Experimental status of the scalar sector at the LHC

On behalf of the ATLAS and CMS Collaborations

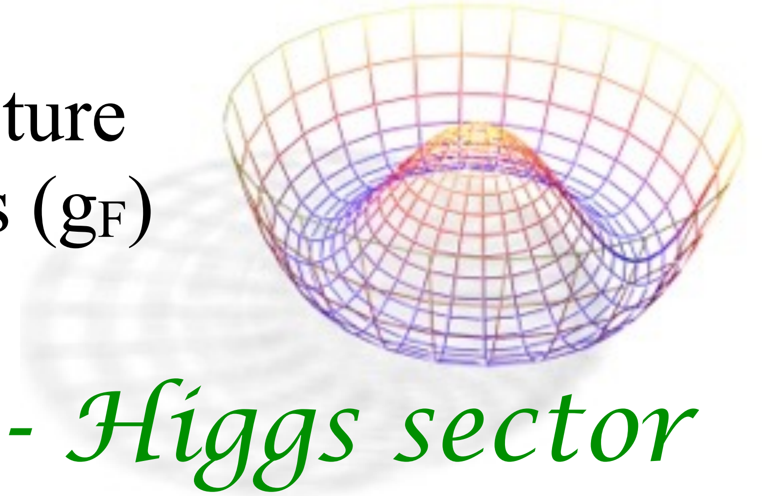
Reisaburo TANAKA
LAL-Orsay, April 18, 2017

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

CNRS IN2P3 Les deux infinis

Higgs Boson Property Measurements

K. Cranmer



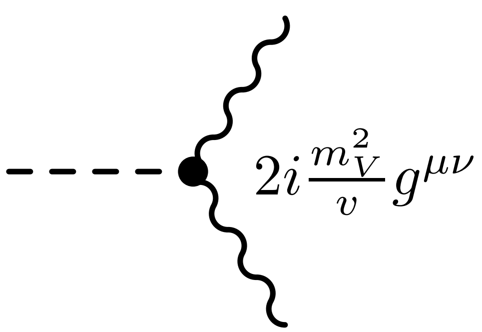
1. Higgs boson mass (M_H) & decay width (Γ_H)
2. Higgs boson quantum numbers J^{PC} and tensor structure
3. Higgs couplings to gauge bosons (g_V) and fermions (g_F)
4. Higgs potential - Higgs self-coupling (λ)

The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

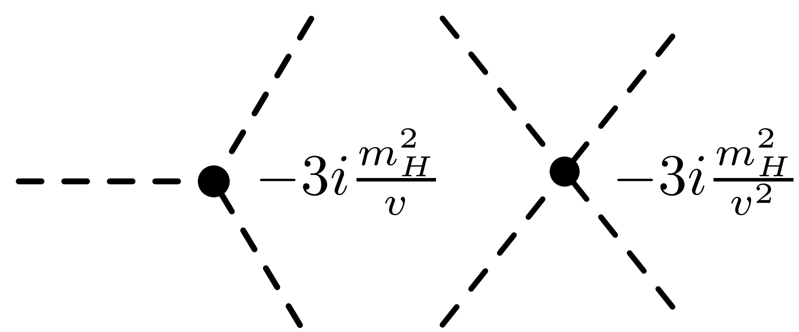
Couplings to
EW gauge bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$



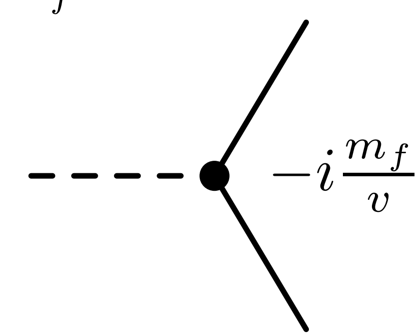
Higgs
self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$



Couplings to
fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value, } 246\,\text{GeV})$$

The ultimate goal of particle physics of today is to fix the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).

Electroweak Symmetry Breaking (EWSB)

LHC early discovery?

Extended Gauge Symmetry

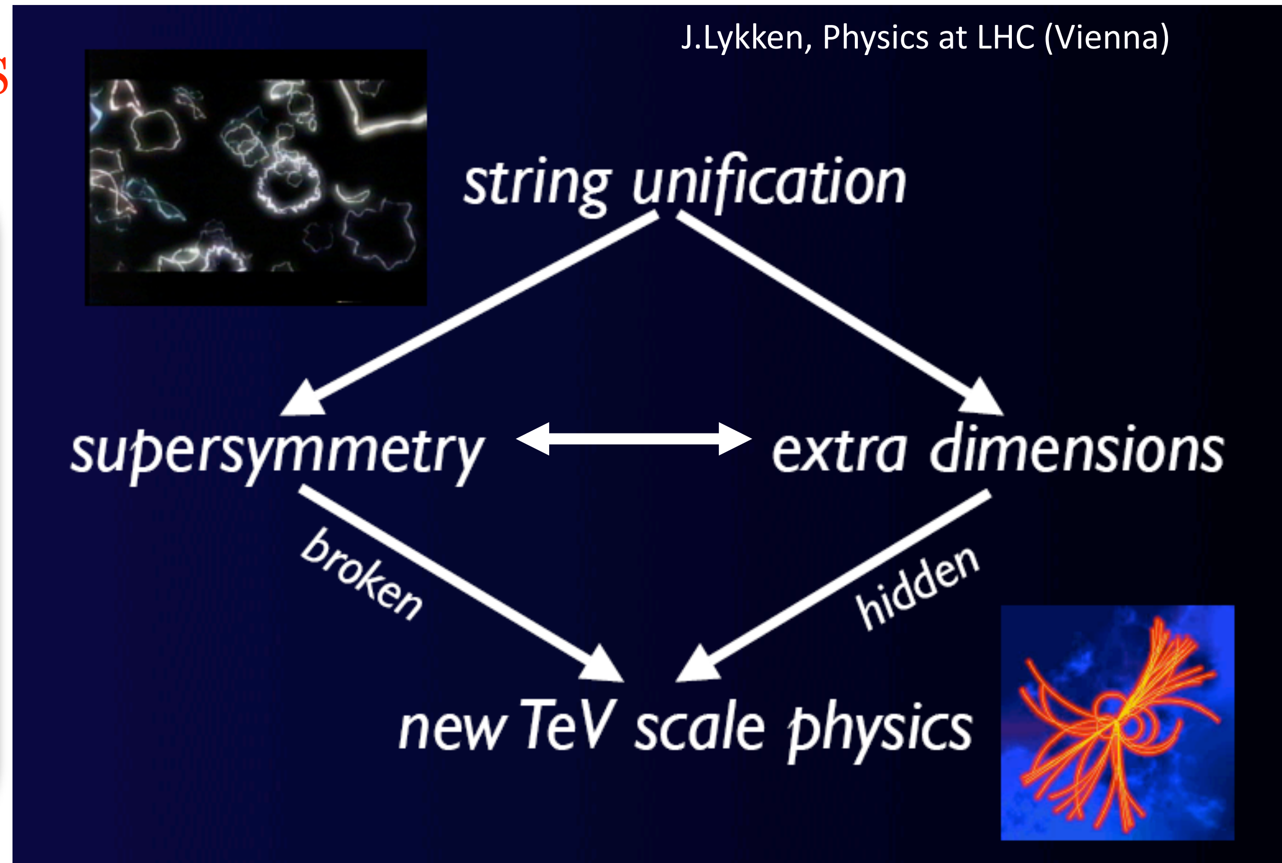
~~Higgsless~~ **Twin Higgs**

Left-Right Symmetric Model, Gauge-Higgs Unification

W', Z'

$\tilde{g}/\tilde{q}$, xMSSM Higgs

SUSY
(m)SUGRA
GMSB
AMSB
Mirage
Split SUSY
RPV, …



Graviton, BH

Extra-Dimension
LED(ADD)
Randall-Sundrum
Universal ED(KK)
…

Resonances

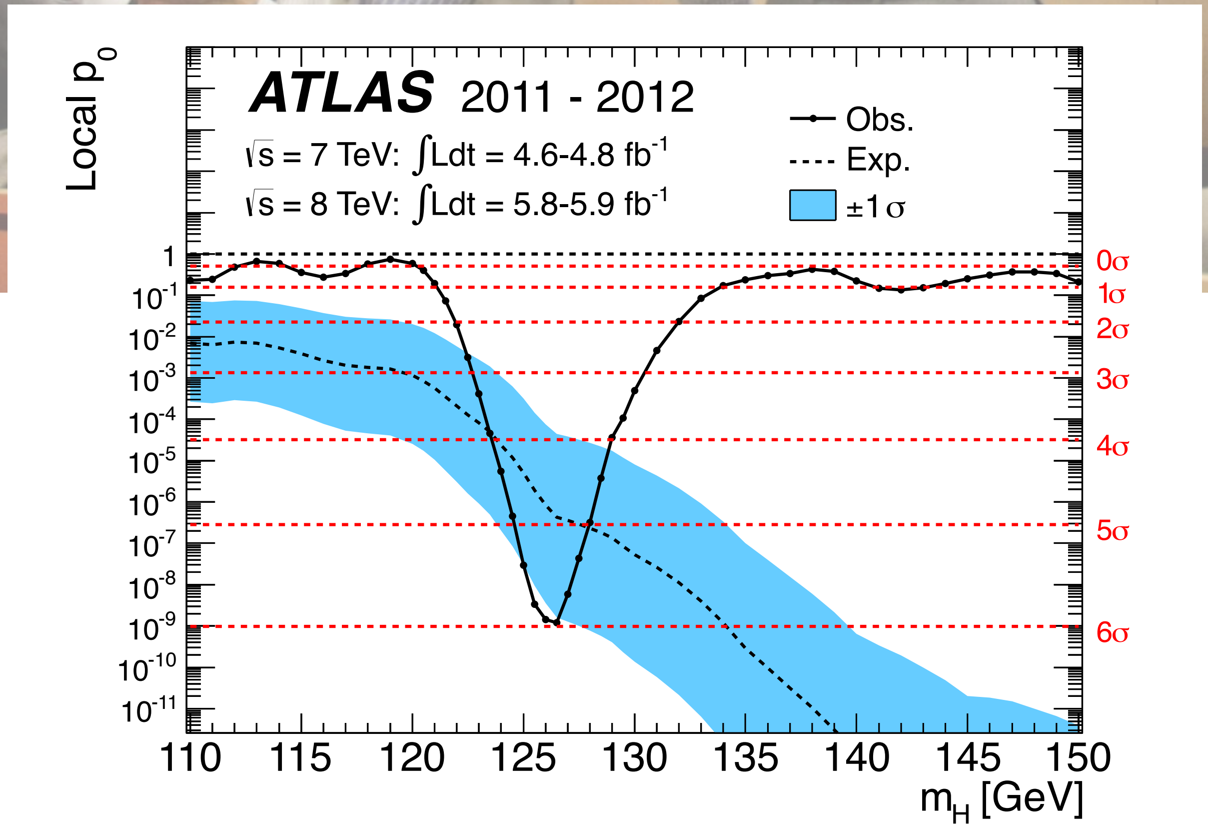
Dynamical Symmetry Breaking
Strong EWSB, Chiral Lagrangian, Technicolor
Top-quark Condensation
Composite Higgs, Little Higgs

Precision EW data

Poor experimentalist's compilation of models. Perhaps "Not even wrong"!

What do we know about the scalar sector 5 years after July 4th 2012 discovery ?

