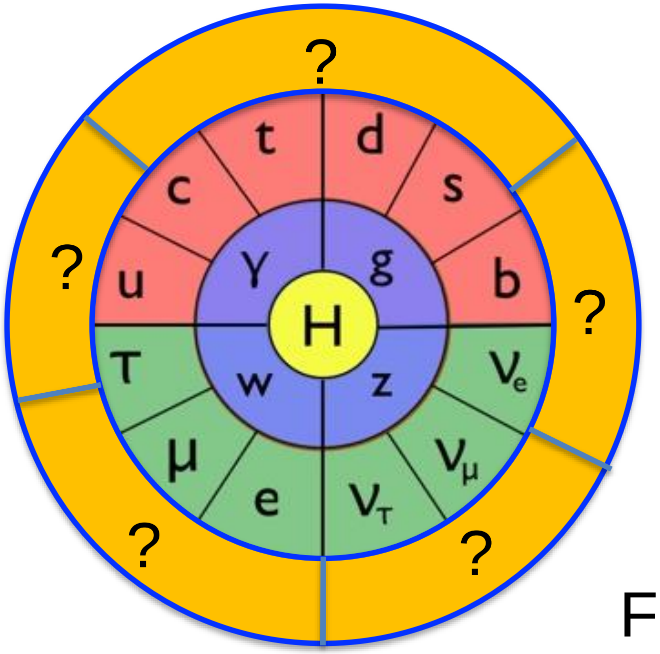
Probing New Physics and the Nature of the Higgs boson at ATLAS



ATLAS EXPERIMENT

Lailin Xu

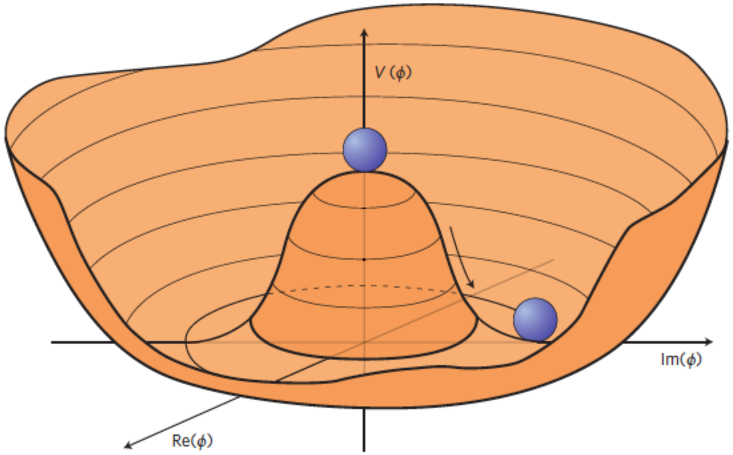
Brookhaven National Laboratory

Fermilab Topic of the Week Seminar, Mar 5, 2019

Outline

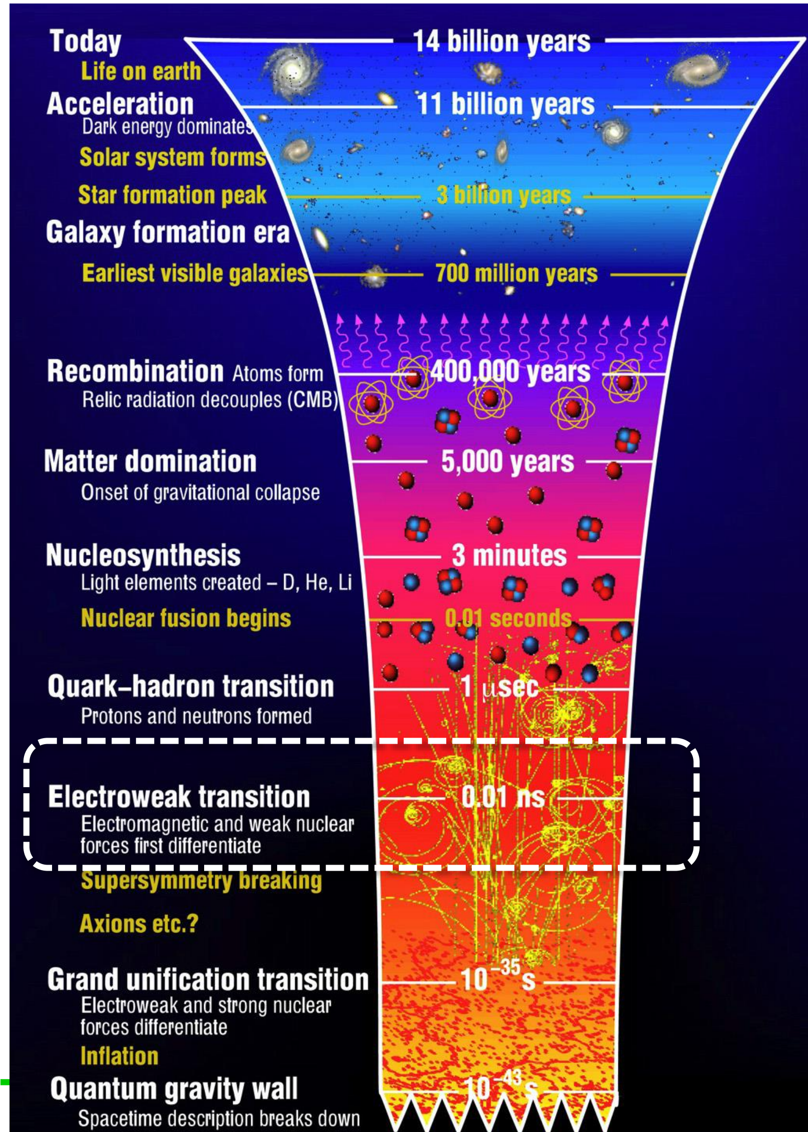
- Introduction
- Overview of Higgs measurements
- Higgs couplings measurements and New Physics constraints
  - Couplings to different particles
  - Couplings at different scales
  - Self coupling
- Prospects of Higgs physics at future colliders
- Summary

Why Higgs boson matters?



The Big-Bang

- Almost all particles massless at the early Universe



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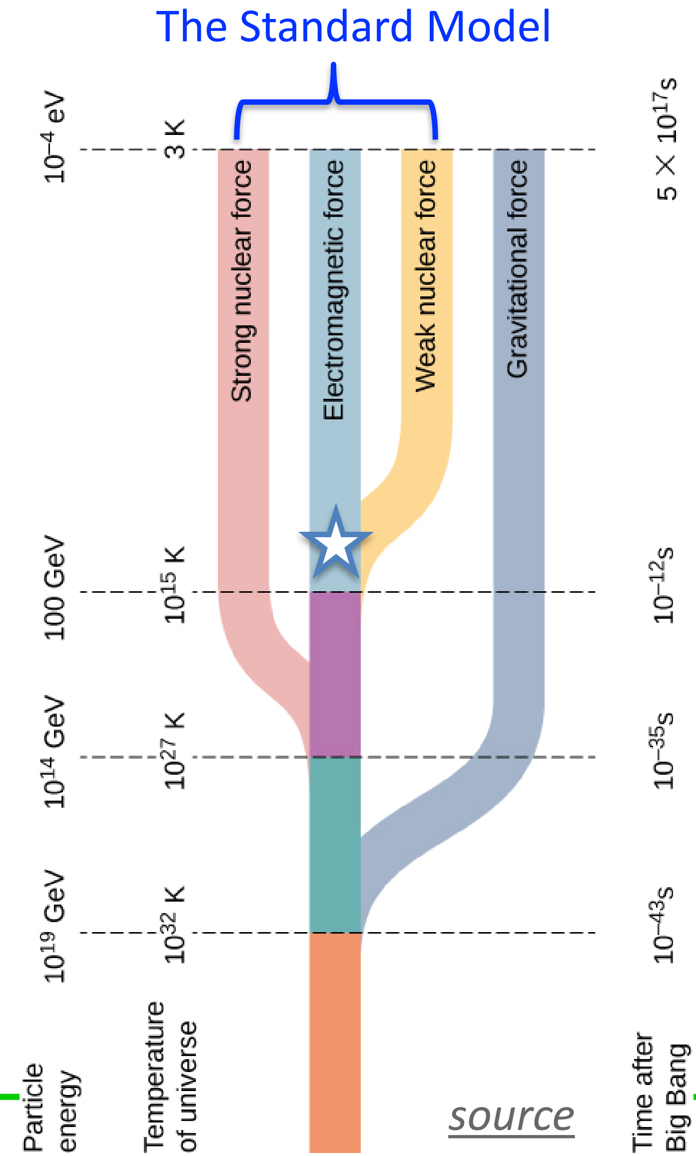

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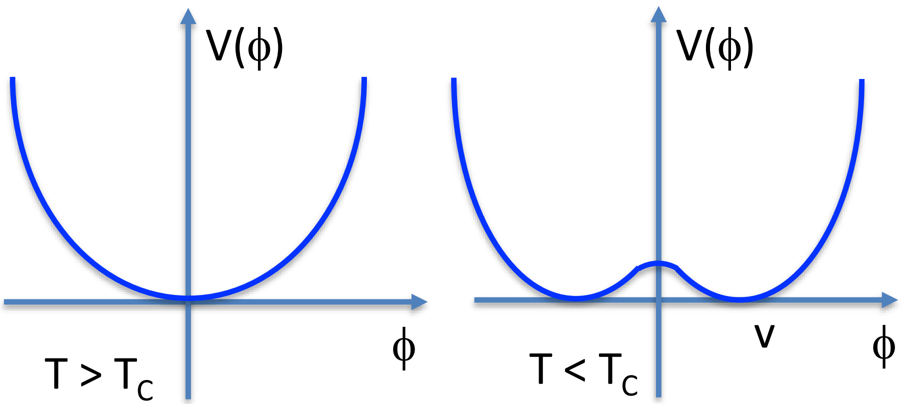
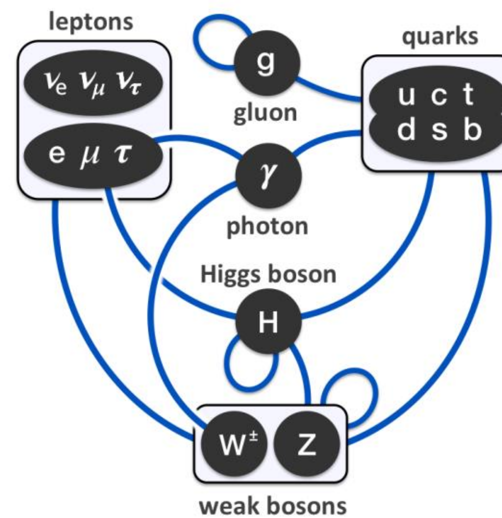
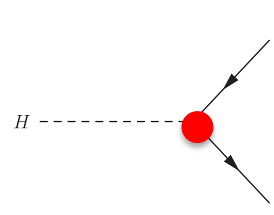
The Higgs mechanism

- Massive elementary particles acquired masses during the electroweak phase transition → electroweak symmetry breaking
- The Higgs potential

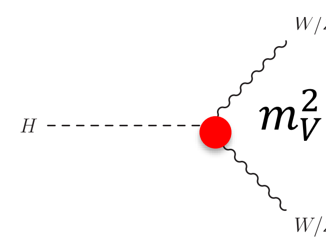
$$\boldsymbol{V}(\phi,T) \approx -\frac{m^2 - \frac{\lambda T^2}{24}}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$







$$m_f = \frac{y_f v}{\sqrt{2}}$$

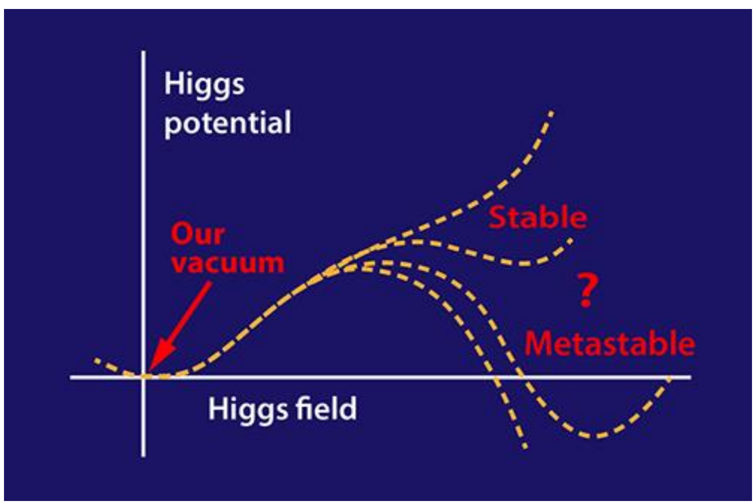


$$m_V^2 = \frac{g_V v}{2}$$

- The Higgs boson
  - Gives masses to both fermions and gauge bosons
  - Higgs mass at tree level: $m_h = \sqrt{2\lambda}v$, no theory prediction
- With Higgs mass known, SM predicts everything else!

Higgs frontier

- Higgs precision era since July 2012
  - Rapid development in both experiment and theory community
- Big questions on the Higgs sector in SM
  - Are all the production mechanisms as expected?
  - Is the Higgs boson solely responsible for EWSB?
  - How electroweak phase transition (EWPT) happened?
  - Higgs at high scale: fate of EW vacuum stability



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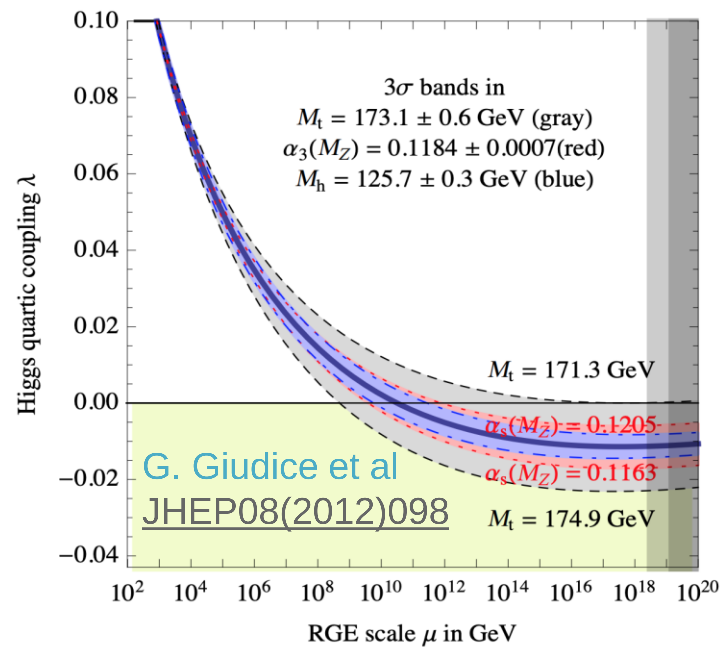
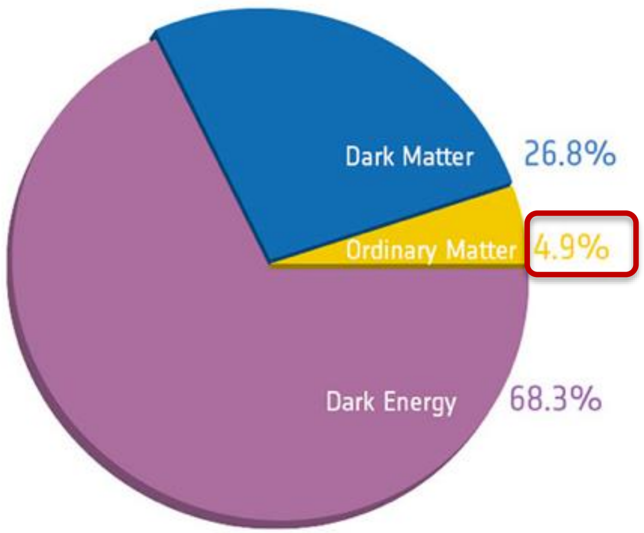
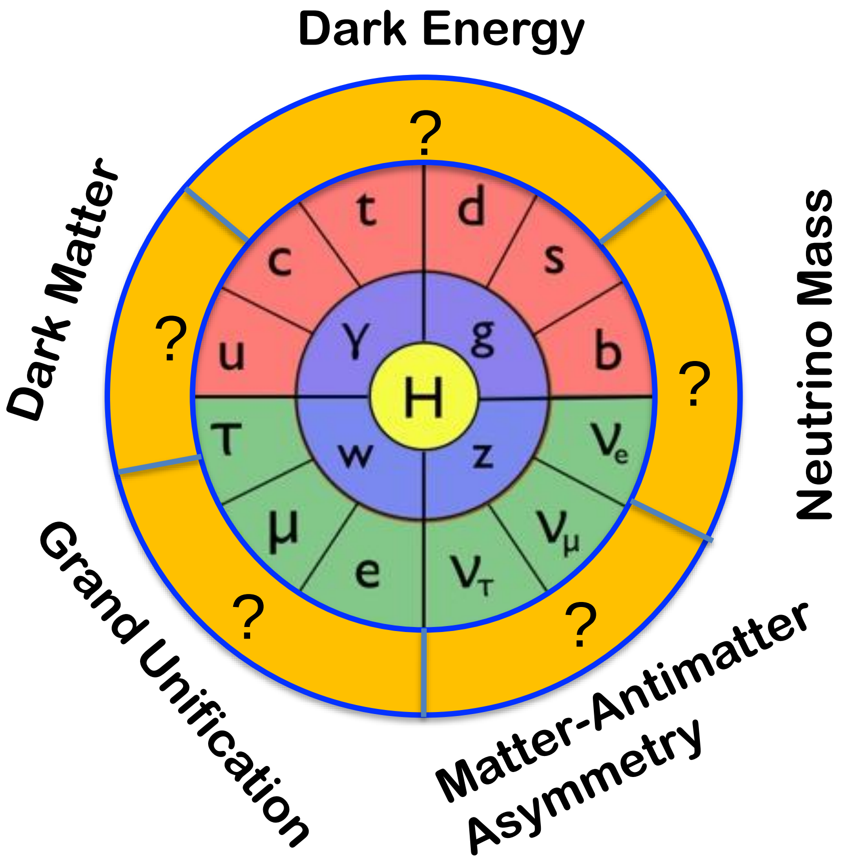


