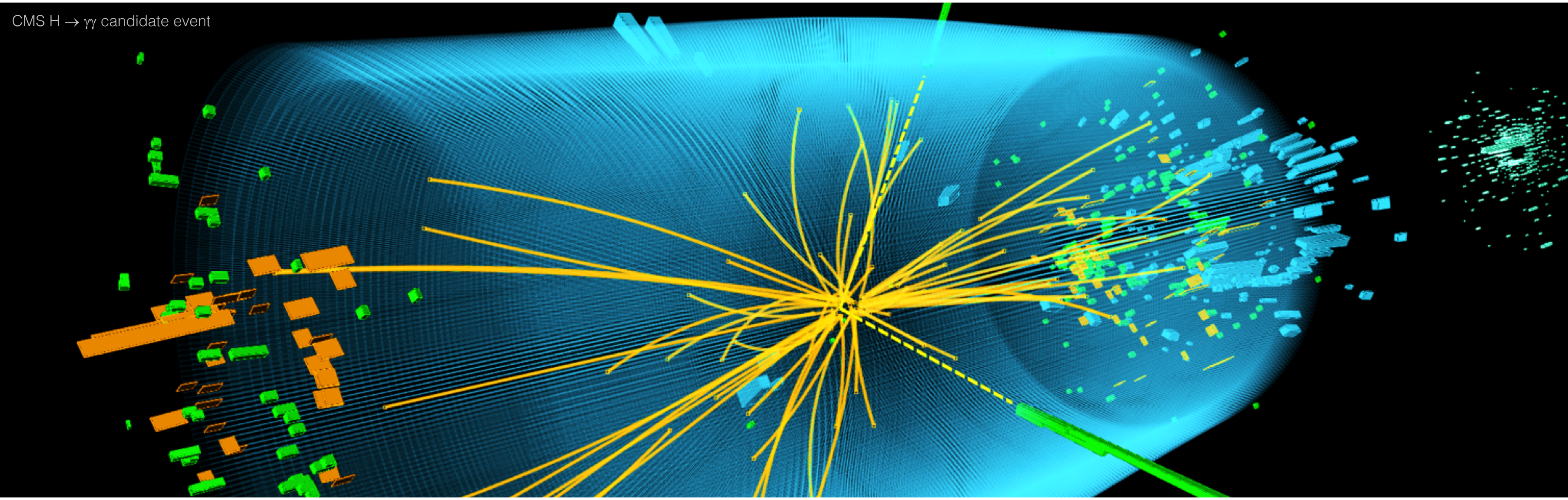
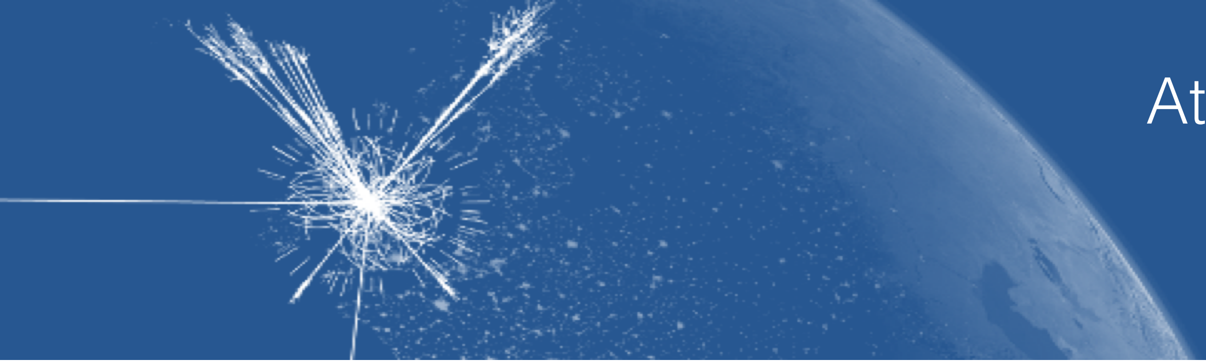
Measurement of Higgs boson properties — What will the (HL-)LHC achieve



Andreas Hoecker

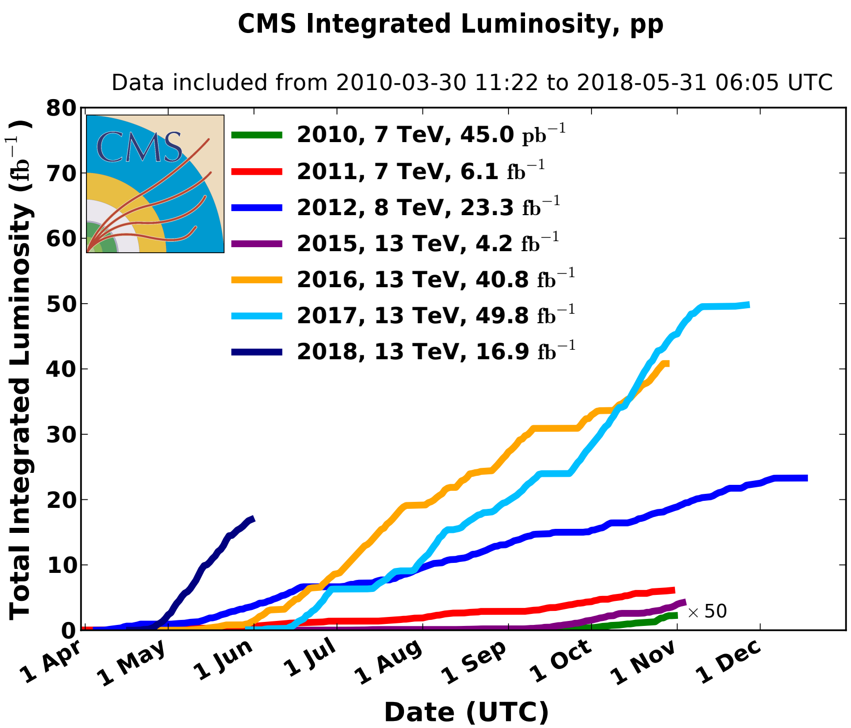
EP/TH Faculty meeting, June 1st, 2018 at CERN

Special thanks to Maria Cepeda, Michael Duehrssen, Luca Malgeri, Brian Petersen for advise

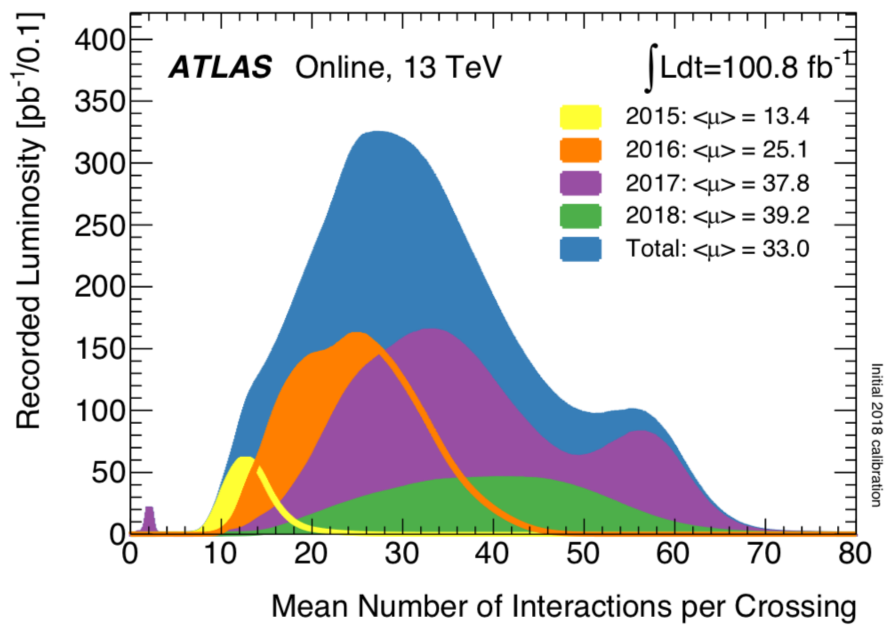


At fixed √s, luminosity is single most important quantity

Integrated delivered luminosity 2010–2018



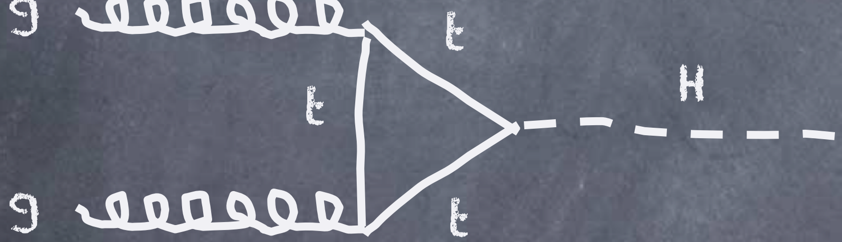
High-luminosity comes with a challenge



Higgs boson production at the LHC

At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,total}$ = 56 pb at $\sqrt{s}$ = 13 TeV for m_H = 125 GeV

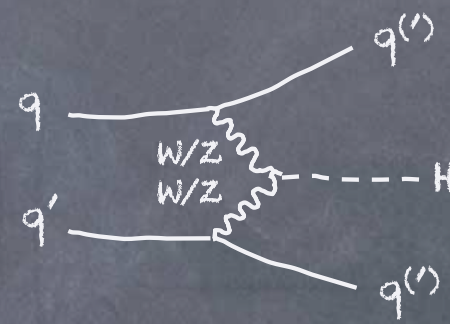
Cross section steeply falling with Higgs mass



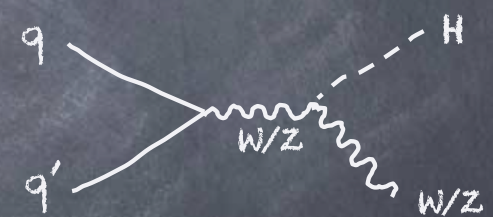
$\sigma_{H,ggF}$ ~ 49 pb at 13 TeV

Total production of almost 6 million SM Higgs bosons of 125 GeV by today in each ATLAS and CMS

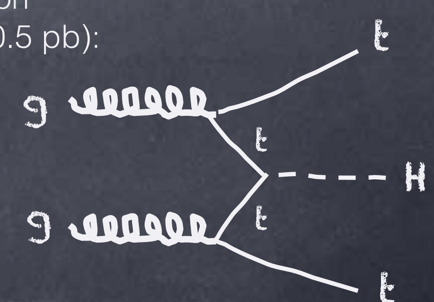
Weak boson fusion ($\sigma_{W/Z+H}$ ~ 3.8 pb):



Higgs-strahlung ($\sigma_{W/Z+H}$ ~ 1.4/0.9 pb):



"ttH" production (σ_{ttH} ~ σ_{bbH} ~ 0.5 pb):



Higgs boson production at the LHC

Because of the coupling to the mass of the decay particles:

… the Higgs decays with preference to the heaviest particles allowed

… the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, W)

At the LHC we measure:

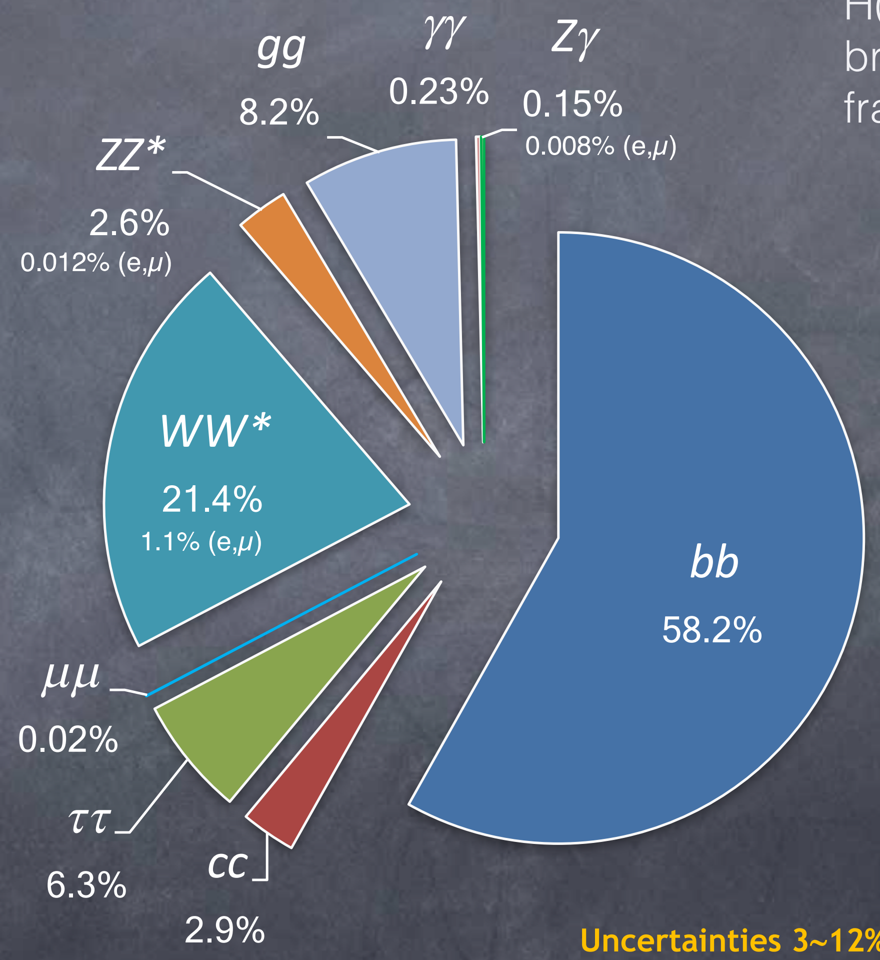
$$\text{Rate}(pp \to H \to f) \propto \sigma_H \cdot \frac{\Gamma_{H\to f}}{\Gamma_H}$$

Higgs boson width Γ_H not directly accessible (except using tricks)

Absolute coupling measurement requires extraction of $\sigma_H \cdot \Gamma_{H\to f}$

Therefore, only coupling ratios model-independent at LHC

H(125 GeV) branching fractions:



Higgs boson production at the LHC

Leptonic (e/μ) and photonic final states provide best discovery significance

- $H \to \gamma\gamma$ / $ZZ^*(\to 4\ell)$ have best mass resoluton

- $H \to WW^* \to 2\ell 2\nu$ good trigger, sustainable background level, and large branching fraction

H(125 GeV)

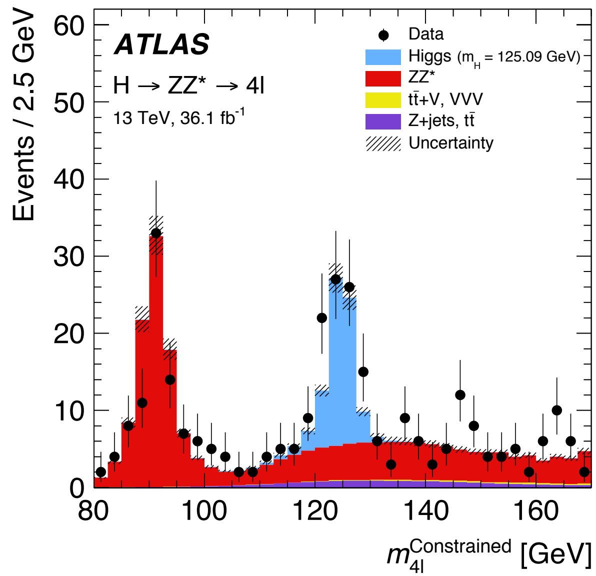
Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ^* \to 4\ell$	1–2%
$H \to WW^* \to 2\ell 2\nu$	20%
$H \to bb$	10%
$H \to \tau\tau$	15%