PLB 716 (2012) 1



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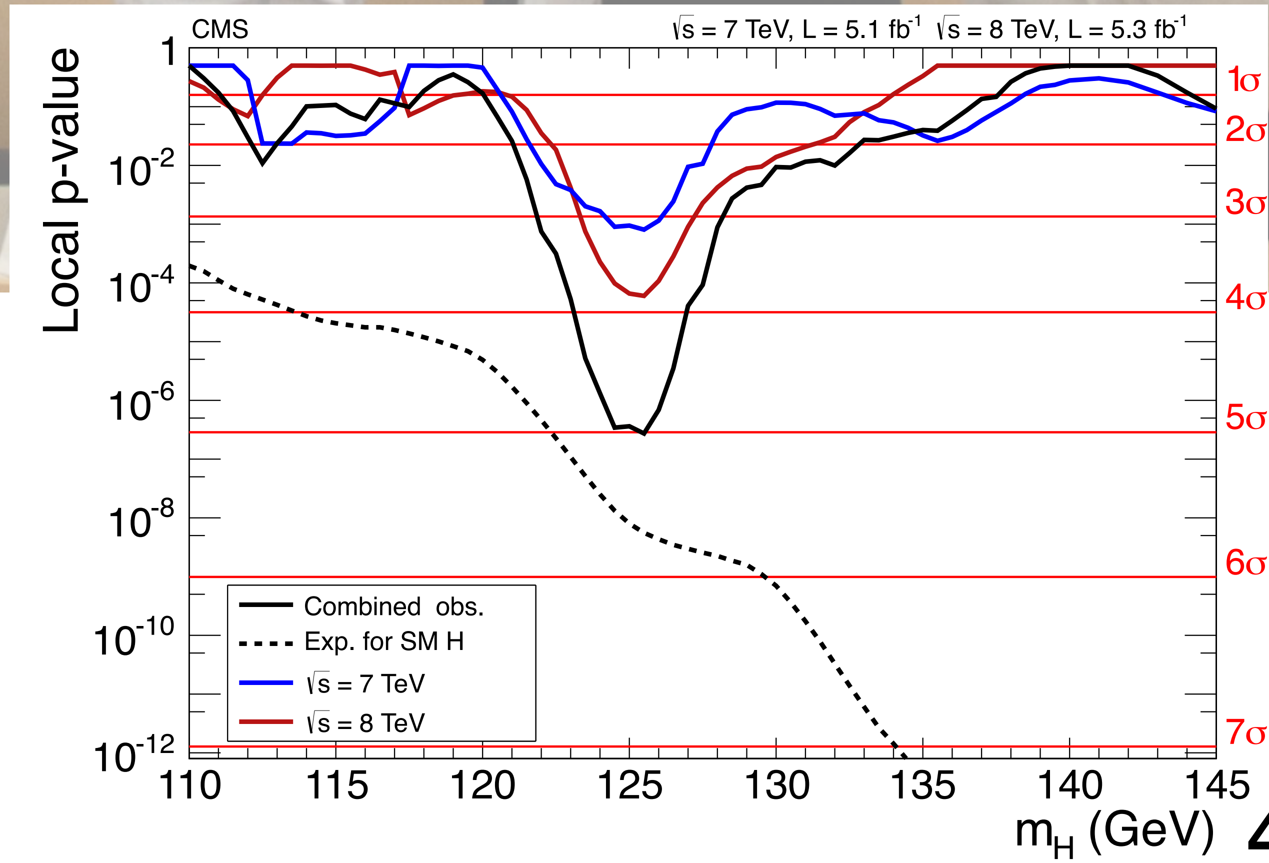
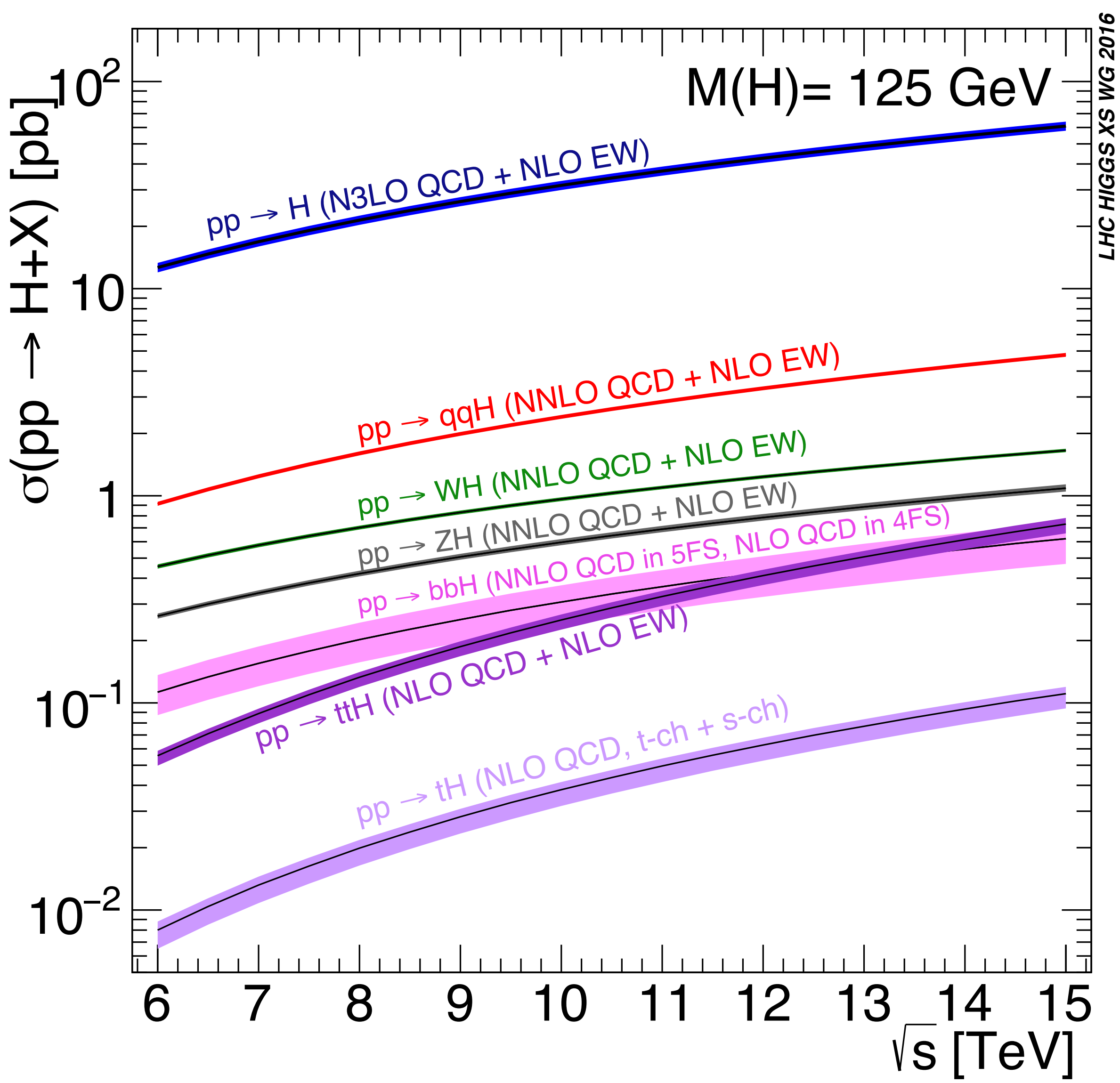
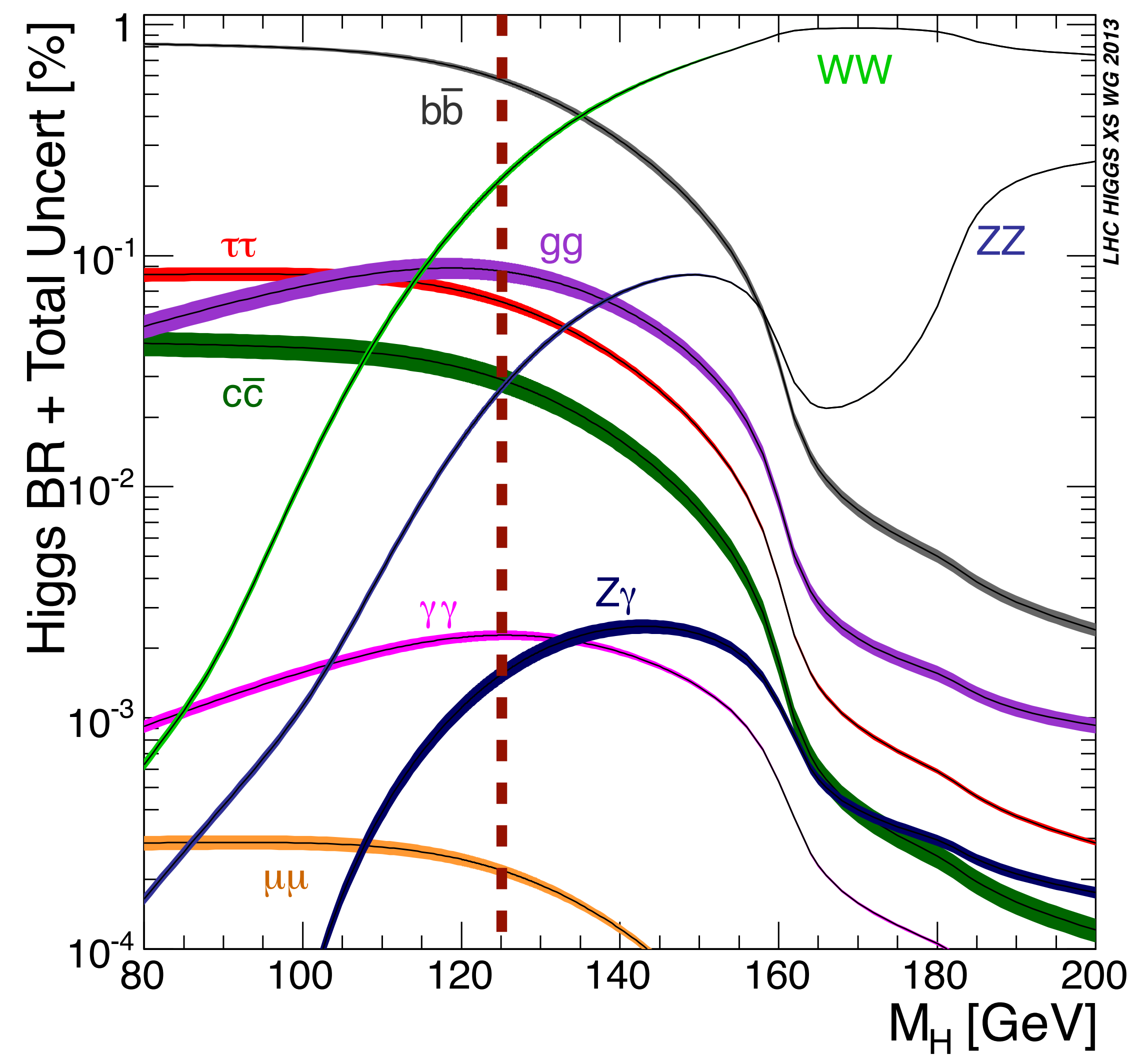


1. Higgs Boson Production and Decay

Higgs Boson Production and Decay





LHC Higgs XS WG CERN Reports

Handbook of LHC Higgs Cross Sections:

1. Inclusive Observables (CERN 2011-002, 151 pp)
2. Differential Distributions (CERN 2012-002, 275 pp)
3. Higgs Properties (CERN 2013-004, 392 pp)
4. Deciphering the nature of the Higgs sector (CERN–2017–002-M, 869 pp)

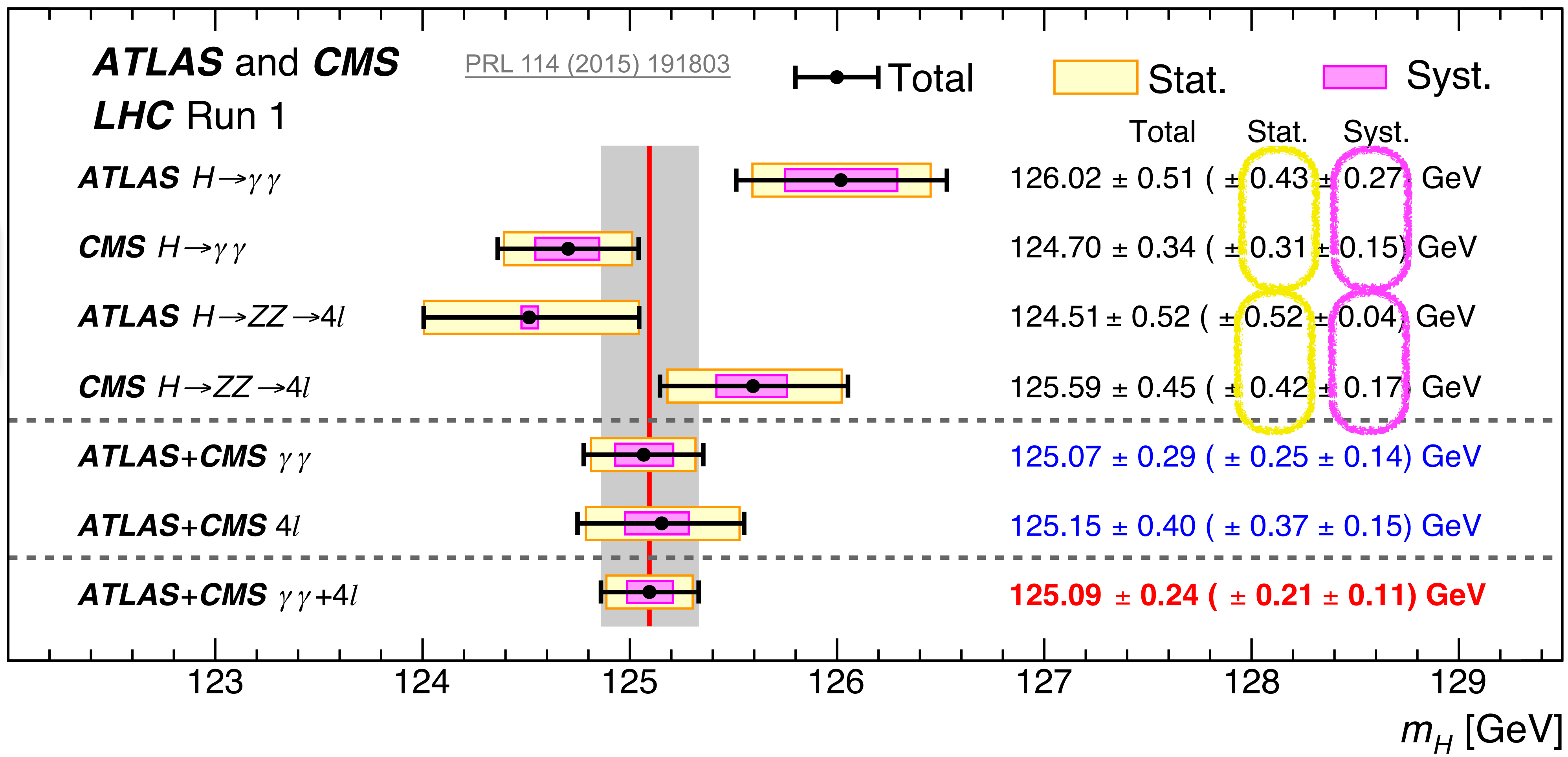
New

2. Higgs Boson Mass, Width and Spin/CP

Higgs Boson Mass

- M_H - the only parameter not fixed in the Standard Model ➪ Fixes $\lambda = \frac{M_H^2}{v^2}$.
- Most precisely determined with H→γγ and 4 lepton channels.
  - γγ: CMS stat. uncert. smaller as core resol., syst. smaller due to homogen. ECAL.
  - 4l: ATLAS small exp. syst. uncert. thanks to improvements in calibration for e/γ and muon.