G. Giudice et al
JHEP08(2012)098

Not the whole story

- Many other open issues in Universe
  - Calling for physics beyond the SM





Higgs and BSM

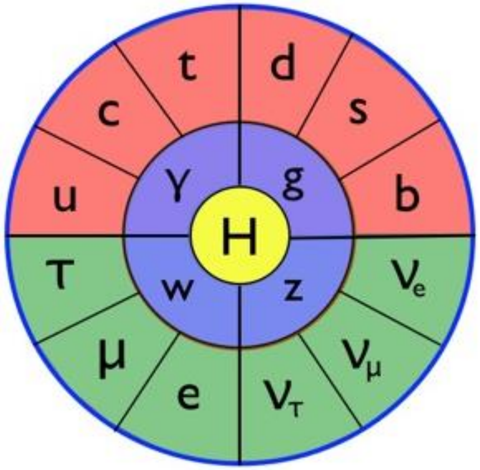
- Crisis?
  - No new physics at TeV found at the LHC yet
  - Absence of detection of dark matter
- "Absence of evidence is not evidence of absence" PDG(2018)
- Higgs physics: No-lose theorem?
  - Deep mysteries of EWSB remain unanswered
  - An invaluable portal to new physics

Measurements:
Mass, width, Spin, CP
Couplings
Differential cross sections

$$H^0$$

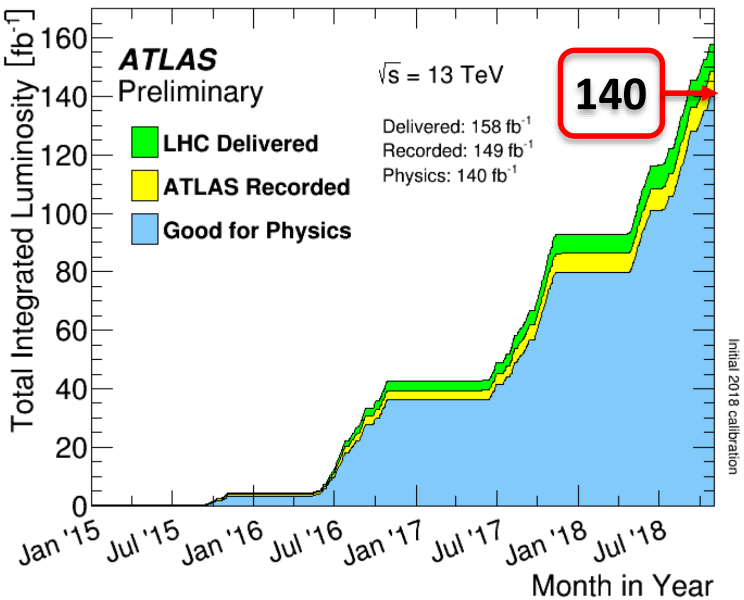
Tool for discovery
Portal to Dark Matter
Portal to Hidden Sectors
Exotic decays

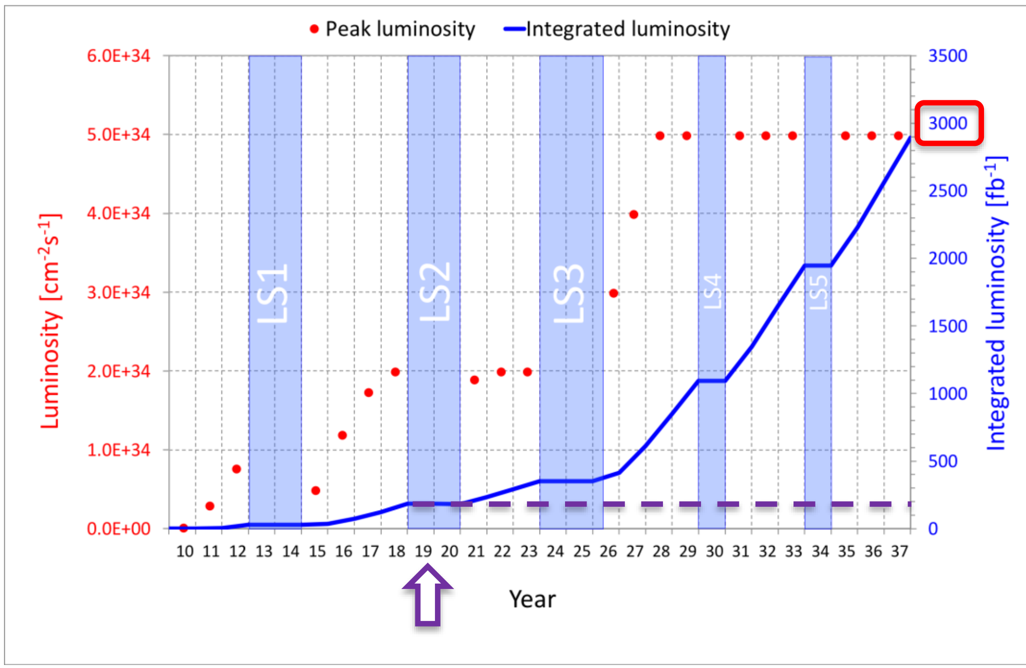
The Higgs Portrait: Overview of latest Higgs results at the LHC



LHC and ATLAS at Run 2

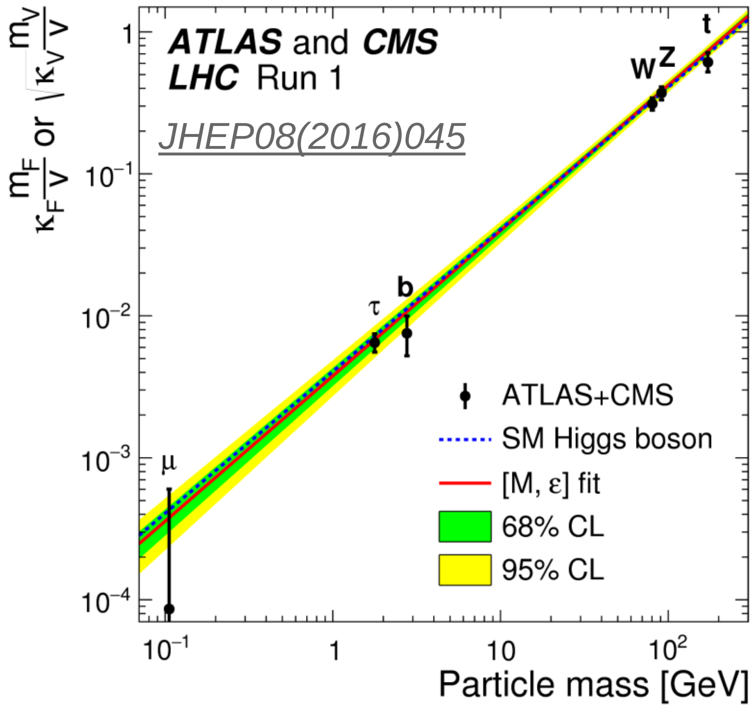
- 140 fb^{-1} pp collision @ 13 TeV collected in 2015-18
  - ~8M Higgs boson produced ($\sigma_{pp \to H}$ ~ 60 pb)
  - Available results: 36 ~ 80 fb^{-1}





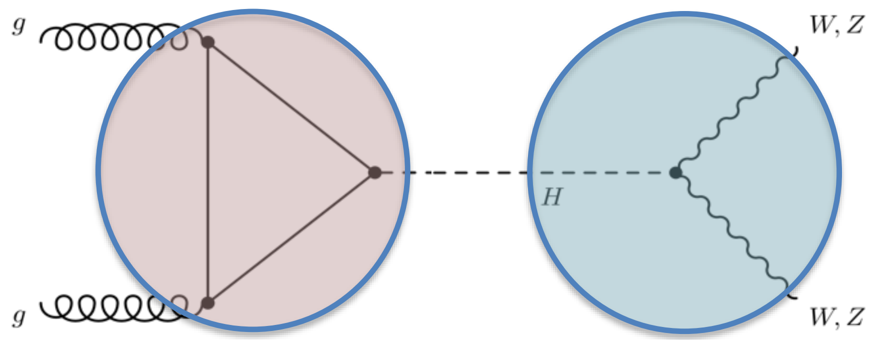
What we have learnt

- Mass: $M_H = 125.09 \pm 0.24$ GeV   ATLAS+CMS: PRL 114 (2015) 191803
- Spin/Parity: 0^+ ATLAS: EPJC 75 (2015) 476, CMS: PRD 92 (2015) 012004
- Width:
  - < 1 GeV (direct)   CMS: JHEP11(2017)047
  - < 14 MeV (indirect)   ATLAS: PLB786(2018)223, CMS:CMS-PAS-HIG-18-002
- Observed direct coupling to:
  - Vector bosons   ATLAS: PLB 716 (2012) 1-29, CMS: PLB 716 (2012) 30
  - τ leptons   ATLAS: arXiv:1811.08856, CMS: PLB 779 (2018) 283
  - Top quarks   ATLAS: PLB 784 (2018) 173, CMS: PRL 120 (2018) 231801
  - Bottom quarks   ATLAS: PLB 786 (2018) 59, CMS: PRL 121 (2018)121801



All measurements compatible with SM predictions!

Probing New Physics and the Nature of the Higgs boson with H→ZZ*→4l



Mixing

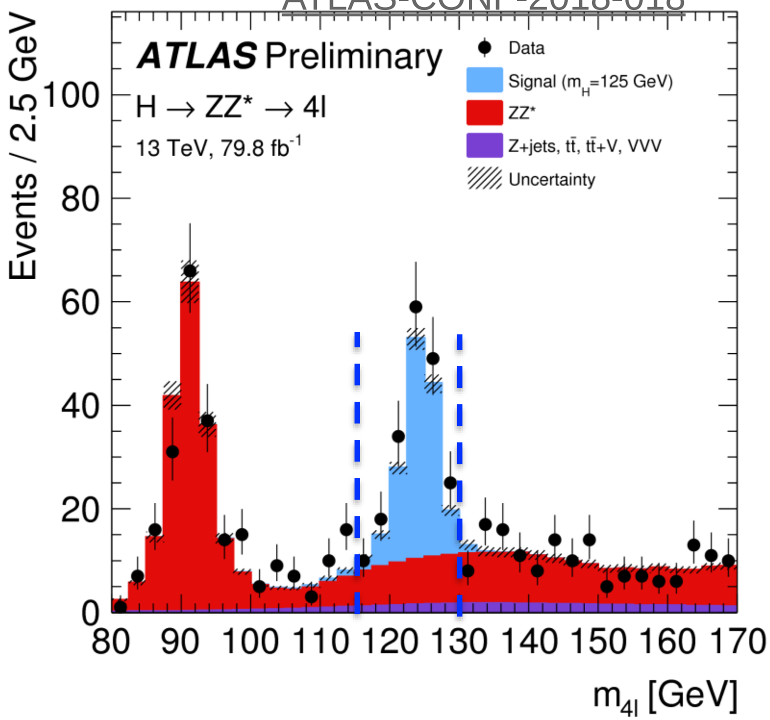
Loops

Decays

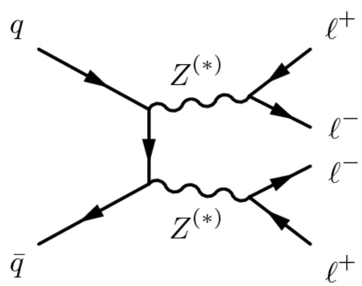
H→ZZ*→4l

- "The golden channel"
  - Fully reconstructed four-lepton final states
  - High S/B ~ 2

ATLAS-CONF-2018-018



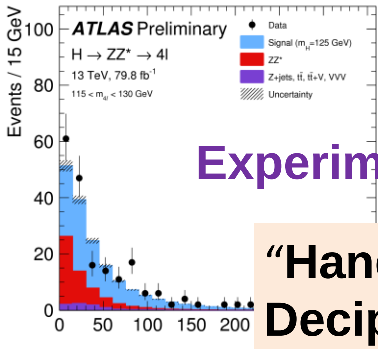
- Event selection:
  - Lepton p_T (20,15,10, 5/7)GeV for μ/e
- Background estimation:
  - ZZ*→4l: Monte Carlo (MC)
  - Mis-identified leptons (Z+jets, tt): data driven



115 GeV< m_{4l} < 130 GeV, 80 fb^{-1} data
195 events observed
112 ± 5 expected H→ZZ*→4l events

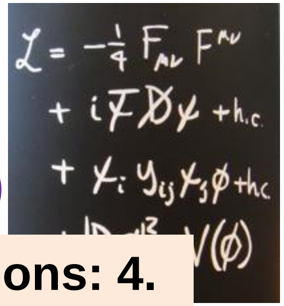
How to characterize Higgs properties

- To connect Experiment and Theory



Experiment

Theory (SM, BSM)



"Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector", LHC Higgs Cross Section Working Group, arXiv:1610.07922
869 pages, … and **1645** citations

Raw experimental
Event rate (N)
Distributions (eg. p_T^{4l})

…rvables (PO)
…effective couplings

Fiducial cross section: $\sigma = \frac{N}{L}$

Differential cross section: $\frac{d\sigma}{dp_T^{4l}}$

Simplified template cross section (STXS)

Signal strength: $\mu = \frac{\sigma}{\sigma^{SM}}$

SMEFT
HEFT
Higgs Characterization framework

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}$$

κ framework:
Ratio of couplings: $\kappa_i = \frac{g_i}{g_i^{SM}}$

$$\sigma_{i \to H \to f} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \frac{\sigma_i^{SM} \Gamma_f^{SM}}{\Gamma_H^{SM}}$$

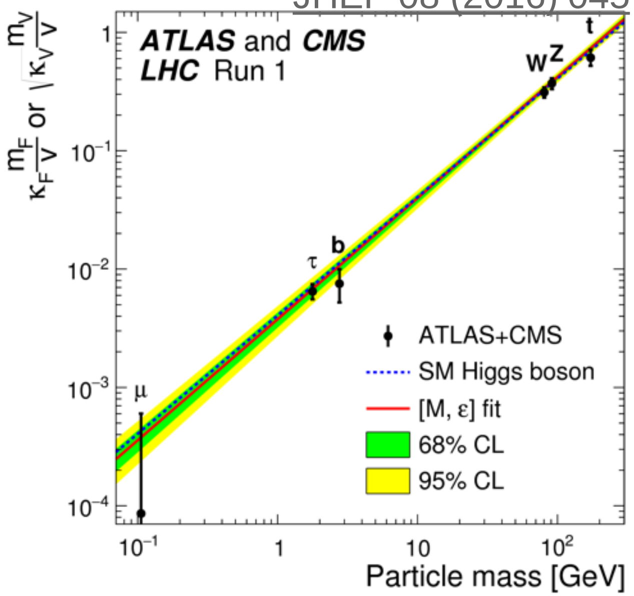
Measurements of the Higgs boson properties:

→ On-shell couplings

Off-shell couplings

Self-couplings

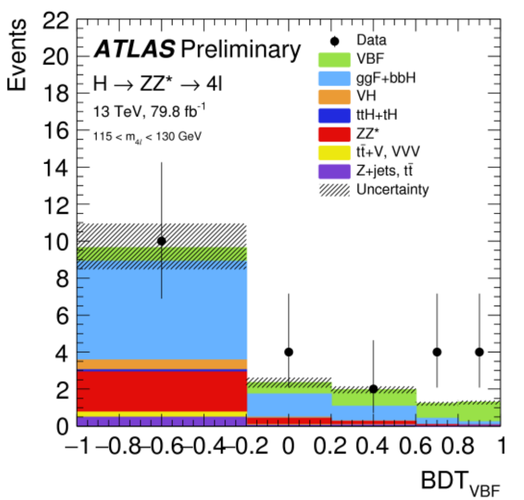
JHEP 08 (2016) 045

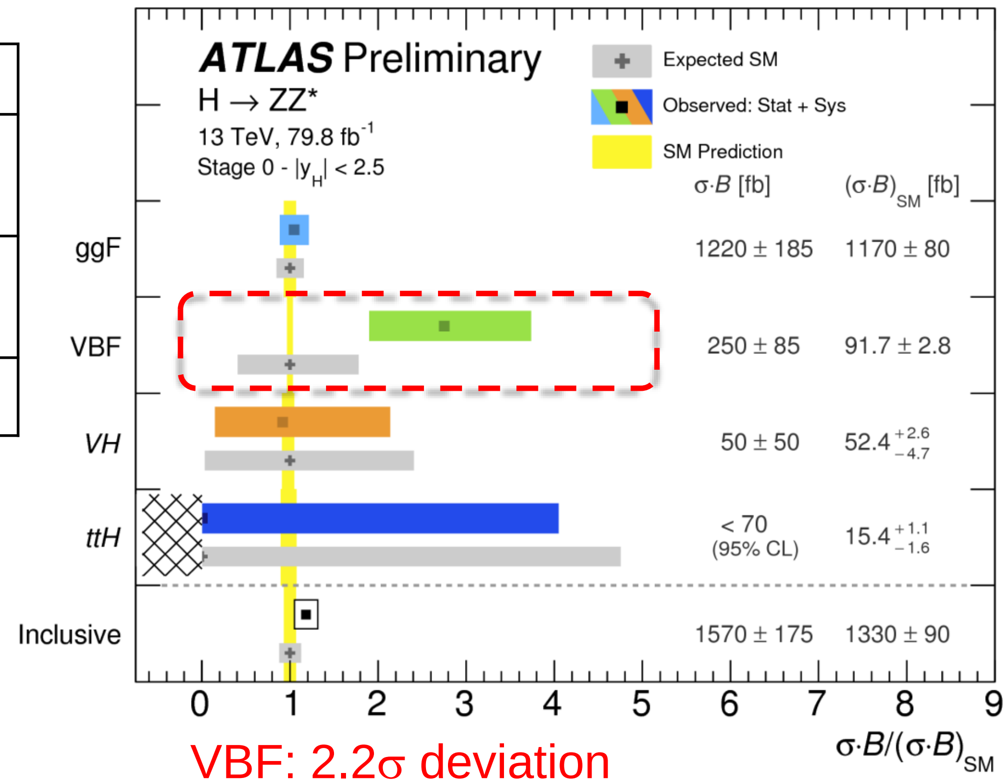


Measurements of production modes

- Event categorization to probe Higgs production modes:
  - 11 bins, based on p_T^H and jet activities (N_{jet}, p_T^j, etc)
  - For example:

Prod. bins		Requirement
ttH	ttH-Had	>=1 b-jet >=4 jets
	ttH-Lep	>=1 b-jet >=2 jets, >=1 lepton
VBF		>=2 jets, m_{jj} > 120 GeV





VBF: 2.2σ deviation

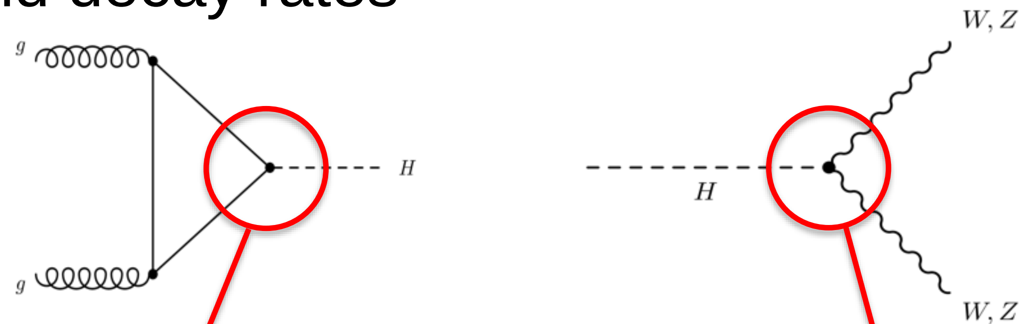
Inclusive

$$\mu = 1.28^{+0.18}_{-0.17}(\text{stat.})^{+0.08}_{-0.06}(\text{exp.})^{+0.08}_{-0.06}(\text{th.}) = 1.28^{+0.21}_{-0.19}.$$

Higgs couplings – the κ framework

- Define coupling modifiers: $\kappa_i = \frac{g_i}{g_{i,SM}}$

- Production and decay rates



$$\sigma_{\text{ggF}} = (1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b)\sigma_{\text{ggF}}^{SM}$$

$$\Gamma_{\text{ZZ}} = \kappa_Z^2\Gamma_{ZZ}^{SM}$$

$$\sigma_{\text{VBF}} = (0.73\kappa_W^2 + 0.27\kappa_Z^2)\sigma_{\text{VBF}}^{SM}$$

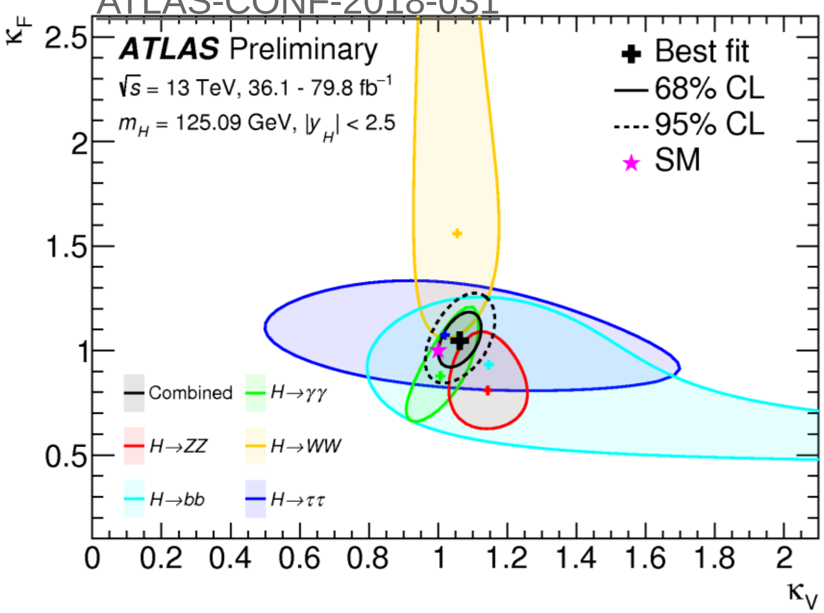
1) SM couplings modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$
2) Allow BSM couplings modifiers: κ_g, κ_γ
3) Allow BSM Higgs decay: B_{BSM}

$$\Gamma_{\text{H}} = \frac{\kappa_H^2\Gamma_H^{SM}}{1-B_{BSM}}$$

Results in the κ framework

- Couplings from combined measurements

ATLAS-CONF-2018-031

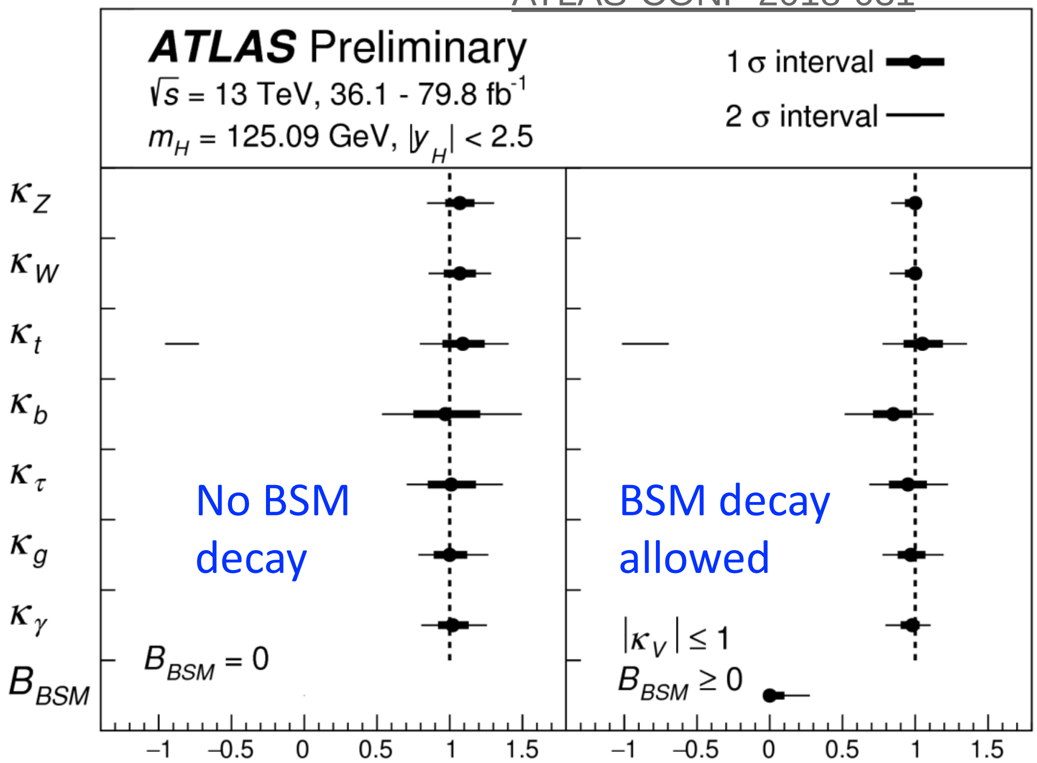


$\kappa_V = 1.06^{+0.04}_{-0.04}$ $(\kappa_V = \kappa_W = \kappa_Z)$

$\kappa_F = 1.05^{+0.09}_{-0.09}$ $(\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu)$

Precision 4~9 %

ATLAS-CONF-2018-031



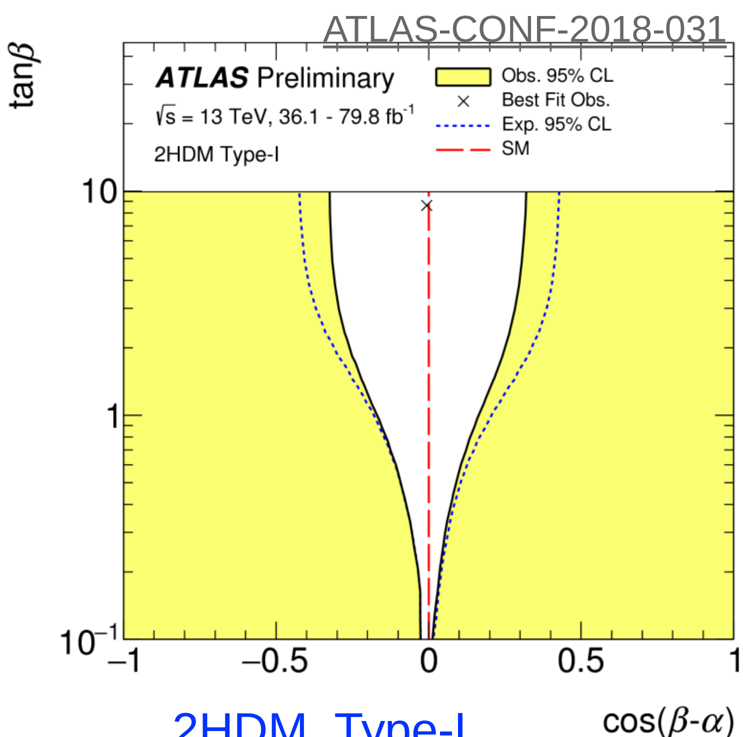
BSM decay: B_{BSM} < 26% @ 95% CL

Direct invisible Higgs search: B_{BSM} < 26%

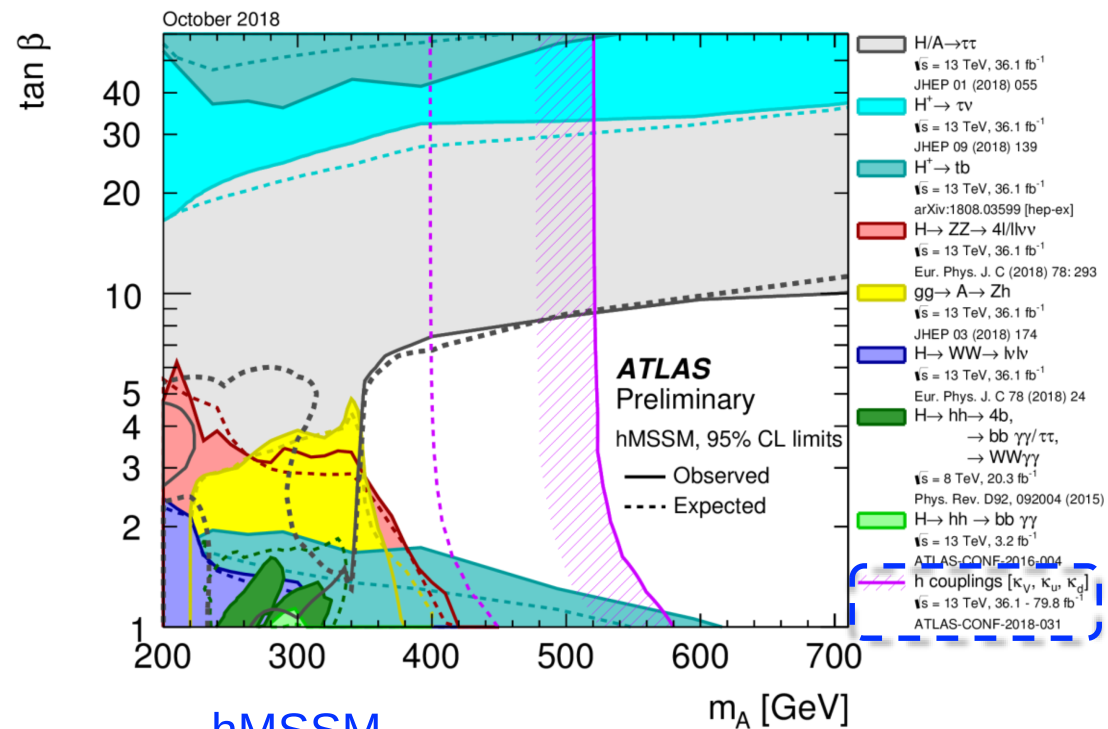
(Run1+2 combined) ATLAS-CONF-2018-054

Constraints on BSM

- Using measured Higgs couplings to constrain new physics
  - Two-Higgs-Doublet model (2HDM)
  - Simplified Minimal Supersymmetric Standard Model (hMSSM)



2HDM, Type-I

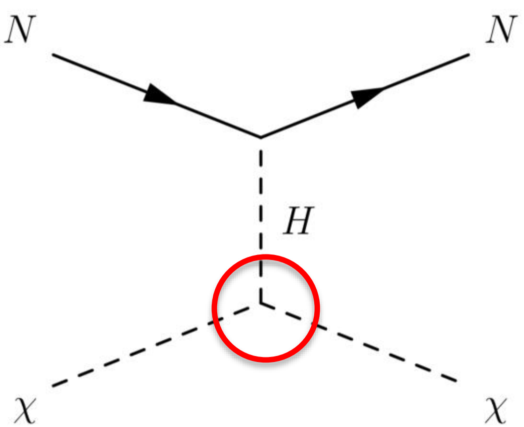


hMSSM

Complementary to direct searches

Higgs portal to Dark Matter

- Assuming dark matter interact SM particles via Higgs portal
  - Translating the limit on B_{BSM} → $H\chi\chi$ coupling
  - → DM-nucleon scattering
  - Unique sensitivity to light dark matter particles



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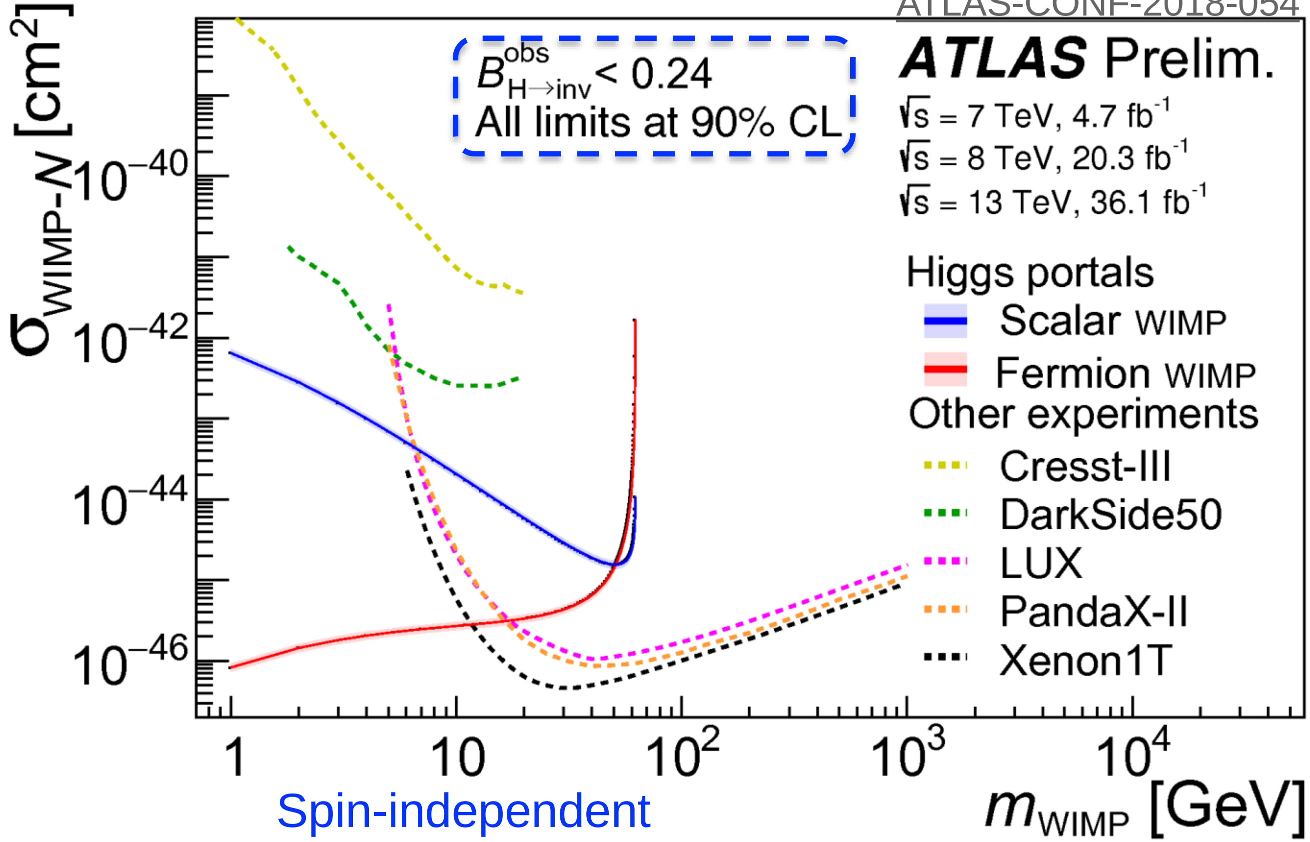
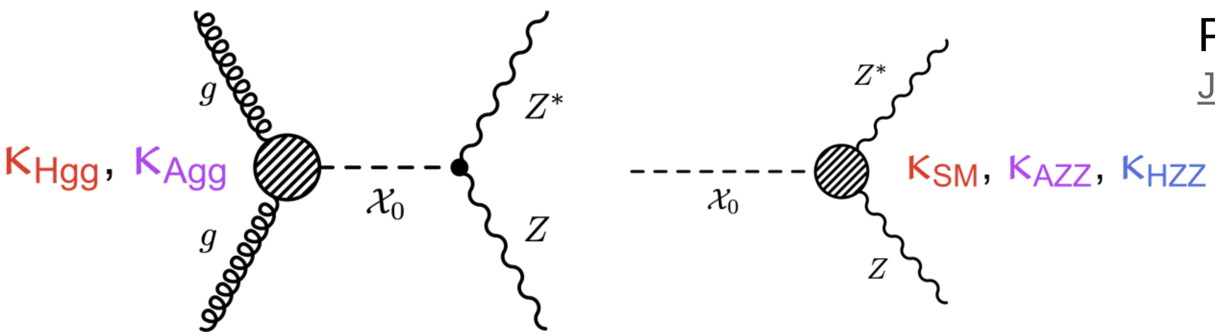