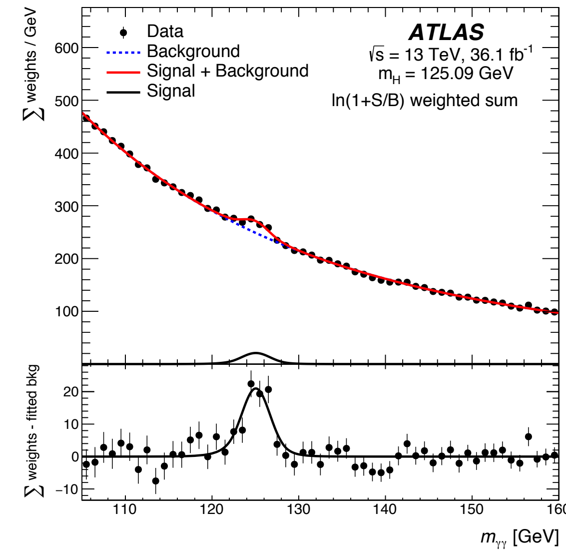
A long time passed since the July 2012 discovery of a “Higgs-like” boson…

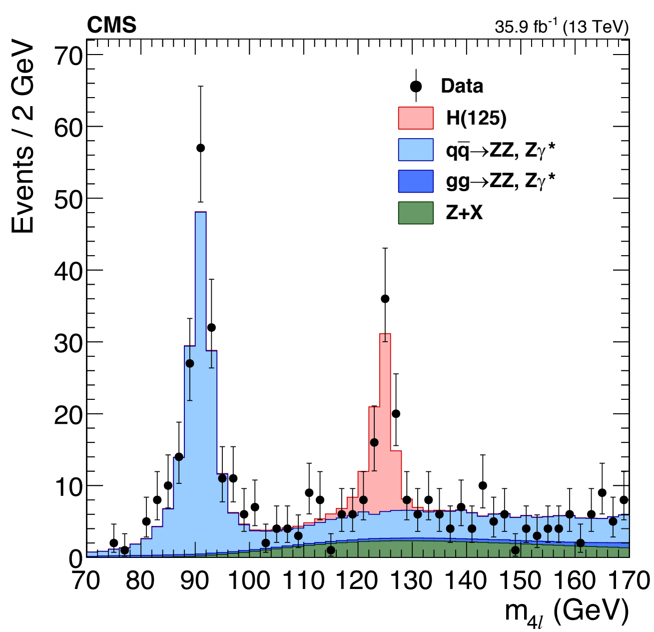
Higgs to diphoton and four-lepton discovery channels

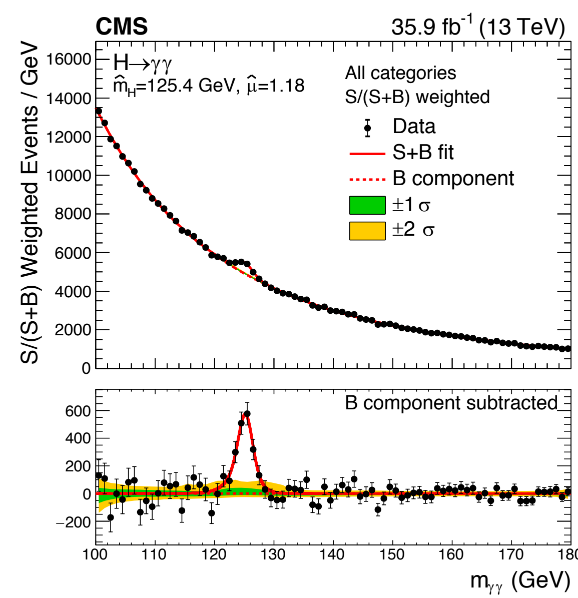
using ~36 fb^{-1} 13 TeV data from Run-2

Watch out for news at LHCP next week









ATLAS & CMS Run-1 combination of Higgs coupling measurements

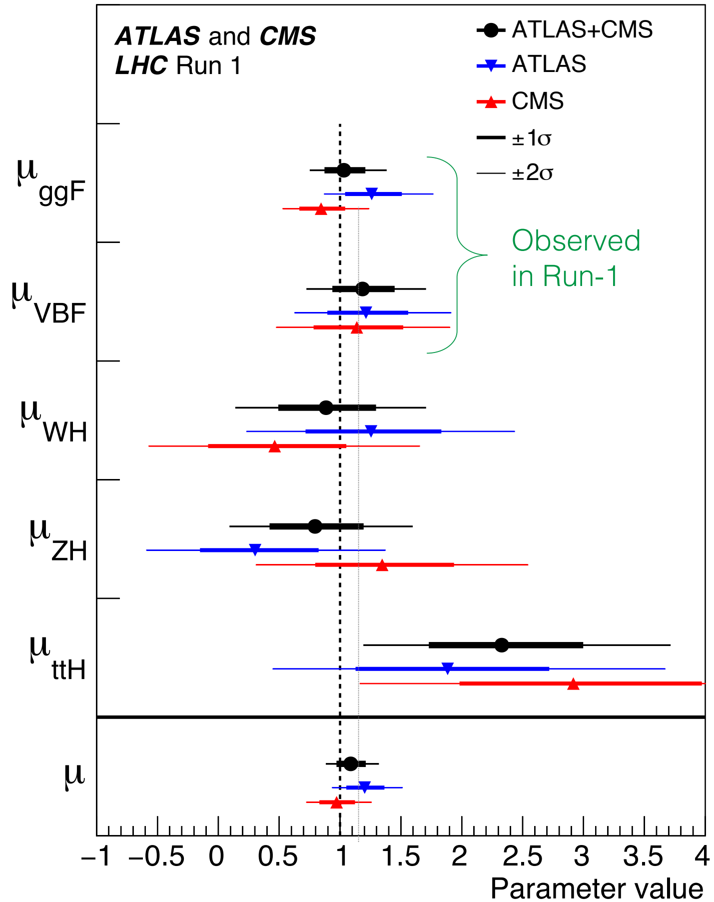
[1606.02266]

Agreement among experiments

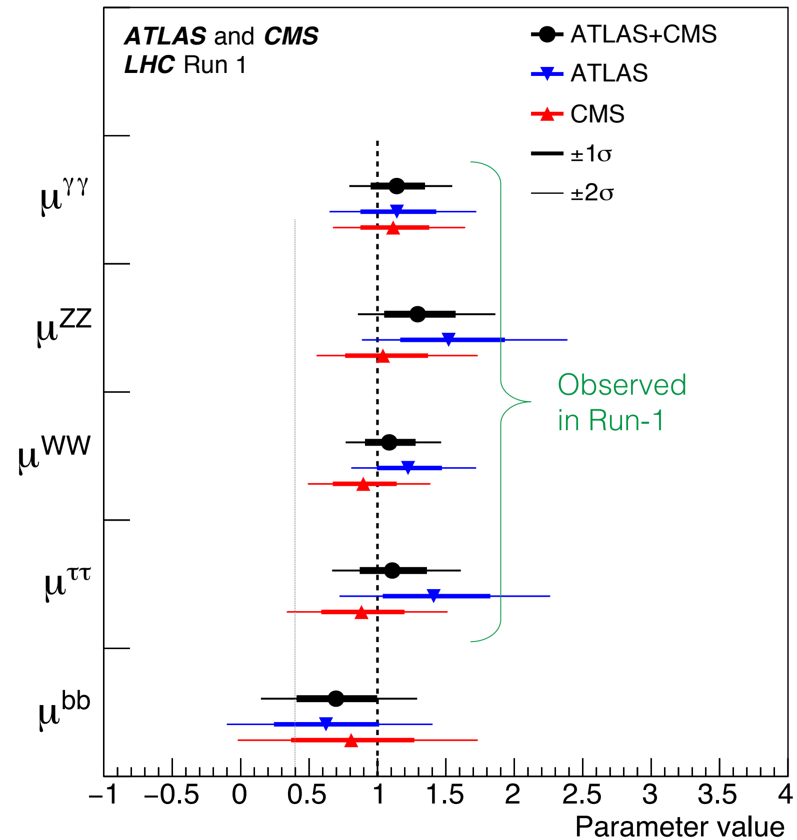
Overall signal strength (Run-1): μ = 1.09 ± 0.11 (A & C)

Run-2: 1.17 ± 0.10 (CMS, all channels, 0.06 stat/syst/sig),
1.09 ± 0.12 (ATLAS, ZZ* + γγ)

Higgs production processes



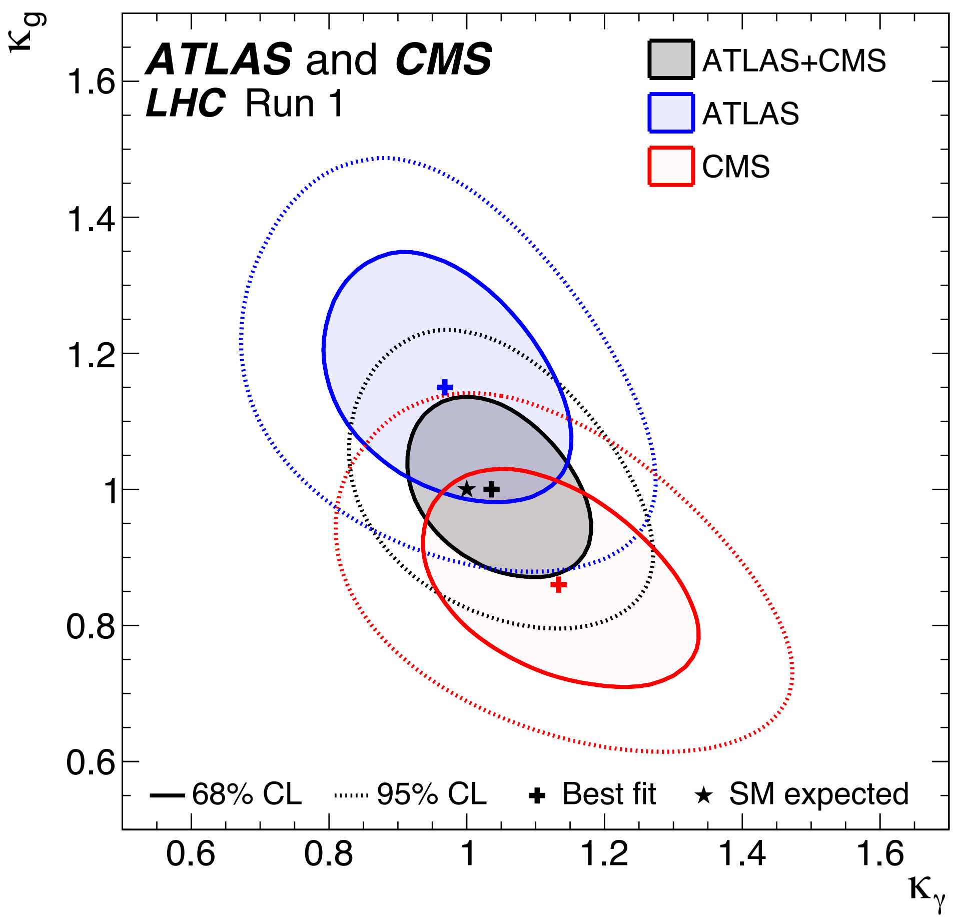
Higgs decay processes

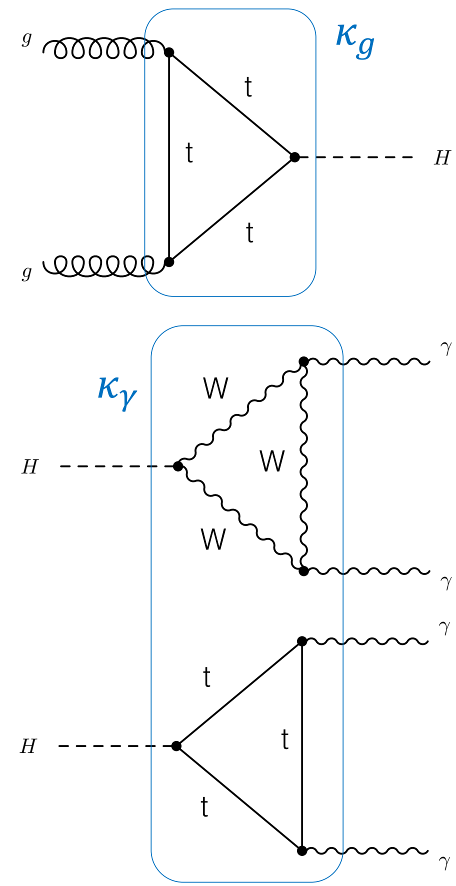


Note that the least model-dependent observables at the LHC are **ratios of couplings**

ATLAS & CMS Run-1 combination of Higgs coupling measurements

[1606.02266]





Couplings to massless particles mediated by loops involving heavy particles

Powerful test for new physics (eg, excludes SM-like heavy 4th fermion generation)

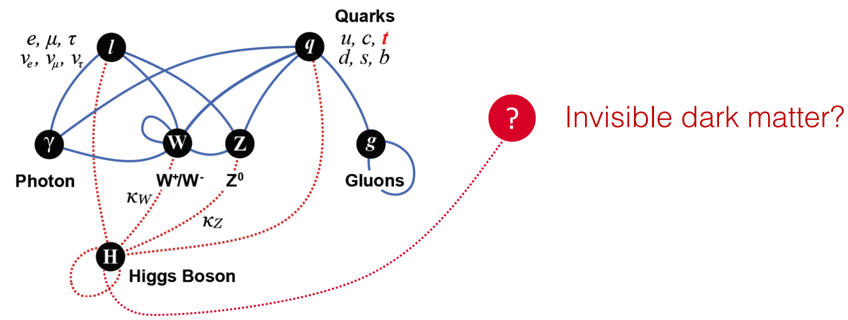
The Higgs boson as a *portal* to beyond the SM physics

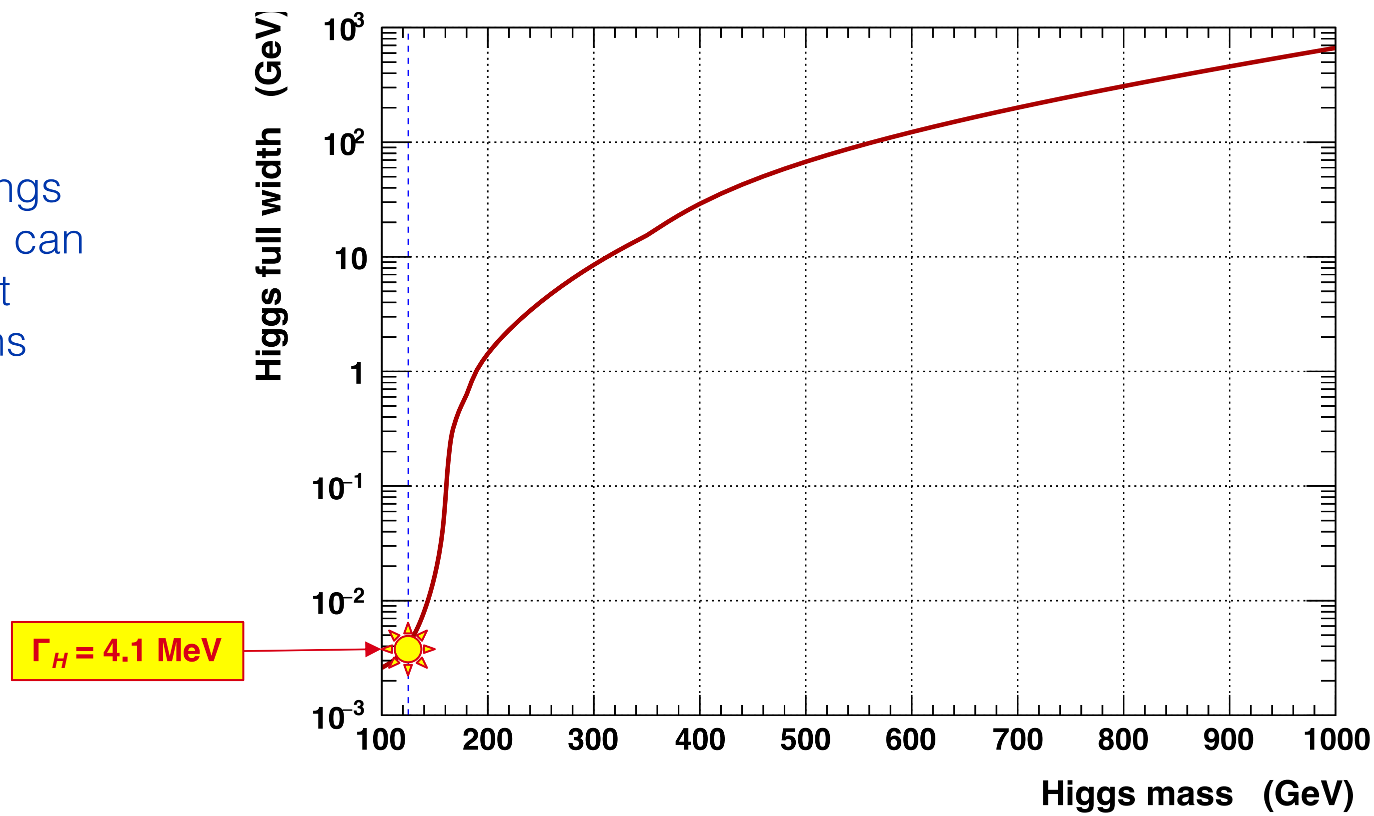
Higgs is narrow: 4.1 MeV

For comparison:

Γ_W = 2.1 GeV
Γ_Z = 2.5 GeV
Γ_{top} = 1.3 GeV

Even small couplings to new light states can measurably distort branching fractions





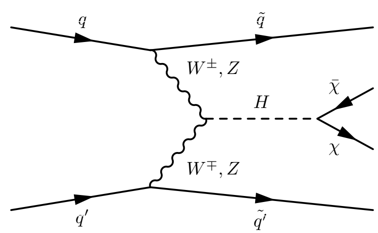
Current status of property measurements

Mass: Run-1 (ATLAS & CMS): 125.09 ± 0.24 GeV | confirmed by ATLAS and CMS with Run-2 data

Spin / CP: Spin 1, 2 excluded with high significance | CP-even, but small CP-odd admixtures possible

Width: < 1.1 GeV from direct measurement | < 13 MeV from off-shell coupling | < 6.2 MeV from fit
SM: 4.1 MeV (both model-dependent)

BR(H → invisible): < 24% from VBF channel (CMS)
(assuming SM production)



SM production and decay channels:

Decay → Production ↓	γγ	ZZ*	WW*	bb	cc	ττ	μμ	Combined
ggF	Observed	Observed	Observed	UL	–	UL	UL	Observed
VBF	UL	UL	UL	UL	–	Evidence	UL	Observed
VH	UL	UL	UL	Evidence	UL	UL	–	Evidence
ttH	UL	UL	Evidence*	UL	–	Evidence*	–	Observed
Combined	Observed	Observed	Observed	Evidence	–	Observed	UL	

* both channels together

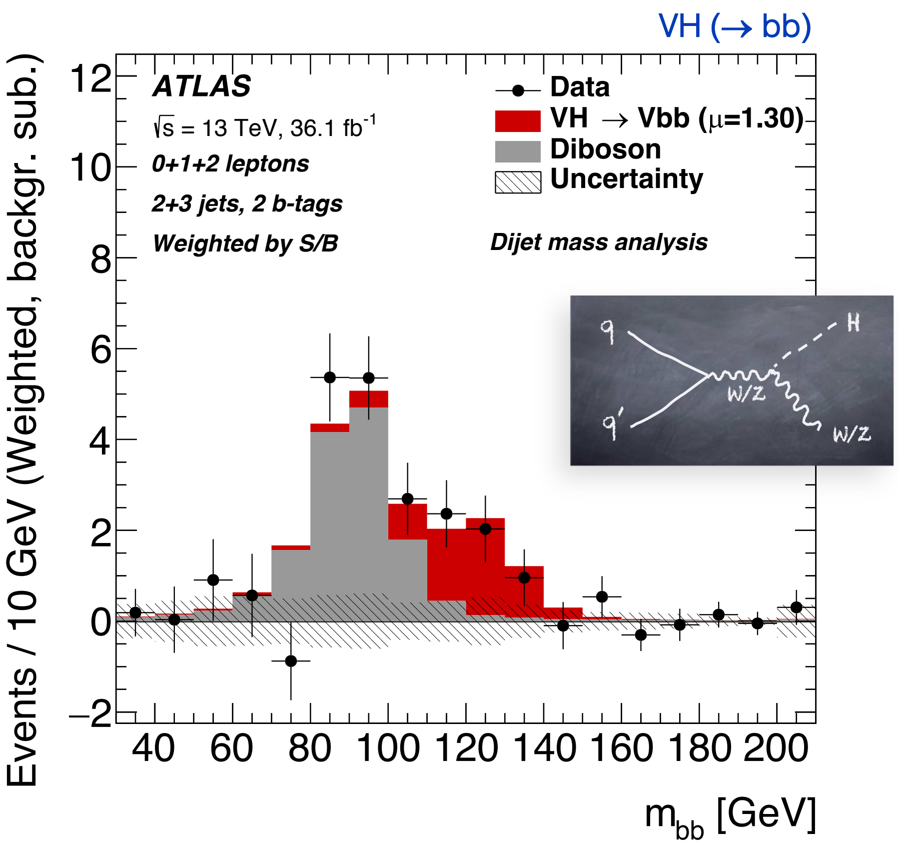
Upper Limit

Closing in on missing channels

2015 + 2016 data, $\sqrt{s}$ = 13 TeV

ATLAS arXiv:1708.03299, CMS arXiv: 1804.02610

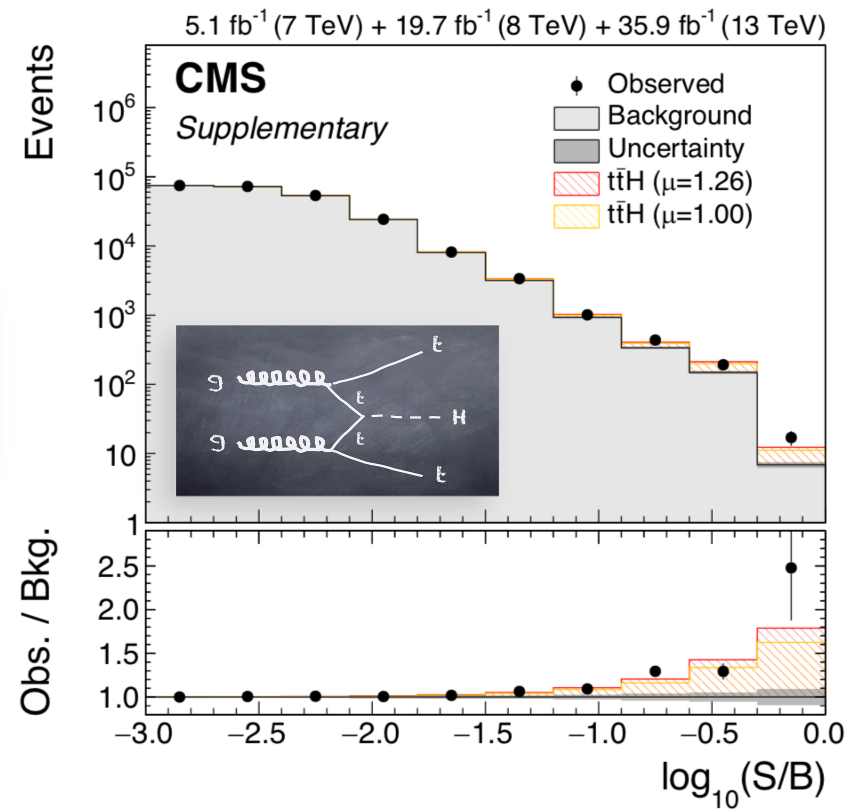
VH (→ bb)



Significance: 3.6 (obs) | 4.0 (exp)

[Combination Run-1 & 2]

ttH (→ all modes)



Significance: 5.2 (obs) | 4.2 (exp)

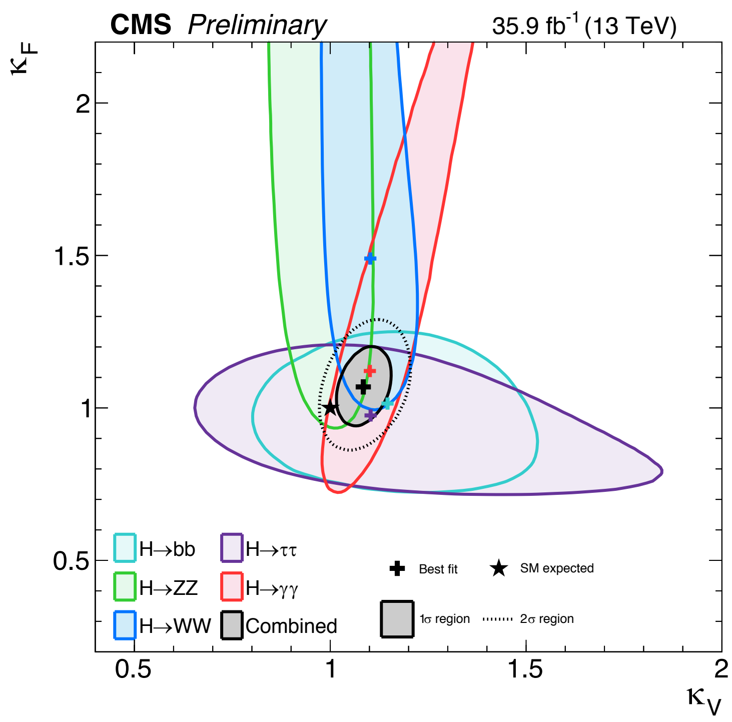
[Combination Run-1 & 2]

Current status of property measurements

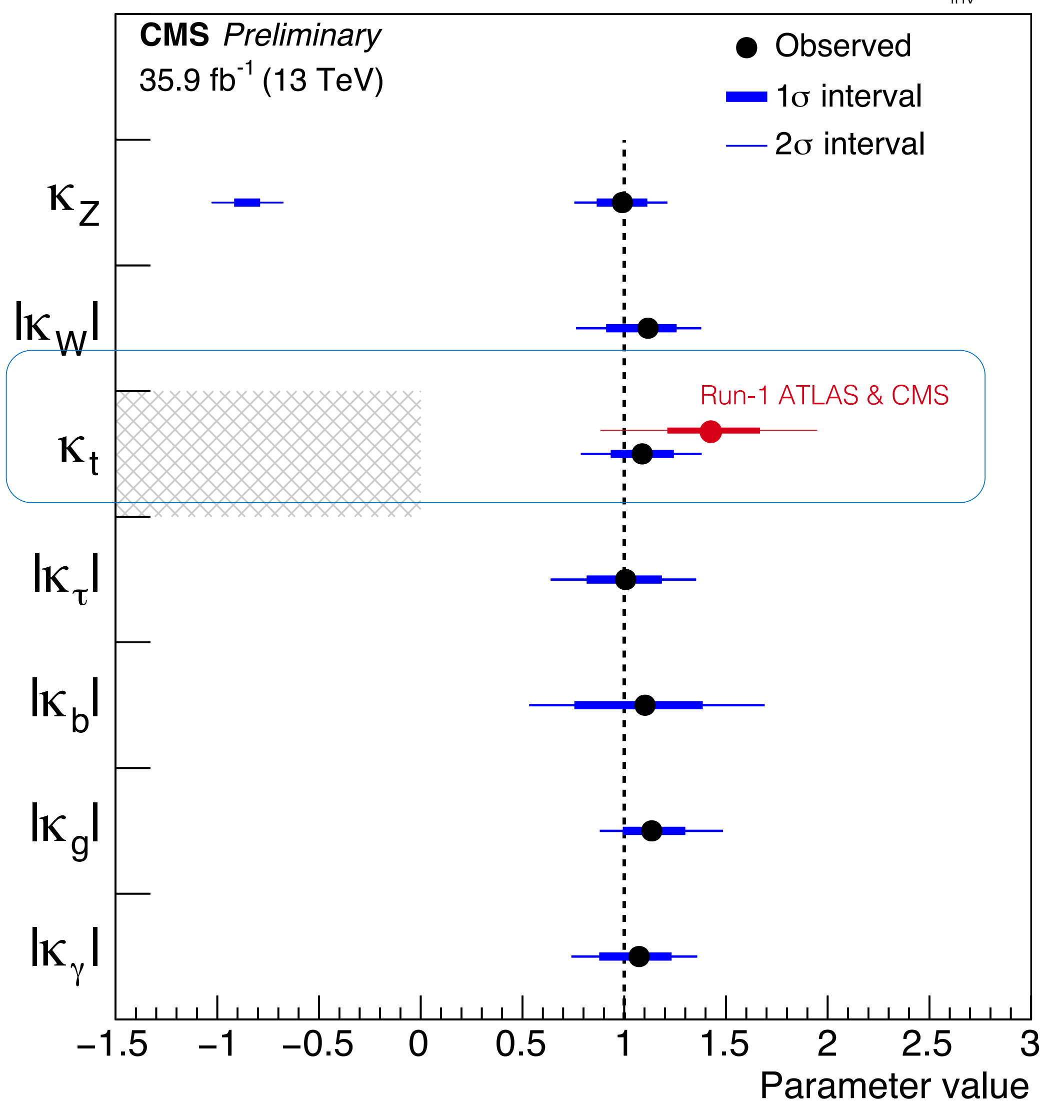
Combined coupling fit (CMS)
2016 data, $\sqrt{s}$ = 13 TeV

CMS-PAS-HIG-17-031

Higgs to boson and fermion coupling modifiers:



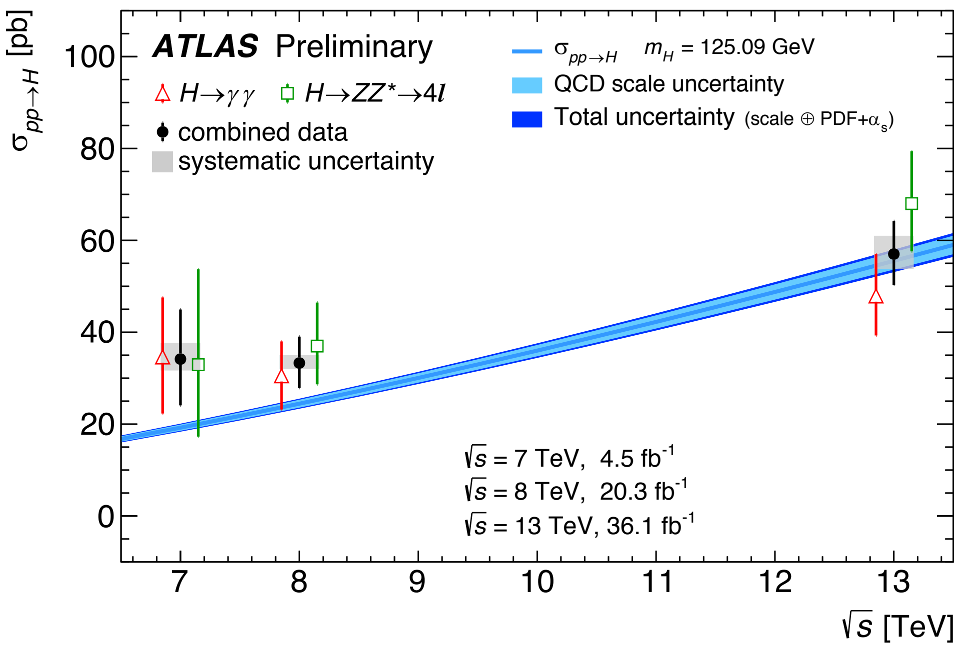
Assumes: BR_{inv} = 0

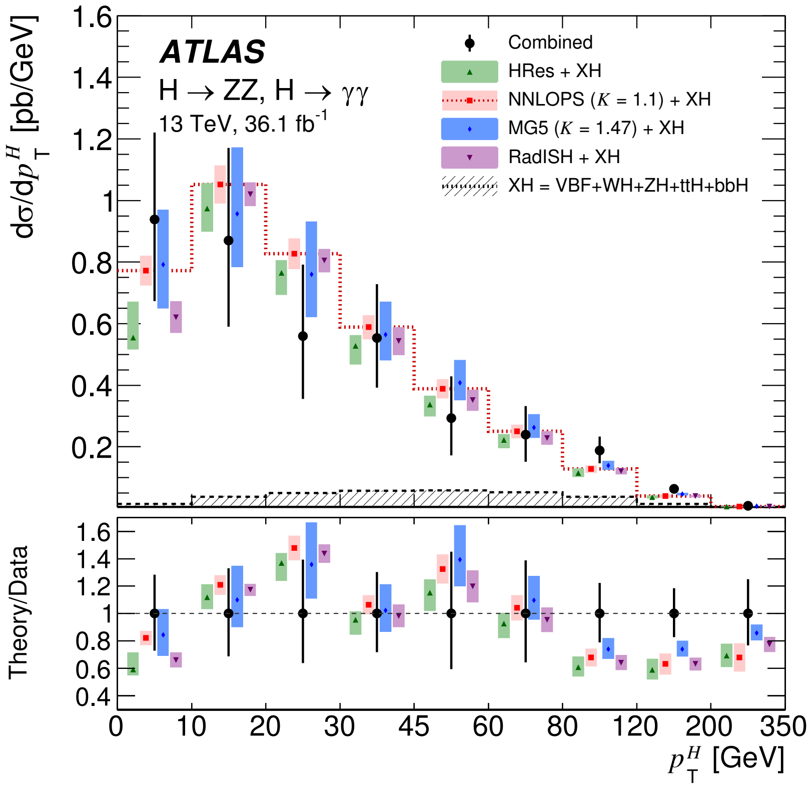


Cross section measurements

2015+2016 data, √s = 13 TeV

ATLAS-CONF-2018-002





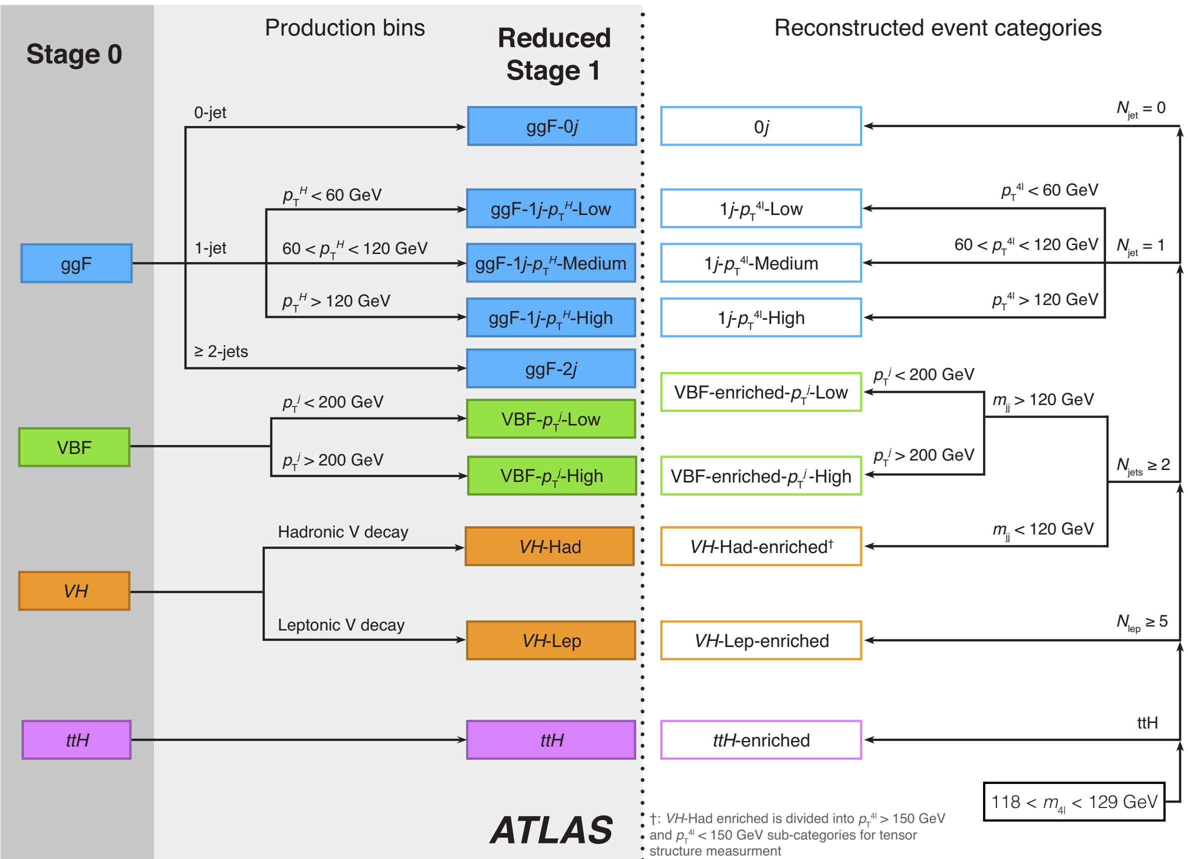
Combination of cleanest γγ and 4-lepton channels provides currently most sensitive differential cross section measurements, but still a long way to go to achieve good precision

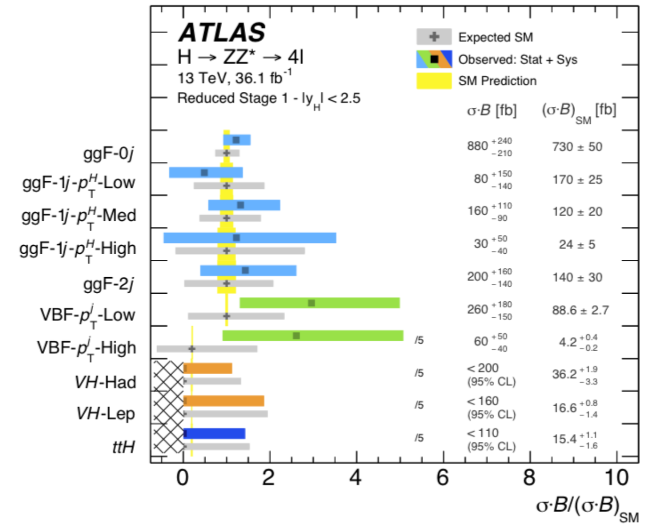
More than observation: detailed measurements

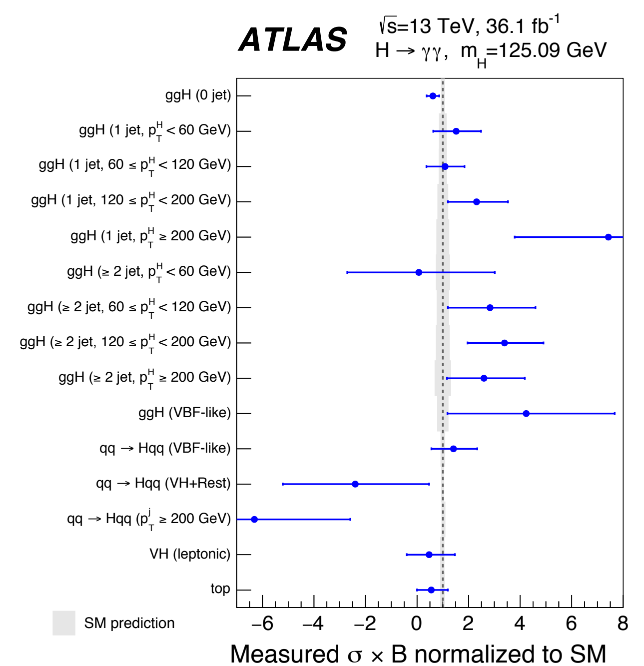
Simplified template cross (STXS) section measurements

2015+2016 data, $\sqrt{s}$ = 13 TeV

ATLAS arXiv:1712.02304, 1802.04146







STXS define particle-level bins to maximize measurement precision and reduce theory dependence

Is the scalar sector just that of the SM ?

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

Diverse search programme at the LHC:

So far no deviation from SM found in any of these searches

BSM Higgs searches

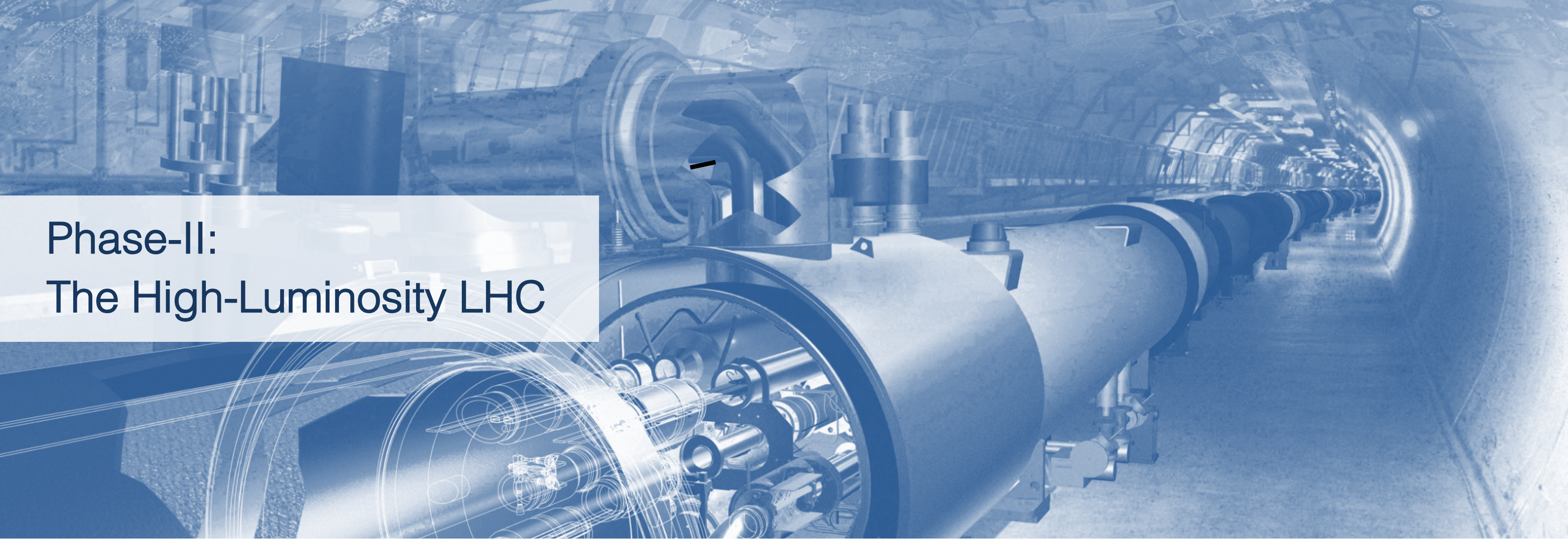
- Light or heavy neutral Higgs bosons
- Charged Higgs boson
- Lepton flavour violating Higgs decays
- Di-Higgs production (resonant or not)
  No sensitivity yet for SM di-Higgs production
- Exotic Higgs decays
- Higgs as portal to hidden sector
- Higgs in BSM decay chains

$$V(\phi) = \mu^2_{<0}\left|\phi\right|^2 + \lambda\left|\phi\right|^4 + Y^{ij}\psi^i_L\psi^j_R\phi$$

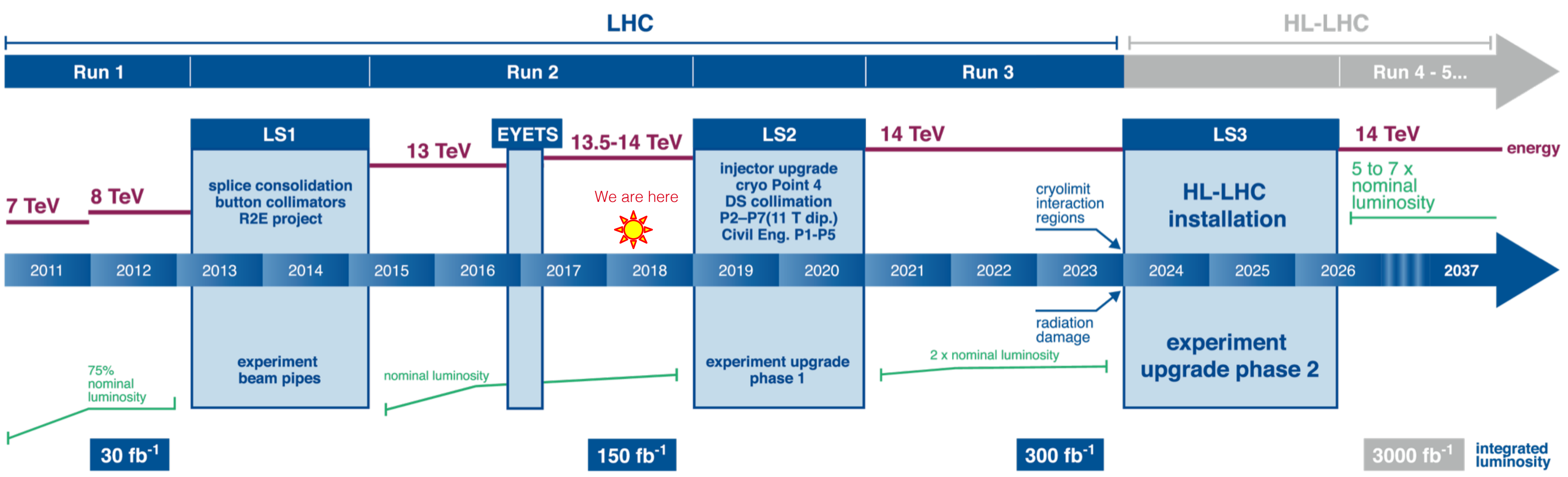
Higgs potential
Is it just the simplest model?