RUN-1



Weight

19%

40%

18%

23%

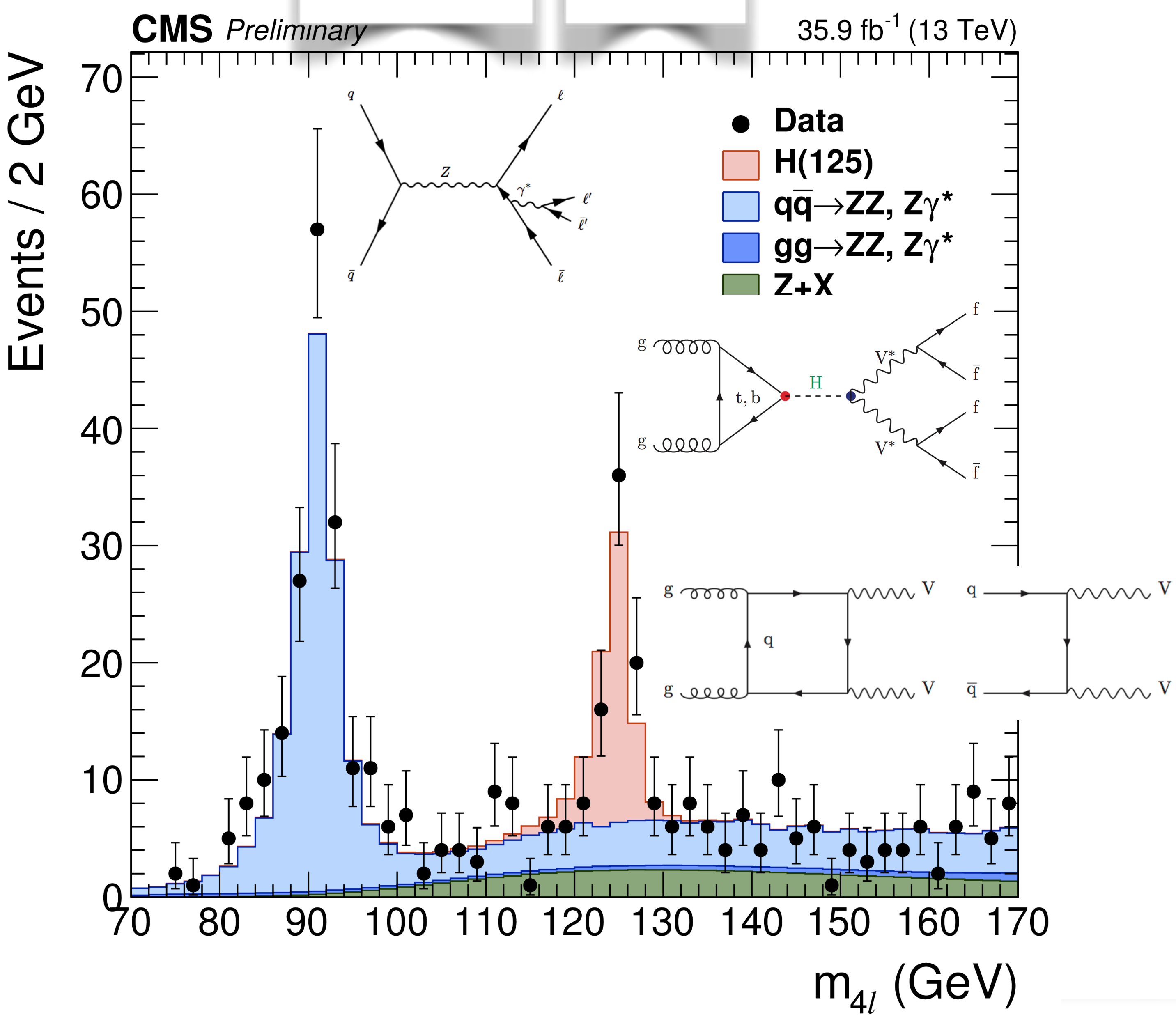
ATLAS+CMS M_H = 125.09 ± 0.21 (stat.) ± 0.11 (syst.) = 125.09 ± 0.24 GeV

- δM_H precision below 0.3% level for single A&C and 0.2% level for combined.
- Already at impressive accuracy (PDG2014: δM_W~190ppm, δM_Z~23ppm, δM_{top}~0.5%).
- Need to further improve in future? (M_{top} more important) For Higgs BR in ILC?

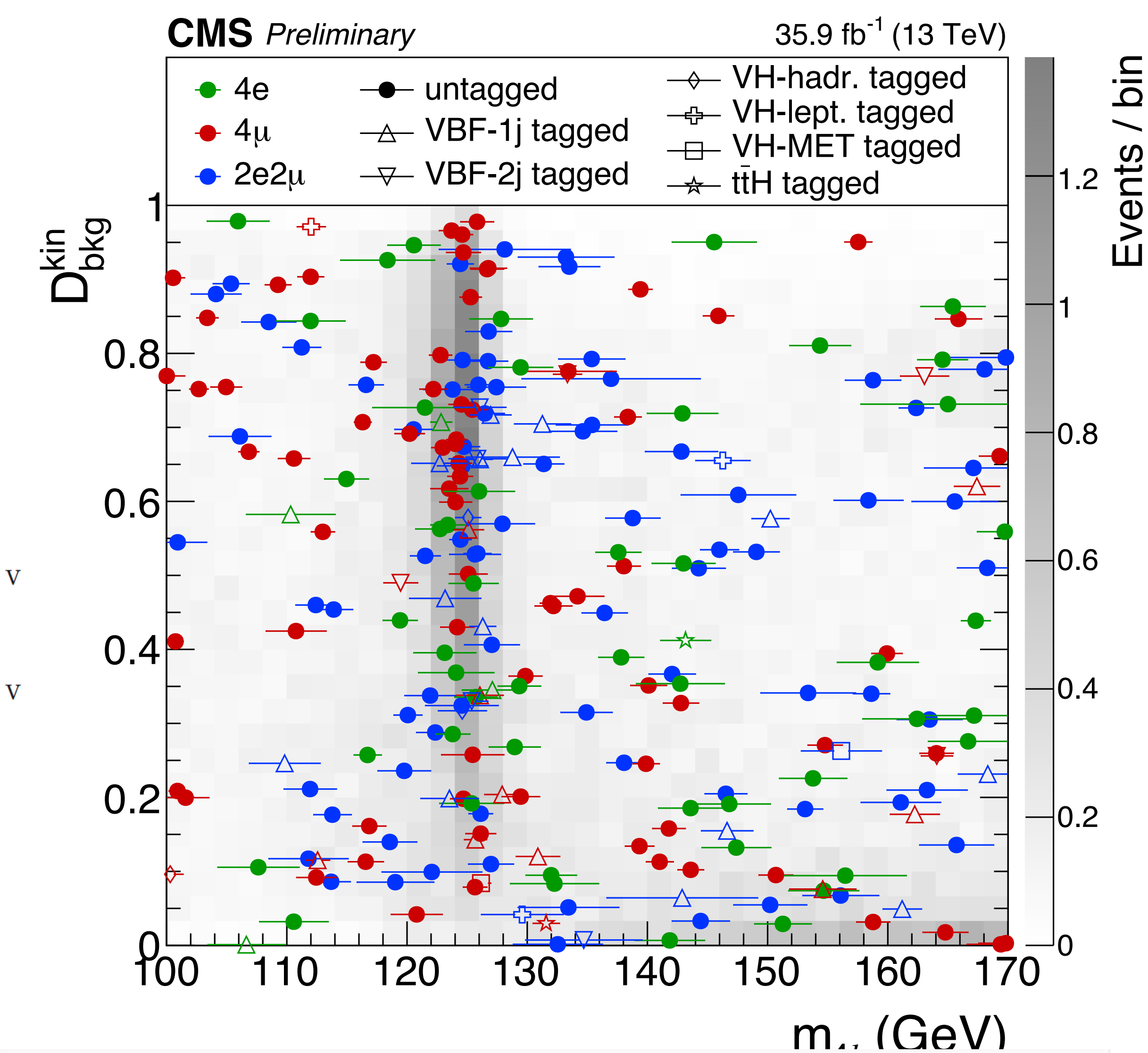
Higgs Boson Mass in H→4l

- Sophisticated 3D analysis with m_{4l} vs kinematical discriminant vs per-event m_{4l} error (CMS).

RUN-2 New CMS-PAS-HIG-16-041



$$\mathcal{D}_{\text{bkg}}^{\text{kin}} = \frac{\mathcal{P}_{0+}^{\text{kin}}}{\mathcal{P}_{0+}^{\text{kin}} + \mathcal{P}_{\text{bkg}}^{\text{kin}}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}^{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0+}^{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$



ATLAS+CMS $M_H = 125.09 \pm 0.21$ **(stat.)** $\pm\ 0.11$ **(syst.)** $= 125.09 \pm 0.24$ **GeV**

CMS: $M_H^{4l} = 125.26 \pm 0.20$ **(stat.)** $\pm\ 0.08$ **(syst.)** $= 125.26 \pm 0.22$ **GeV**

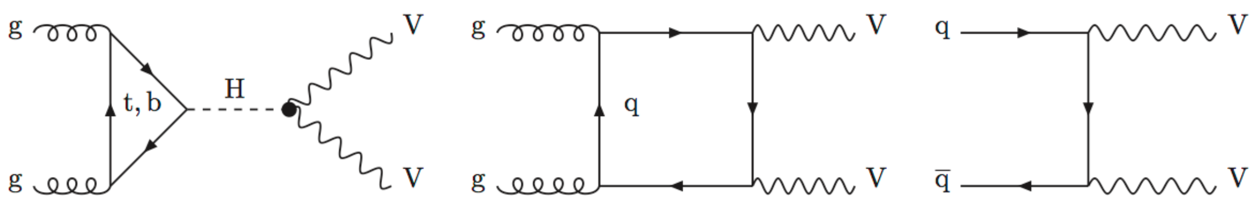
CMS has analyzed > 2 more events than RUN-1 ATLAS&CMS !

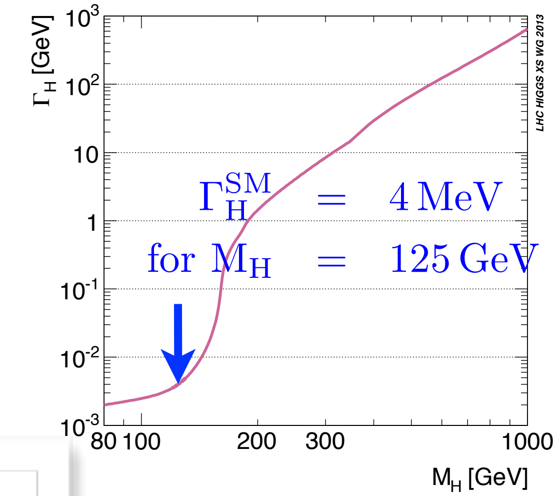
Higgs Width via Interferometry in H→4l

- Kauer-Passarino-Caola-Melnikov Effect
  - Off-shell signal cross section is independent of Γ_H !
  - On-shell signal cross section is proportional to $1/\Gamma_H$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{(2M_Z)^2}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{m_H \Gamma_H}$$