Spin-independent

Probing CP nature of the Higgs boson

- Why still interesting to measure CP properties
  - Still room for anomalous couplings due to CP violation
  - Electroweak Bayrogensis needs large CPV (Sakharov's criteria)

- Effective Lagrangian with CP-even and CP-odd operators
  - κ_{SM} and κ_{Hgg} modify SM interactions (== 1 for SM)
  - BSM couplings: CP-even κ_{HZZ}, CP-odd: κ_{AZZ}, κ_{Agg}

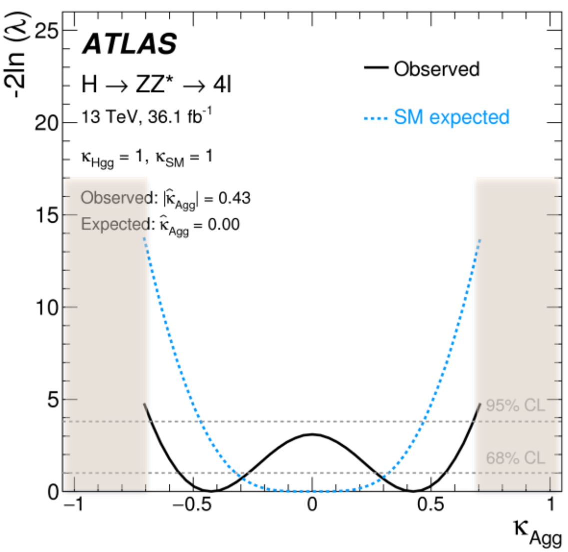


Higgs characterization model, P. Artoisenet et al JHEP11(2013)043

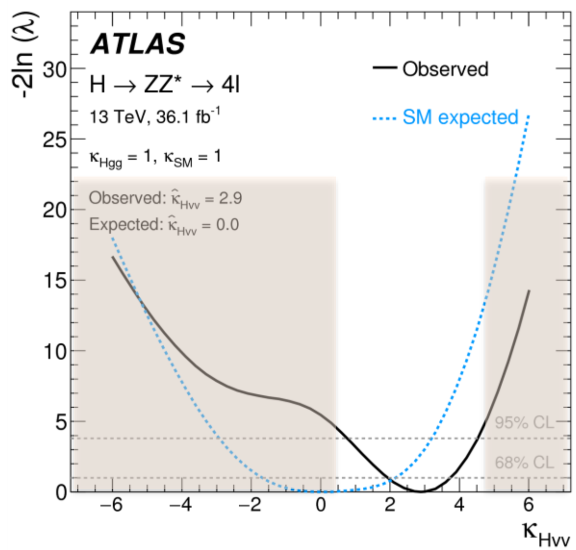
CP measurements

- Constraints on CP-mixing and CP-violation
  - Using event rates

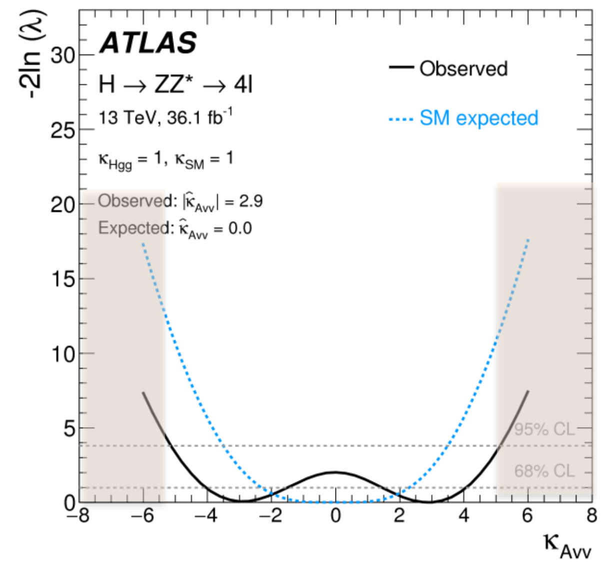
JHEP 03 (2018) 095



κ_{Agg} [-0.68, 0.68]



κ_{HZZ} [0.8, 4.5]



κ_{AZZ} [-5.2, 5.2]

Sensitivity can be further improved by using event kinematic information

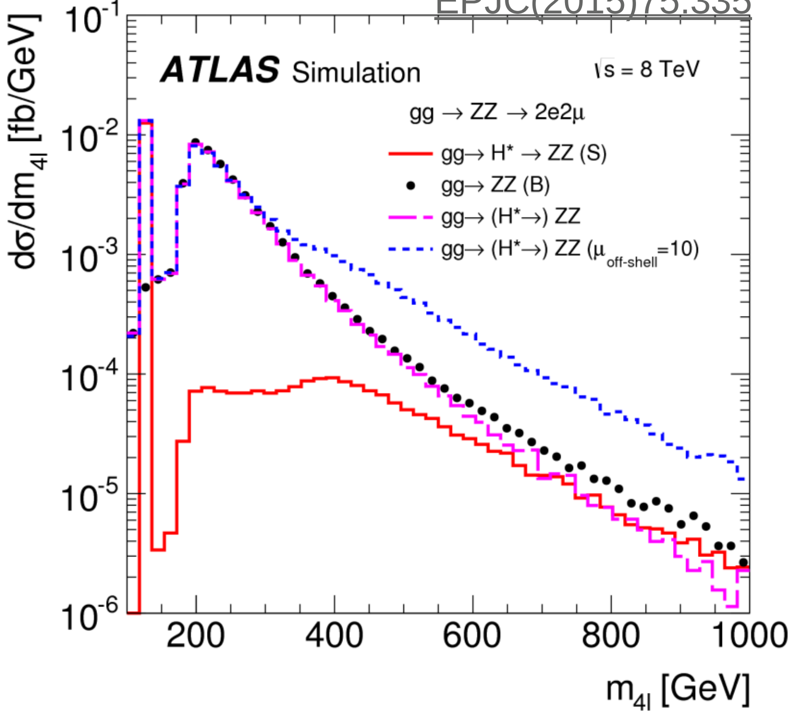
Measurements of the Higgs boson properties:

On-shell couplings

→ Off-shell couplings

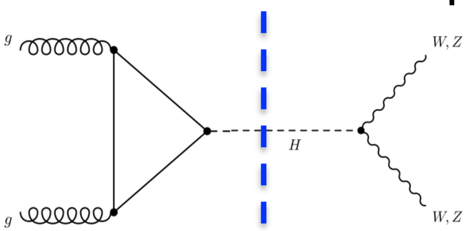
Self-couplings

EPJC(2015)75:335



Higgs boson width

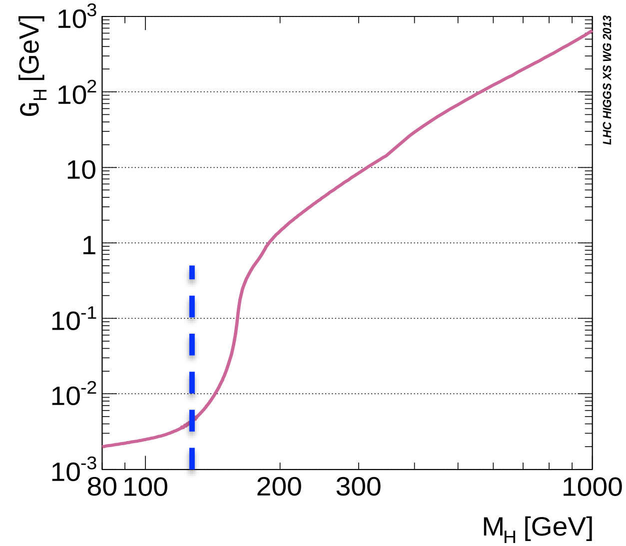
- How wide the Higgs boson is?
  - Γ_H^{SM} = 4.1 MeV @ m_H=125 GeV
- Two implications:
  - Zero width approximation (ZWA)



$$\sigma_{i\to H\to f} = \sigma_{i\to H} BR_{H\to f} \propto \frac{g_i^2 g_f^2}{\Gamma_H}$$

Degeneracy: Invariant if $g \to g\varepsilon, \Gamma_H \to \Gamma_H \varepsilon^4$

  - Can we measure it at the LHC?
    - Seems impossible due to detector resolution



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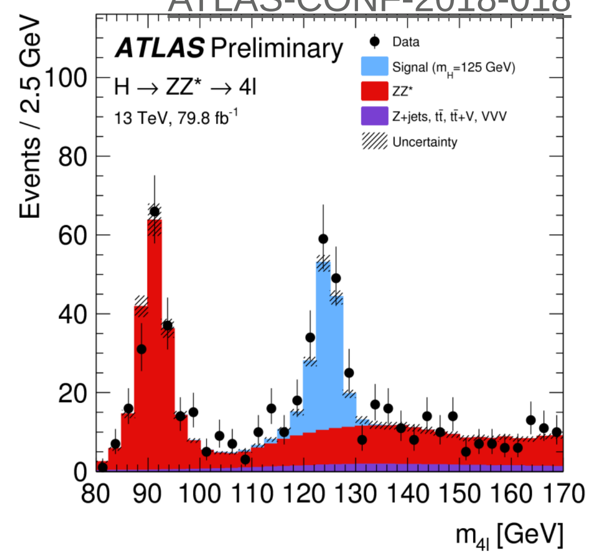
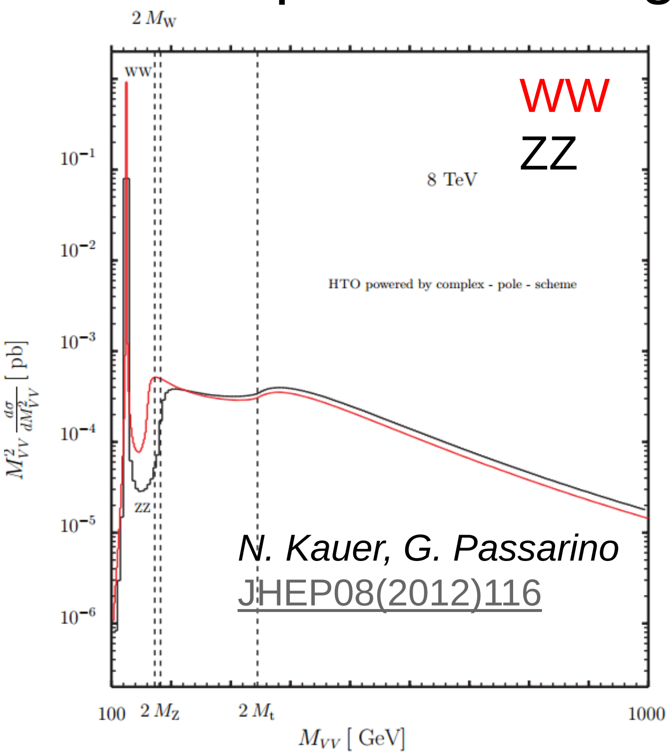
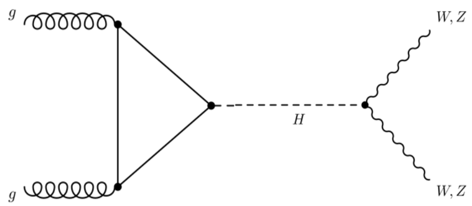


Off-shell Higgs

- Is ZWA precise enough?





$$\frac{d\sigma_{gg\to H\to VV}}{dM^2_{VV}} \propto \frac{g^2_{Hgg} g^2_{HVV}}{\left(M^2_{VV} - M^2_H\right)^2 + M^2_H \Gamma^2_H}$$

Higgs has a long tail

Off-shell

	Tot [pb]	$M_{ZZ} > 2\,M_Z$ [pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

- Off-shell Higgs
  - A unique phase space
  - Characterize Higgs couplings at high scale
  - Sensitive to new physics

Bounding the Higgs width

- Off-shell effect makes Higgs width measurement possible

$$\frac{d\sigma_{gg\to H\to VV}}{dM_{VV}^2} \propto \frac{g_{Hgg}^2 g_{HVV}^2}{\left(M_{VV}^2 - M_H^2\right)^2 + M_H^2 \Gamma_H^2}$$

on-shell: $m_{4l} \sim m_H$ $\quad \sigma_{gg\to H\to ZZ}^{\text{on-shell}} \sim \frac{\kappa_{g,on}^2 * \kappa_{V,on}^2}{\Gamma_H/\Gamma_{SM}} = \mu_{\text{on-shell}}$

off-shell: $m_{4l} - m_H >> \Gamma_H$ $\quad \sigma_{gg\to H\to ZZ}^{\text{off-shell}} \sim \kappa_{g,off}^2 * \kappa_{V,off}^2 = \mu_{\text{off-shell}}$

Breaks the degeneracy!

- Assuming $\kappa_{g,on} = \kappa_{g,off}$ and $\kappa_{V,on} = \kappa_{V,off}$

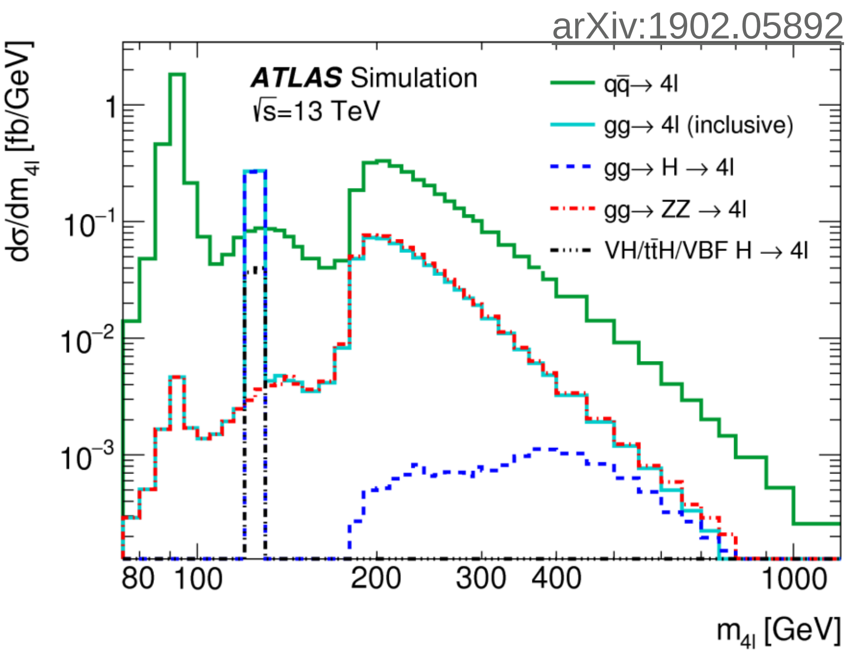
$$\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{SM}$$

  – Measuring both on- and off-shell production could constrain Higgs width

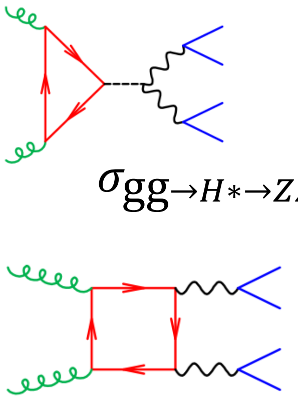
F. Caola, K. Melnikov
PRD88(2013)054024

Going off-shell

- More challenging to go beyond the Higgs peak region
  - Higher background events from qq→ZZ
  - Negative interference between gg→H*→ZZ and gg→ZZ continuum



