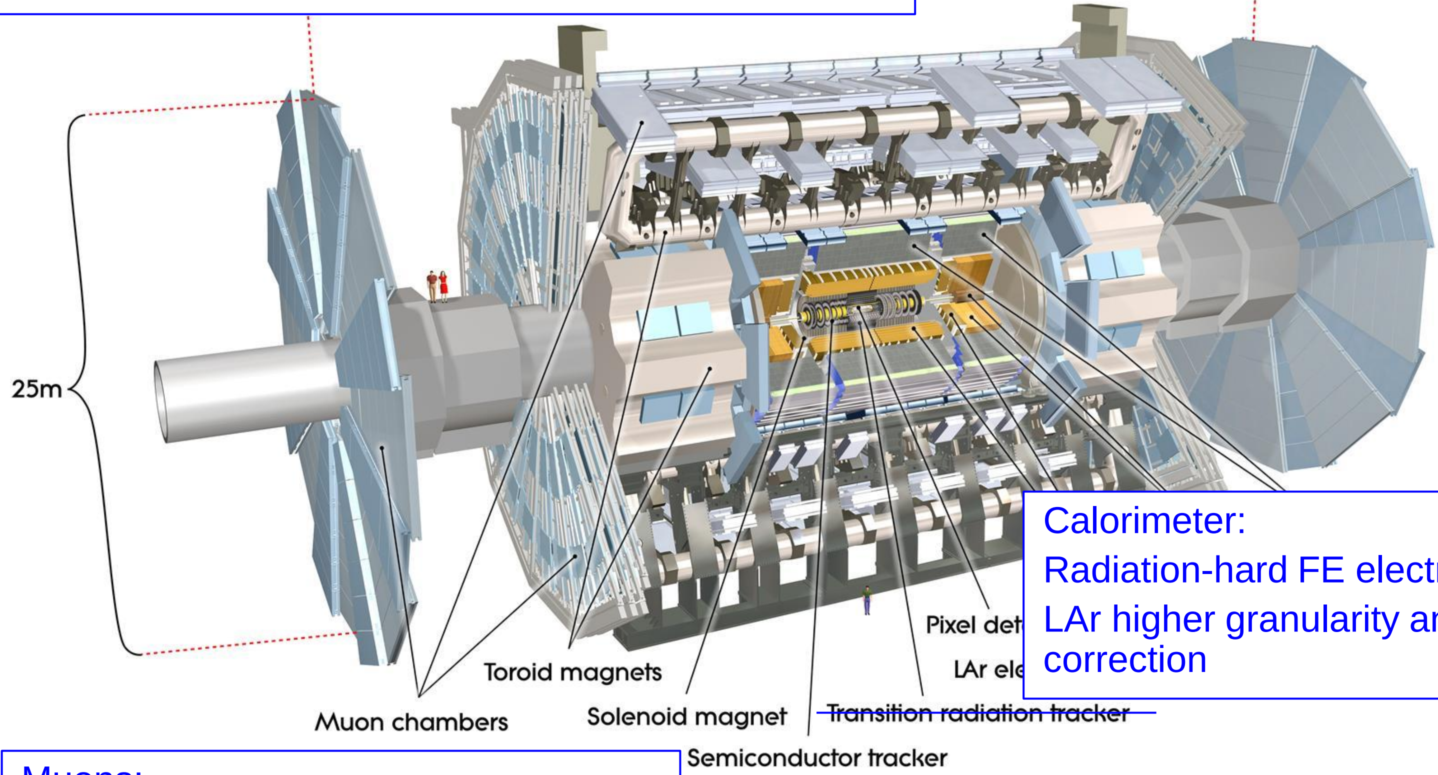
caveats: this averages over p_T, current measurements average over eta

bottom line:
better performance, more precision
will highlight some places this appears in measurements

ATLAS Phase 2 upgrade highlights

Trigger:
Hardware (“Level 0”) redesigned for granularity & flexibility
EF enhancements lower single-object thresholds

Timing:
LGAD layers in front of LAr endcap provide timestamps for forward tracks



Calorimeter:
Radiation-hard FE electronics
LAr higher granularity and active pileup correction

Muons:
Increased trigger geometric coverage

Silicon tracking:
Replace TRT with expanded strip tracker
Smaller pixels with more acceptace ($|\eta| < 2.5 \rightarrow 4.0$)

ATL-PHYS-PUB-2019-005

Predicting the future

- **Cross sections** scaled from 13 → 14 TeV
- **Statistical uncertainties** estimated from expected integrated luminosity
- **Detector improvements**: expanded capabilities (timing), acceptance (forward tracking), more detector layers …

  → *Based on simulated detector performance when feasible*
- **Systematic uncertainties** are the human factor in our measurement

  → ***Express limitations of techniques and knowledge***

  → *Different approaches*
  - Use **current best values, unchanged (S1)**
  - **"YR18" improved uncertainties agreed by ATLAS and CMS (S2):** theory uncertainties 50% of current, experimental uncertainties scale with statistics to "floor" defined by expected detector performance

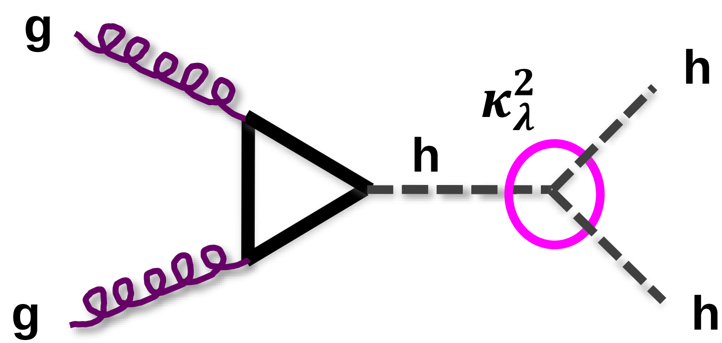
Easier

↓

Harder

Higgs pair production

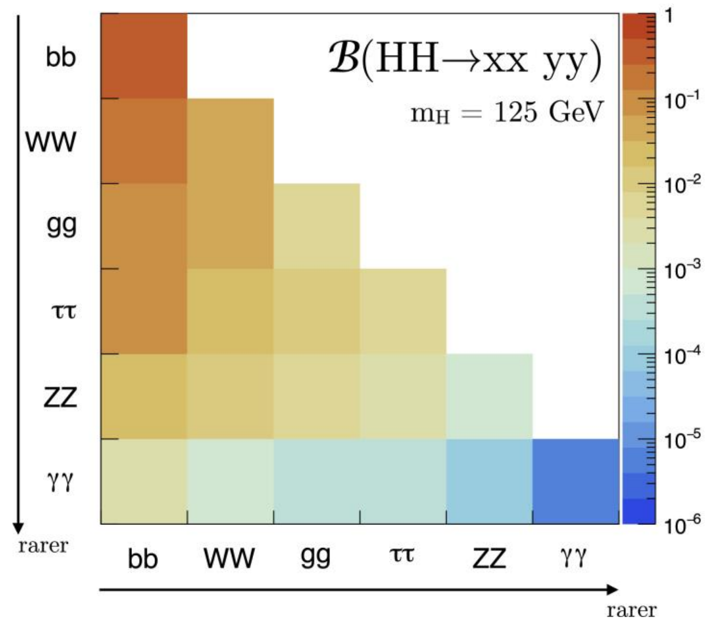
- A flagship measurement of HL-LHC
- Directly examines the shape of the Higgs potential
  - → *Implications for electroweak baryogenesis*
- Channels with highest BR don't dominate sensitivity
  - → *systematics and/or large backgrounds*
- Both experiments expect 3σ evidence (in SM case)



$$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$$

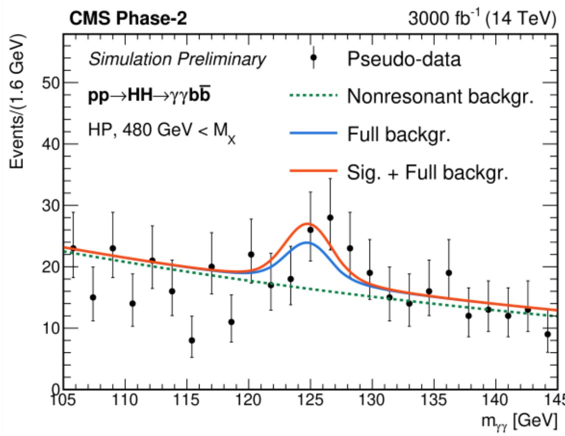
	ATLAS	CMS
bbbb	0.61	0.91
bb$\tau\tau$	**2.1**	1.4
bb$\gamma\gamma$	2.0	**1.8**
bbWW($\ell\nu\ell\nu$)		0.56
bbZZ($\ell\ell\ell\ell$)		0.37
combination	**3.0**	**2.6**