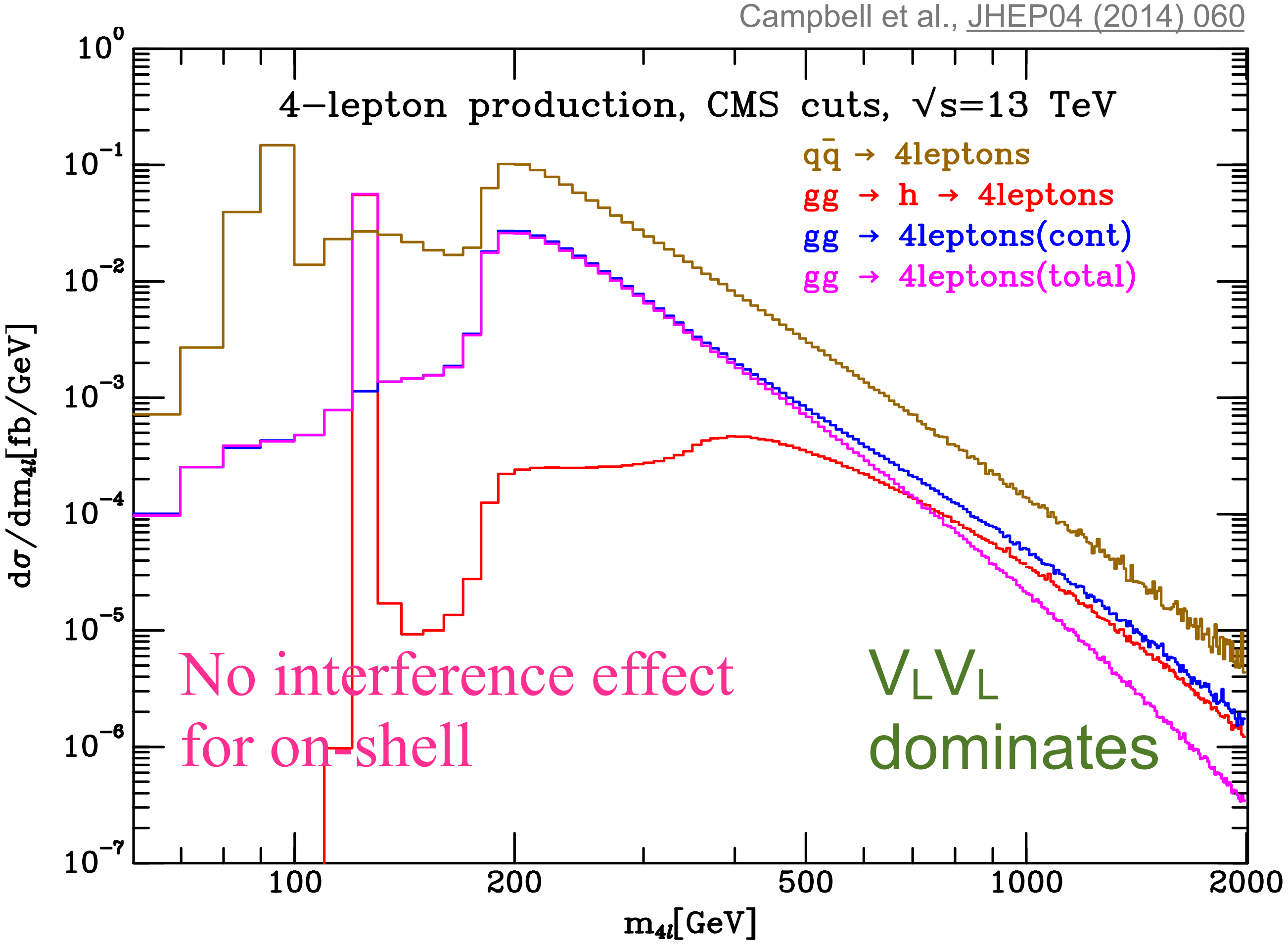


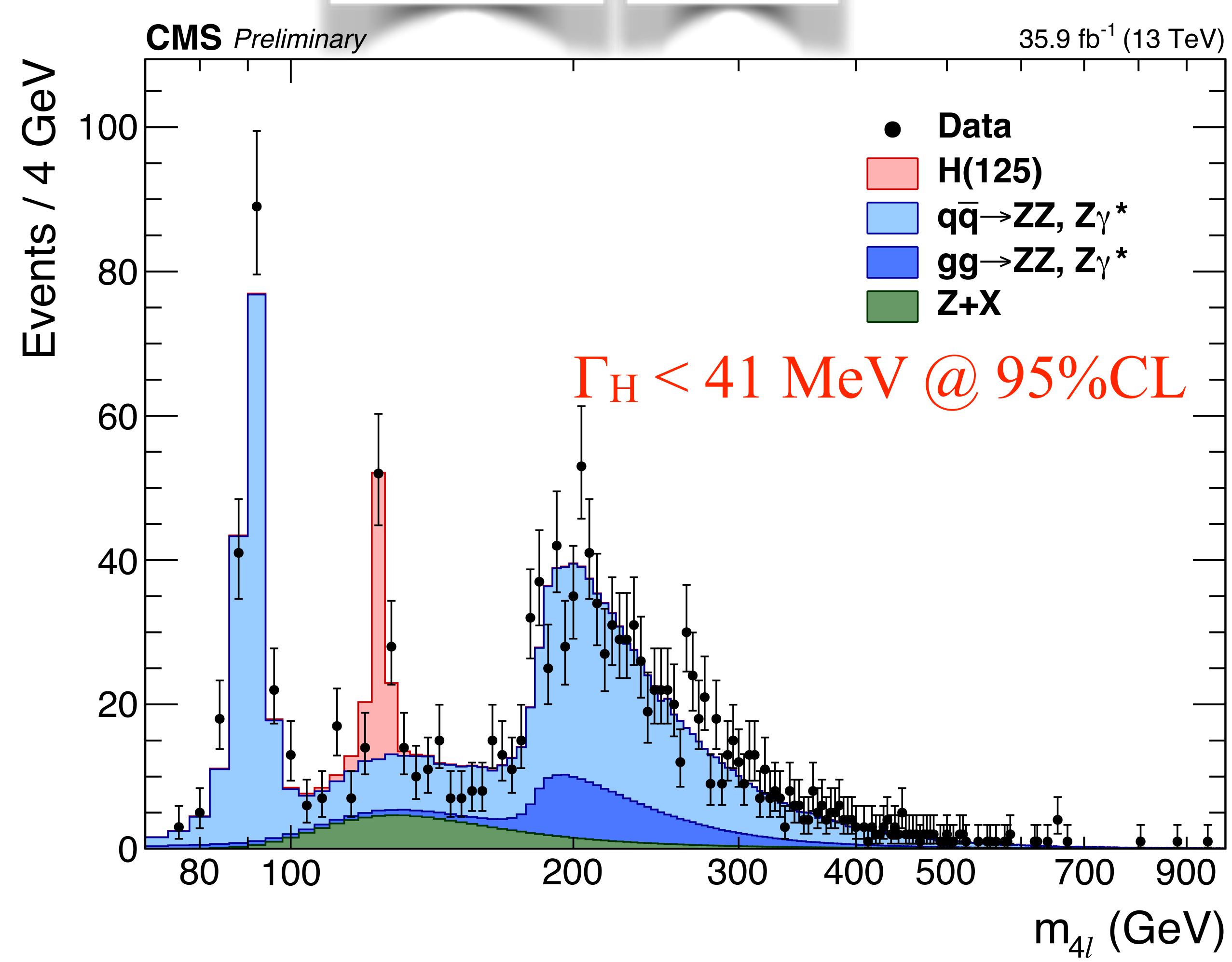


RUN-2 **New**

CMS-PAS-HIG-16-041

Campbell et al., JHEP04 (2014) 060





➩ Interpretation rather should be done in term of off-shell coupling.

Higgs Boson Quantum Numbers

- What are the quantum numbers of observed state X ?
  - J^{PC}: J=spin, P=parity, C=charge conjugation
- Spin0: Standard Model Higgs boson
  - The Standard Model Higgs boson is scalar particle (0^+).
  - CP-mixing/violation in spin-0 can exist but small in many BSM models.
- Spin1: Landau-Yang theorem
  - Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of massless particles.
  - Observation of $H \rightarrow \gamma\gamma$ rules out the possibility that the new resonance has spin 1, and fixes *C*=1 (barring *C* violating effects in the Higgs sector).
  - This theorem strictly applies to an on-shell resonance (*i.e.* small width hypothesis).
- Spin2: graviton
  - Theoretically difficult. Velo-Zwanziger problem with U(1) gauge field.
  - Who will be responsible for electroweak symmetry breaking?
  - Why haven't we observed analogous KK excitations of SM gauge bosons?

Studied with $H \rightarrow \gamma\gamma$, ZZ^* and WW^* in RUN-1 and confirmed it is 0^+.

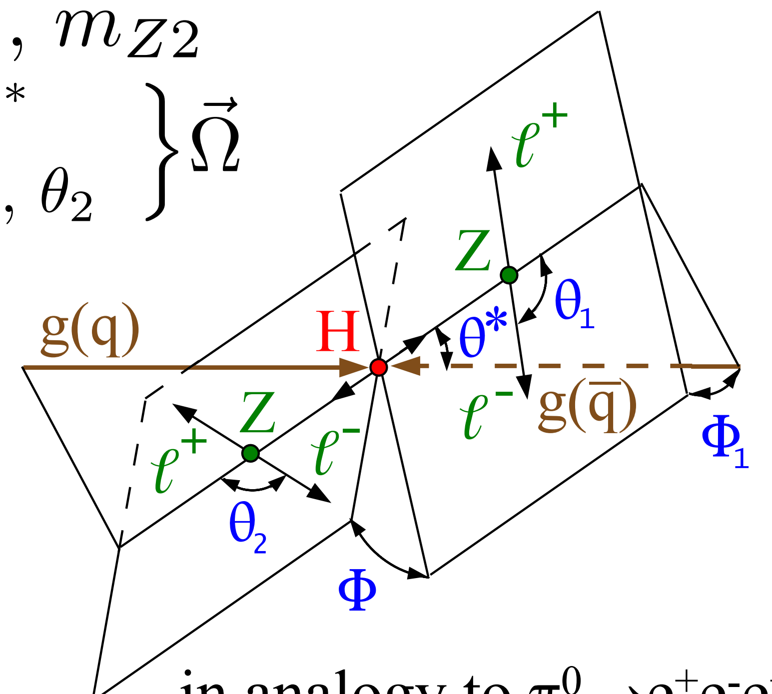
Higgs spin/CP: combined results

RUN-1

$pp \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$

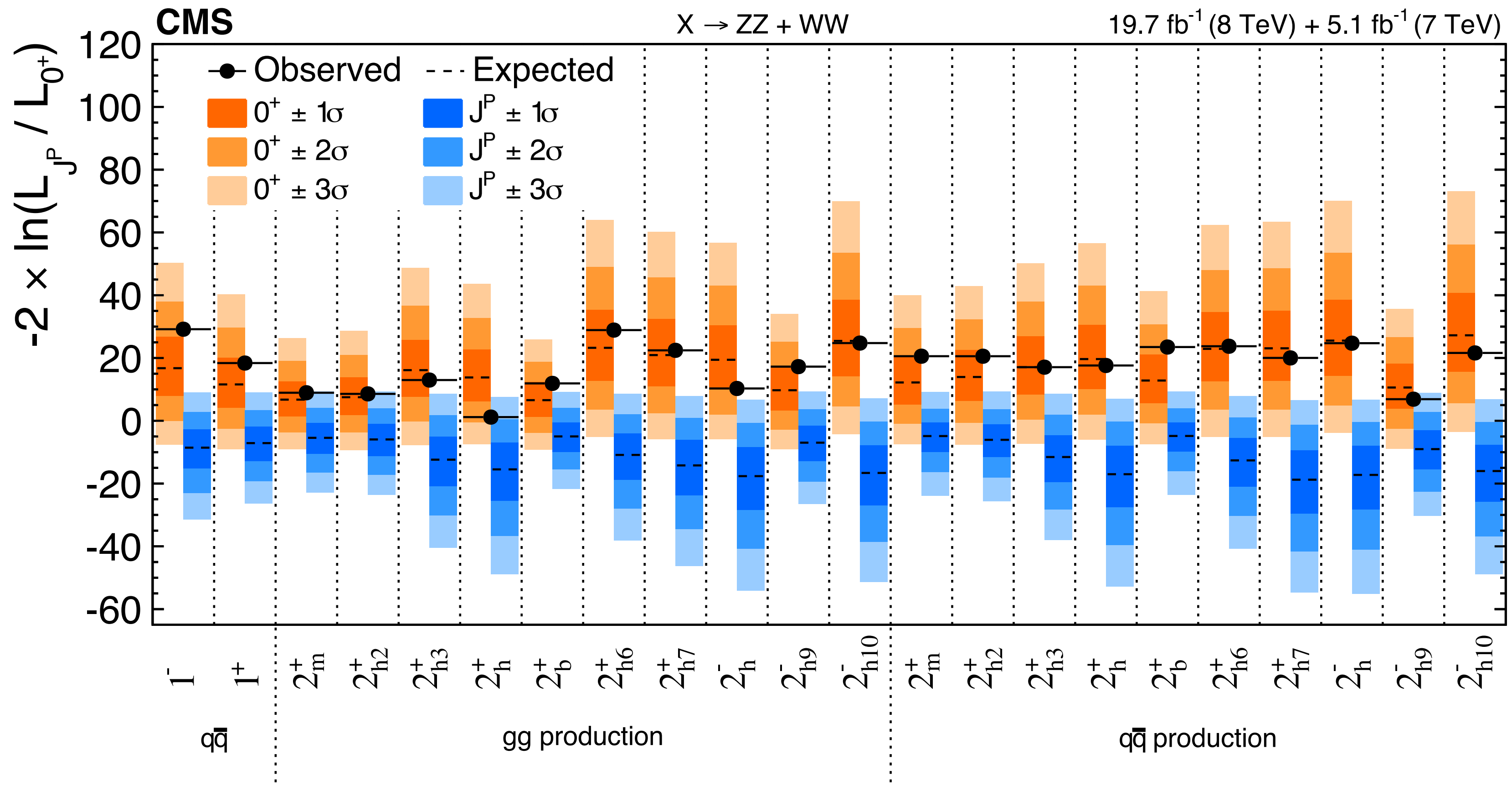
$m_{Z1},\ m_{Z2}$

$\left.\begin{array}{l}\Phi_1,\ \theta^* \\ \Phi,\ \theta_1,\ \theta_2\end{array}\right\}\vec{\Omega}$



in analogy to $\pi^0 \to e^+e^-e^+e^-$

PRD 92 (2015) 012004



No event yield information (cross section) was used but shape only in the analyses.

PLB 726 (2013) 120

- Exclude pure $J^P=0^-$, $1^\pm$, 2^+ (minimal coupling) at more than 99% C.L.
- But note that LHC has not tested all models !
- Large CP-mixing/violation is still possible.

3. Higgs Boson Couplings to EW Gauge Bosons

LHC Higgs XS WG CERN Report 3

Higgs signal-strength

LO κ-framework

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

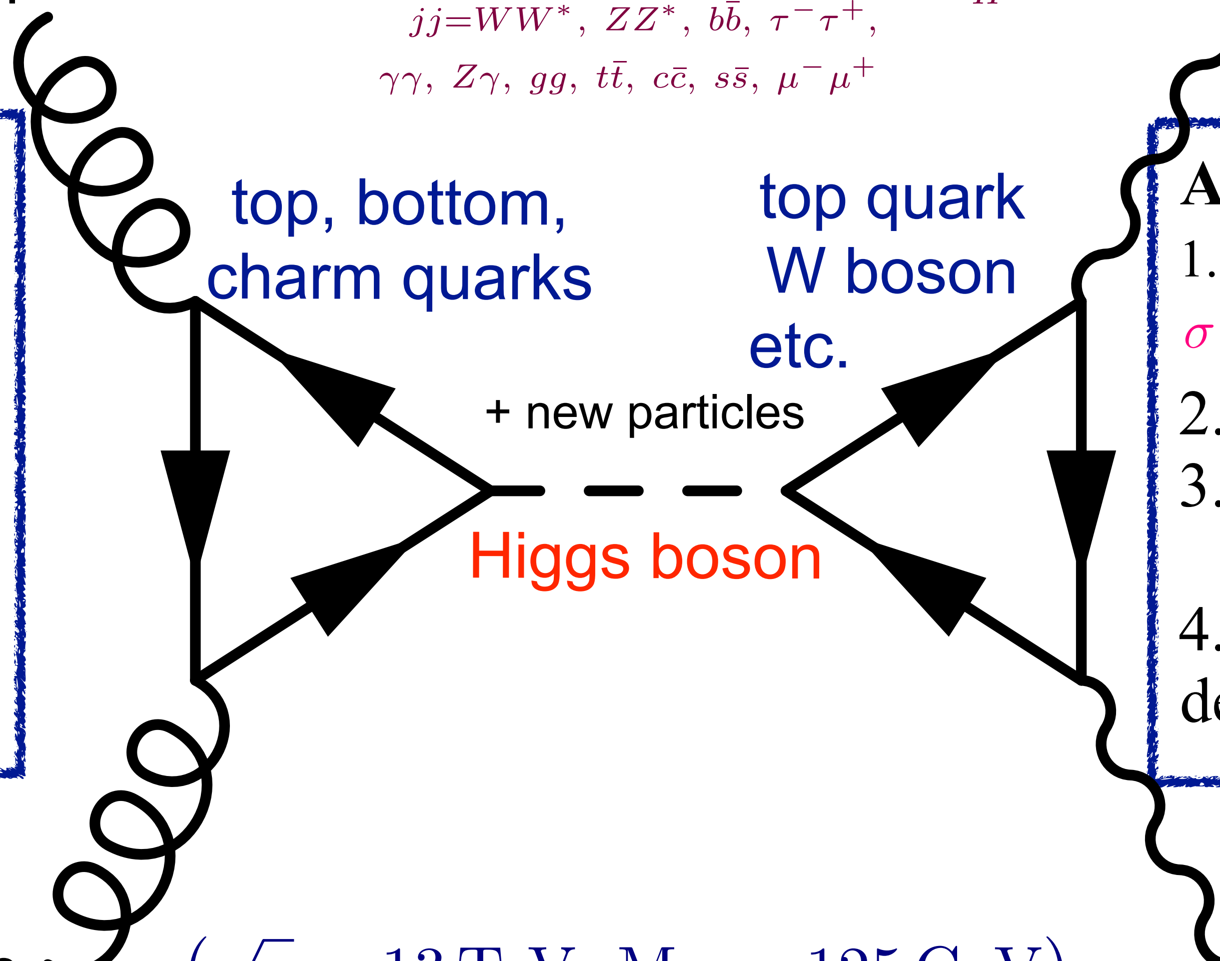
$$\mu = \frac{(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma)}{\{\sigma(gg \to \mathrm{H}) \cdot \mathrm{BR}(\mathrm{H} \to \gamma\gamma)\}_{\mathrm{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

$$\kappa_{\mathbf{H}}^{\mathbf{2}} = \sum_{\substack{jj=WW^*,\, ZZ^*,\, b\bar{b},\, \tau^-\tau^+,\\ \gamma\gamma,\, Z\gamma,\, gg,\, t\bar{t},\, c\bar{c},\, s\bar{s},\, \mu^-\mu^+}} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

- Measure with coupling scale factors κ_i.
- The coupling of SM particles to Higgs boson scales with particle mass:

$$g_F = \sqrt{2}\frac{m_f}{v},\ g_V = 2\frac{m_V^2}{v}$$

- Holds up to electroweak effects of O(5-10%).