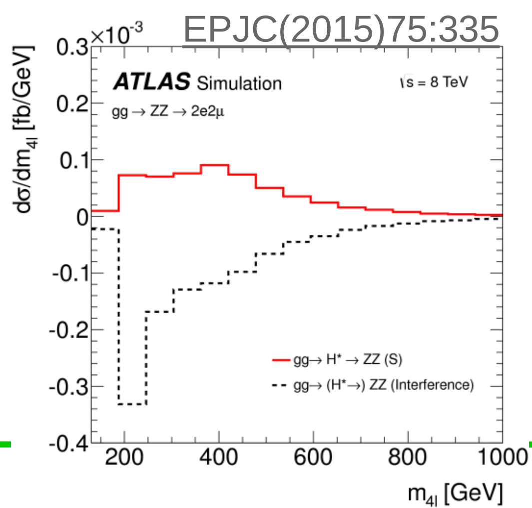
Higgs Signal



$$\sigma_{gg\to H*\to ZZ} \propto \mu_{\text{off-shell}}$$

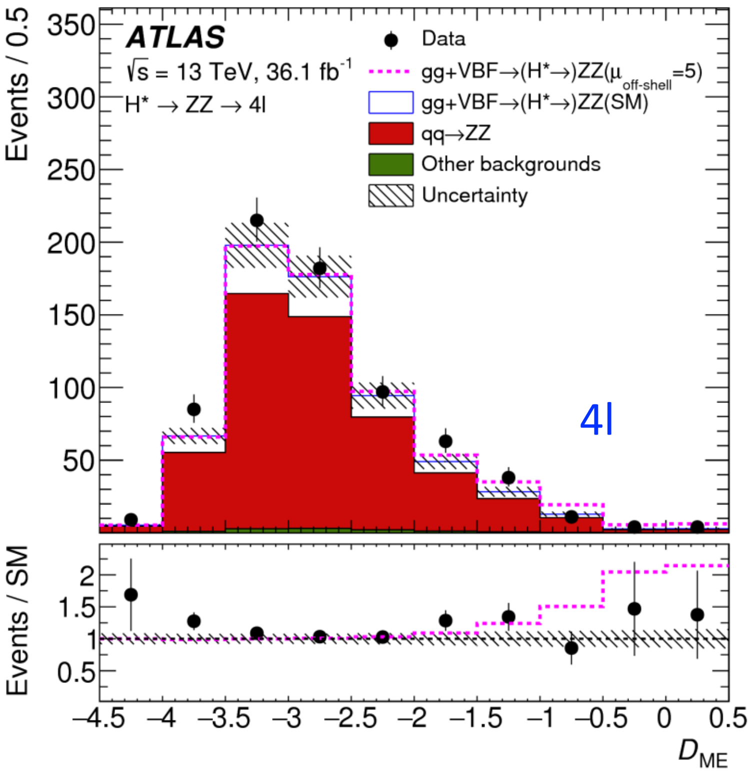
Continuum background

$$\sigma_{\text{interf.}} \propto \sqrt{\mu_{\text{off-shell}}}$$



How to measure $\mu_{\text{off-shell}}$

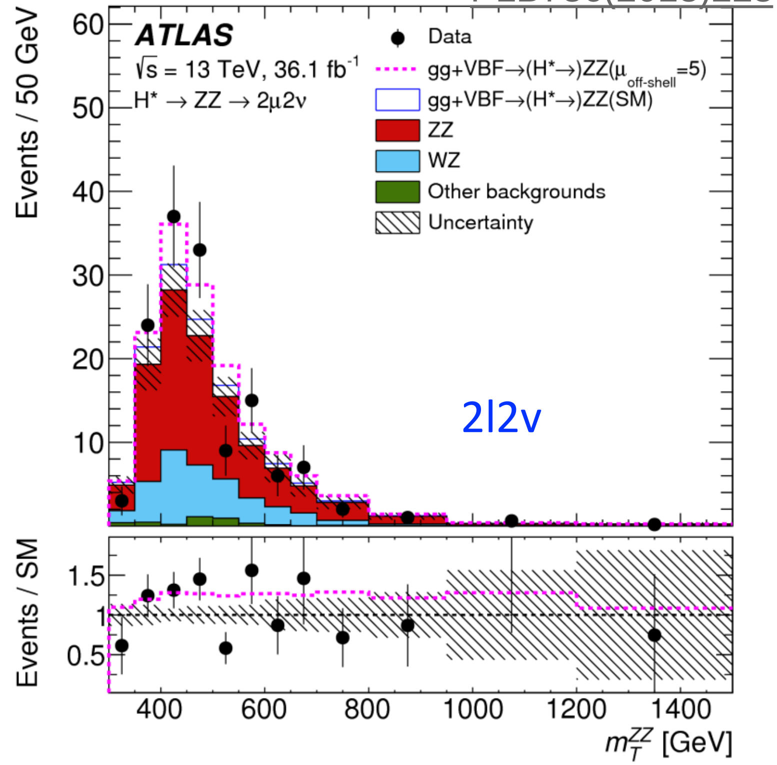
- Using high mass ZZ events (m_{ZZ}> 2m_Z)
- H*→ZZ→2l2v viable



Matrix-element discriminant

$$D_{\text{ME}} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

PLB786(2018)223



Transverse mass

$E_{\mathrm{T}}^{\text{miss}}$> 175 GeV

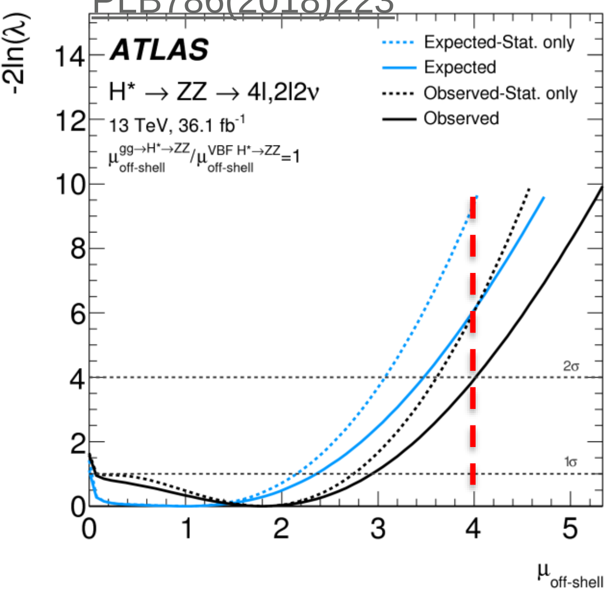
J. Campbell et al, JHEP04(2014)060

Results

- Measurements of off-shell production
  - Off-shell: H*→ZZ→4l, H*→ZZ→2l2v
- and Higgs width
  - On-shell: H→ZZ*→4l

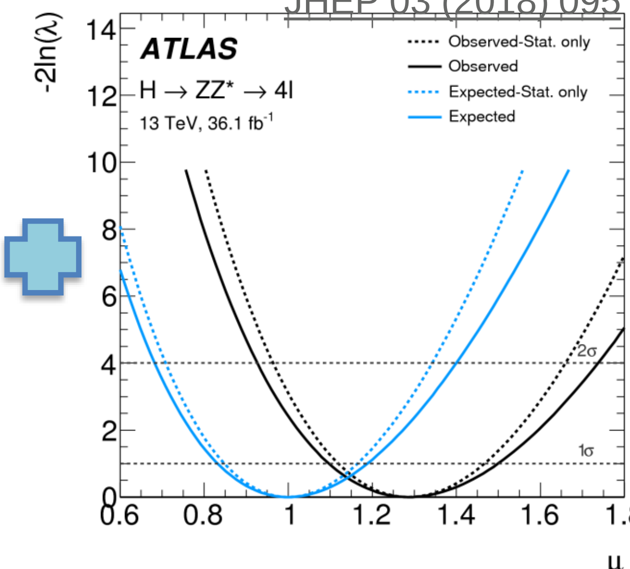
$$\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{SM}$$

PLB786(2018)223

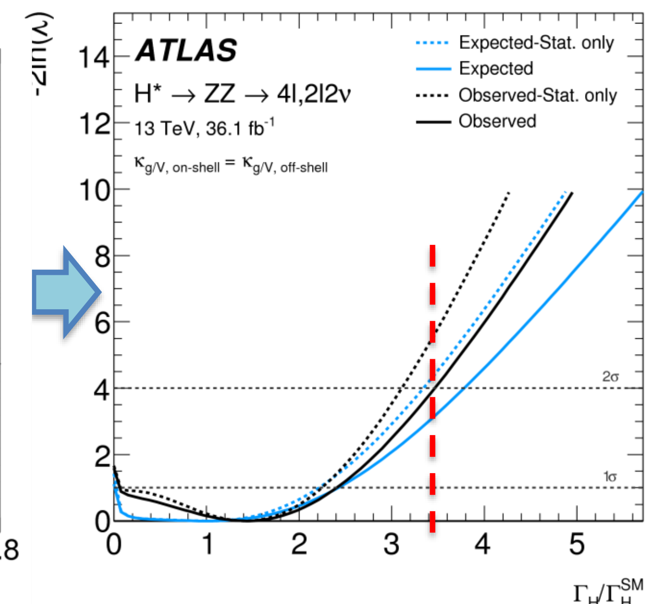


$\mu_{\text{off-shell}}$

JHEP 03 (2018) 095



$\mu_{\text{on-shell}}$



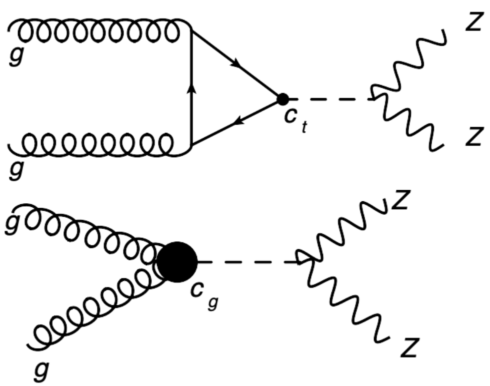
$\Gamma_H < 15$ MeV @ 95% CL

Direct measurement:

$\Gamma_H < 1.1$ GeV (JHEP11(2017)047)

Constraints on BSM

- Off-shell Higgs has unique sensitivity to new physics
  - BSM contribution grows with $\hat{s}$ → high energy bins become important



Assuming new physics enters the loop, with effective couplings c_t, c_g for gg→H

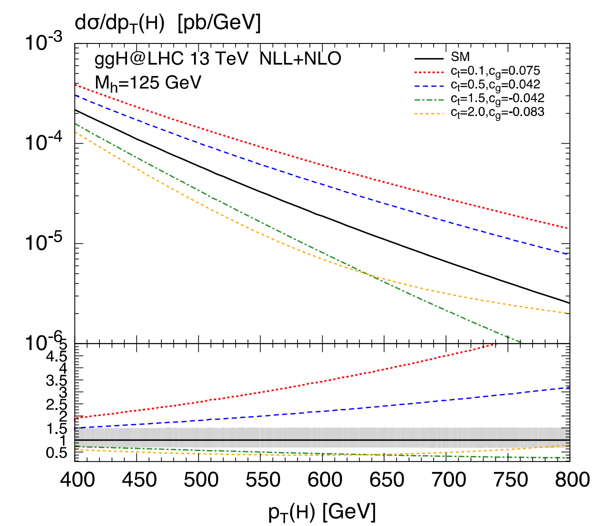
$$\mathcal{L} \;=\; -c_t \frac{m_t}{v}\bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu},$$

On-shell Higgs production $\sigma \sim |c_t + c_g|^2$

- To break the degeneracy
  - ttH production
  - Boosted Higgs via pp→ H+jets
  - Off-shell Higgs — C. Grojean et al, JHEP05(2014)022; C. Grojean et al, JETP120(2015)354
  - Di-Higgs production

S. Dawson et al, PRD91(2015)115008

M. Grazzini et al JHEP03(2017)115



Constraints on BSM (2)

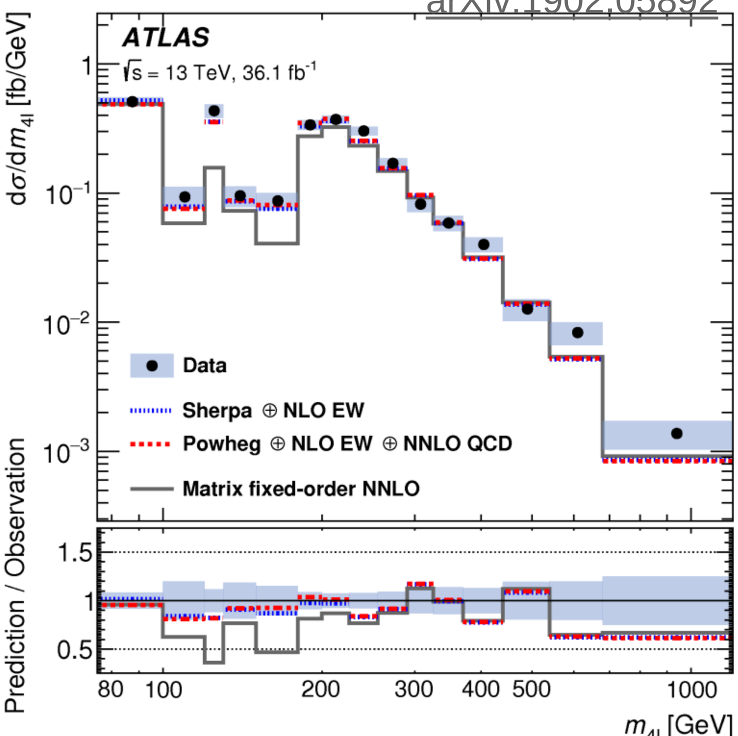
- Off-shell Higgs to constrain c_t, c_g
  - Using unfolded m4l spectrum

C. Grojean et al, JETP120(2015)354

gg→4l

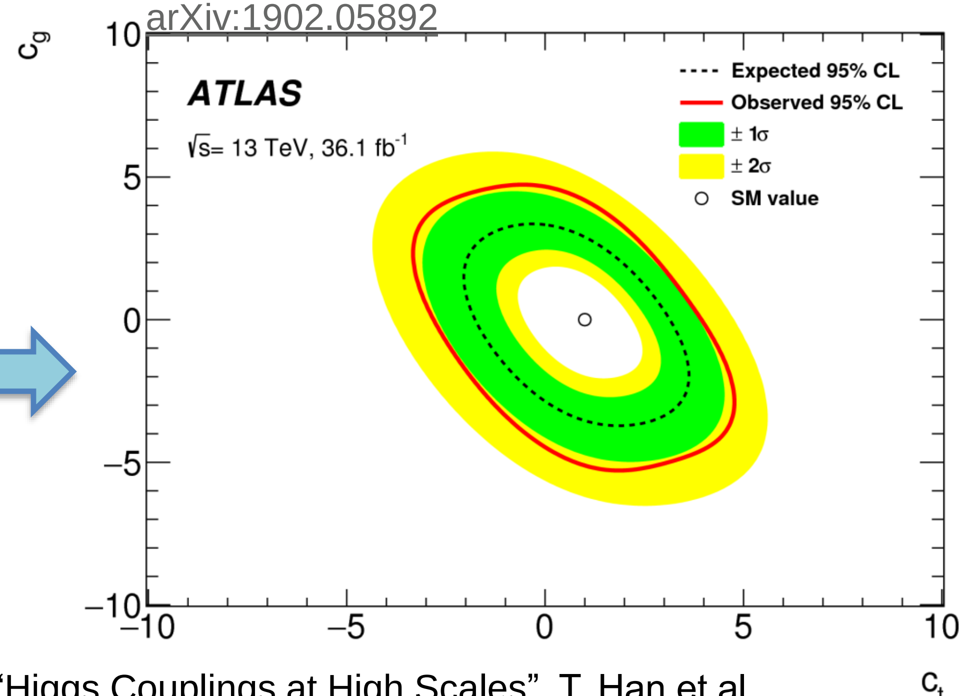
$$\frac{d\sigma(c_t,c_g)}{dm_{4\ell}} = F_0 + F_1\left(c_t + c_g\frac{F_\Delta(\infty)}{\mathrm{Re}\,F_\Delta(m_t)}\right)^2 + F_3\left(c_t + c_g\frac{F_\Delta(\infty)}{\mathrm{Re}\,F_\Delta(m_t)}\right) + F_2c_t^2 + F_4c_t\,,$$

arXiv:1902.05892



pp→4l

arXiv:1902.05892



"Higgs Couplings at High Scales", T. Han et al PRD.98(2018)015023

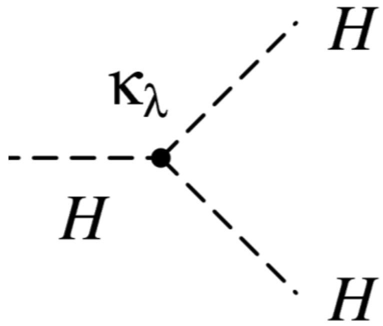
"Off-shell Higgs Probe to Naturalness", T. Han et al PRL120(2018)111801

Measurements of the Higgs boson properties:

On-shell couplings

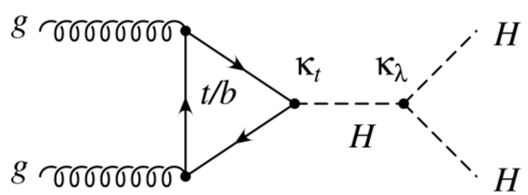
Off-shell couplings

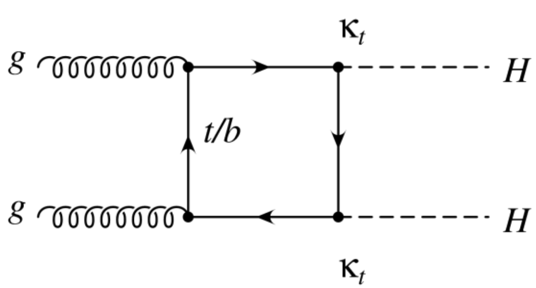
→ Self-couplings



DiHiggs production

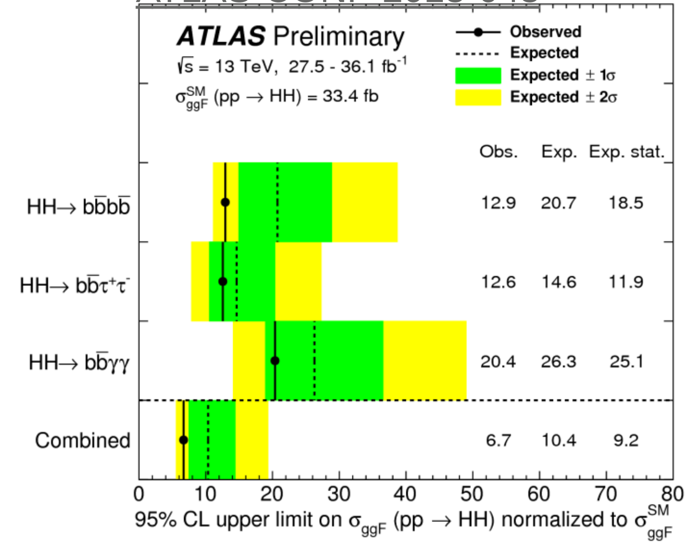
- Direct probe of Higgs self-coupling and Higgs potential
  - Challenging due to low rate, $\frac{\sigma_{gg\to H}}{\sigma_{gg\to HH}} \sim 1500$
  - Sensitive to new physics → implication on EW Phase Transition