summary drawn from tables in following slides

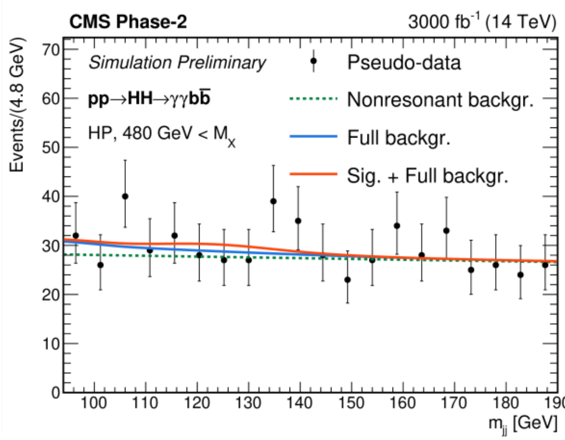


Reviews in Physics 5 (2020) 100039

CMS HH



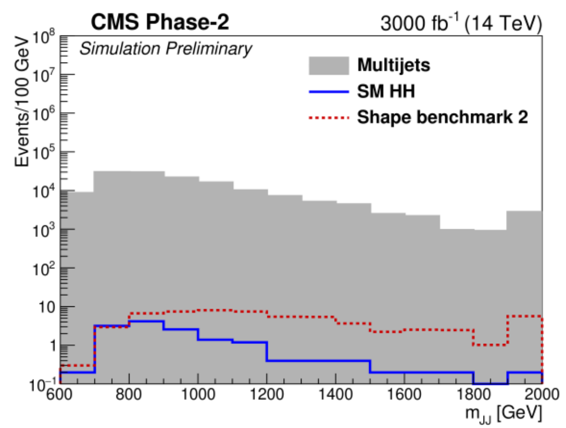
diphoton mass

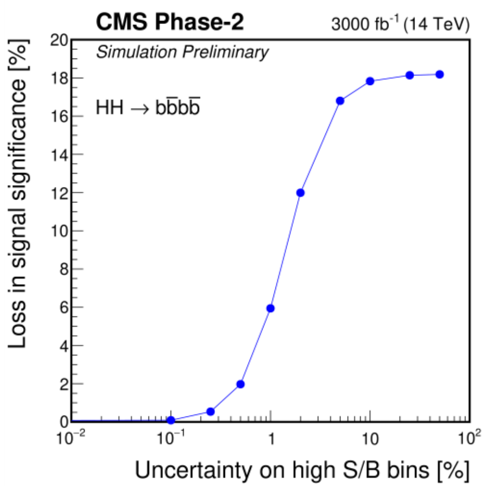


dijet mass

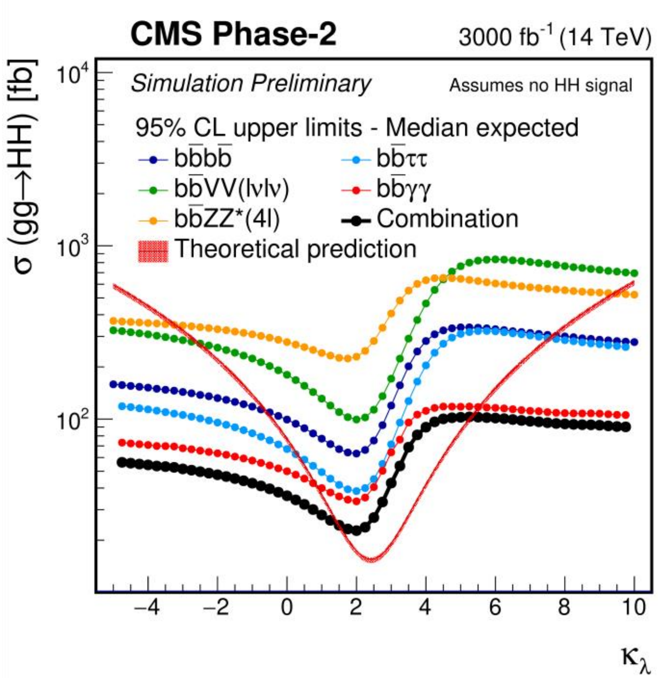
CMS-PAS-FTR-18-019

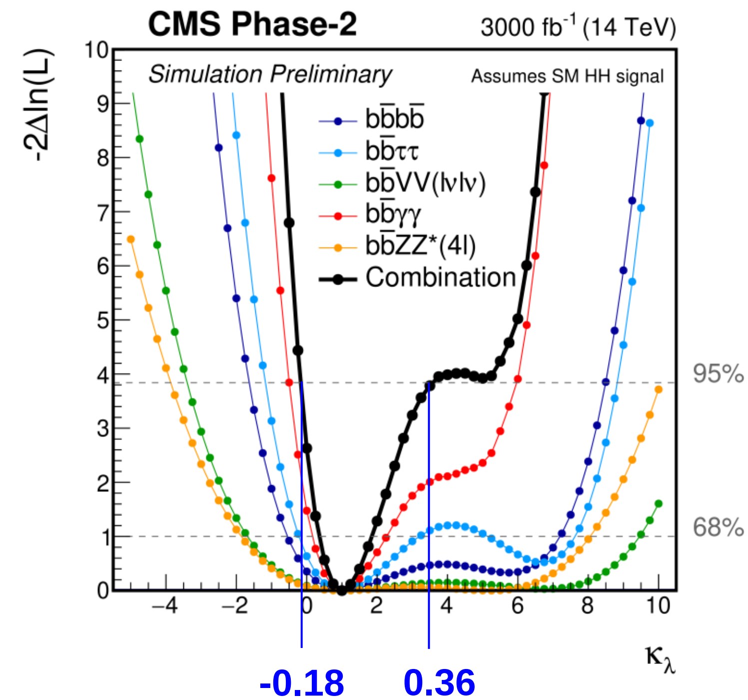
- Parametric detector model (Delphes)
- Most sensitive analysis: bbγγ
  - → *Double resonance search with BDT classifier*
  - → *Main background (ttH, H→ γγ) evident in $m_{\gamma\gamma}$*
- Largest branching ratio: 4b
  - → *Large multijet background with substantial uncertainty on estimate*





CMS HH





branching ratio	Channel	Significance Stat. + syst.	Significance Stat. only	95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$ Stat. + syst.	95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$ Stat. only
33.6%	bbbb	0.95	1.2	2.1	1.6
7.3%	$bb\tau\tau$	1.4	1.6	1.4	1.3
1.7%	$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
0.26%	$bb\gamma\gamma$	1.8	1.8	1.1	1.1
0.015%	$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
	Combination	2.6	2.8	0.77	0.71

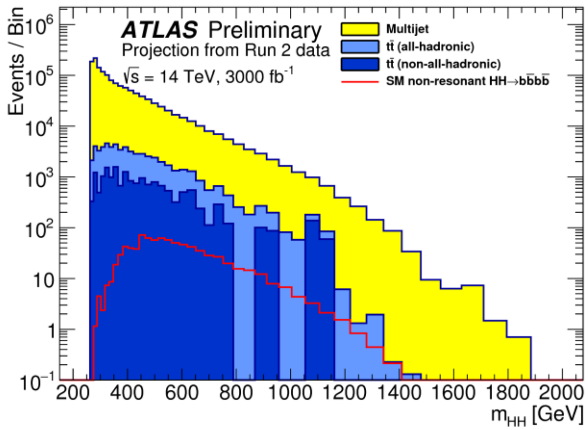
Insight from Run 2 results: b-tagging is leading experimental uncertainty (2.8% for 4b,1810.11854)