Assumptions

1. narrow width approx.
$\sigma \cdot \mathbf{BR}\ (\mathbf{ii} \to \mathbf{H} \to \mathbf{ff}) = \frac{\sigma_{\mathbf{ii}} \cdot \Gamma_{\mathbf{ff}}}{\Gamma_{\mathbf{H}}}$
2. only 1 SM-like Higgs
3. SM tensor structure (spin 0, CP-even)
4. on-shell production and decay (no-sense for offshell).

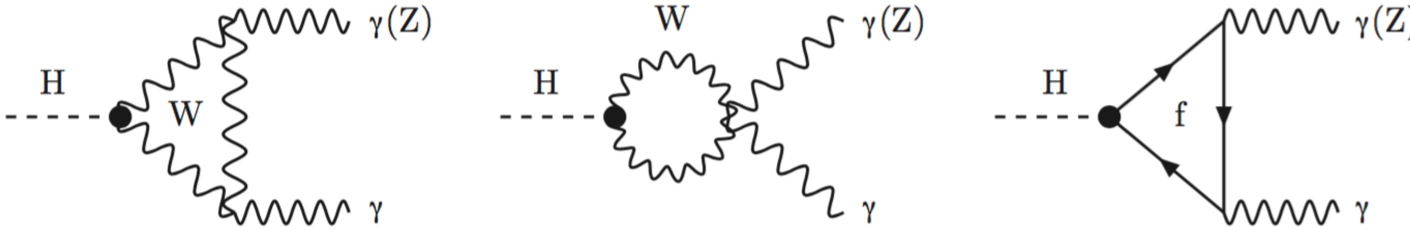
$$\left(\sqrt{s} = 13\,\mathrm{TeV},\ \mathrm{M_H} = 125\,\mathrm{GeV}\right)$$

$$\begin{aligned}\kappa_g^2(\kappa_t, \kappa_b, \kappa_c) &= 1.040\kappa_t^2 + 0.002\kappa_b^2 + 0.00002\kappa_c^2 \\ &- 0.038\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0004\kappa_b\kappa_c\end{aligned}$$

$$\kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

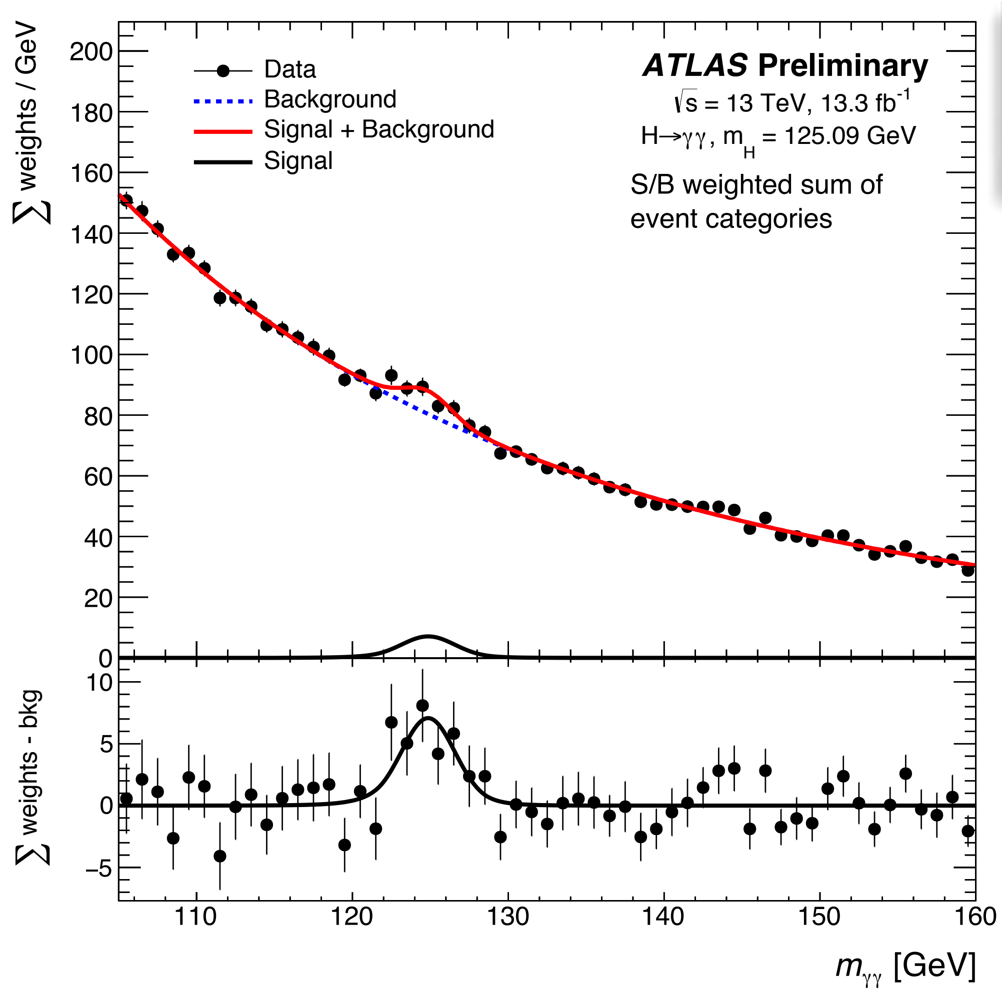
Destructive interference in both gg→H (top-bottom) and H→γγ (W-top) loops.

$H\to\gamma\gamma$



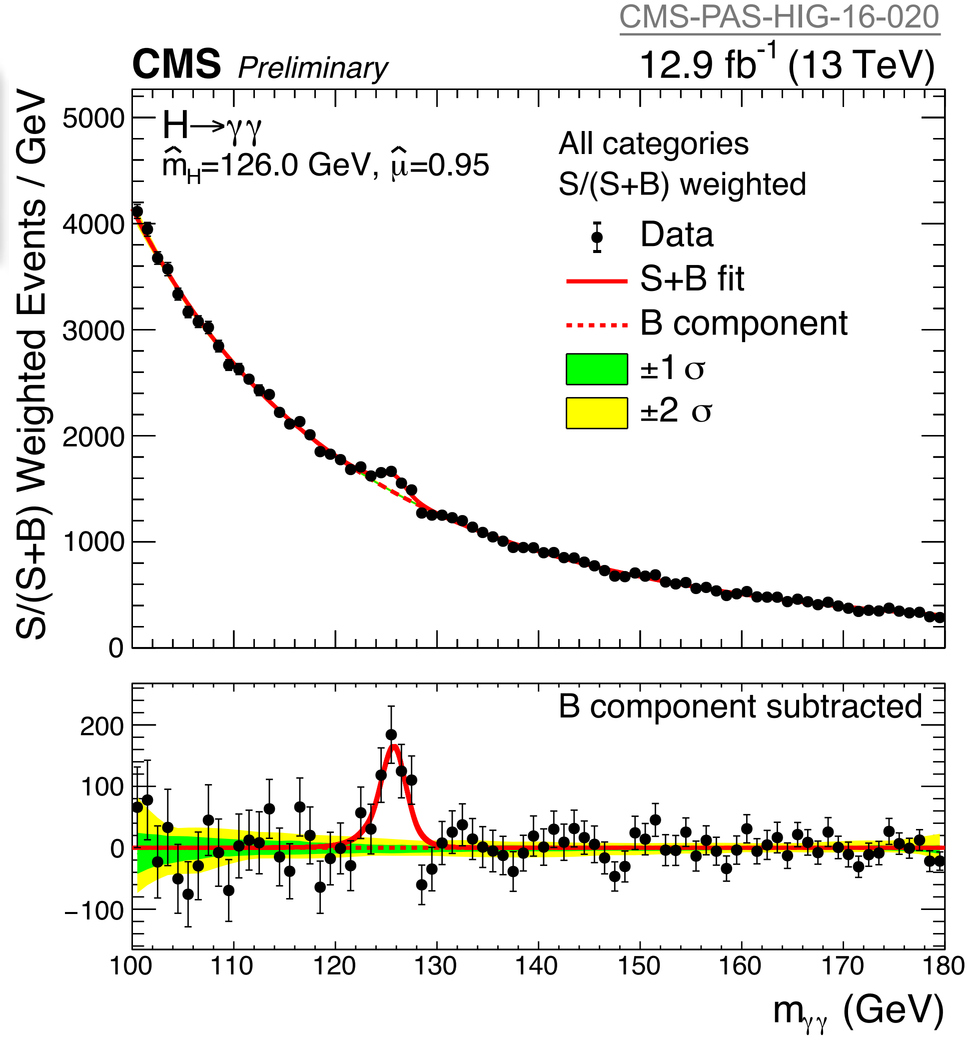
- Despite small BR($H\to\gamma\gamma$)=2.27×10^{-3} for M_H=125GeV, very clean signal.
- Large continuum backgrounds (γγ, γ+jets, fake photons).
- Signals are extracted by fitting the diphoton invariant mass spectrum.
  - Key issues: background shape, photon energy calibration from $Z\to e^+e^-$ and isolation.
- Re-discovery of Higgs boson at $\sqrt{s}$=13TeV.
  - Maximal observed significance by CMS is 6.1σ @ M_H=126GeV.

ATLAS-CONF-2016-067



RUN-2

CMS-PAS-HIG-16-020

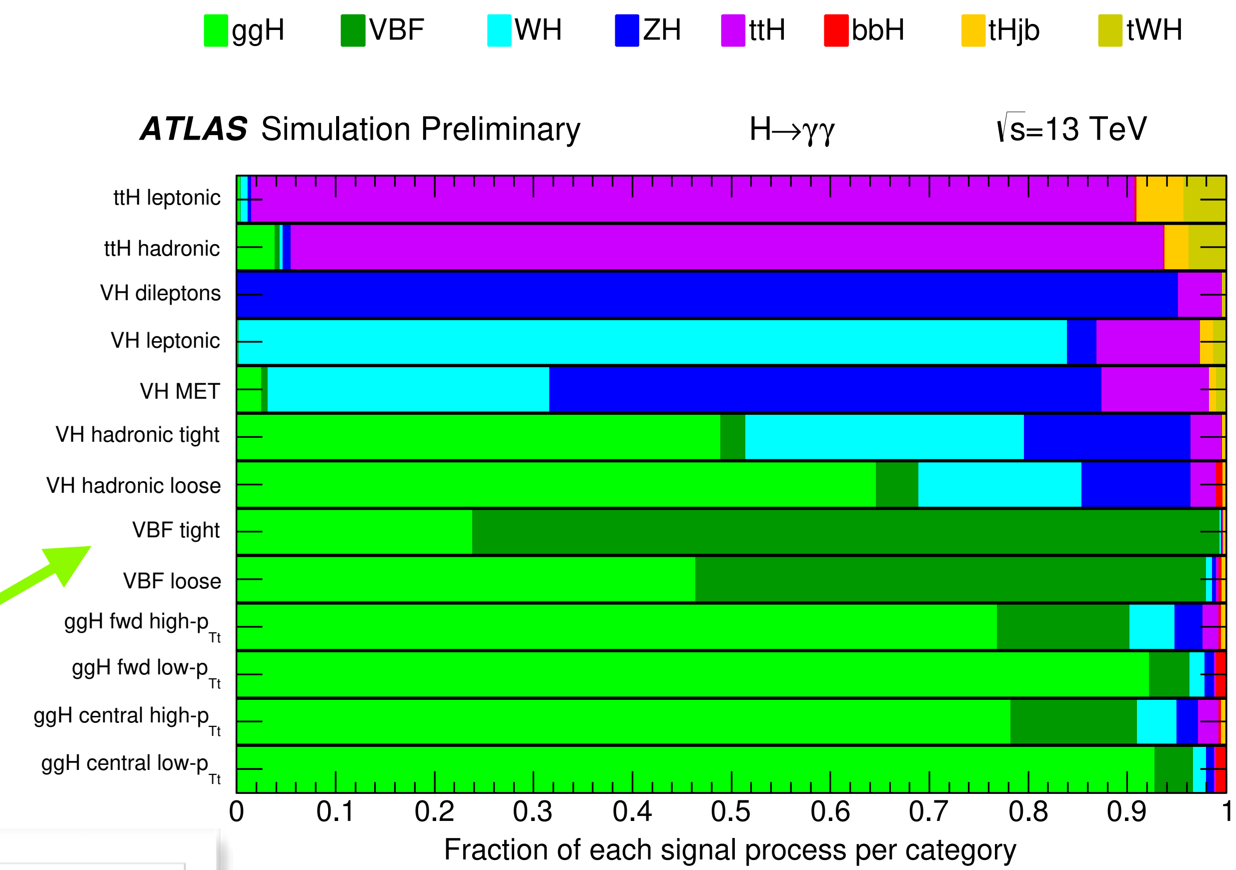


ATLAS-CONF-2016-067

H→γγ

- Signal strength is obtained for each Higgs boson production mode.
- Categorize events by production topology
  - ttH, VH, VBF and ggF (with p_T)