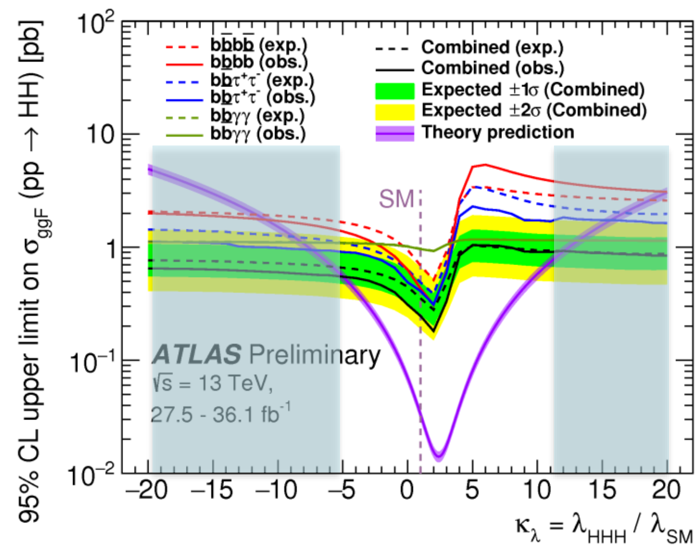




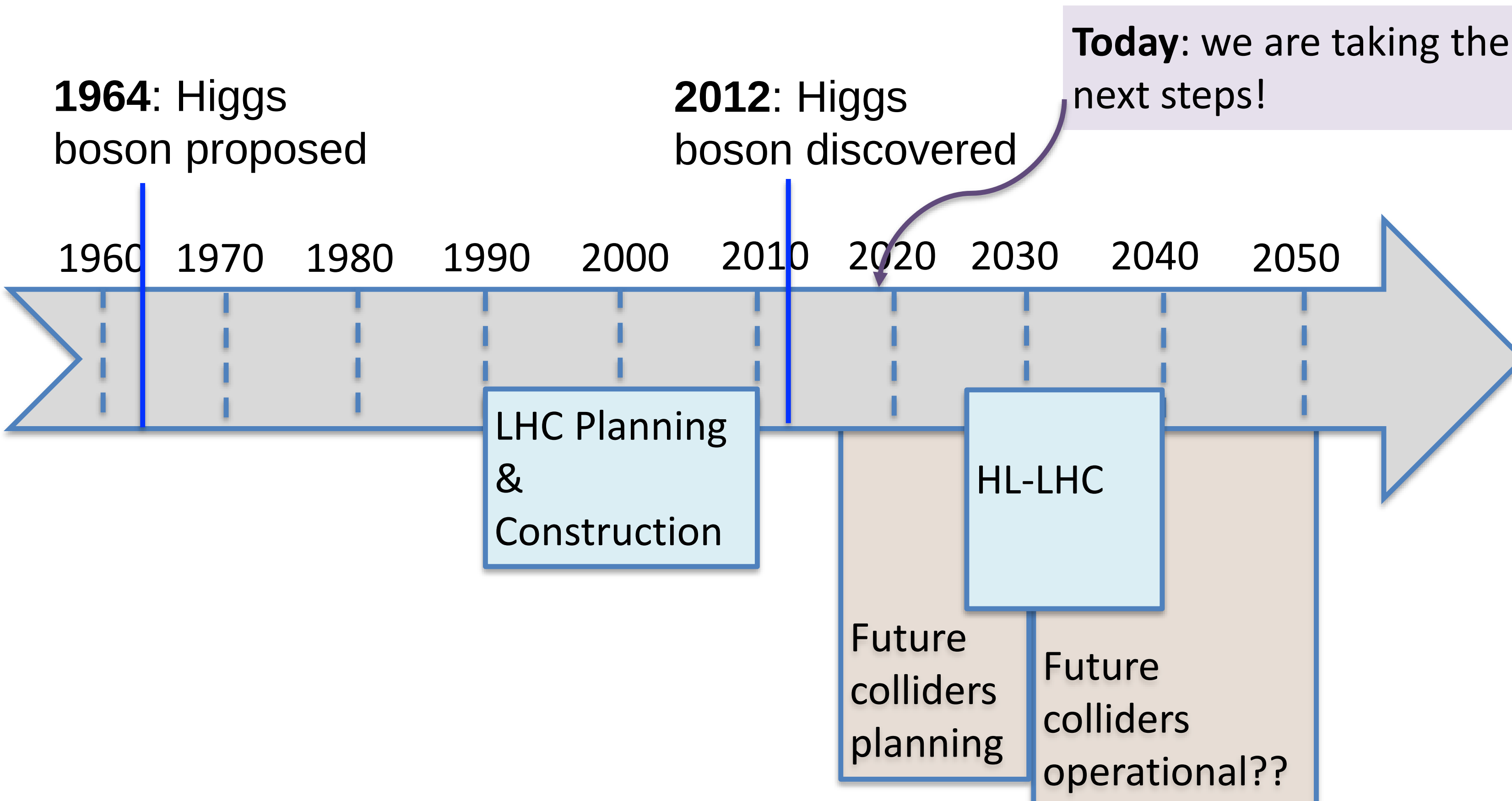
Similar to off-shell, measuring deficit in data

ATLAS-CONF-2018-043





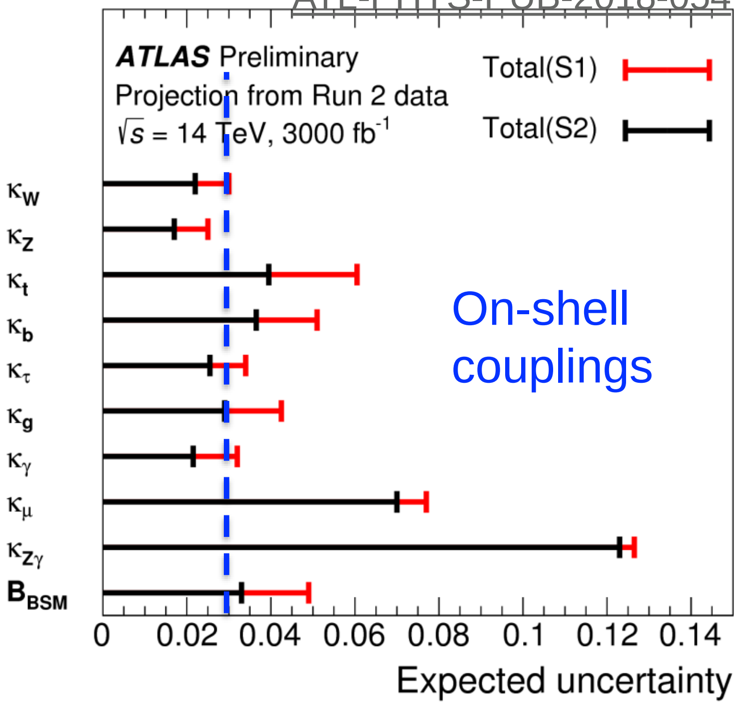
Prospects at the HL-LHC and Future Colliders



Prospects for Higgs properties measurements

- Current measurements are statistically limited
  - 4l, 80 fb^{-1}: $\mu = 1.19 \pm 0.12(stat.) \pm 0.06(exp.)^{+0.08}_{-0.07}(th.)$
- High luminosity LHC:
  - Limited by the large theory uncertainties

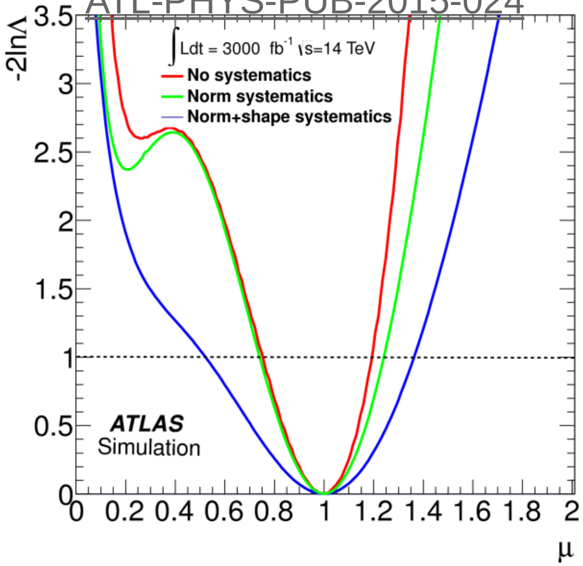
ATL-PHYS-PUB-2018-054



On-shell couplings

CEPC, 5 ab^{-1}, O(0.01)

ATL-PHYS-PUB-2015-024

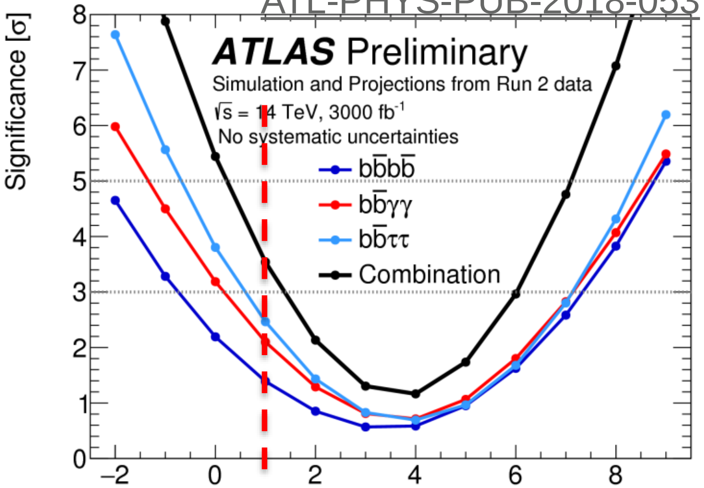


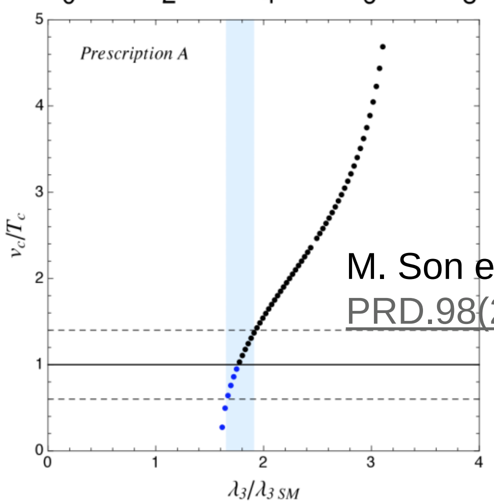
Off-shell couplings
O(20%) stat. only

Higgs self-coupling

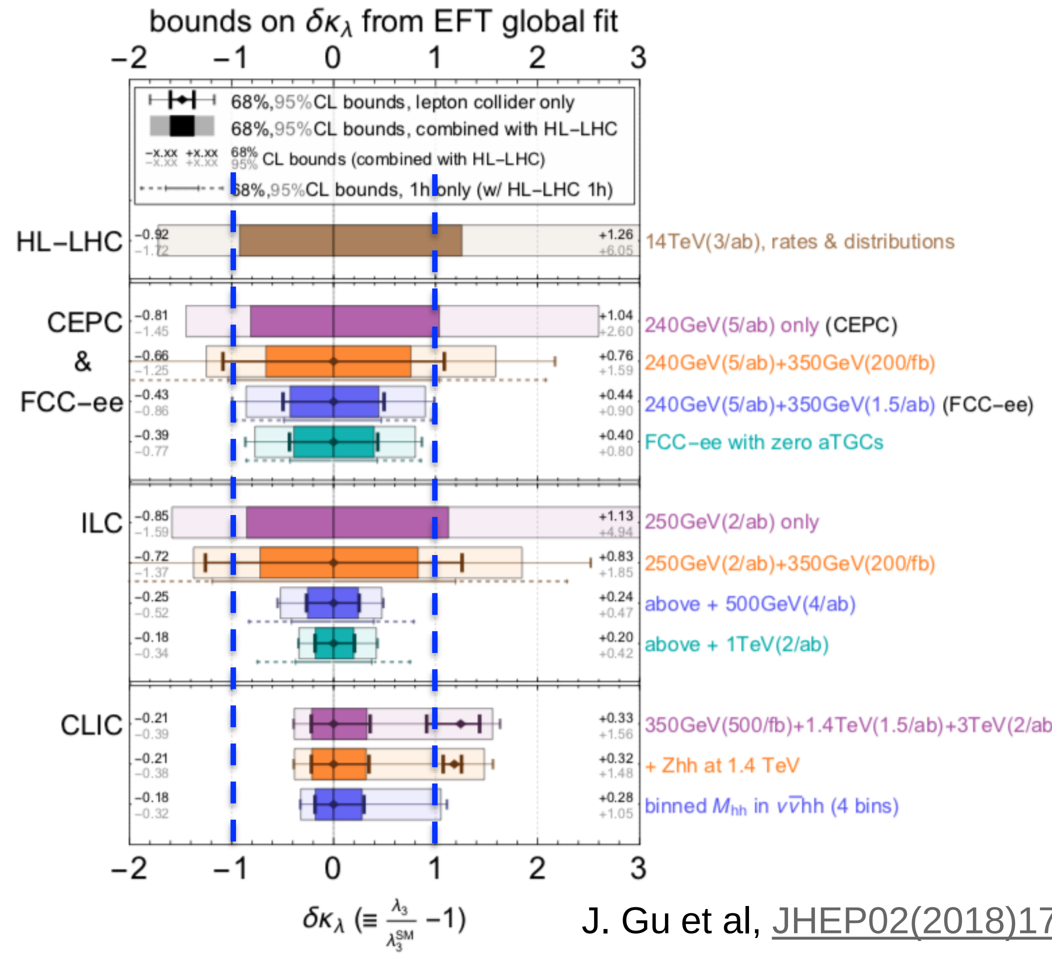
- DiHiggs: flagship physics for HL-LHC
  - κ_λ : precision of O(10) now, O(1) at HL-LHC

ATL-PHYS-PUB-2018-053





M. Son et al, PRD.98(2018)075



J. Gu et al, JHEP02(2018)178

ILC@1 TeV: O(0.2), 100 TeV *pp*: O(0.05)

Conclusion

- Higgs couplings measurement: crucial to probe the nature of EWSB and New Physics
  - On-shell couplings: precision era O(0.1)
  - Off-shell couplings: Higgs at high scale, O(3)
  - Self-coupling: benchmark for HL-LHC, O(10)

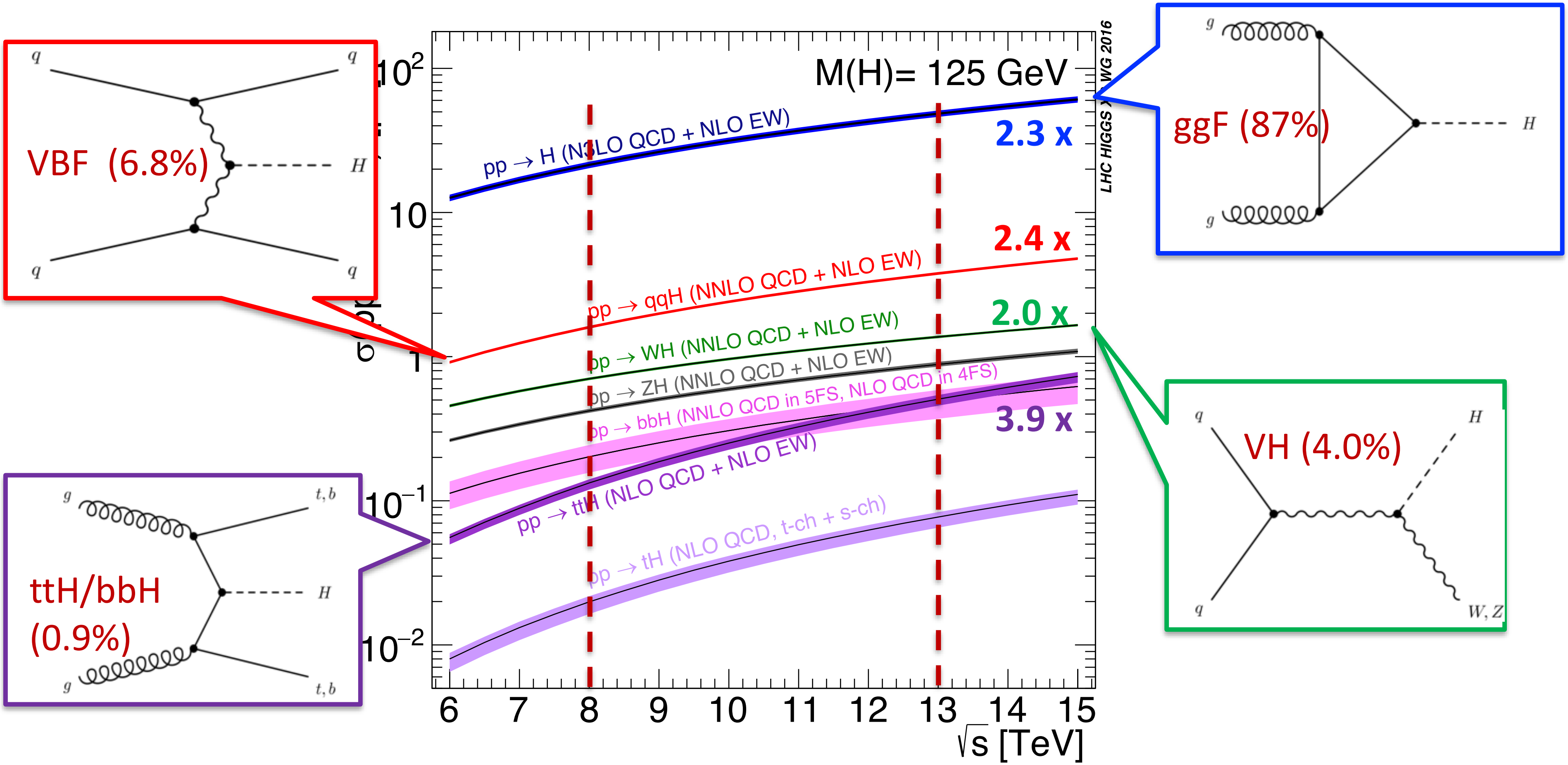
"Improved precision equates to discovery potential" FCC CDR