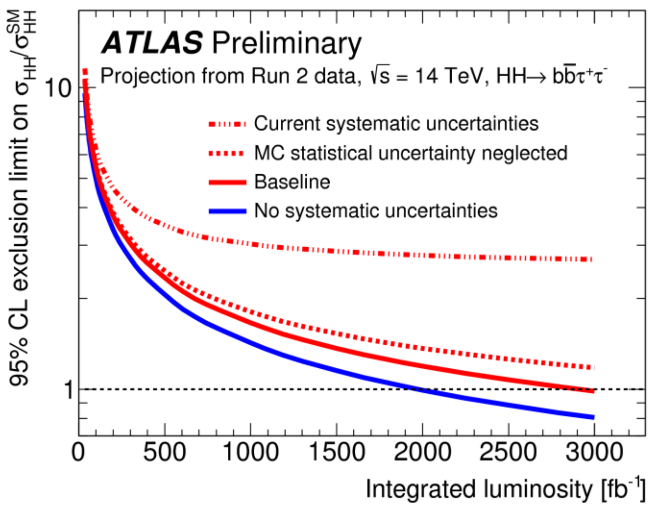
For leading channels, statistical uncertainty is dominant

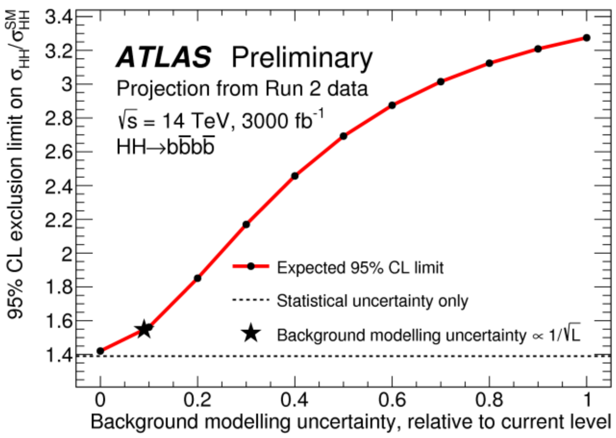
CMS-PAS-FTR-18-019

ATLAS HH

- Extrapolation from Run 2 analysis, with smeared truth-level simulation for $bb\gamma\gamma$
- Expected **8% improvement in b-tagging** efficiency included based on simulation of new tracker
- **bbbb analysis: multijet background** significant as for CMS
- $bb\tau\tau$ highlights **MC statistical uncertainties**, other prospects analyses set them to zero







ATL-PHYS-PUB-2018-053

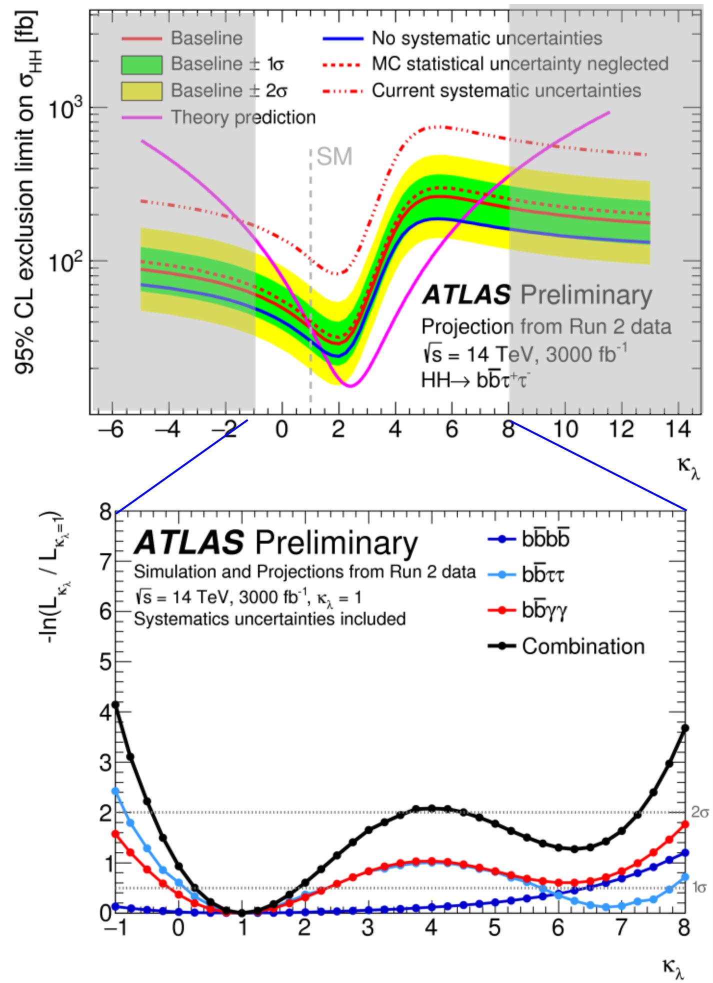
ATLAS HH

Expected significance

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Limits on scale of triple Higgs coupling assuming the SM

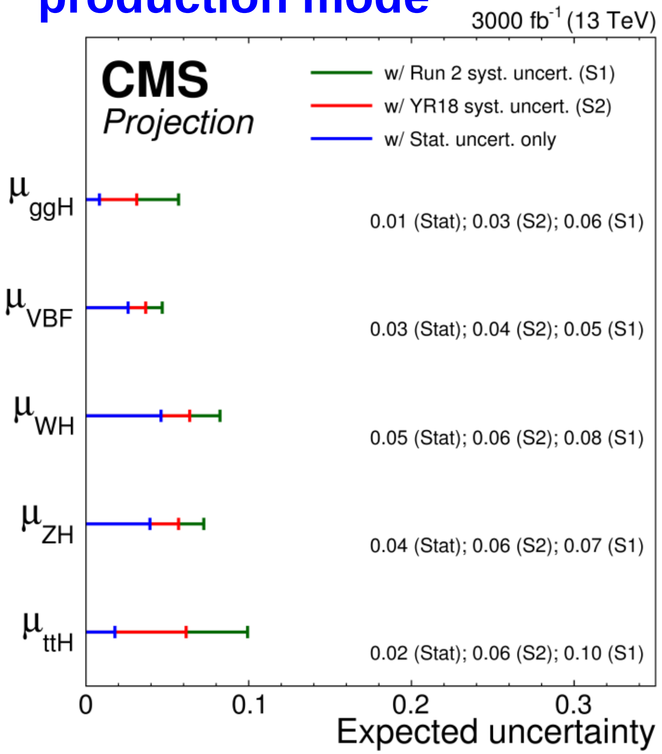
Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \le \kappa_\lambda \le 1.7$	$-0.10 \le \kappa_\lambda \le 2.7 \cup 5.5 \le \kappa_\lambda \le 6.9$
Systematic uncertainties	$0.25 \le \kappa_\lambda \le 1.9$	$-0.4 \le \kappa_\lambda \le 7.3$



ATL-PHYS-PUB-2018-053

CMS Higgs couplings

production mode



		3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp
μ_{ggH}	S1	5.7	0.8	5.4	0.9	1.2
	S2	3.1	0.8	2.8	0.6	0.9
μ_{VBF}	S1	4.7	2.6	3.0	1.3	2.1
	S2	3.7	2.6	2.1	0.3	1.6
μ_{WH}	S1	8.2	4.6	2.9	3.3	5.2
	S2	6.4	4.6	1.4	2.7	3.2
μ_{ZH}	S1	7.2	3.9	5.1	2.5	2.1
	S2	5.7	3.9	3.0	2.3	1.7
μ_{ttH}	S1	9.9	1.8	8.3	4.1	3.1
	S2	6.2	1.8	4.2	3.4	2.4

Limiting uncertainties boxed in red

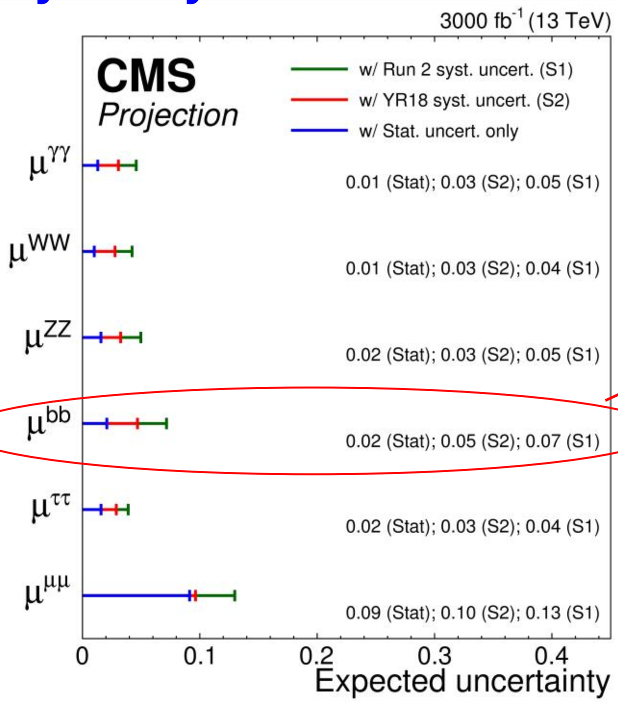
not knowledge of measured cross section, but do count in SM comparisons