Large ggF contamination in VBF category



RUN-2

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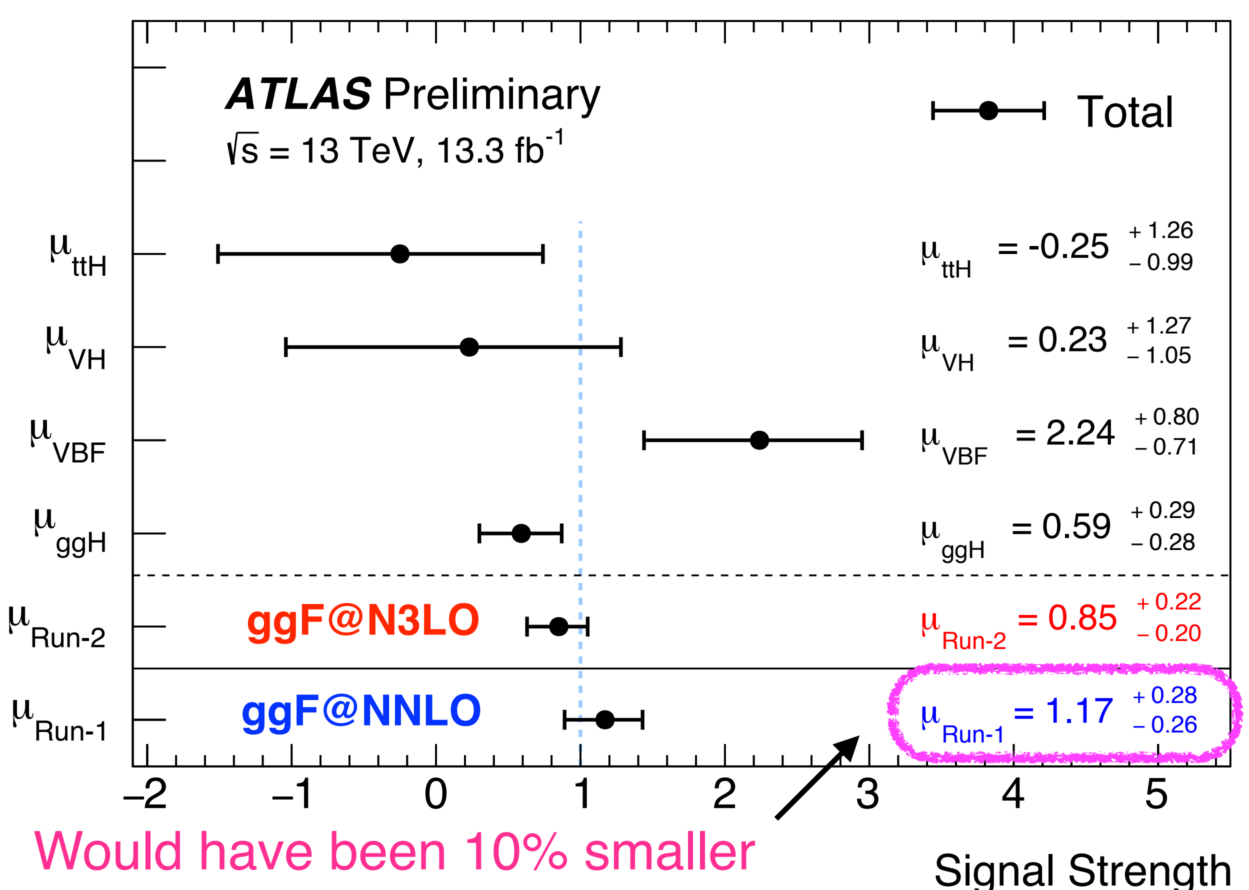
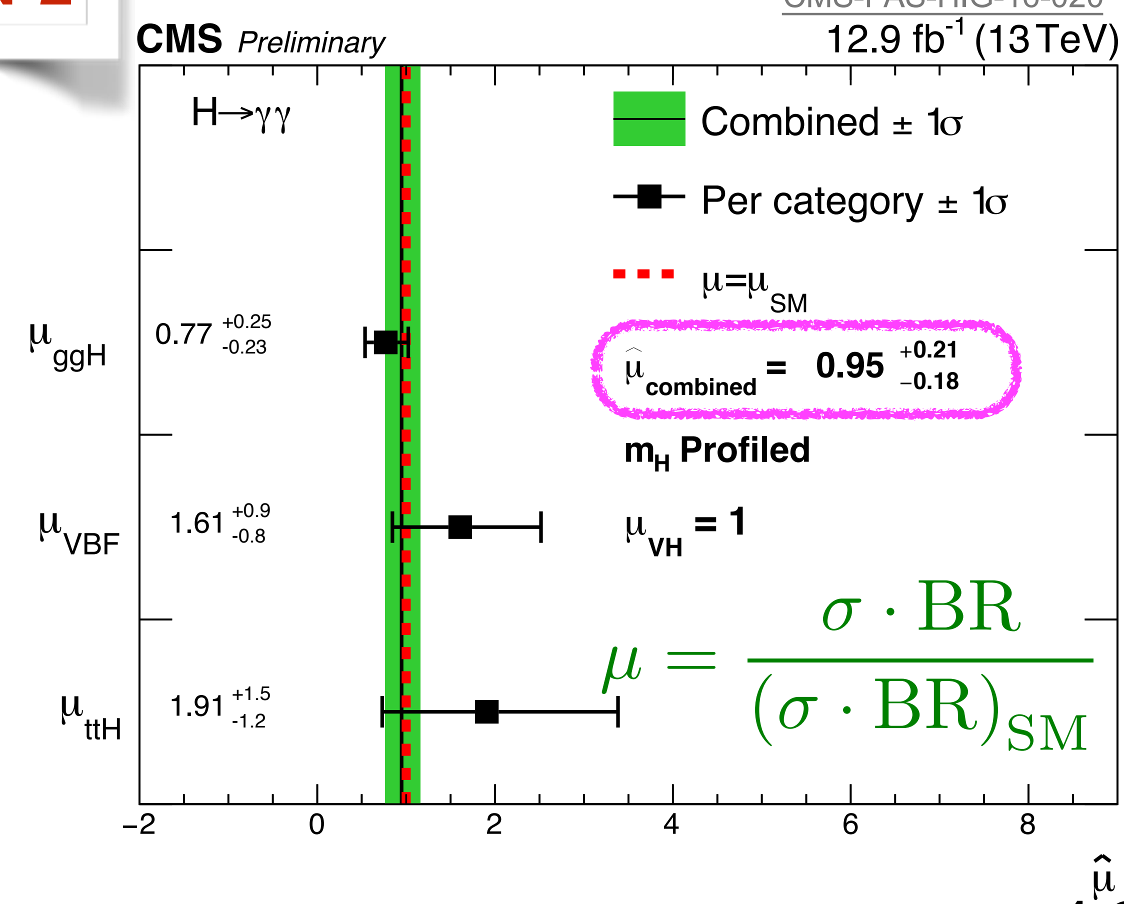


Would have been 10% smaller if ggF@N3LO calculation used.

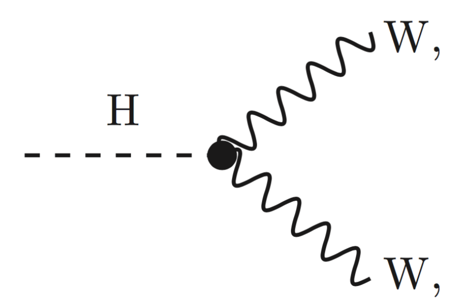
CMS-PAS-HIG-16-020



$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

H→ZZ*→4 leptons

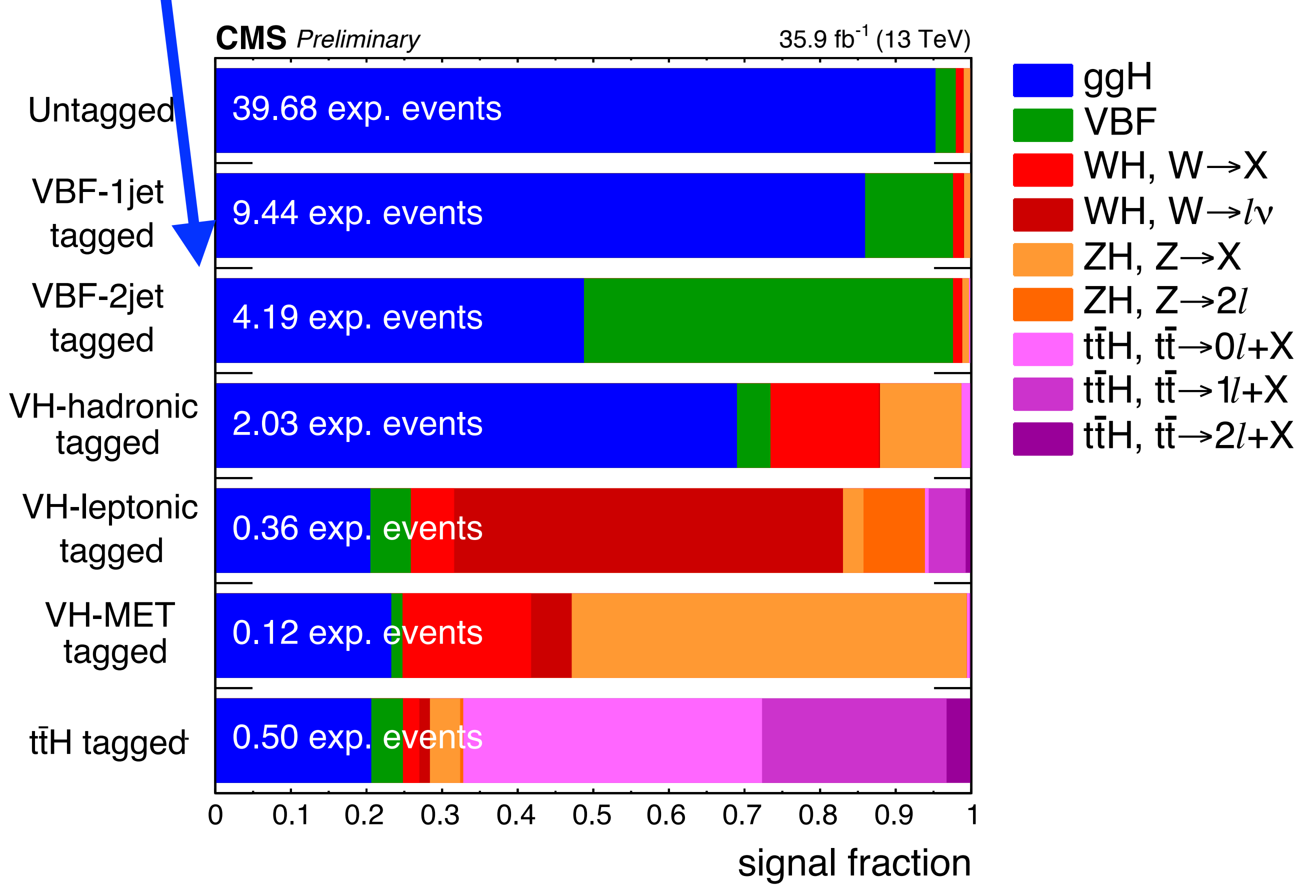
- Despite small BR(H→4l)=1.24x10^{-4} (l=e,μ) for M_H=125GeV, very clean signal S/B>2.
- Irreducible ZZ background and reducible backgrounds from Zbb, ttbar, etc.
- Events are categorized in ggF, VBF, VH and ttH production modes.
  - Categorized in # of jets, b-jets and additional leptons.
  - Key issues: lepton reconstruction down to p_T~5 GeV.