Improved theoretical predictions are essential, especially for HL-LHC

- New ideas and New colliders essential to continue exploring the unknown

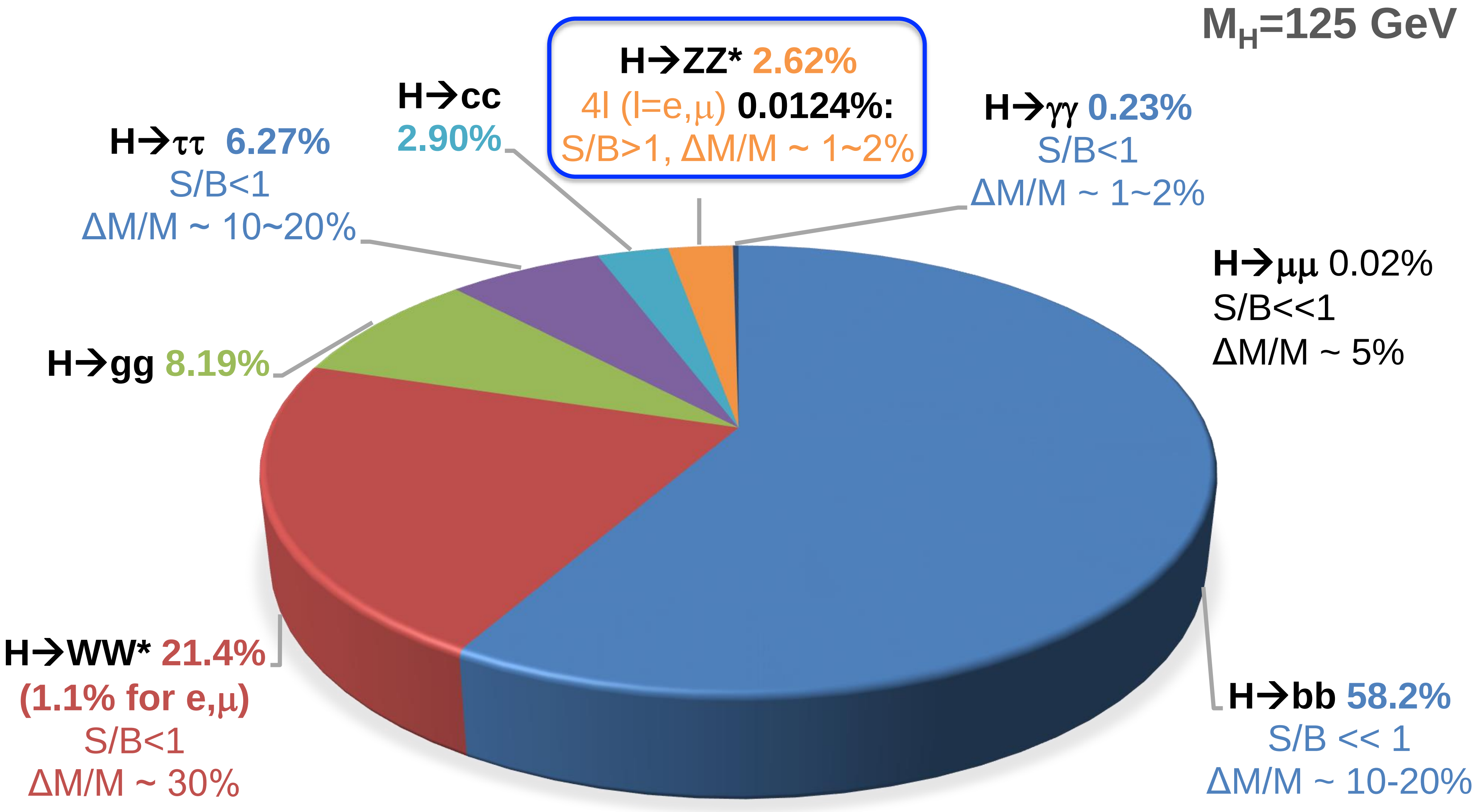
Backup

How to make a Higgs boson



$\sigma_{pp\rightarrow H}$ = 55.7 ± 2.5 pb @ 13 TeV

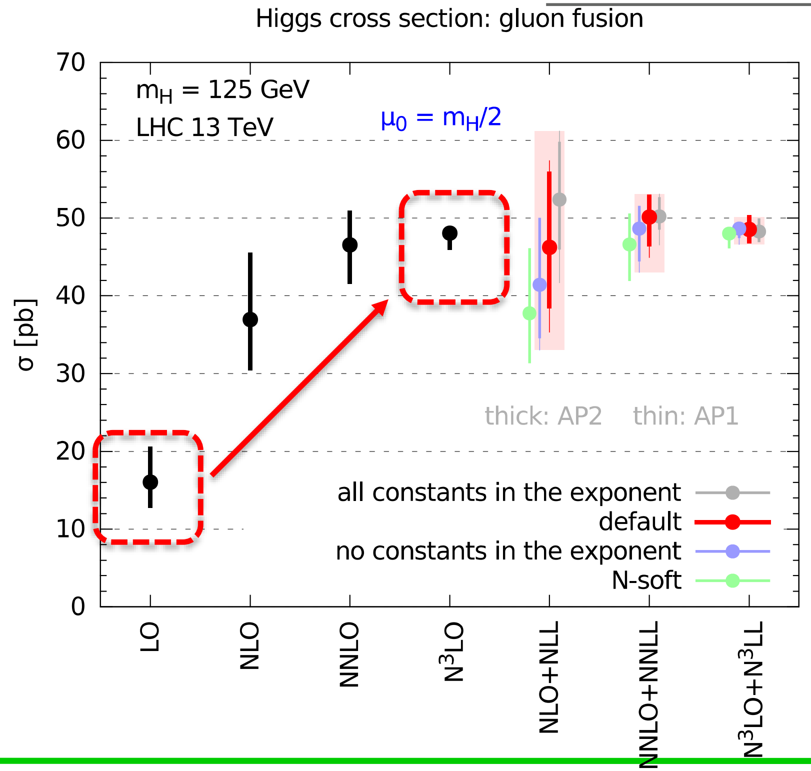
How to see a Higgs boson



Theory predictions

- High accuracy in QCD (+EW) predictions is crucial
- ggF:
  - Total cross section: N^3LO QCD + NLO EW (LHCXSWG)
    - NNLOPS
    - MG5_aMC@NLO 0,1,2 jets @NLO with FxFx merging
    - HRes 2.3

LHCXSWG, *arXiv:1610.07922*



- VBF, VH: NNLO QCD
  - PowhegBox
- ttH, bbH: NLO QCD
  - MG5_aMC@NLO

XH = VBF + VH + ttH + bbH

Experimental explorations

- Production modes and decays studied in ATLAS

Observed / Investigated	Inclusive (ggF mostly)	VBF	VH	ttH
Combination of decays	Observed	Observed	Observed	Observed (★)
H→ WW* → lvlv	Observed	Investigated	Investigated	Investigated
H→ ZZ* → 4l	Observed	Investigated	Investigated	Investigated
H→ $\gamma\gamma$	Observed	Investigated	Investigated	Investigated
H→ Zγ	Investigated	Investigated		
H→bb	Investigated	Investigated	Observed (★)	Investigated
H→ $\tau\tau$	Observed	Investigated	Investigated	Investigated
H→cc			Investigated	
H→ $\mu\mu$	Investigated	Investigated		
H→ invisible		Investigated	Investigated	

⇐ Event categorization

⇑ Higgs decay

★ Recent 5σ observations!

Systematic uncertainties

Table 4: Estimated theoretical uncertainties from missing higher orders.

Partial width	QCD	electroweak	total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 5\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$

Uncertainties on the branching ratio,
LHCXS WG arxiv:1610.07922

PLB786(2018)223

Systematic uncertainty	95% CL upper limit on $\mu_{\text{off-shell}}$		
	$ZZ \to 4\ell$	$ZZ \to 2\ell 2\nu$	Combined
QCD scale $q\bar{q} \to ZZ$	4.2	3.9	3.2
QCD scale $gg \to (H^* \to)ZZ$	4.2	3.6	3.1
Luminosity	4.1	3.5	3.1
Remaining systematic uncertainties	4.1	3.5	3.0
All systematic uncertainties	4.3	4.4	3.4
No systematic uncertainties	4.0	3.4	3.0

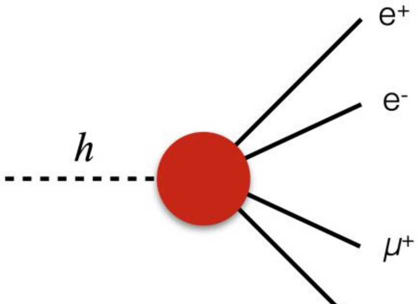
Systematic uncertainties (2)

Measurement [-0.5ex]	Experimental uncertainties [%] Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	Theory uncertainties [%] ZZ^* backgr.	Signal PDF	QCD scale	Parton Shower	Composition
Fiducial cross section									
	2.8	4.3	< 0.1	0.3	1.6	0.6	0.5	0.4	0.1
Per decay channel fiducial cross sections									
4μ	2.8	3.9	< 0.1	0.3	1.6	0.6	0.4	0.6	0.2
$4e$	2.8	9.0	< 0.1	1.0	1.6	0.6	0.8	0.5	0.1
$2\mu 2e$	2.7	8.6	< 0.1	0.9	1.5	0.6	0.7	0.5	0.1
$2e2\mu$	2.8	3.6	< 0.1	0.4	1.8	0.6	0.7	0.5	0.2
Stage-0 production bin cross sections									
ggF	2.9	3.9	1.3	0.7	2.3	0.4	2.1	0.7	-
VBF	1.7	1.5	10.5	0.5	2.3	2.3	9.5	5.1	-
VH	2.0	1.7	7.8	1.8	5.6	2.1	14.9	3.1	-
ttH	2.5	1.9	3.9	1.5	1.9	0.3	8.8	9.6	-

Uncertainties on H4l measured fiducial xsec,
ATLAS-CONF-2018-018

Constrains on BSM

- Using the framework of pseudo-observables (PO)

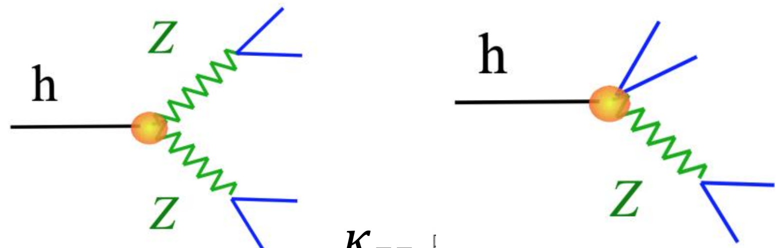


$e = e_L, e_R$

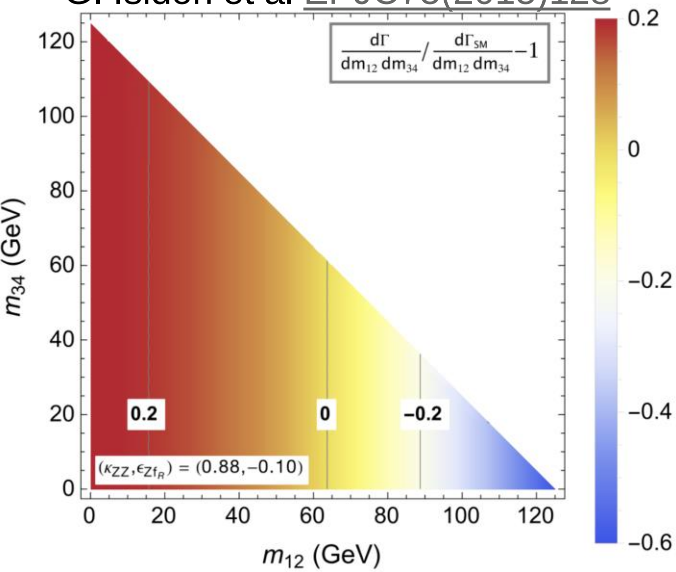
One example form factor for the contact interaction of the h→ 4l decay

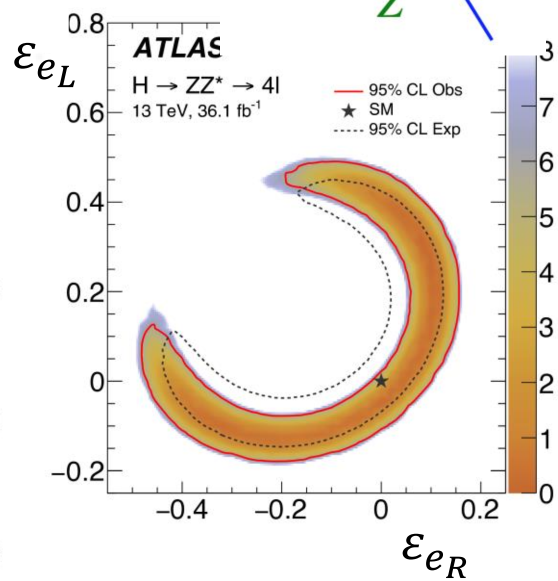
$$F_1^{ff'}(q_1^2, q_2^2) = \kappa_{ZZ} \frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2} \frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2} \frac{g_Z^f}{P_Z(q_1^2)} + \Delta_1^{\rm SM}(q_1^2, q_2^2)$$

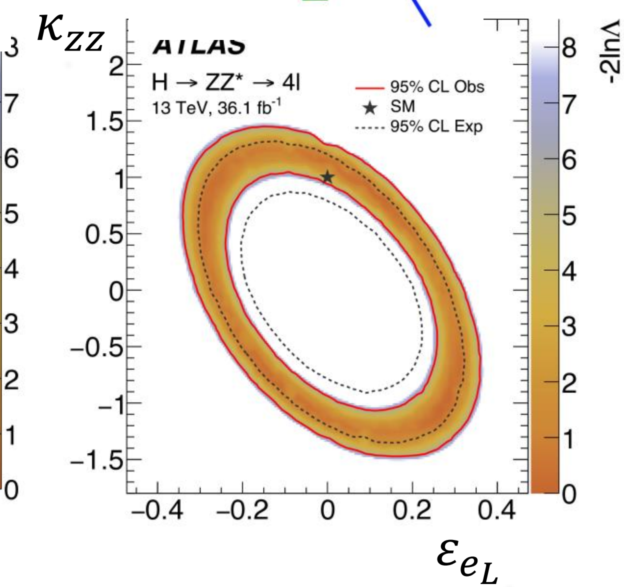
PO κ_{ZZ}, $\varepsilon_{e_{L,R}}$ change the both the decay rate and kinematics



G. Isidori et al EPJC75(2015)128







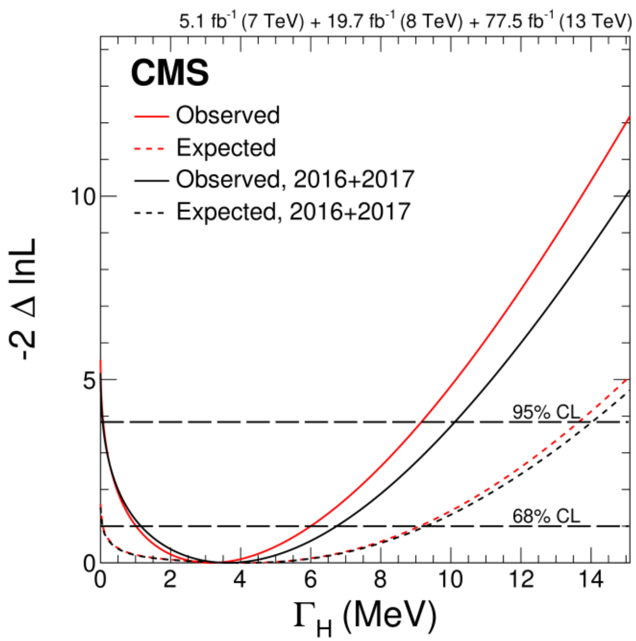
CMS off-shell

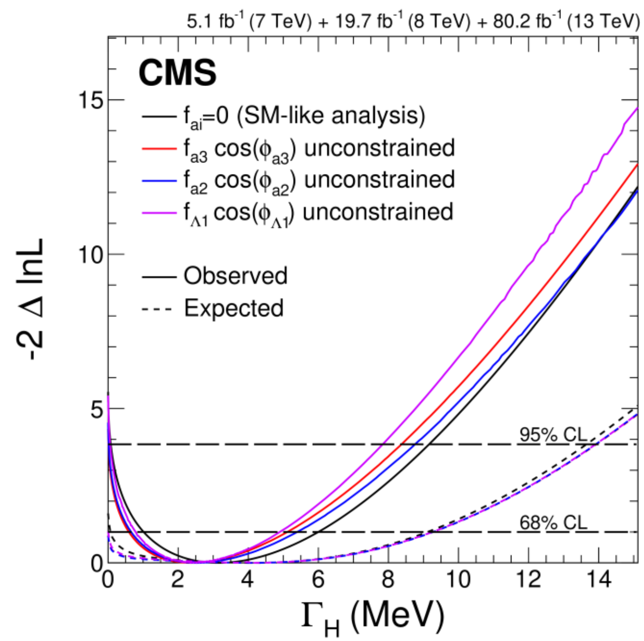
- CMS results (4l channel only): arXiv:1901.00174
  - Three categories: VBF, VH, others
  - Combined run 1 and run 2 (80 fb^{-1}) results