- VBF and ZH remain limited by statistical uncertainties
- Theoretical and experimental uncertainties limit others

CMS-PAS-FTR-18-011

CMS Higgs couplings

by decay channel



Zoom in on VHbb (associated production via WH, ZH)

	S1	S2
Total uncertainty	7.3%	5.1%
Signal theory uncertainty	5.4%	2.6%
Inclusive	4.6%	2.2%
Acceptance	2.7%	1.3%
Background theory uncertainty	2.8%	2.3%
Experimental uncertainty	2.6%	2.2%
b-tagging	2.2%	2.0%
JES and JER	0.7%	0.6%
Statistical uncertainty	3.2%	3.2%

Broadly similar for ATLAS

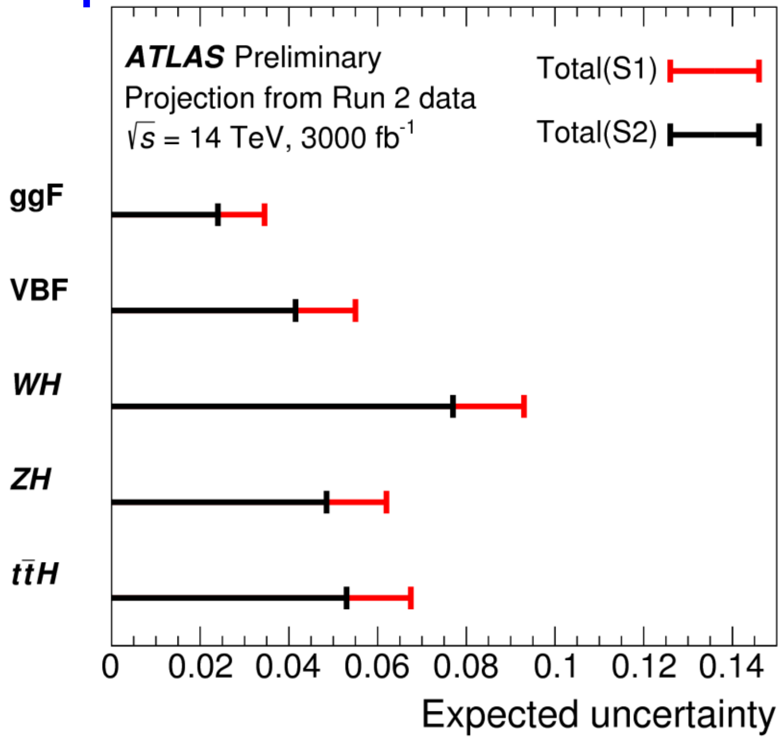
Importance of understanding b-tagging

μ^{bb} above also includes other production modes (VBF, boosted ggH)