The next steps

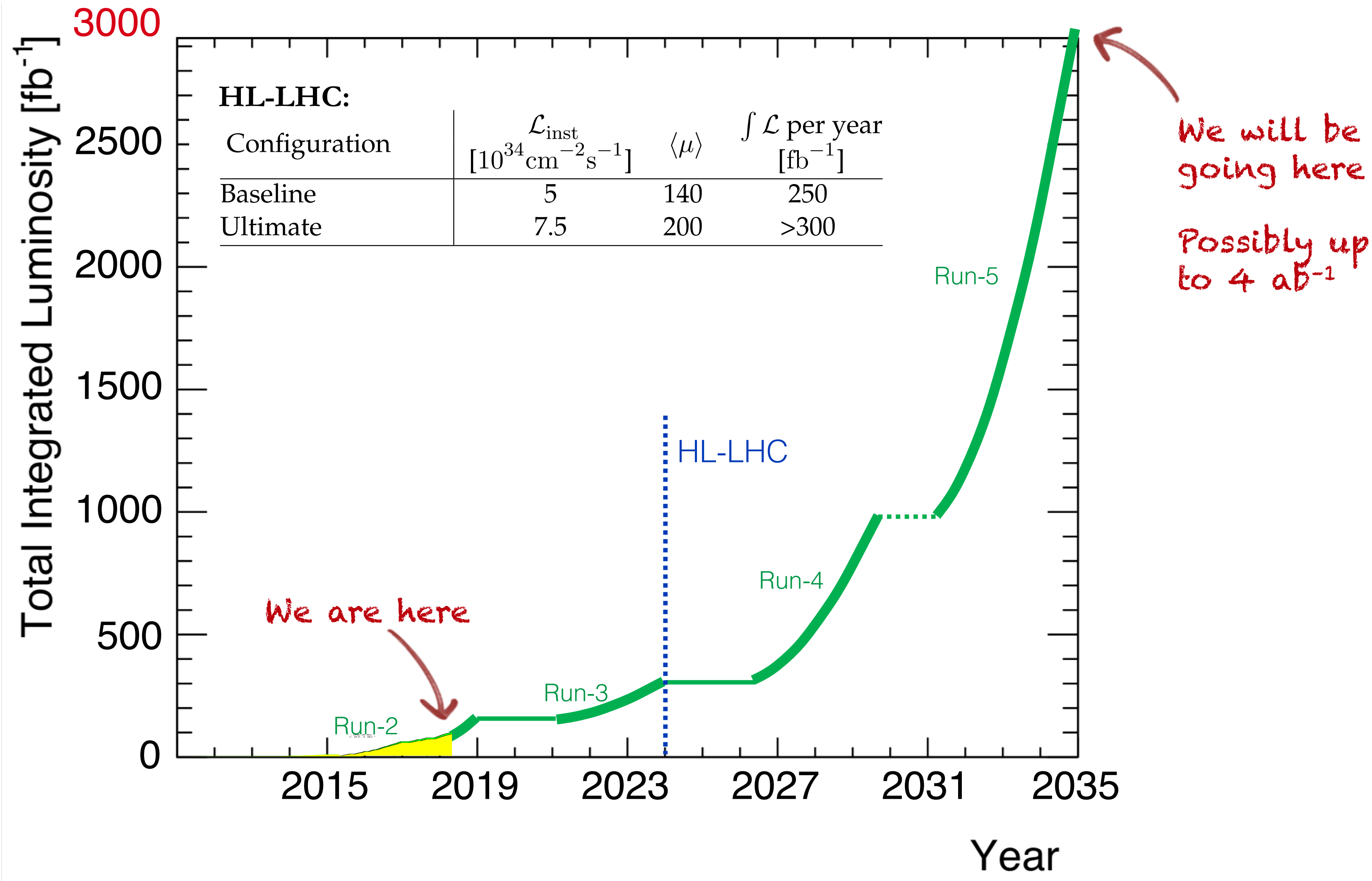
Phase-II:
The High-Luminosity LHC



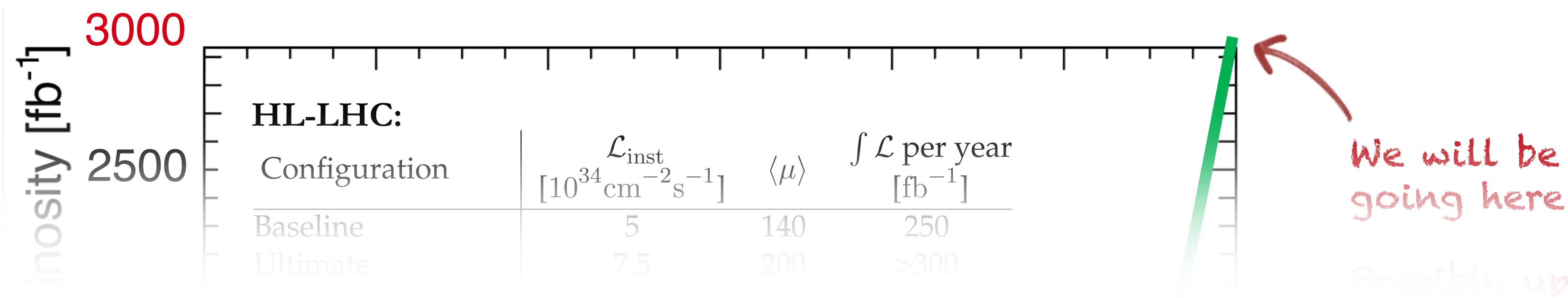
LHC / HL-LHC Plan



Expected integrated luminosity of LHC & HL-LHC

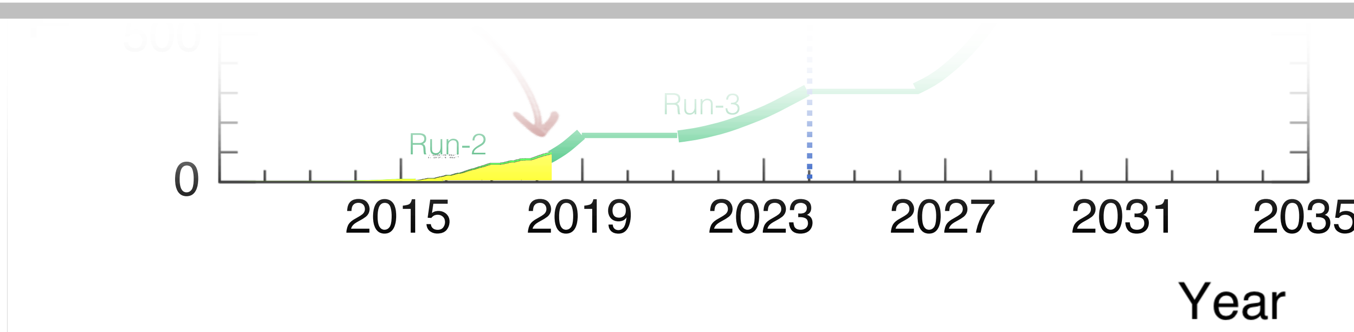


Configuration	$\mathcal{L}_{inst}$ [10^{34}cm^{-2}s^{-1}]	$\langle\mu\rangle$	$\int\mathcal{L}$ per year [fb^{-1}]
Baseline	5	140	250
Ultimate	7.5	200	>300

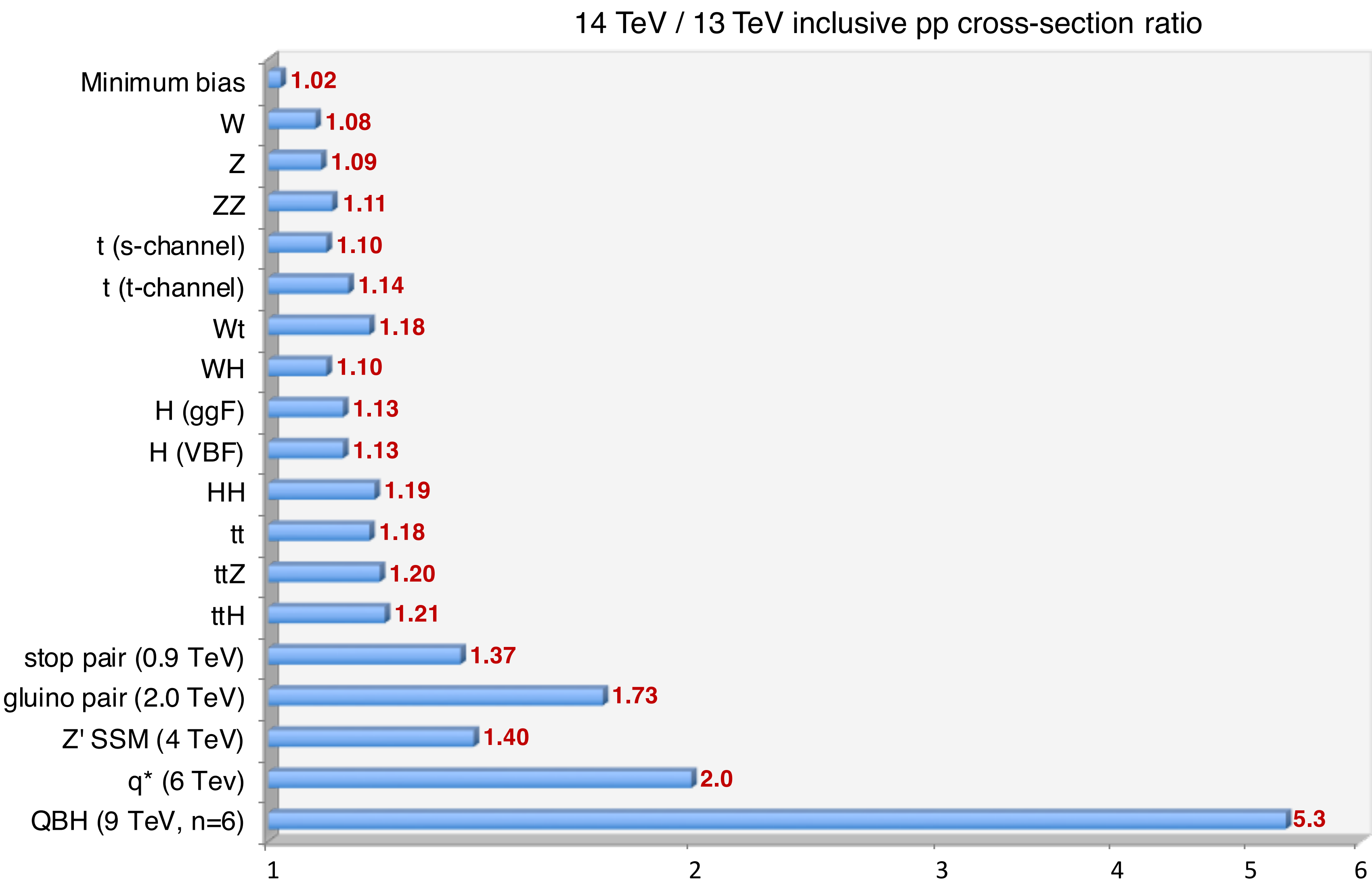


HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4 ab^{-1}) than that expected for full Run-2 (~150 fb^{-1} at 13 TeV)

With 3 ab^{-1}: 190 million H and 120 thousand HH (ggF) produced (SM)



14 TeV proton–proton centre-of-mass energy

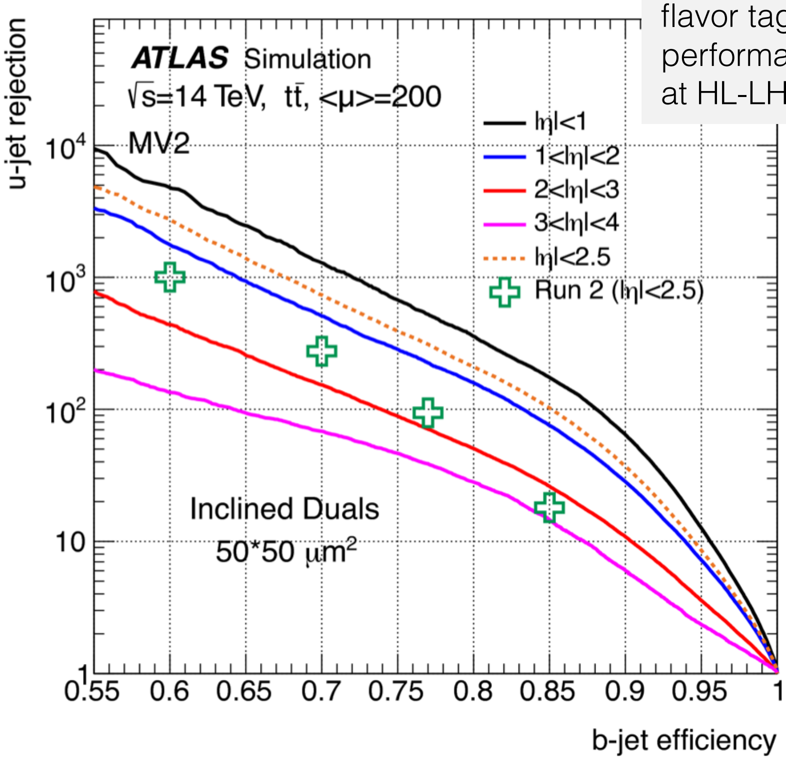


ATLAS & CMS Detector performance

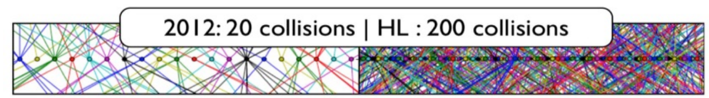
The performance of trigger and physics object reconstruction degrades with pileup

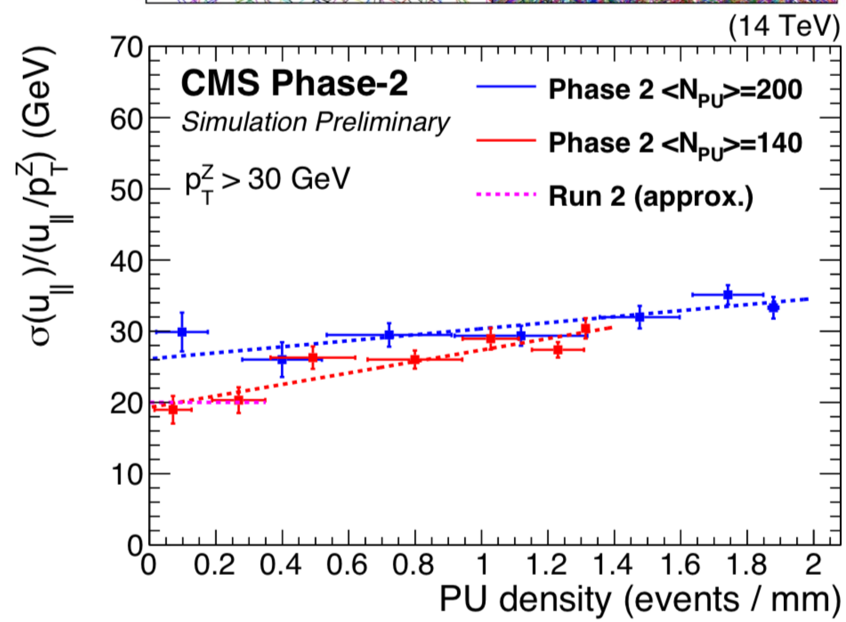
Upgrades of HL-LHC (Phase-II) detectors designed to recover Phase-0 performance under high pileup

- Improved trigger (L1 tracking, μ, e/γ, (b-)jets, E_T^{miss}), latency and bandwidth (~10 kHz output rate)
- Improved pileup rejection (extended tracking acceptance, better z-vertex resolution, timing detectors)
- Improved radiation hardness



Expected flavor tagging performance at HL-LHC





Parallel p-flow MET resolution vs. pileup density in Z → μμ events using PUPPI pileup mitigation

Higgs physics programme at the HL-LHC in a nutshell

Higgs properties:

- mass (well known), width (through interference measurements)
- spin (0^+ established), CP (odd admixture possible) — not discussed today

Rare Higgs decays:

- Observation of $H \to \mu\mu$, $H \to Z\gamma$, HH production (constraint on Higgs self coupling)
- Search for very rare (eg, $H \to M\gamma$, $M=J/\psi$, ϕ, ρ), difficult ($H \to cc$) or anomalous decays (invisible or new particles, or flavour violating)

Higgs couplings:

- Study of Higgs production and anomalous couplings by differential cross-section measurements
- Global and partially global coupling fits: experiments moving from “kappa” interpretation to EFT

New physics in Higgs production or other scalar states

- Search for anomalous FCNC through top decays, Higgs production via SUSY cascades, etc.
- Search for additional scalar particles

Methodology of HL-LHC studies

- The experiments use full or parameterised fast simulation tuned to full simulation of upgraded detectors, together with overlaid pileup and simplified analyses to explore HL-LHC reach

- Alternatively, current full analyses are extrapolated to HL-LHC energy and conditions

– In both cases bold assumptions on evolution of theoretical uncertainties made

– Both methods suffer from caveats. Many studies are pessimistic

– Most of the studies shown here will be updated for the HL-LHC Yellow report; next preparatory meeting: 18–20 June: https://indico.cern.ch/event/686494