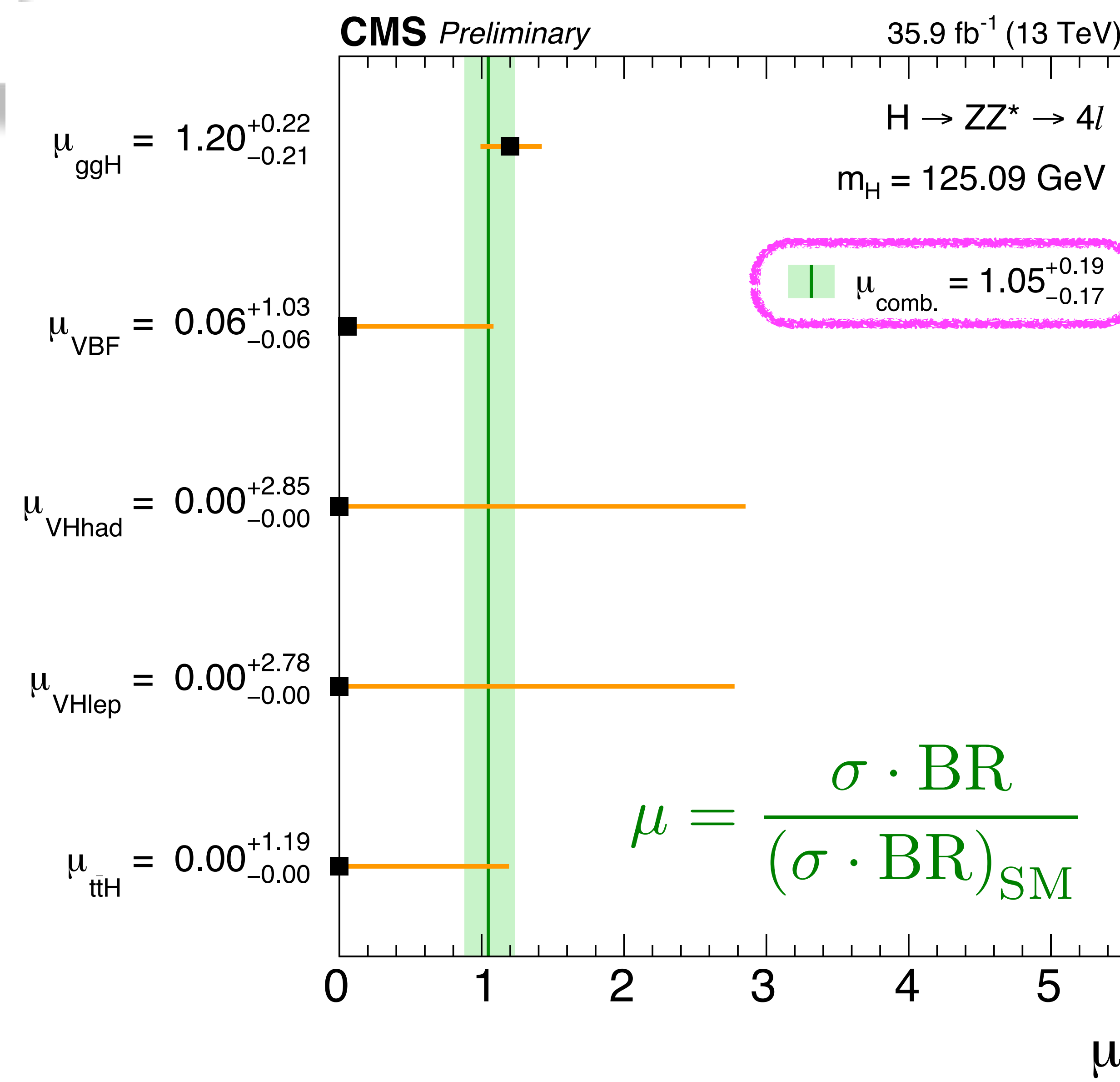
RUN-2 **New**

Large ggF contamination in VBF category

CMS-PAS-HIG-16-041



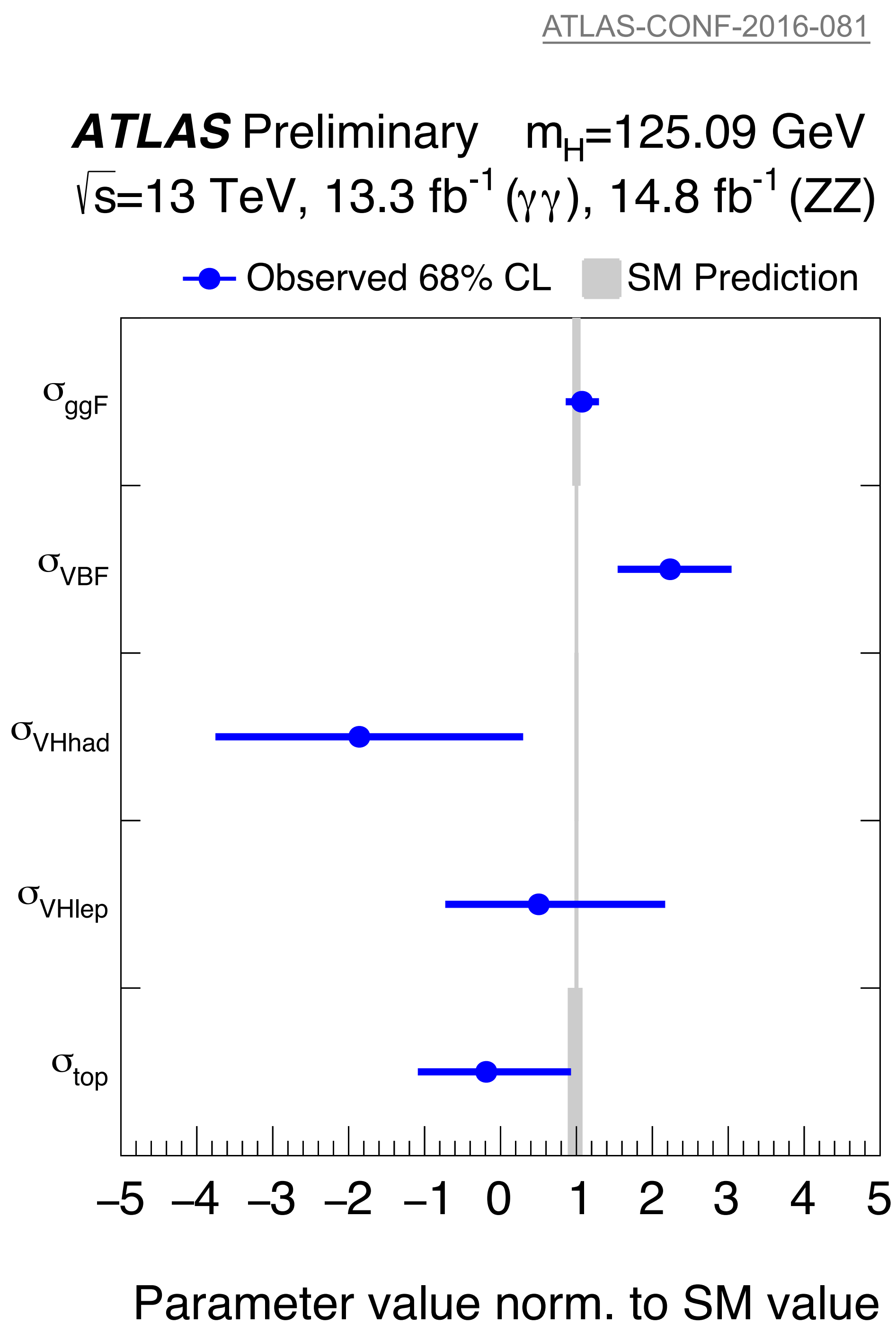
CMS-PAS-HIG-16-041

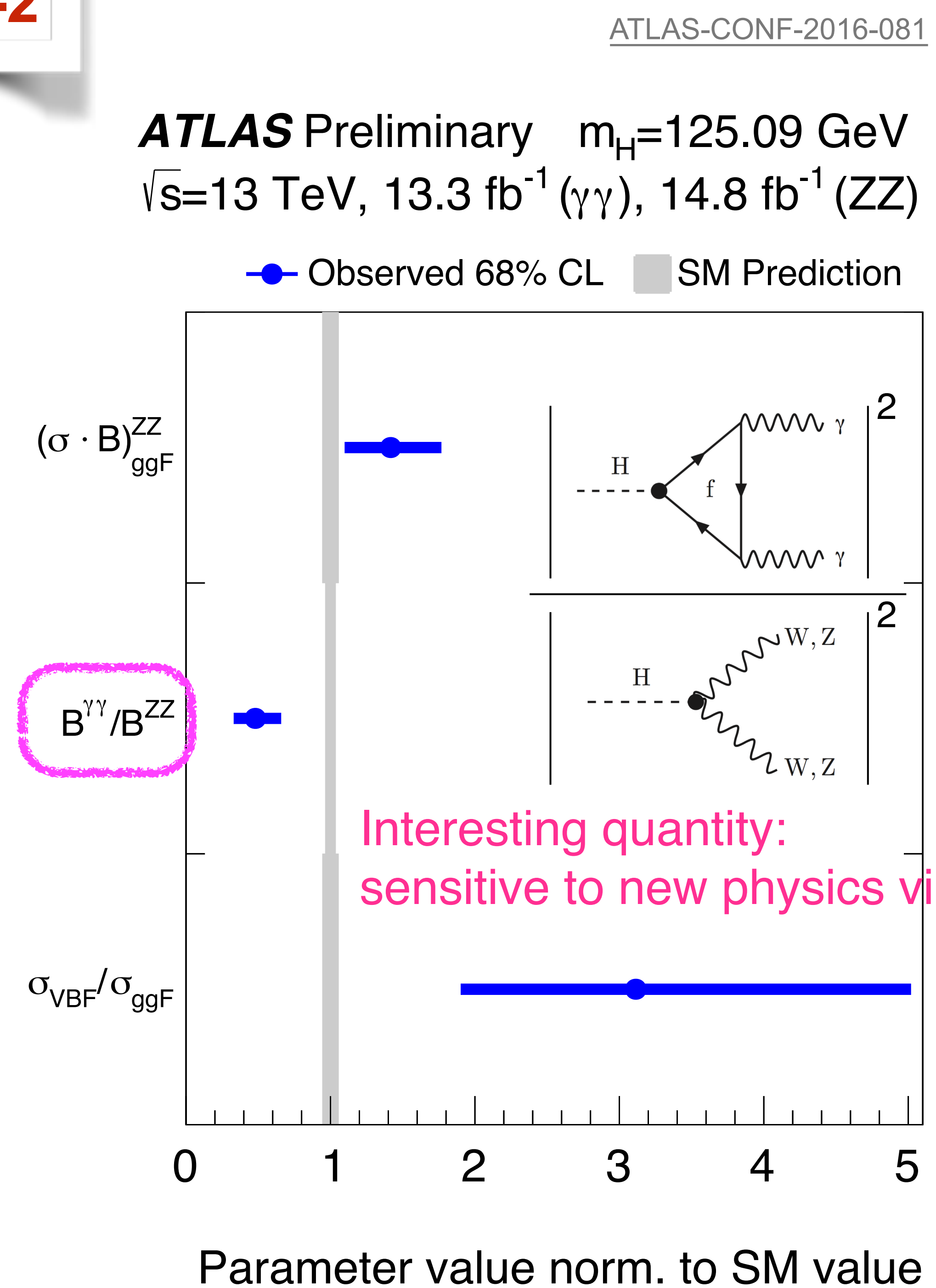


$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

H→γγ and H→ZZ*→4 leptons Combination

RUN-2

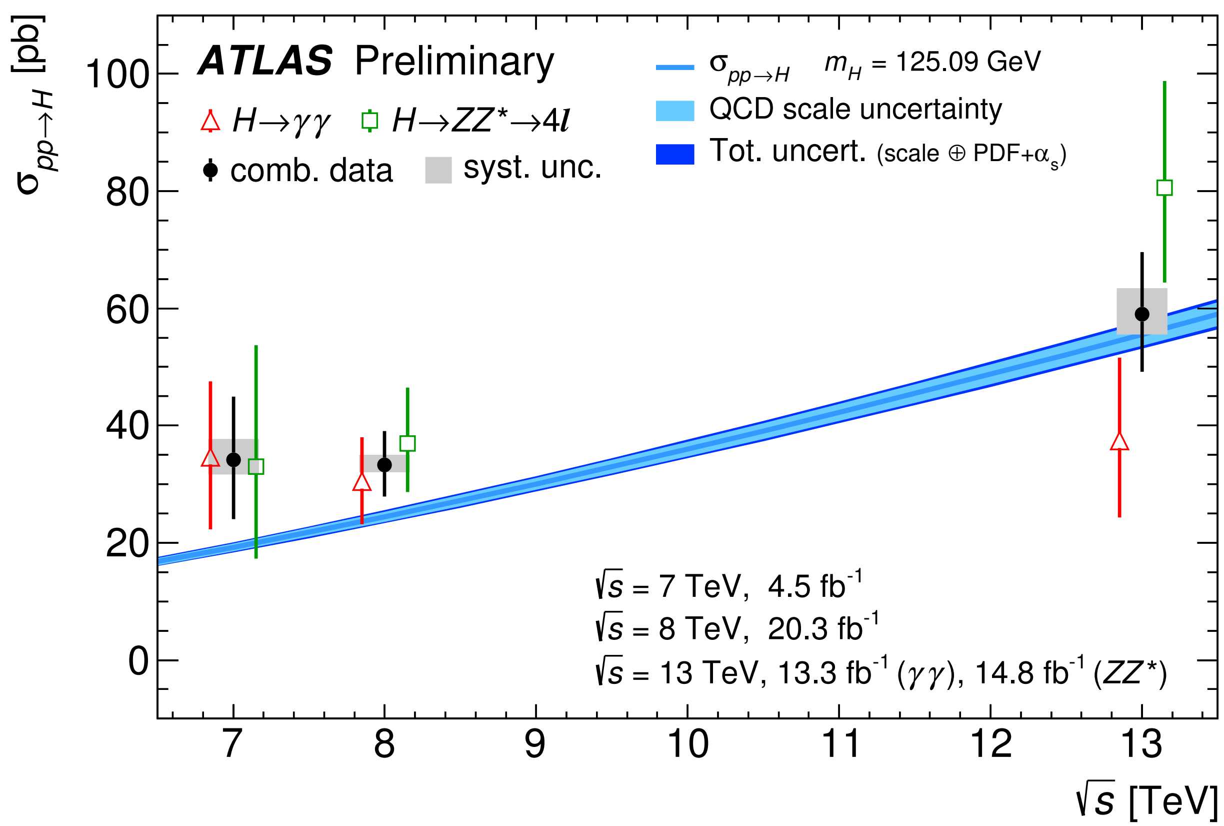




Interesting quantity:
sensitive to new physics via loop in γγ

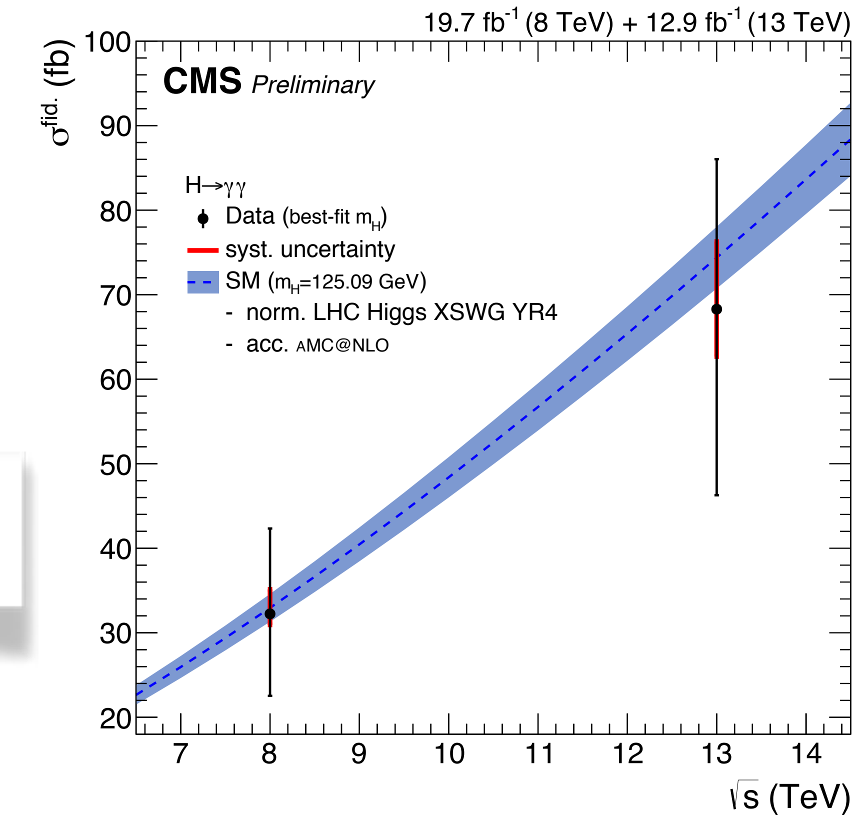
Total/Fiducial cross sections

ATLAS-CONF-2016-081



RUN-2

CMS-PAS-HIG-16-020



- Tremendous progress in QCD and EW theory predictions.