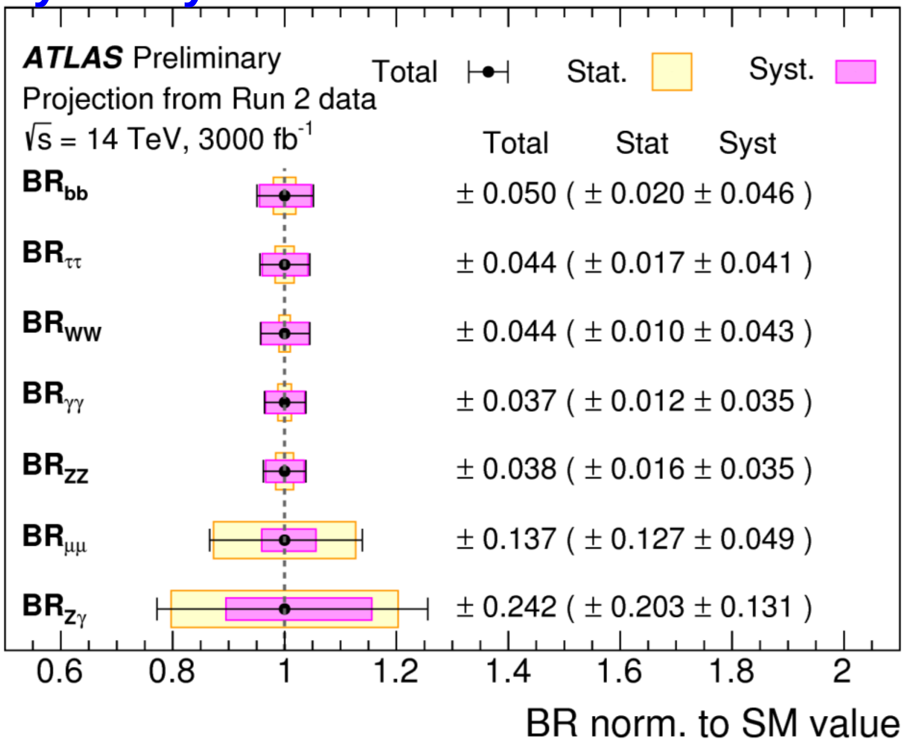
CMS-PAS-FTR-18-011

ATLAS H couplings

production mode



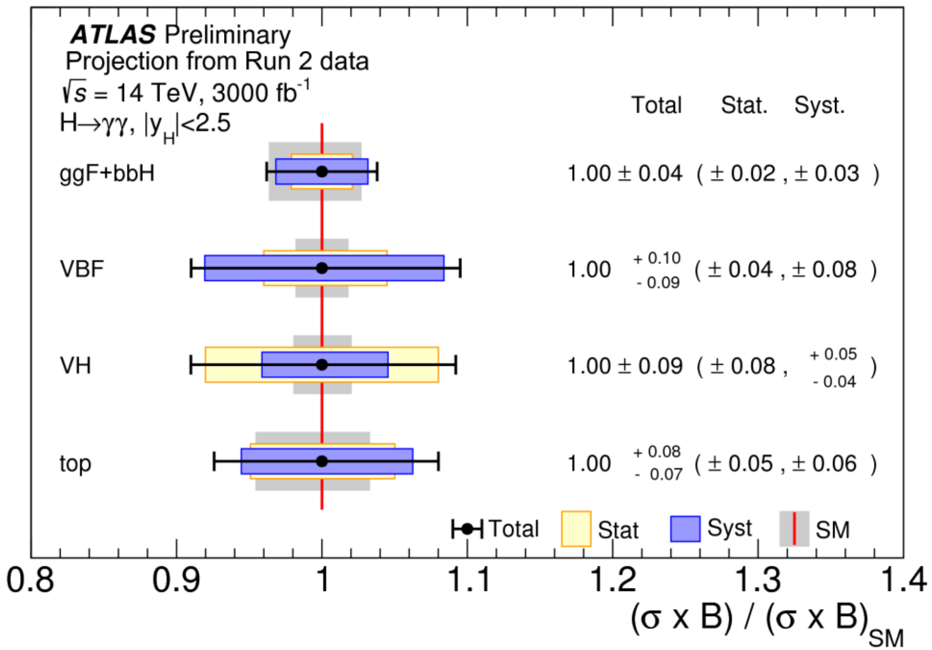
by decay channel



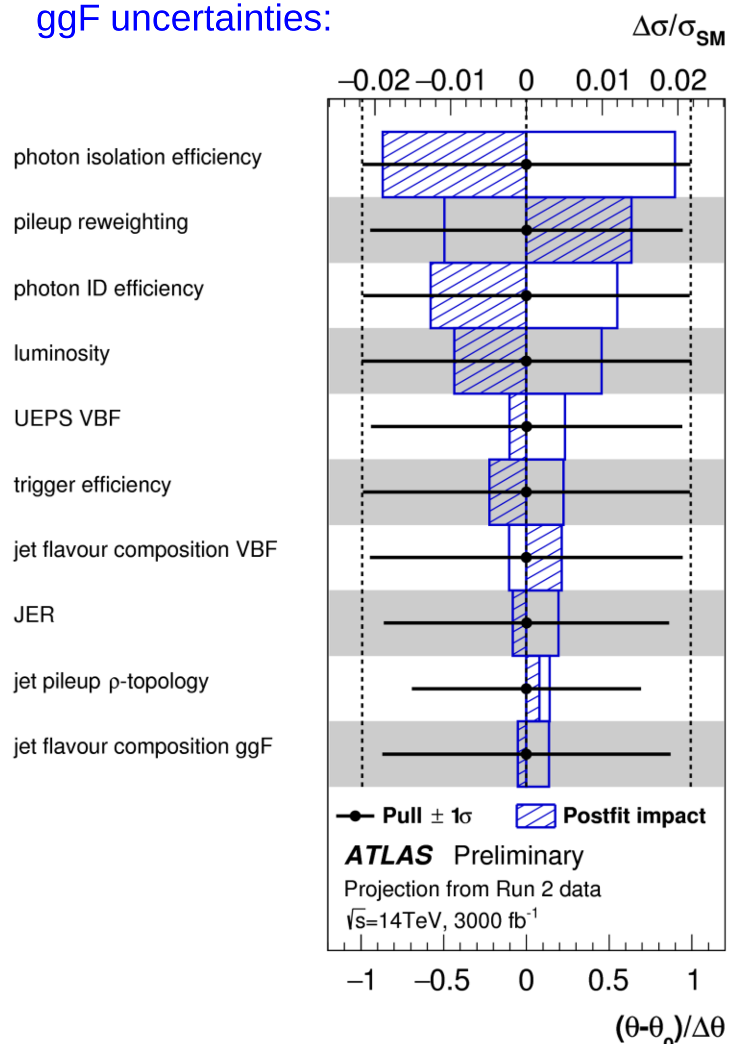
- Statistical uncertainty smaller than systematic for all but rarer $\mu\mu$, $Z\gamma$ channels
- Similar ratio of systematic / statistical uncertainty for bb, $\tau\tau$, WW
- Look at limiting factor for precision in three different channels: $\gamma\gamma$, WW, bb
  - → *Uncertainty breakdown for the most sensitive final state*
  - → *A simplification, but still instructive*

ATL-PHYS-PUB-2018-054

ATLAS H couplings $\gamma\gamma$



ggF uncertainties:



- **Limited by understanding of reconstruction**
- Systematics-limited in all but VH
- Main uncertainties from photon isolation and identification uncertainty, pileup-related

ATL-PHYS-PUB-2018-054

ATLAS H couplings WW

- **Limited by methods (background estimation)**
  - → *S/B ~ 10% and simple sideband subtraction is not an option*
  - → *Fake lepton background a notorious challenge*
  - → *Large background from WW must be extremely well-controlled*

ggF uncertainties:

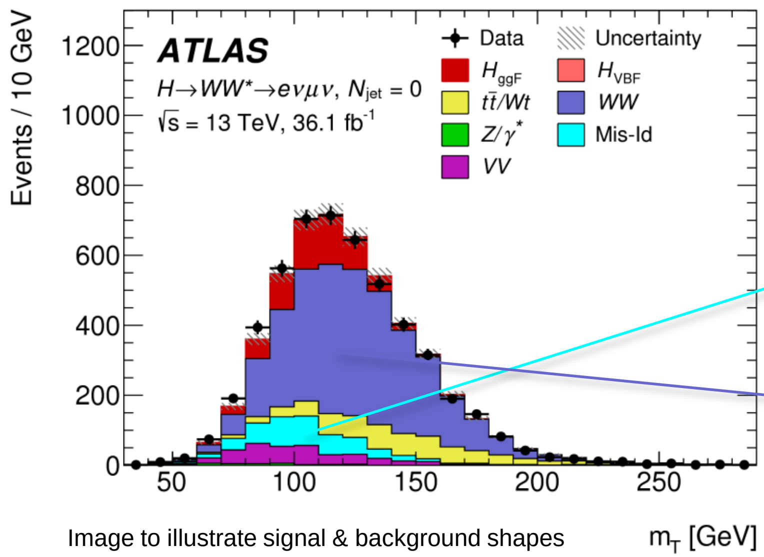
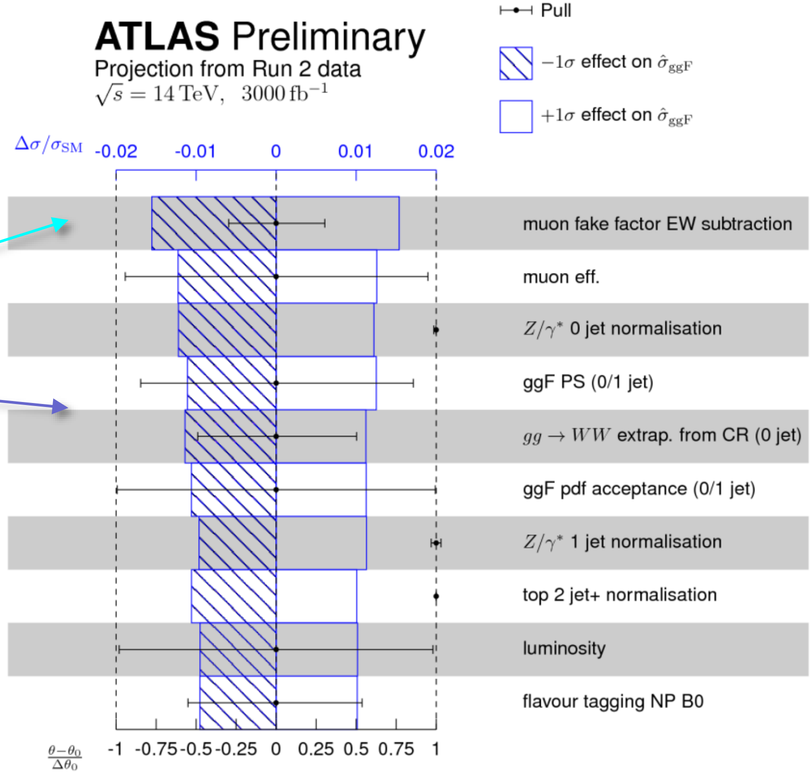


Image to illustrate signal & background shapes
Phys. Lett. B 789 (2019) 508,
$\mu_{ggF} = 1.10 \pm 0.20$

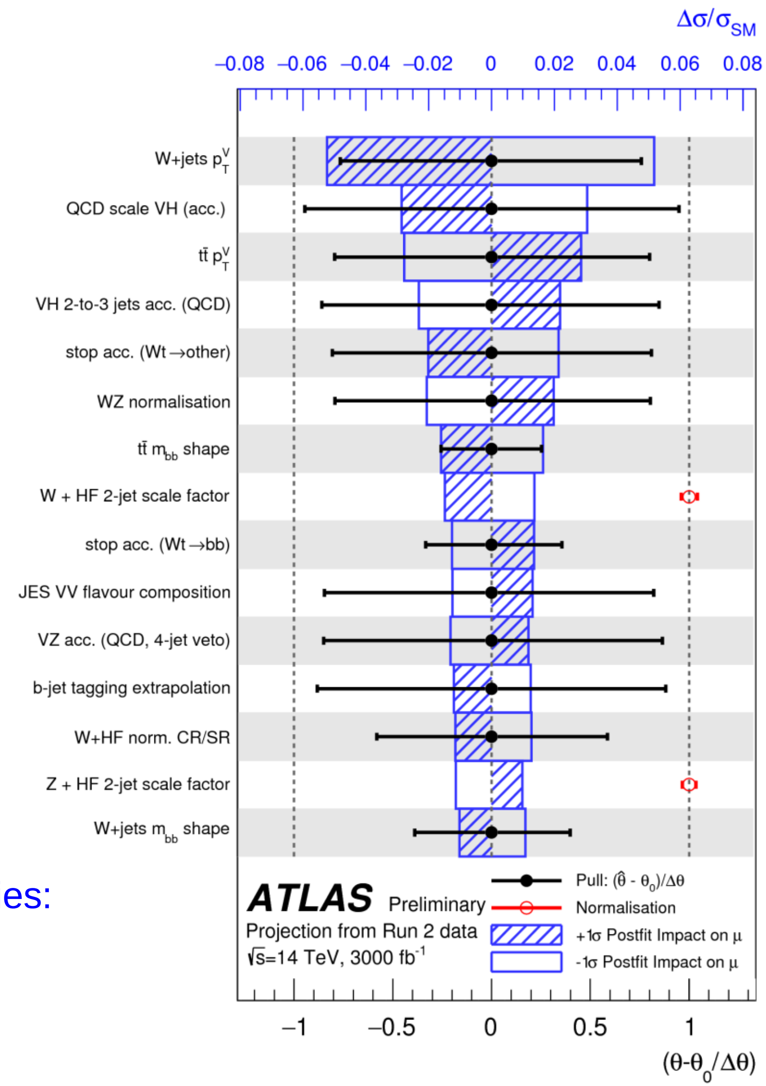


ATL-PHYS-PUB-2018-054

ATLAS H couplings Vhbb

- **Limited by theoretical modeling**
  - → *QCD scale*
  - → *Vector boson transverse momentum model*
- Jet energy scale contribution from uncertainty in flavor composition
- **b-jet tagging not primary**