– All studies shown here for 3 ab^{-1} and assuming 200 or 140 pileup events on average per bunch crossing

Coupling to 2nd generation: Higgs decay to H → μμ (BR: 0.022% in SM)

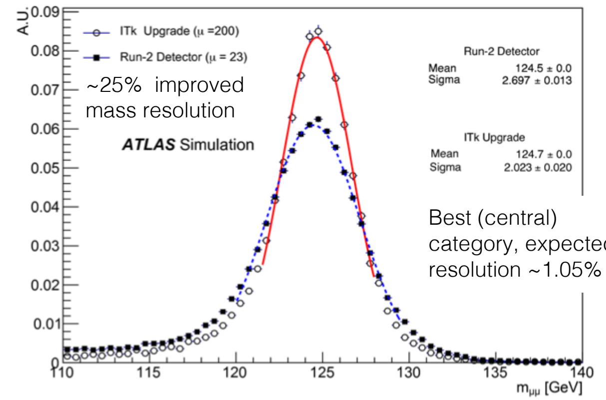
Upgraded detectors feature improved di-muon mass resolution

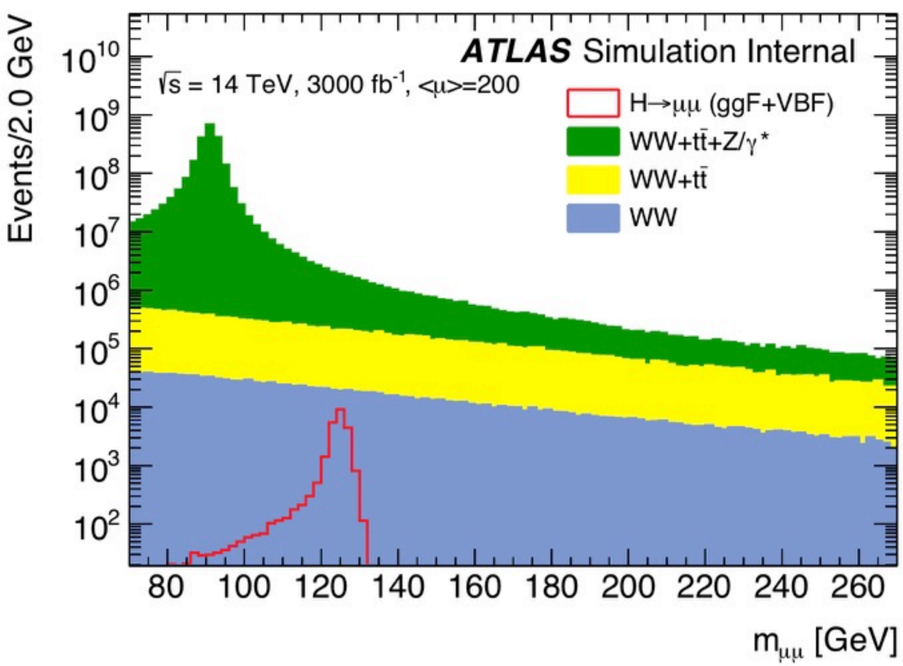
If SM branching fraction, H → μμ could be observed in Run-3 (ATLAS & CMS combined)

Cross-section times branching fraction measurement to ~13% (ATLAS), 10% (CMS) precision for 3 ab^{-1}

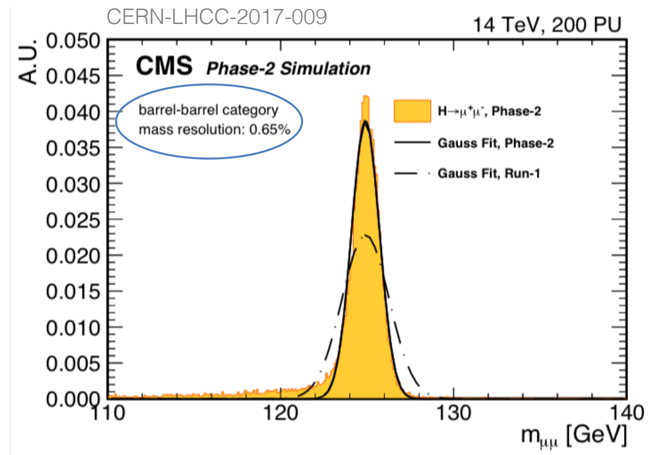
Challenging data-driven Drell-Yan background determination

ATLAS ITk Strip TDR: CERN-LHCC-2017-005





CMS Tracker TDR: CERN-LHCC-2017-009



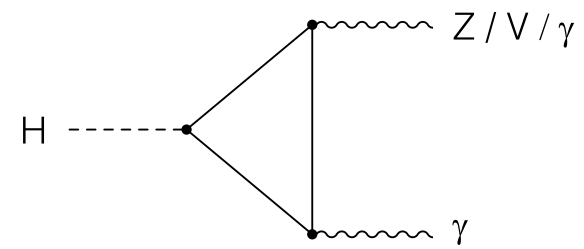
Rare loop decay to $H \to Z\gamma$ (BR: 0.15% in SM, 0.010% with $Z \to ee, \mu\mu$)

Large background from Z production with radiative photons

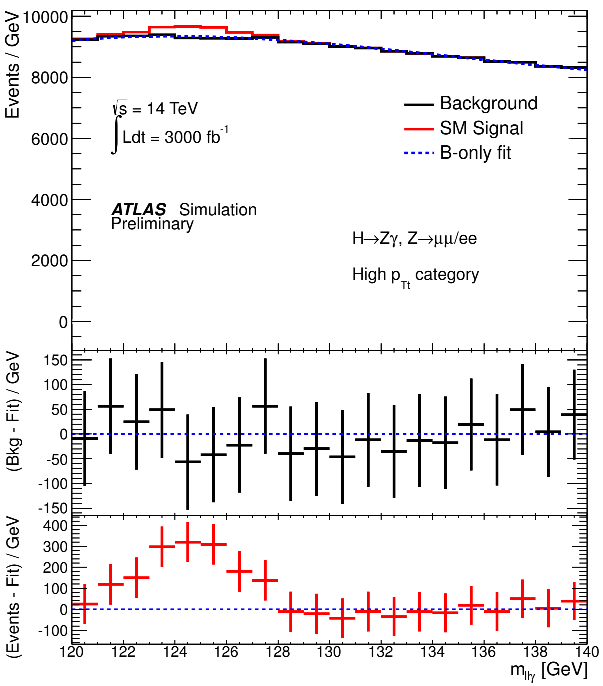
Observation with combined ATLAS & CMS dataset expected with 3 ab^{-1}

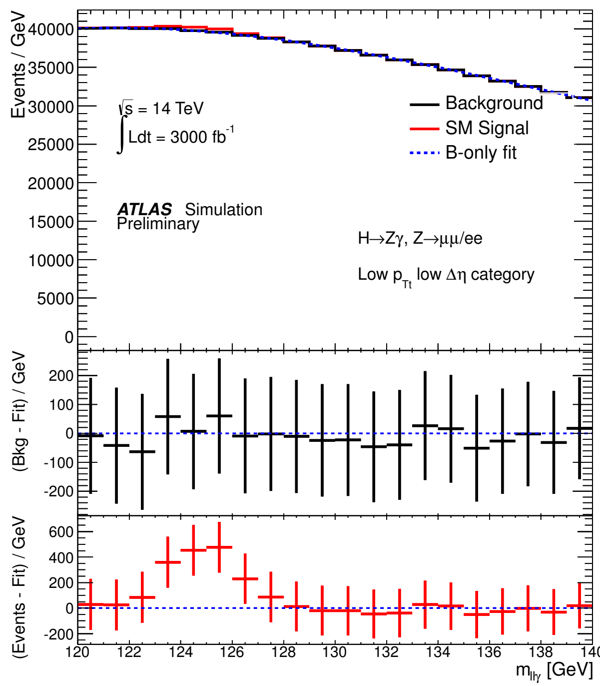
Combined statistical precision of about 15% on cross-section

Challenging data-driven background determination



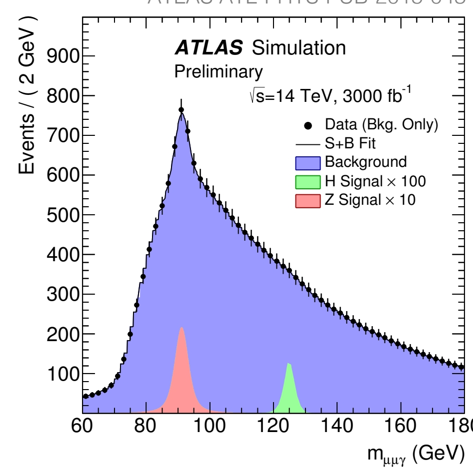
ATLAS ATL-PHYS-PUB-2014-006





Also searches for, eg, $H \to J/\psi\ \gamma$ with expected sensitivity of 15 times SM prediction (BR: 2.9 10^{-6})

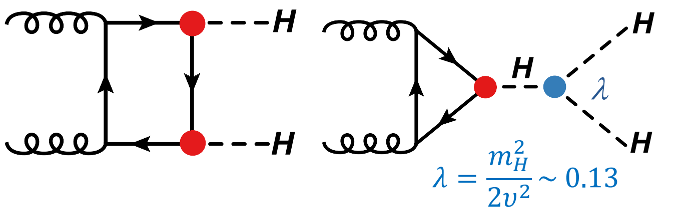
ATLAS ATL-PHYS-PUB-2015-043



Di-Higgs production

HH cross section predicted to 40 ± 2 fb at 14 TeV,
ie, >1000 times smaller than for single Higgs production

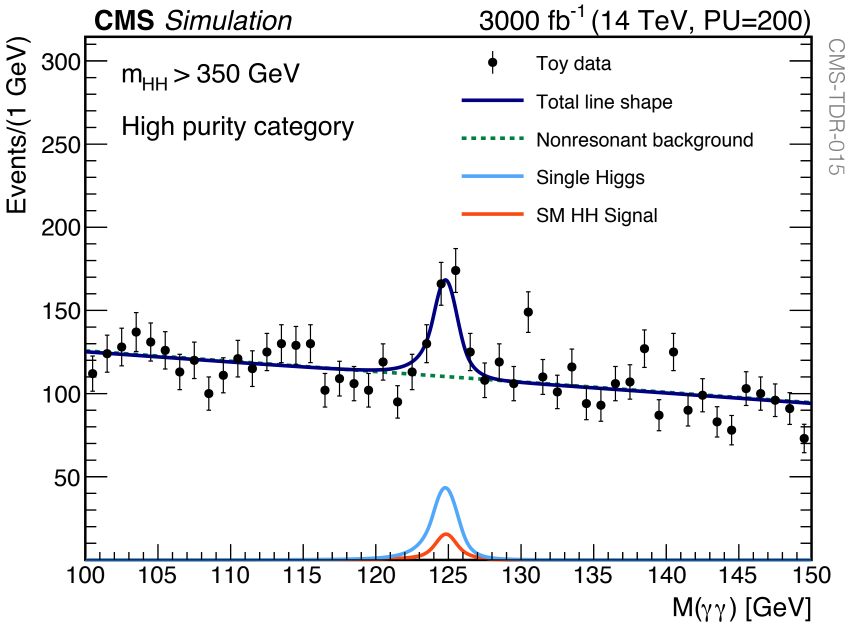
Sophisticated analyses needed, room for innovation;
Extrapolation uncertainty in continuum background prediction

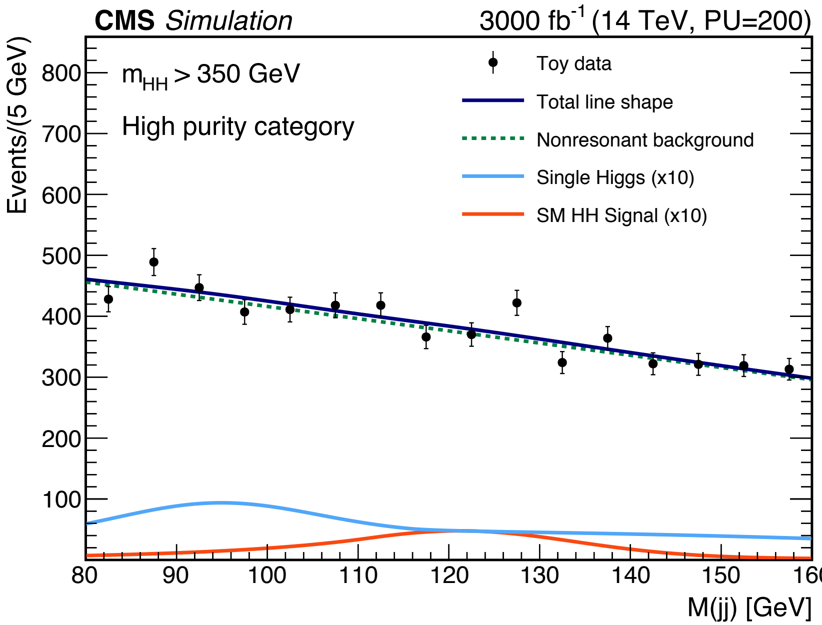


Best channels: $bb\gamma\gamma$ (BR = 0.26%), $bb\tau\tau$ (7.3%), bbbb (33%), bbWW, 25% → combination

Currently (36 fb^{-1} at 13 TeV) for $bb\gamma\gamma$: $\mu_{HH} < 19$ (17_{exp}) [CMS, using LO signal simulation, some effect on acceptance]

Projection to HL-LHC ($bb\gamma\gamma$, 2017): ~1.5σ significance, CMS combines w/ $bb\tau\tau$ in HL-LHC TP (2015): 1.9σ





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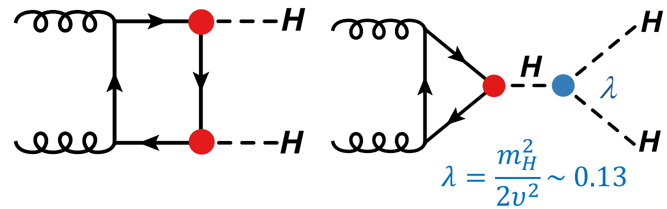
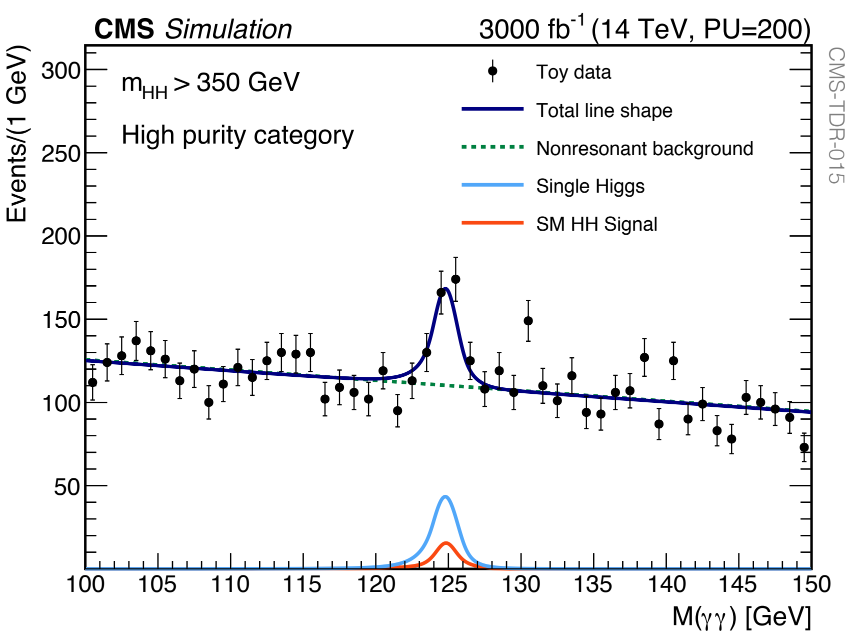