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.78^{+0.72}_{-0.53}$ [0.02, 2.28]	$1.00^{+1.20}_{-0.99}$ [0.0, 3.2]
$\mu_{\text{F}}^{\text{off-shell}}$	$0.86^{+0.92}_{-0.68}$ [0.0, 2.7]	$1.0^{+1.3}_{-1.0}$ [0.0, 3.5]
$\mu_{\text{V}}^{\text{off-shell}}$	$0.67^{+1.26}_{-0.61}$ [0.0, 3.6]	$1.0^{+3.8}_{-1.0}$ [0.0, 8.4]

→ 95% CL upper limit

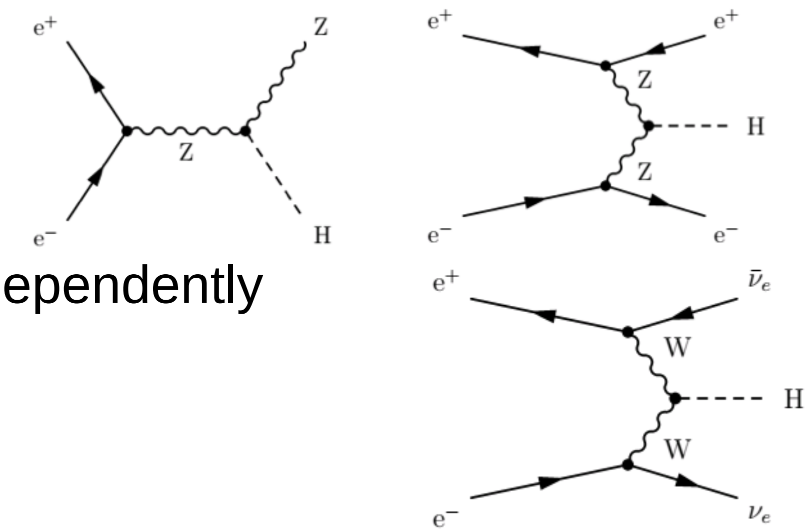
Expected sensitivity comparable to ATLAS results (36 fb^{-1}, 4l +2l2v): $\mu_{\text{off-shell}} < 3.4$
Phys. Lett. B 786 (2018) 223



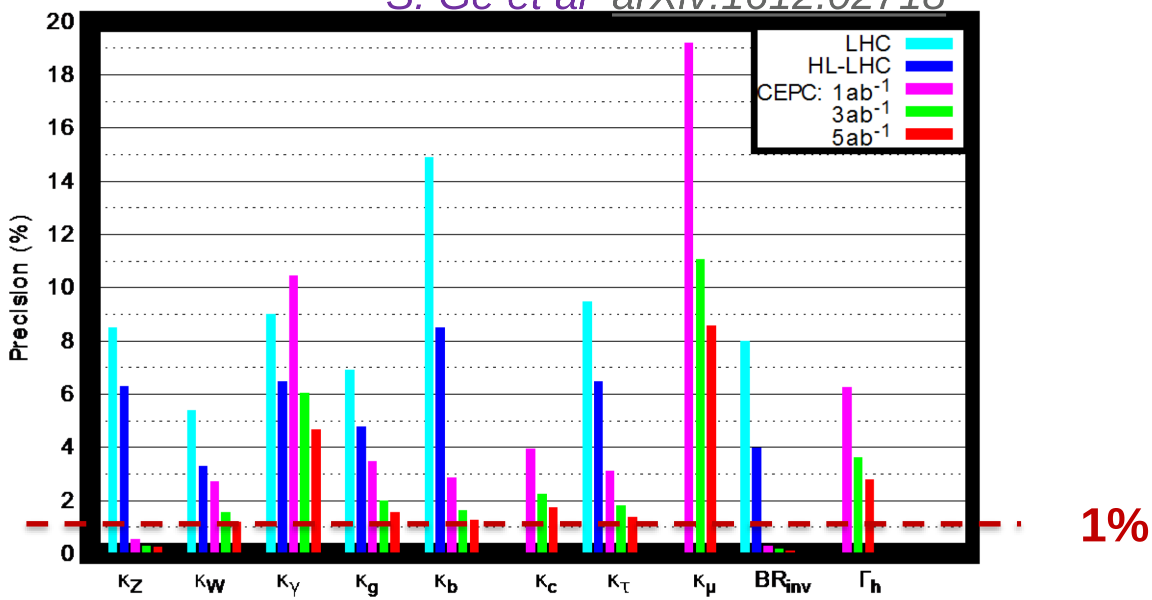


Prospects for Higgs properties measurements

- Prospects for future lepton collider
  - Much cleaner environment
  - Much smaller systematic uncertainties
  - Measure the Higgs decay Br model-independently
- CEPC 5ab^{-1} can reach O(1%)
  - ~1M Higgs bosons



S. Ge et al arXiv:1612.02718



Coupling modifications by new physics

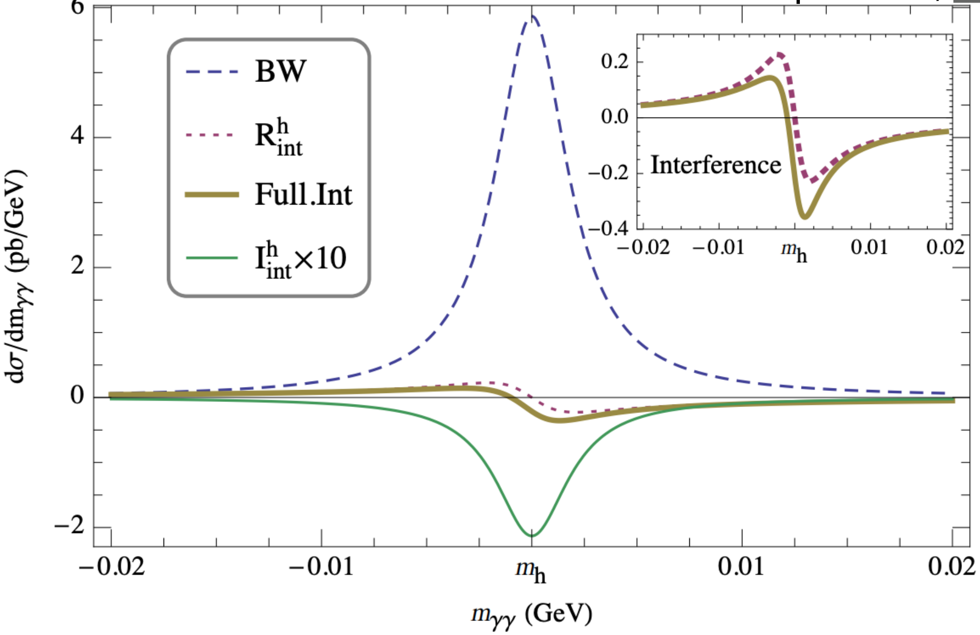
Generic size of Higgs coupling modifications from the Standard Model values when all new particles are M ~ 1 TeV and mixing angles satisfy precision electroweak fits.
Snowmass "Higgs working group report", arXiv:1310.8361

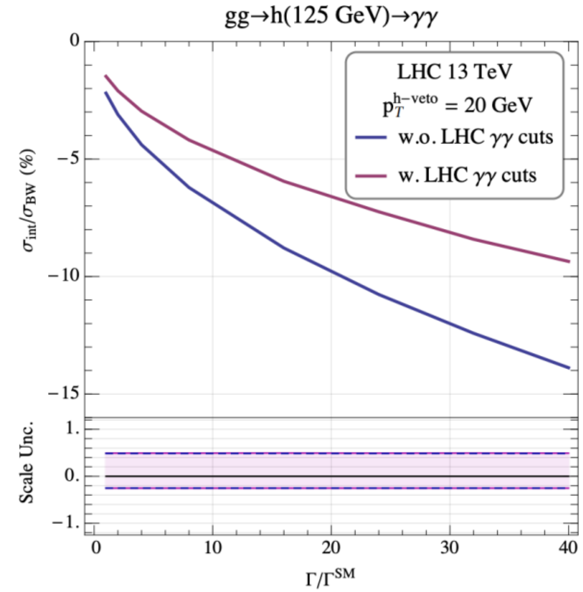
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

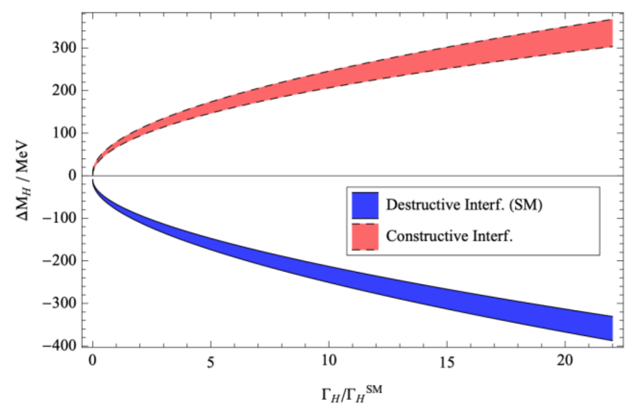
Interference effect in H→γγ

- Interference between gg→H→γγ (on-shell) and gg→γγ
  - Imaginary part: 2% reduction in the overall rate
  - Real part: mass shift
  - Both effects could be used to probe Γ_H

J. Campbell et al, PRL119(2017)1







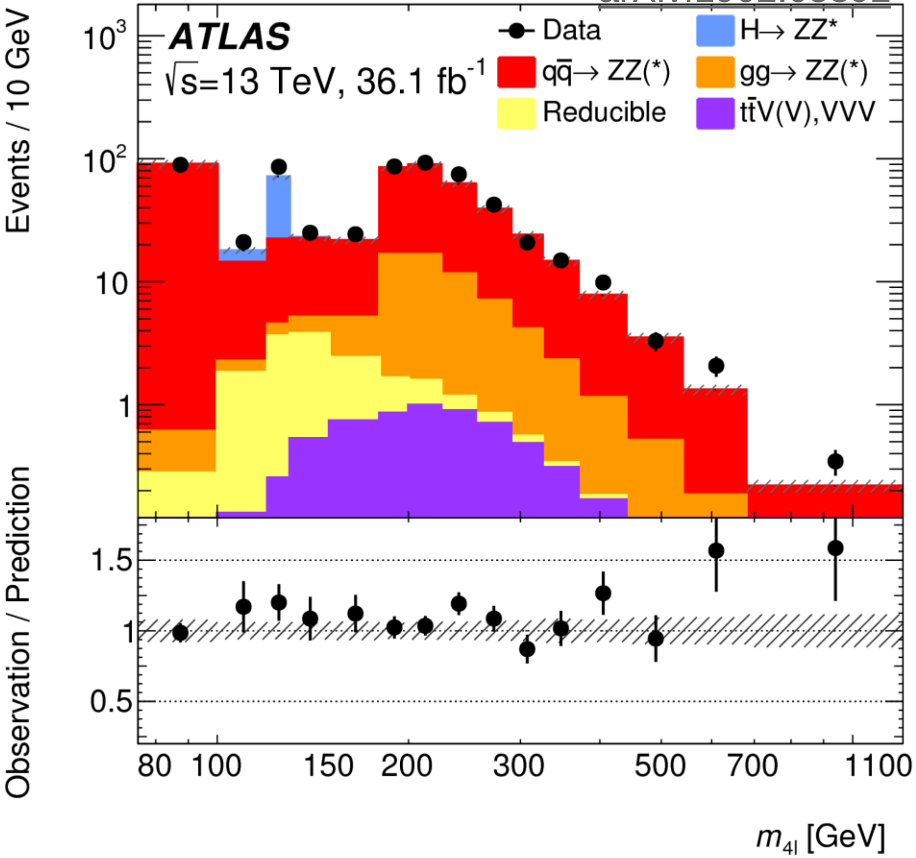
Δm_H = −35 ± 9 MeV (ATL-PHYS-PUB-2016-009)

L. Dixon, PRL.111(2013)111802
L. Dixon, M. Siu, PRL90(2003)252001

M4l

- Inclusive 4l invariant mass spectrum

arXiv:1902.05892



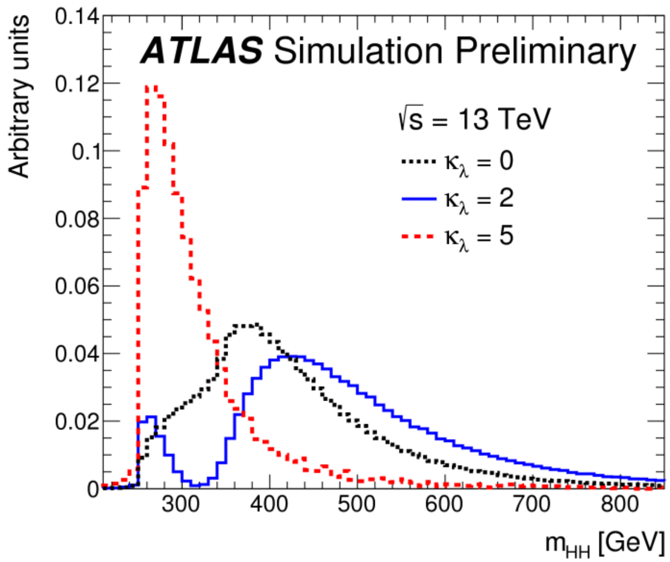
ATLAS-CONF-2018-018

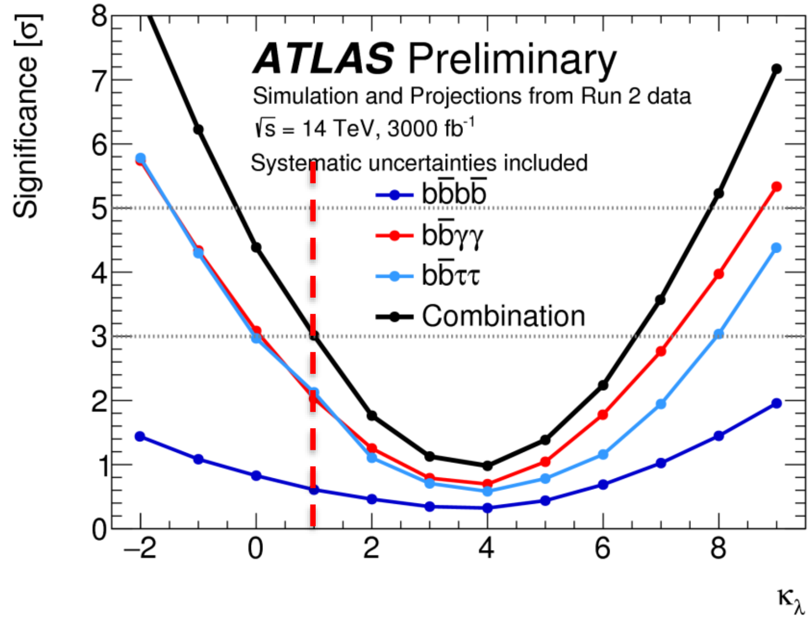
Leptons and jets	
eptons:	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
ets:	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
emove jets with:	$\Delta R(\text{jet}, \ell) < 0.1$
Lepton selection and pairing	
epton kinematics:	$p_T > 20, 15, 10$ GeV
eading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
ubleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
lass requirements:	50 GeV$< m_{12} < 106$ GeV and 12 GeV $< m_{34} < 115$ GeV
epton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
lass window:	115 GeV $< m_{4\ell} < 130$ GeV
extra leptons with $p_T > 12$ GeV:	Quadruplet with the largest ME

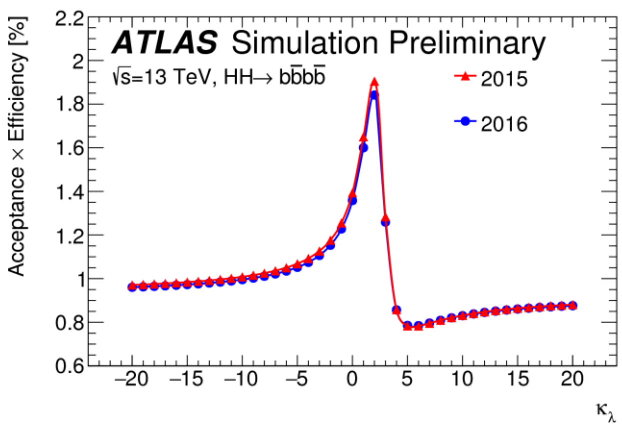
DiHiggs

- Higgs self coupling changes both signal cross sections and kinematic shapes

ATLAS-CONF-2018-043







Vacuum stability

A. Andreassen et al
PRD.97.056006(2018)