WH uncertainties:



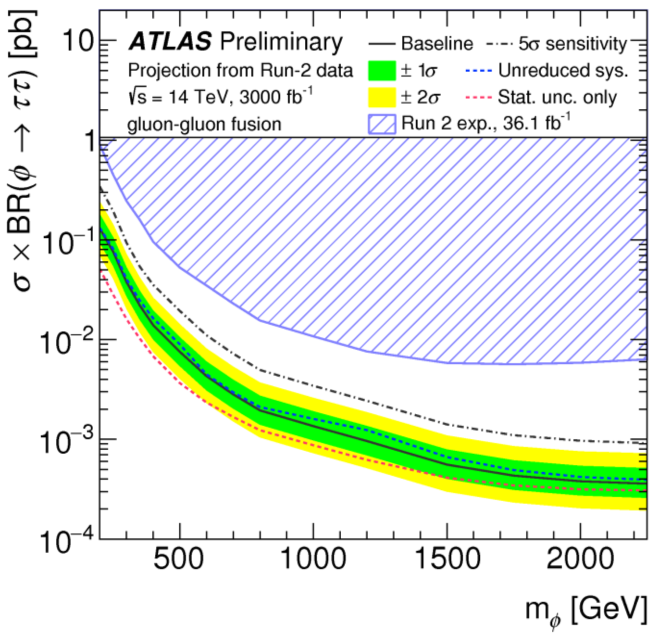
ATL-PHYS-PUB-2018-054

BSM searches

- Searches that improve most are those currently limited by **statistics** or **detector** capabilities

Detector: New heavy scalar to ττ

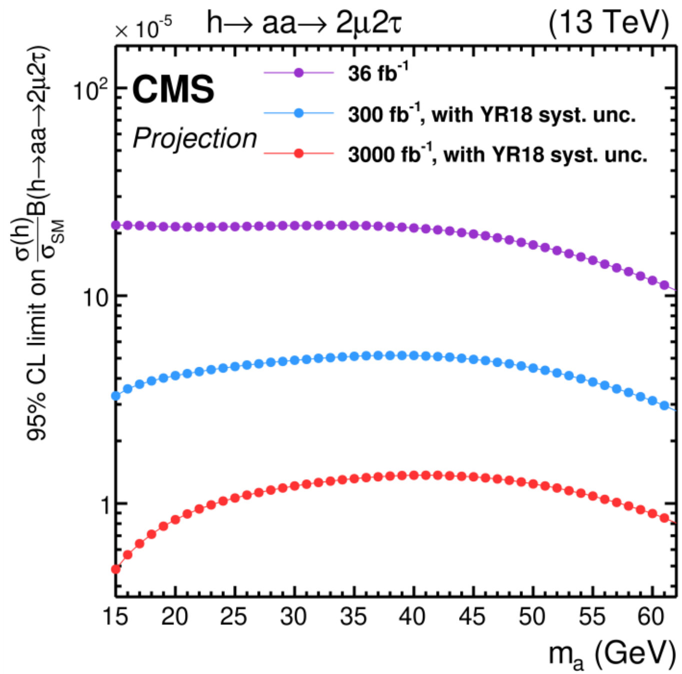
→ *Improved tau identification (better tracker) and more acceptance*



(ATL-PHYS-PUB-2018-050)

Statistics: h(125) to light pseudoscalars ("a") to ττbb or ττμμ

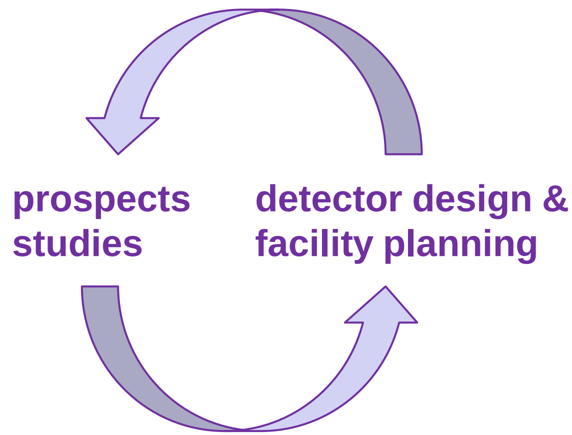
→ *2HDM+S well-motivated model and less constrained than 2HDM*



(CMS-PAS-FTR-18-035)

Summary

- Projected measurements **motivate new facilities**
  - → *HL-LHC, HE-LHC, ILC, FCC, muon collider…*
- Requires good understanding of **planned detector upgrades**
  - → *Which are themselves motivated by the physics goals*
- **Stringent tests** of SM-like observed Higgs boson
  - → ***4-5% total uncertainty** in "big 5" channels (WW, ZZ, $\gamma\gamma$, bb, $\tau\tau$)*
  - → *Different limitations in different channels: statistics, background-estimation methods, particle identification*
- Expect **evidence for Higgs pair production**
  - → *Non-SM signal potentially larger (or smaller)*
- Next up: resumption of **Snowmass**
  - → *CMS and ATLAS have both submitted LoIs*
  - → *Aiming for improved analysis strategies and new channels in next round of prospects*
- Detector upgrades now starting construction – looking forward to the data!



backup

HL-LHC overview

- Start of the high-luminosity LHC (HL-LHC) in 2027 will be the culmination of over a decade of intensive work
- 14 TeV proton-proton collisions, **3000-4000** fb^{-1} at instantaneous luminosity of 2 x 10^{35} $cm^{-1}s^{-1}$
- Comparison: Run 3 imminent at 13 TeV (possible upgrade to 14 TeV), **300-350** fb^{-1} and inst lumi up to 2 x 10^{34} $cm^{-1}s^{-1}$
- Up to 140-200 interactions per bunch crossing

Common systematics

Table 1: The "floor" systematic uncertainties for the HL-LHC.

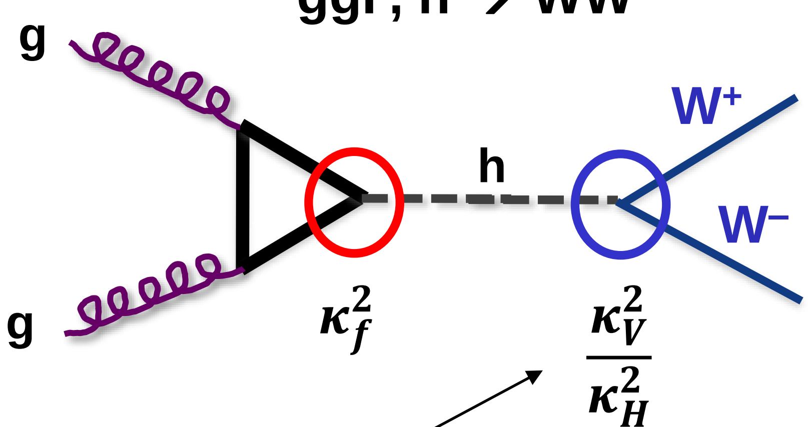
Uncertainty	Working point/ component	Value
Electron ID	All WPs, $p_T > 20\,GeV$	0.5%
	All WPs, $10 < p_T < 20\,GeV$	2.5%
Photon ID		2%
Muon ID	All WPs	0.5%
Tau ID	All WPs	2.5%
Jet energy scale	Total	1–2.5%
	Absolute scale	0.1–0.2%
	Relative scale	0.1–0.5%
	PU	0–2%
	Jet flavor	0.75%
Jet energy resolution		3–5% as a function of η
b-tagging	b jets (all WPs)	1%
	c jets (all WPs)	2%
	Light jets, loose WP	5%
	Light jets, medium WP	10%
	Light jets, tight WP	15%
	Subjet b tagging	1%
	Double c tagging	
p_T^{miss}	Propagate jet energy corrections uncertainties (must)	
	Propagate jet energy resolution uncertainties (recommended)	
	Vary unclustered energy by 10% (recommended)	
Integrated luminosity		1%