Sophisticated analyses needed, room for innovation;
Extrapolation uncertainty in continuum background prediction

Best channels: bbγγ (BR = 0.26%), bbττ (7.3%), bbbb (33%), bbWW, 25% → combination

Currently (36 fb^{-1} at 13 TeV) for bbγγ: $\mu_{HH} < 19$ (17_{exp}) [CMS, using LO signal simulation, some effect on acceptance]

Projection to HL-LHC (bbγγ, 2017): ~1.5σ significance, CMS combines w/ bbττ in HL-LHC TP (2015): 1.9σ



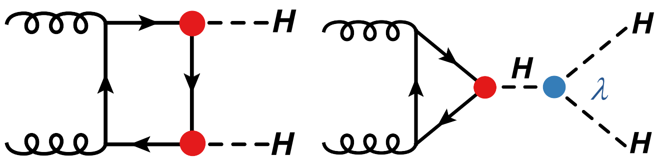
It is not yet established which of the three main channels will be best

The bbbb channel strongly depends on the lowest jet p_T trigger threshold and on top background modelling

Combining ATLAS & CMS in all channels, hoping for analysis improvements, and including new channels may give 3σ HH sensitivity with 3 ab^{-1}

Constraints on Higgs trilinear self coupling λ_{HHH}

Constraint on λ_{HHH} by simulating NLO MC HH samples for different λ_{HHH} values. Effects on total HH cross section and acceptance

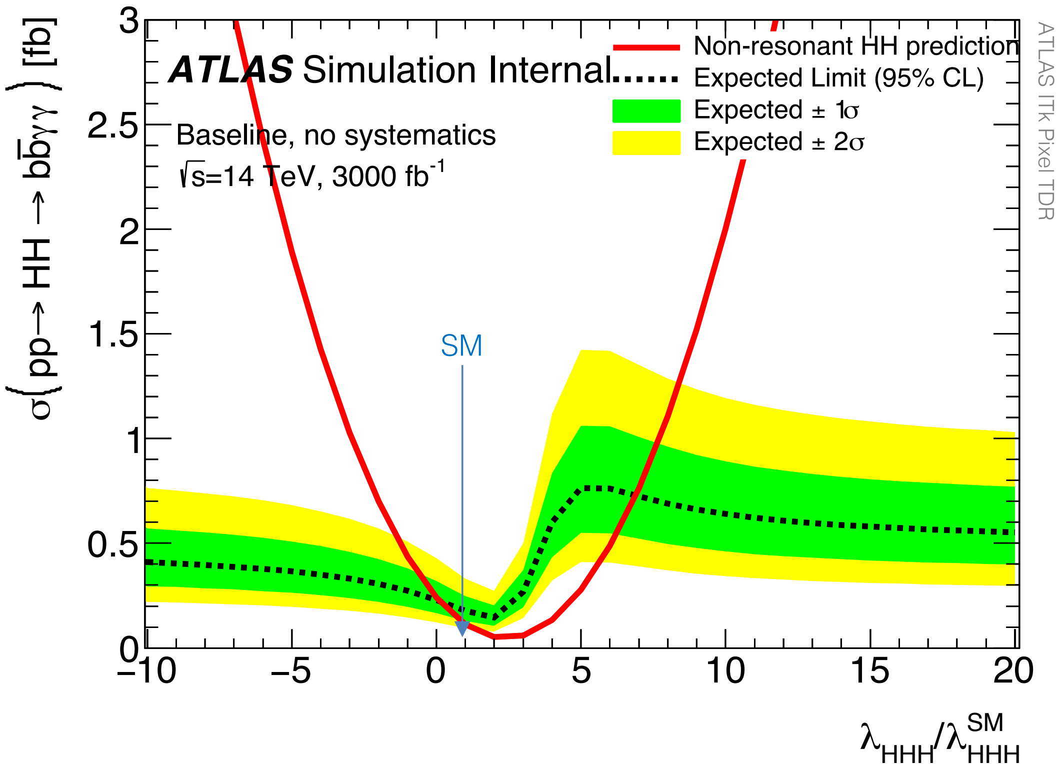


LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

Sensitivity to H self coupling rises at low m_{HH}

Projection to HL-LHC (bbγγ, 2017)



95% CL limit: $0.2 < \lambda / \lambda_{SM} < 6.9$ (bbγγ)

These analyses use only inclusive rates. Fitting differential variables such as m_{HH}, $p_{T,H}$ close to threshold should allow to improve the constraint on λ (but hard for bbbb channel, so : bbγγ and bbττ best for λ)

[See, eg, 1607.07441]

λ_{HHH} also affects single-H production at NLO through internal H loops
→ Complementary information from differential H cross-section measurements

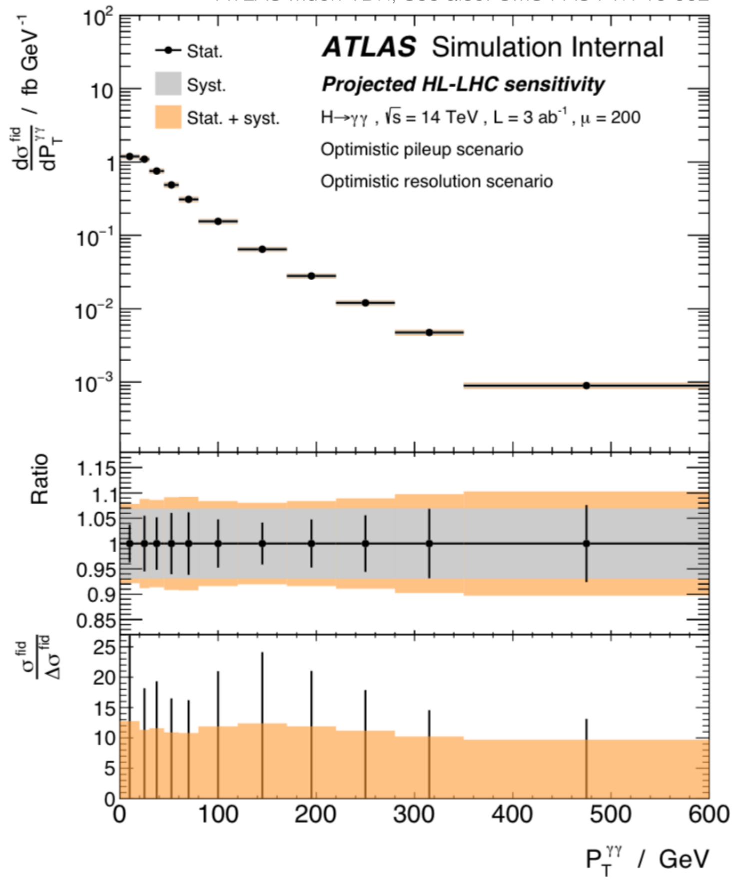
Higgs production: differential cross-section measurements

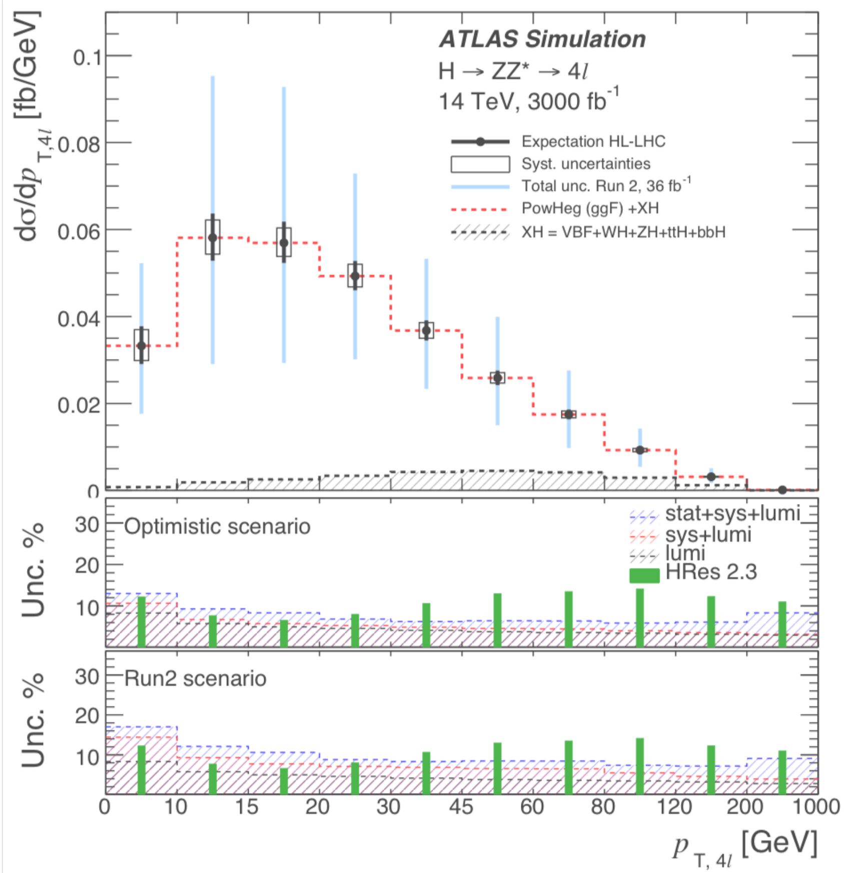
The H $\to \gamma\gamma$, 4ℓ channels will dominate most precise differential cross-section measurements at the HL-LHC

Inclusive spectra with 5% statistical uncertainty up to 400 GeV

Sensitive to Higgs to b/c coupling and QCD at low p_T, and to top coupling and BSM at high p_T

ATLAS-Muon-TDR; See also: CMS-PAS-FTR-16-002

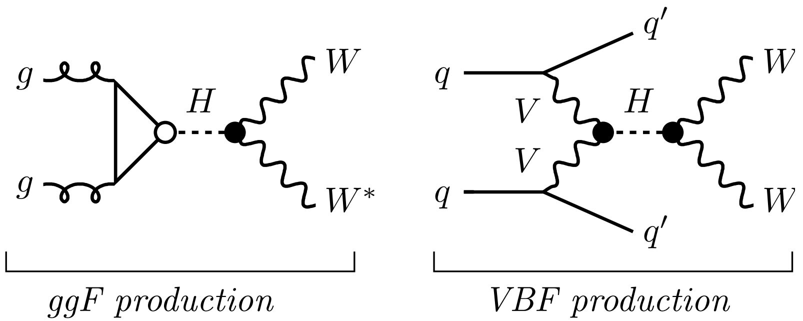




VBF coupling measurements

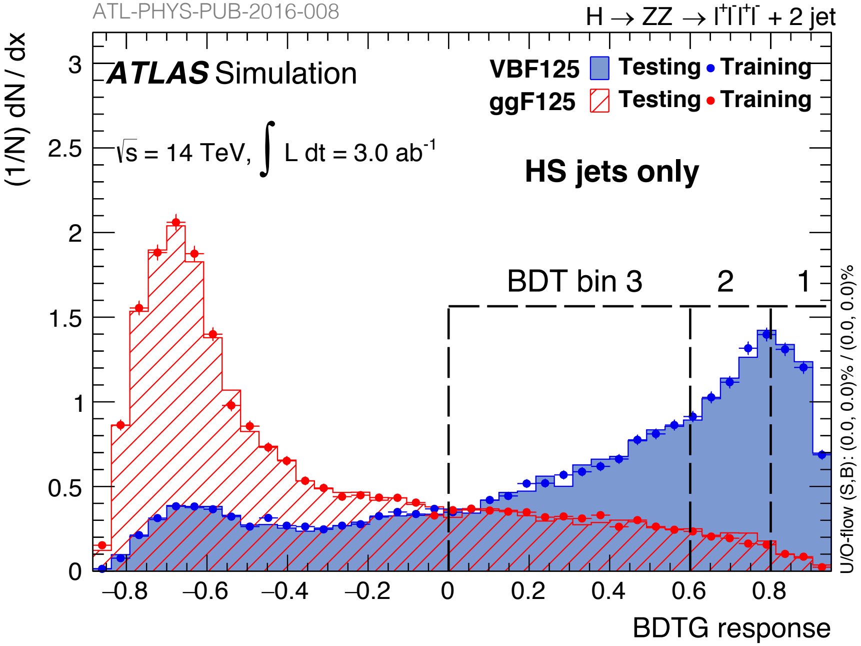
A study with H → WW* → eνμν projects a measurement of VBF signal strength to ~14% precision with 3 ab^{-1}

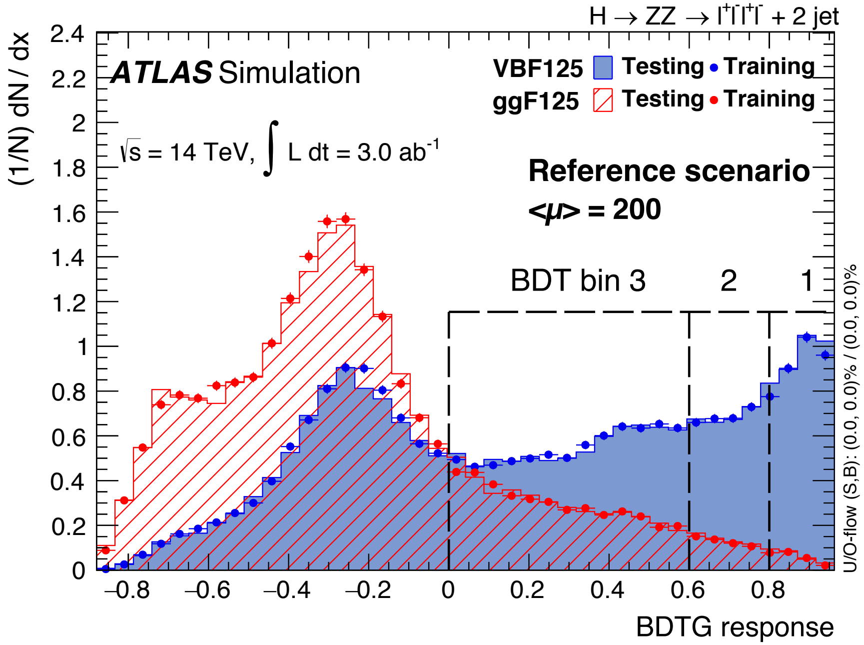
ATL-PHYS-PUB-2016-018



H → γγ, 4ℓ achieve similar VBF precision. A study using 4ℓ resulted in ~15% precision on signal strength using a BDT to separate VBF from ggF

ATL-PHYS-PUB-2016-008

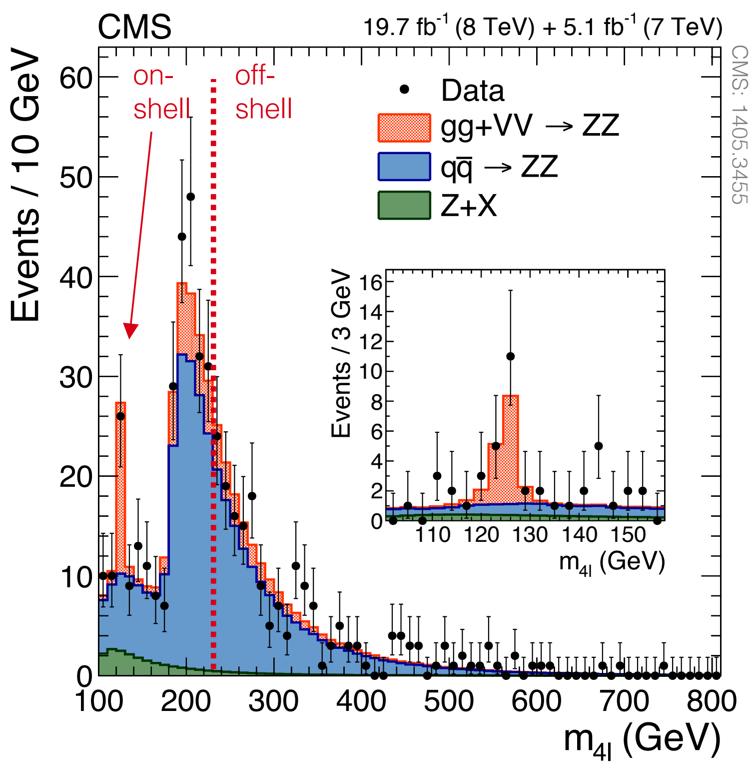




Off-shell coupling measurement

Both CMS and ATLAS have constrained the Higgs off-shell coupling and through this obtained upper limits on the Higgs total width Γ_H. Current limit Γ_H < 22 MeV at 95% CL ($\Gamma_{H,SM}$ = 4.1 MeV).