Indirect tests

"kappa" framework

- Rescaling of processes according to **LO vertices**
- Simple to implement in statistical frameworks for immediate interpretation of new results

ggF, h → WW*



scale factor for total width

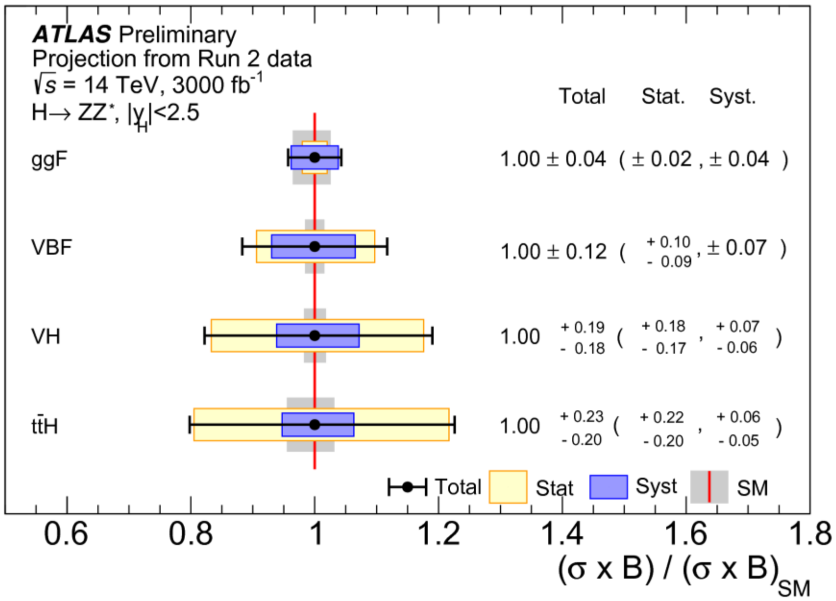
Effective Field Theory (HEFT, SMEFT)

- **Model-independent**, gauge-invariant parameterization of all operators respecting symmetries of the SM

  → *Subtleties in implementation of EWSB distinguish approaches*
- Allows **new structure in interactions**, not just rescaling of existing processes
- **Inclusive**: incorporates not just Higgs observables but other precision measurements (top, W, Z, at LHC, Tevatron, LEP)

ATLAS H couplings ZZ4l

- Statistics dominated in all but ggF

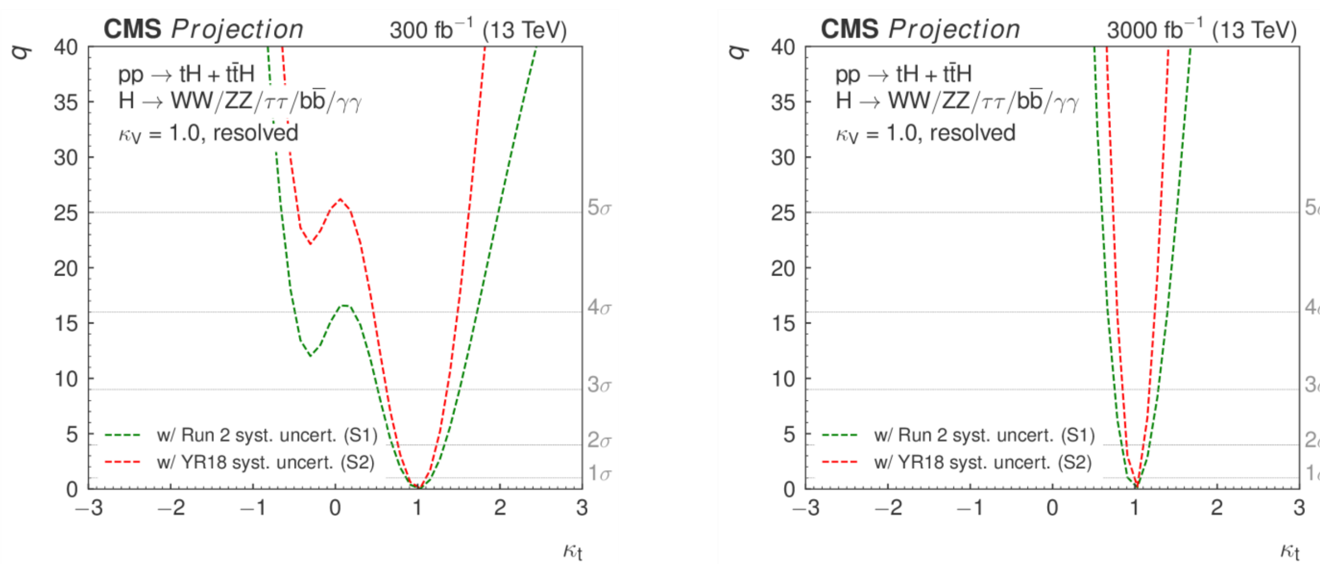


ATL-PHYS-PUB-2018-054

CMS: sign of top coupling

- Dedicated tHq analyses have no sensitivity at SM values but channel is dramatically enhanced for non-SM couplings

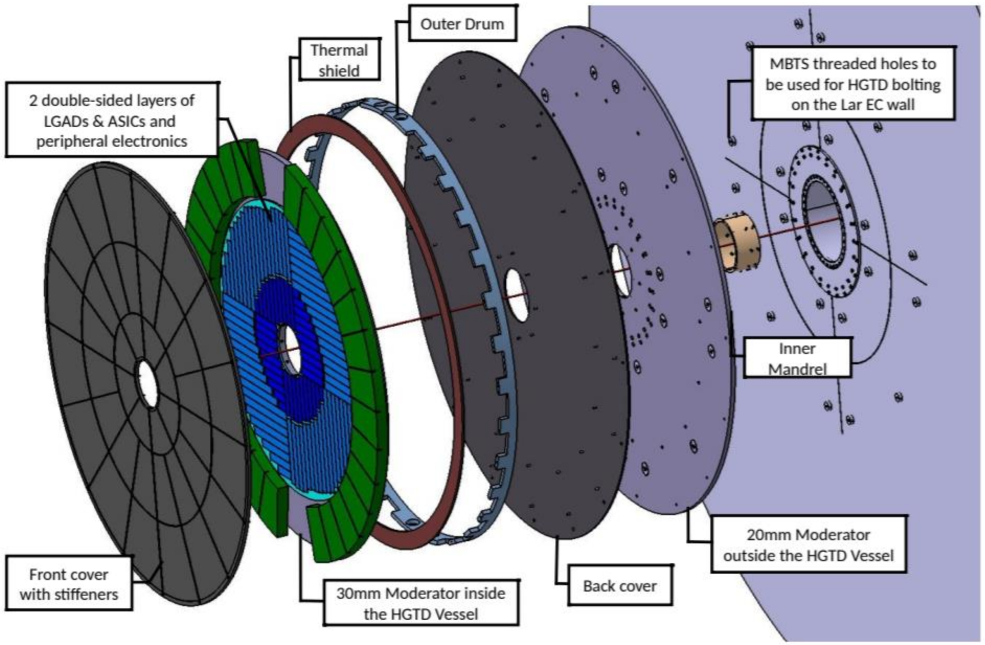
Additional data resolves sign ambiguity

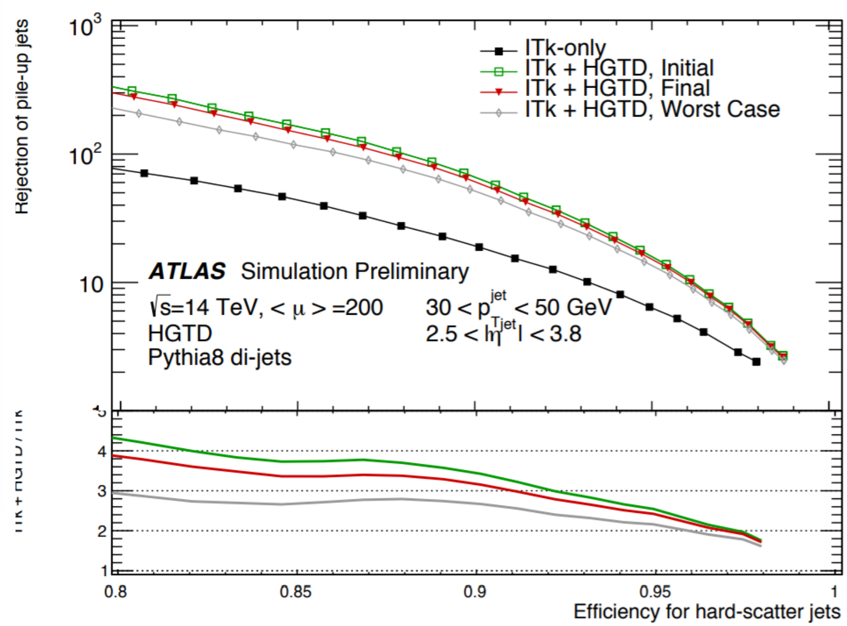


CMS-PAS-FTR-18-011

ATLAS Phase 2 detector

- Completely new: HGTD
  - → *LGAD technology*
  - → *Coverage in forward region to target jets*
  - → *3 ps timing resolution per track (42-60 ps per hit)*

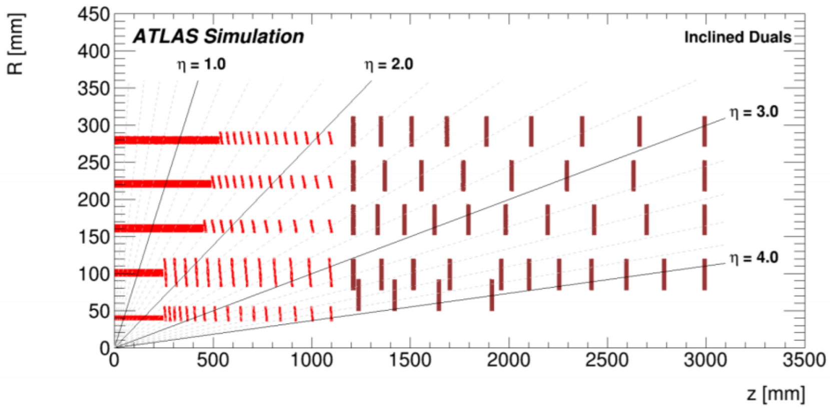


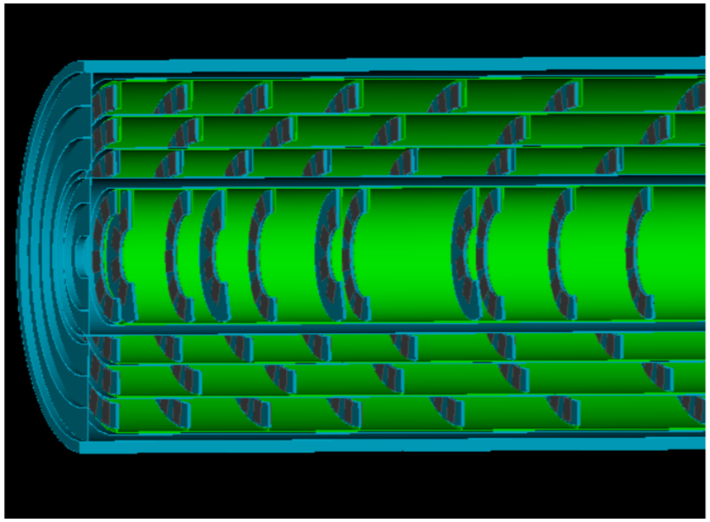


LHCC-P-012

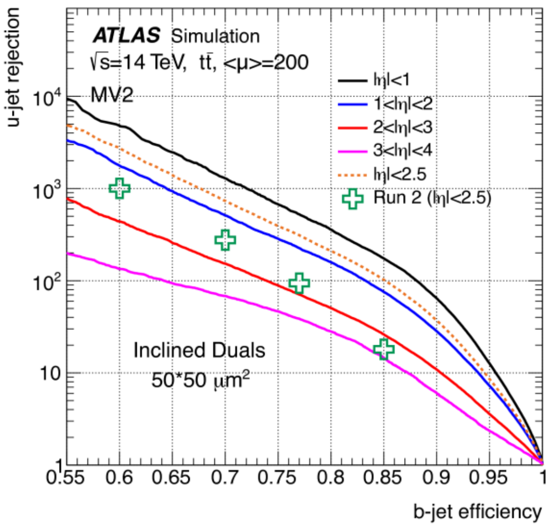
ATLAS Phase 2 detector

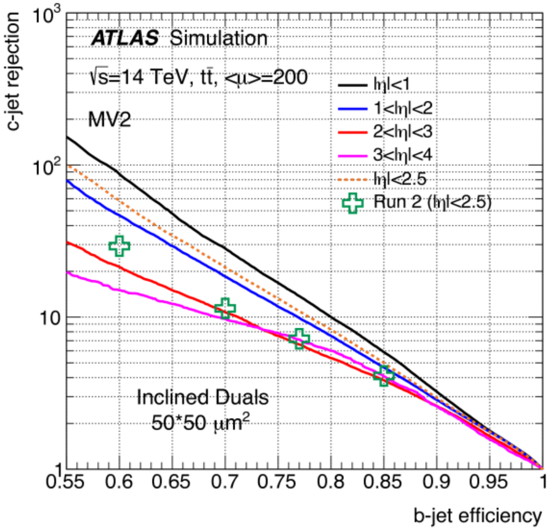
Inclined Modules maintain track hits with fewer total planes → less material





- Improvements in b-tagging efficiency (and uncertainty) expected from improved pixel detector





ATLAS-TDR-030

Evolution of projections

- Making projections of Higgs measurements is as old as the Higgs boson itself
- *How have our expectations changed over the years?*
- Surprisingly difficult to compare new and old projections
  - → *Priority measurements in Run 1 & 2 have shifted*
  - → *How we think about these measurements has evolved*
    - "signal strength" μ → cross section x BR
    - "kappa" scale factors to STXS and EFT

CMS-PAS-FTR-18-019

CMS-PAS-FTR-15-002

CMS-PAS-FTR-15-002	Channel	Significance Stat. + syst.	Significance Stat. only	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ Stat. + syst.	95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ Stat. only
	bbbb	0.95	1.2	2.1	1.6
0.9σ	$bb\tau\tau$	1.4	1.6	1.4	1.3
	$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
1.7σ *	$bb\gamma\gamma$	1.8	1.8	1.1	1.1
	$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
1.9σ	Combination	2.6	2.8	0.77	0.71

* I subtracted in quadrature from the combination (ignores correlations)

Evolution of couplings – ATLAS

- Only comparable numbers are in couplings baseline measurements
- Doubled the expected precision
- Muon coupling (κ_μ) least changed: statistics-dominated
- Most dramatic: κ_b 11% → 4.4%
  → *Tempting to ascribe to b-tagging with machine learning, but ML already in use by then (though methods have advanced)*

Nr.	Coupling	3000 fb^{-1} Theory unc.: All	Half	None
7	κ_Z	4.3%	3.9%	3.8%
	κ_W	4.8%	4.1%	3.9%
	κ_t	8.2%	6.1%	5.3%
	κ_b	12%	11%	10%
	κ_τ	9.8%	9.0%	8.7%
	κ_μ	7.3%	7.1%	7.0%

ATL-PHYS-PUB-2014-016

POI	Scenario	Precision
κ_W	HL-LHC S1	$^{+0.028}_{-0.027}$
	HL-LHC S2	$^{+0.019}_{-0.019}$
κ_Z	HL-LHC S1	$^{+0.026}_{-0.025}$
	HL-LHC S2	$^{+0.017}_{-0.017}$
κ_t	HL-LHC S1	$^{+0.043}_{-0.041}$
	HL-LHC S2	$^{+0.030}_{-0.029}$
κ_b	HL-LHC S1	$^{+0.064}_{-0.060}$
	HL-LHC S2	$^{+0.044}_{-0.043}$
κ_τ	HL-LHC S1	$^{+0.038}_{-0.036}$
	HL-LHC S2	$^{+0.028}_{-0.027}$
κ_μ	HL-LHC S1	$^{+0.079}_{-0.076}$
	HL-LHC S2	$^{+0.070}_{-0.071}$

ATL-PHYS-PUB-2018-054