The method uses the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings. One can then determine Γ_H from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

With L_2 = 3000 fb^{-1}, one may find:

$$\mu^{(L2)}_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}\ \text{(stat+sys)}$$

$$\Rightarrow \quad \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}$$

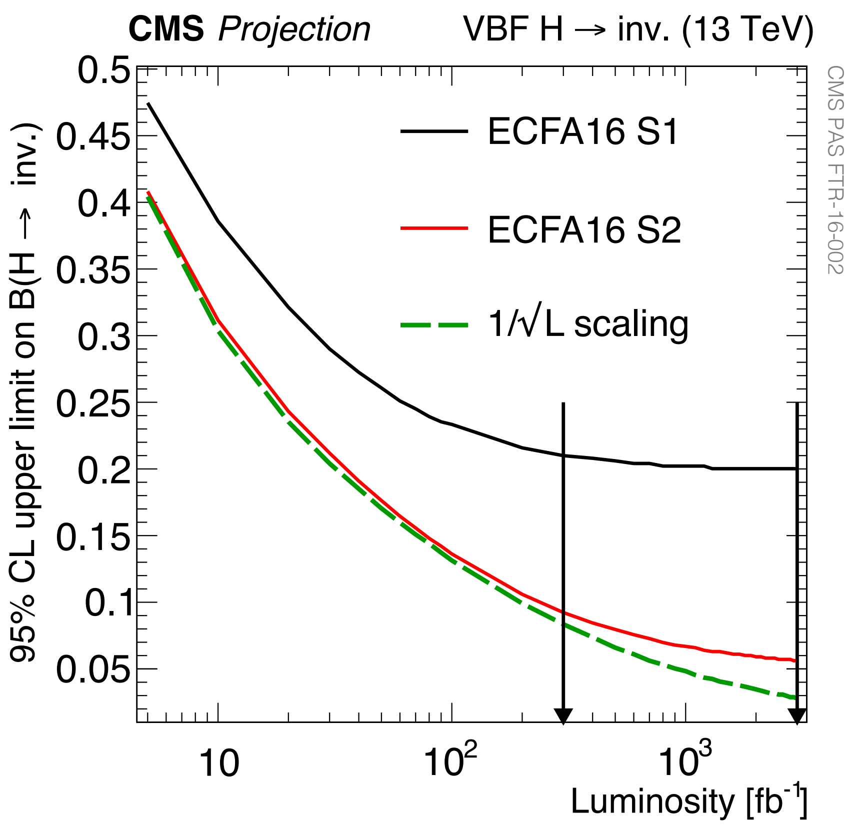
ATLAS: ATL-PHYS-PUB-2015-024

Large theory uncertainty (~30%) from gg → ZZ

Higgs → invisible constraints

If dark matter (DM) is a thermal relic of the early universe and it is light enough so the Higgs can decay to it, it leads to invisible Higgs decays

Such decays can be detected through Higgs VBF, ZH or ISR-jet production, or in a model-dependent way through the coupling fit (eg, assuming SM couplings to SM particles)



Best limit of ~3% on H → invisible branching fraction at 3 ab^{-1} (reminder: current limit: 24%)

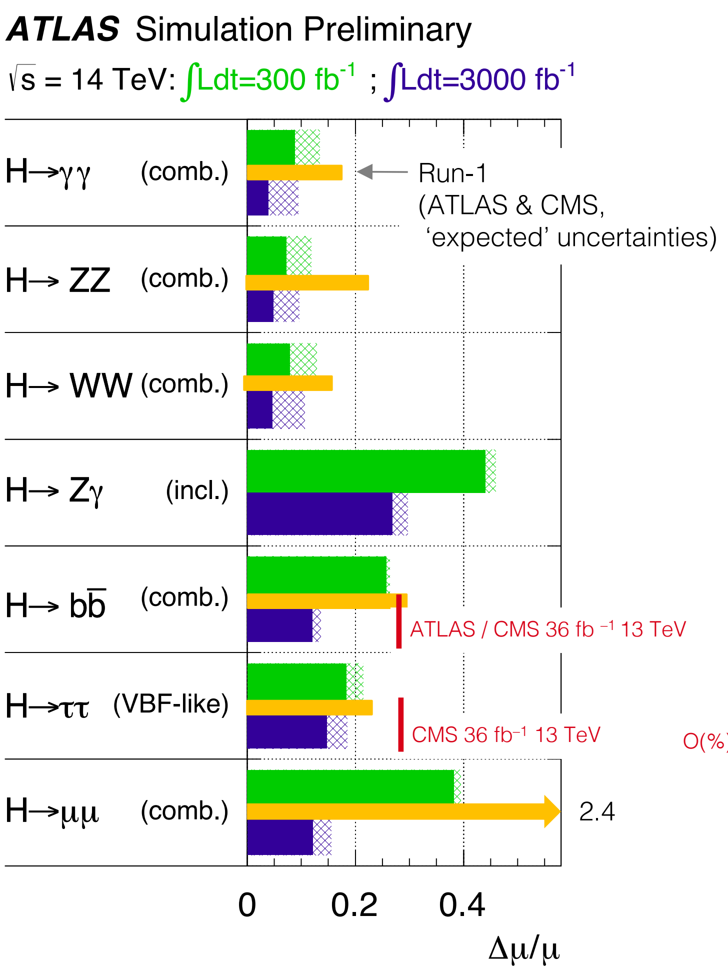
However, systematics limited so difficult extrapolation

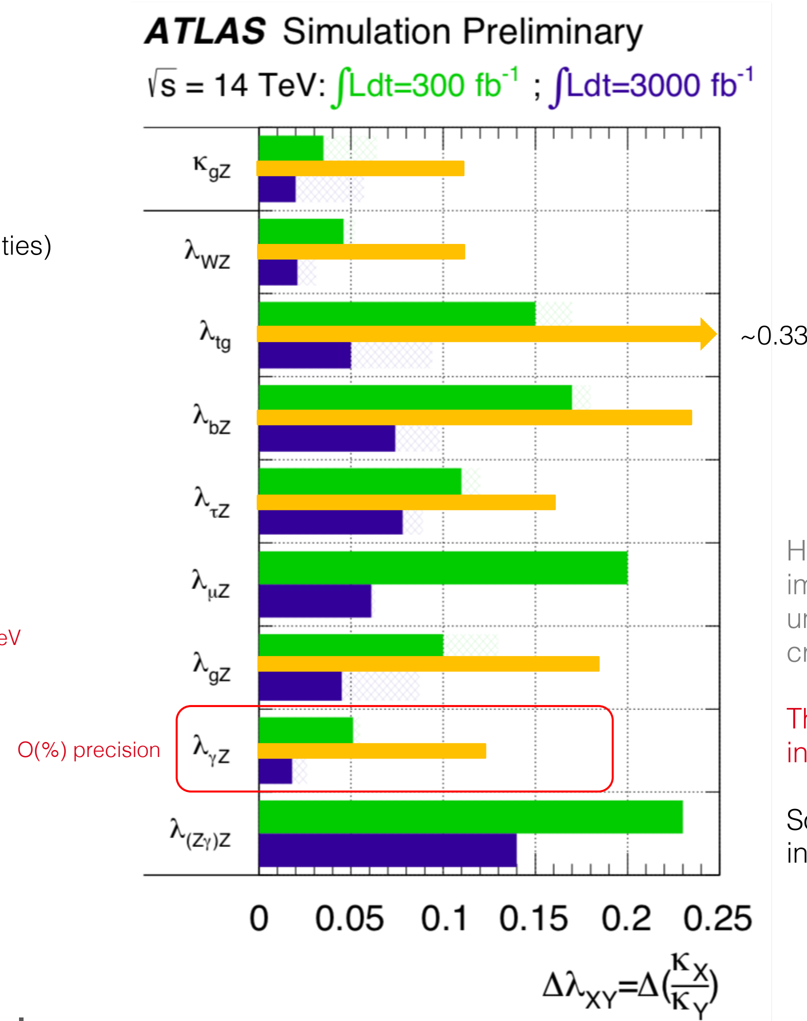
An extrapolation of the combined coupling fit under SM hypothesis gives H → invisible limits of 9% (13% when including theory uncertainties)

ATL-PHYS-PUB-2014-017

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange)

Conservative extrapolation: does not include improved detector design, large theoretical uncertainties, simplified analyses





$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Hatched areas indicate impact of theoretical uncertainties on expected cross-sections

Theory uncertainty limiting in several cases

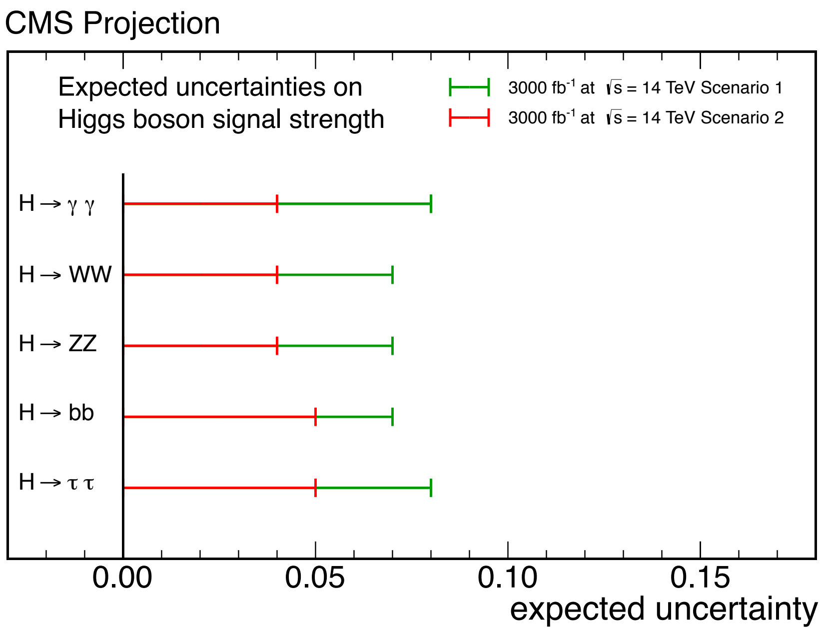
Some uncertainties cancel in ratios

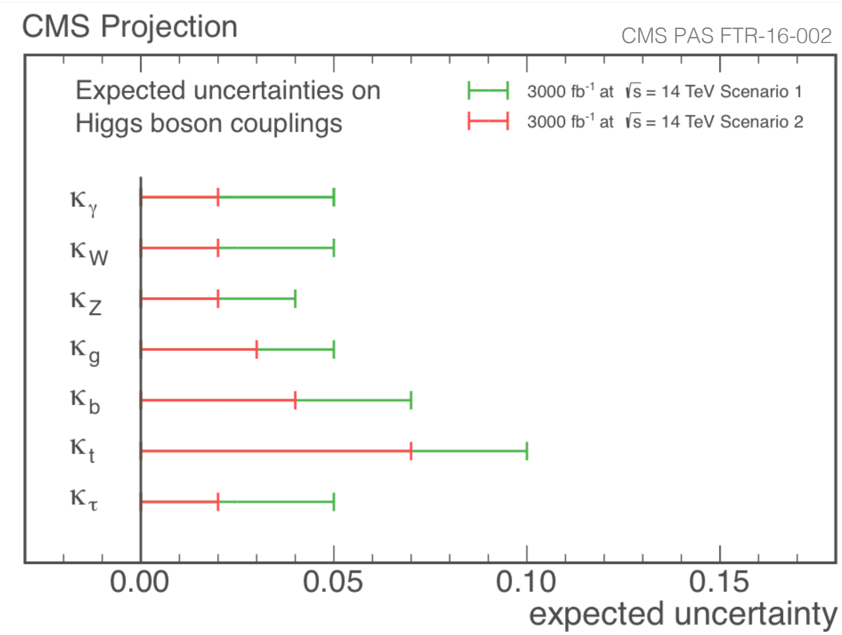
4–5% for main channels, 10~20% on rare modes

Higgs couplings — CMS (Status 2013 + 2016 updates)

Signal strength and coupling modifier uncertainties for two scenarios: (1) as today, (2) systs: exp/$\sqrt{L}$, theo/2

Detector and pileup effects for HL-LHC not included, no lower bound on systematic uncertainty
More complete updated study (ECFA 2016) for H → γγ, ZZ* finds slightly larger uncertainties for Scenario 2





Signal strength (%) measurements for Scenarios [1,2]:

Snowmass-13

L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

ECFA-16:

	$\gamma\gamma$	ZZ
μ	[4, 10]	[5, 8]
μ(ttH)	[11, 17]	[31, 32]
μ(VBF)	[13, 29]	[16, 17]

Private outlook for 3 ab^{-1} combined ATLAS & CMS targets

Results cooked up by me from public material (mainly: ECFA PUB notes and Phase-II TDRs)

To be taken with the grain of salt. This will be replaced by serious Yellow Book studies

Projected uncertainties (in %) on signal strengths for ATLAS & CMS combined with 3 ab^{-1} each, neglecting theory uncertainties on $\sigma \cdot$BR denominator and choosing optimistic systematic scenarios

Channel	Inclusive	VBF	VH	ttH	References	
$\gamma\gamma$	3	10	12	8	ATL-PHYS-PUB-2014-016 CMS PAS FTR-16-002	
ZZ*	3	12	15	18	ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008 CMS PAS FTR-16-002	Considering 4ℓ channel only
WW*	5	11	–	15 ?	ATL-PHYS-PUB-2016-018	Fully systematics limited
$\tau\tau$	–	10	–		ATL-PHYS-PUB-2014-018 CMS: 1307.7135	Fully systematics limited
$\mu\mu$	8	–	–	18	CERN-LHCC-2017-005 CERN-LHCC-2017-009	
bb	–	?	10 ?	?	ATL-PHYS-PUB-2014-016 CMS: 1307.7135	Fully systematics limited
$Z\gamma$	15	–	–	–	ATL-PHYS-PUB-2014-006	

LHCb adds sensitivity to $H \to cc$ of ~5 · BR(SM) with 300 fb^{-1}

LHCb-CONF-2016-006

ATLAS study indicates $\mu <$ ~6 at 95% CL (in preparation)

Interesting cross-section ratio (or analysis control region) with ttZ

'?' means hard to estimate due to strong systematics dependence

Uncertainties on coupling modifiers ~2 times lower

Some conclusions

We live in **data-driven times**, experiment must guide us to the next stage. That means we need a **broad and diverse research programme. Higgs physics is key in that programme**.

The HL-LHC will make a strong impact on Higgs property measurements. It has sensitivity to discover rare Higgs decays to $\mu\mu$ and $Z\gamma$, and to study couplings to bosons and third generation fermions to a few percent precision.

Strong constraints on invisible decays can be obtained.

Di-Higgs production can likely be seen, but a significant measurement of Higgs self-coupling seems beyond reach. However, important constraints can be obtained.

Higgs measurements in conjunction with other SM sectors such as diboson and top will allow to obtain coherent information in the framework of EFT or model extensions of the SM.

Precision measurements in the SM sector will contribute to these constraints.

Extra slides