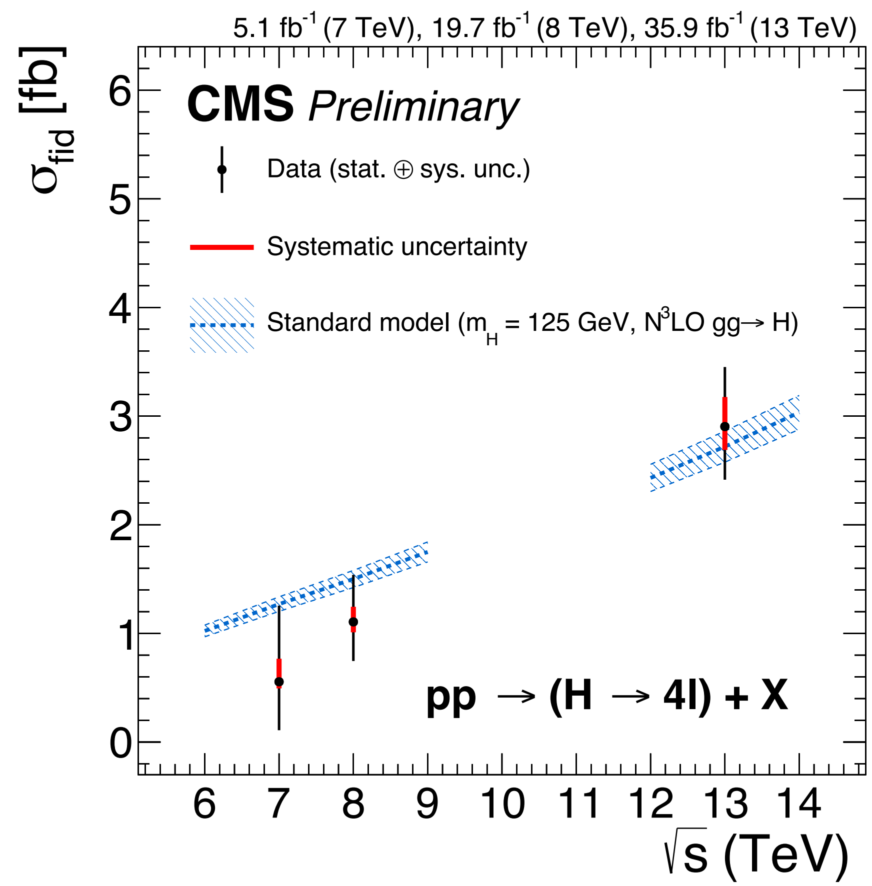
  ggF prediction in N3LO QCD

  - **scale uncertainty ±8% (NNLO) ↘ ±4% (N3LO)**
  - **PDF+α_s uncertainty ±7% ↘ ±3% (new PDF4LHC)**

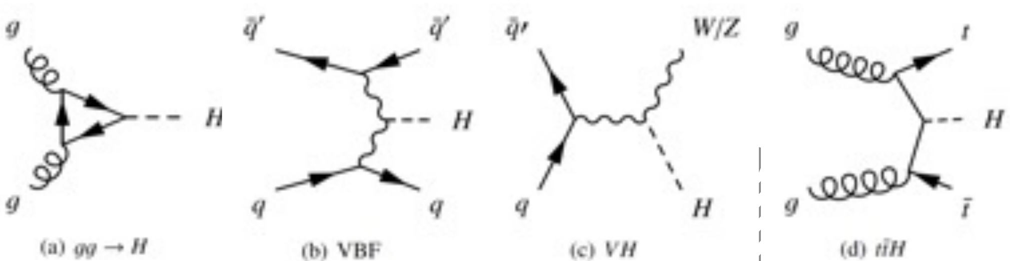
"... EXP precision is very far away (TH went ahead 15 years of EXP?), but it would be better to have numbers with best precision."
[email by Reisaburo Tanaka to the ggF conveners]

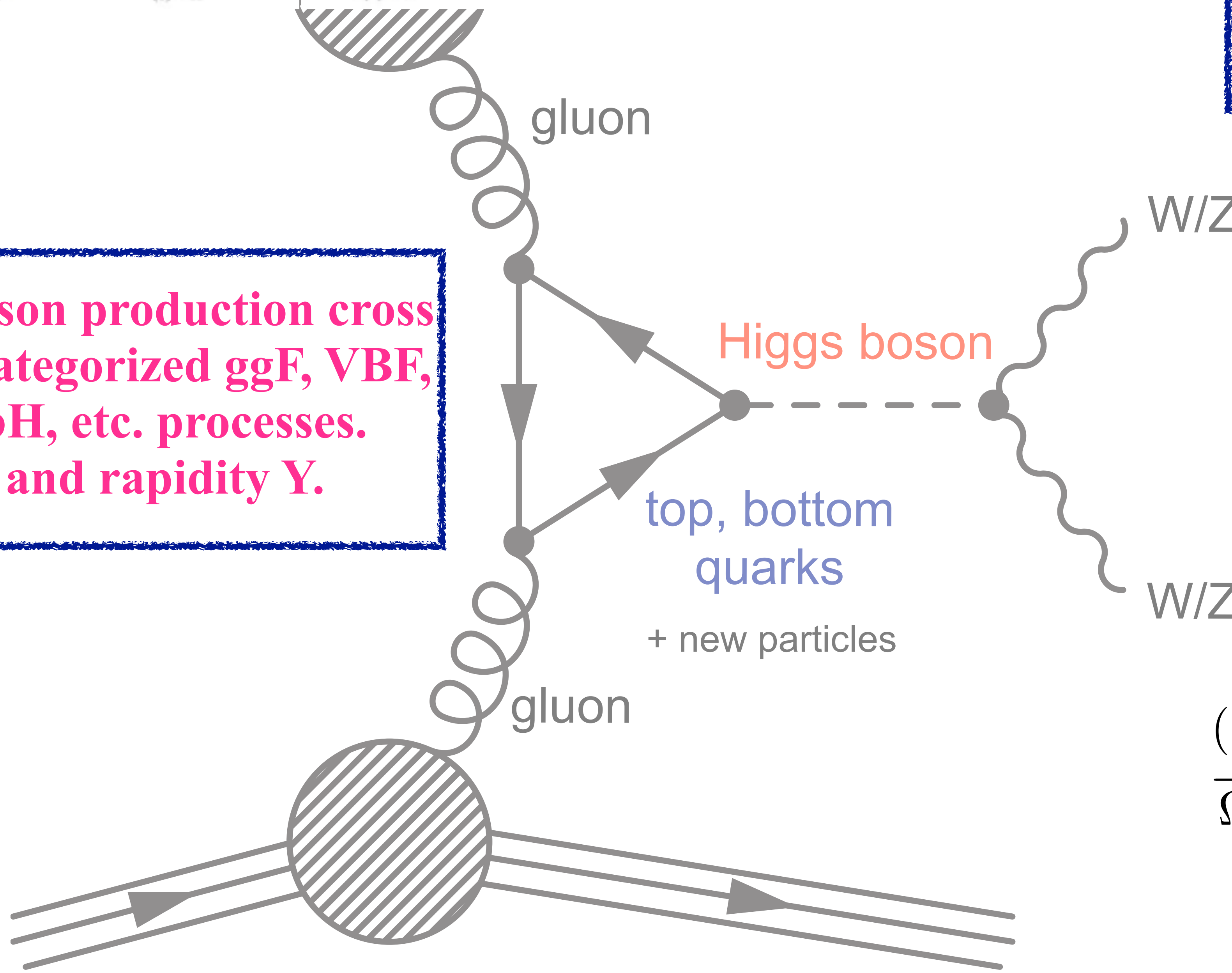
Giulia Zanderighi

"Precision theory for precise measurements at LHC and future colliders", Vietnam, 2016.



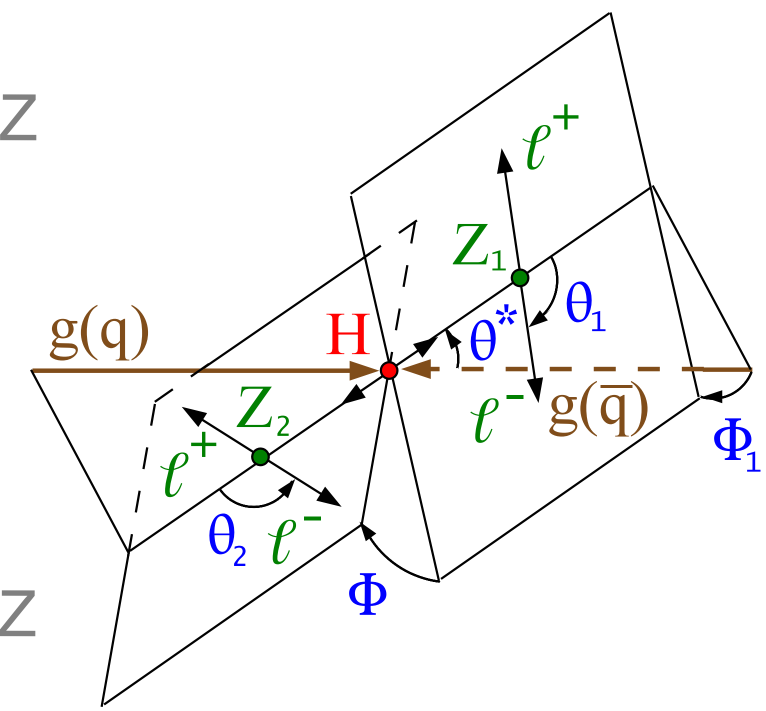
Use of Higgs Production and Decay Information





1) Higgs boson production cross section in categorized ggF, VBF, VH, ttH, bbH, etc. processes.
2) Higgs p_T and rapidity Y.

3) Higgs boson decay kinematical variables (8D in H→4l)

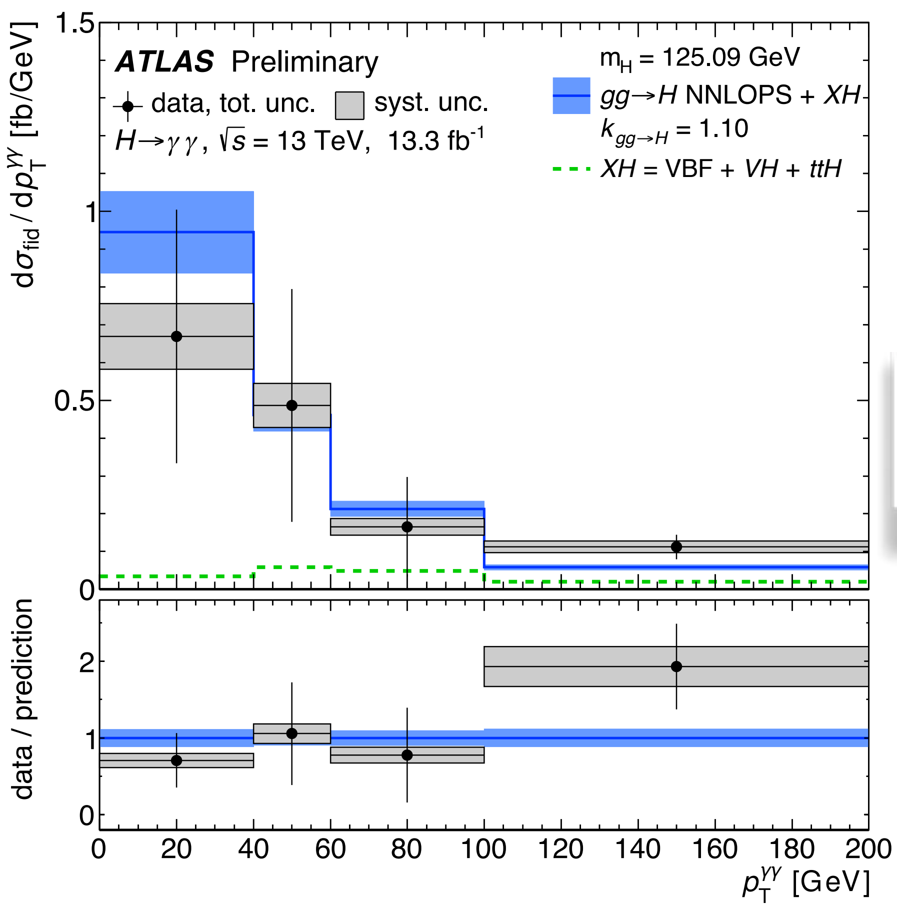


$$(M_{4\ell}, M_{Z_1}, M_{Z_2}),$$
$$\overrightarrow{\Omega} = (\theta^*, \cos\theta_1, \cos\theta_2, \Phi_1, \Phi)$$

Use combined information of Higgs production and decay!

Differential Distributions

ATLAS-CONF-2016-067



RUN-2

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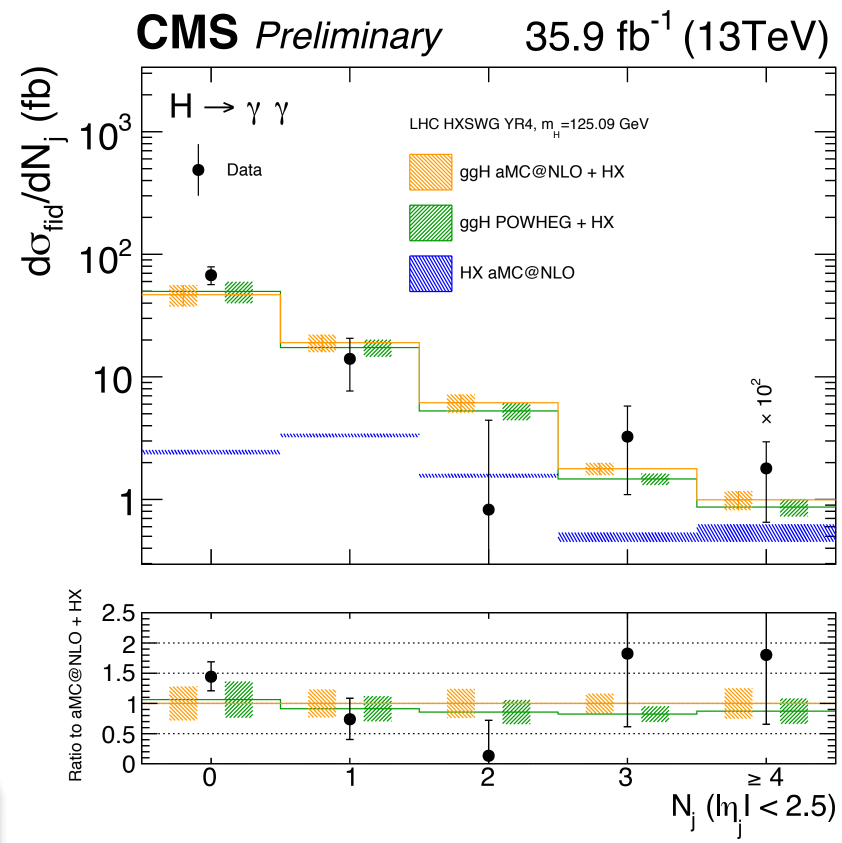
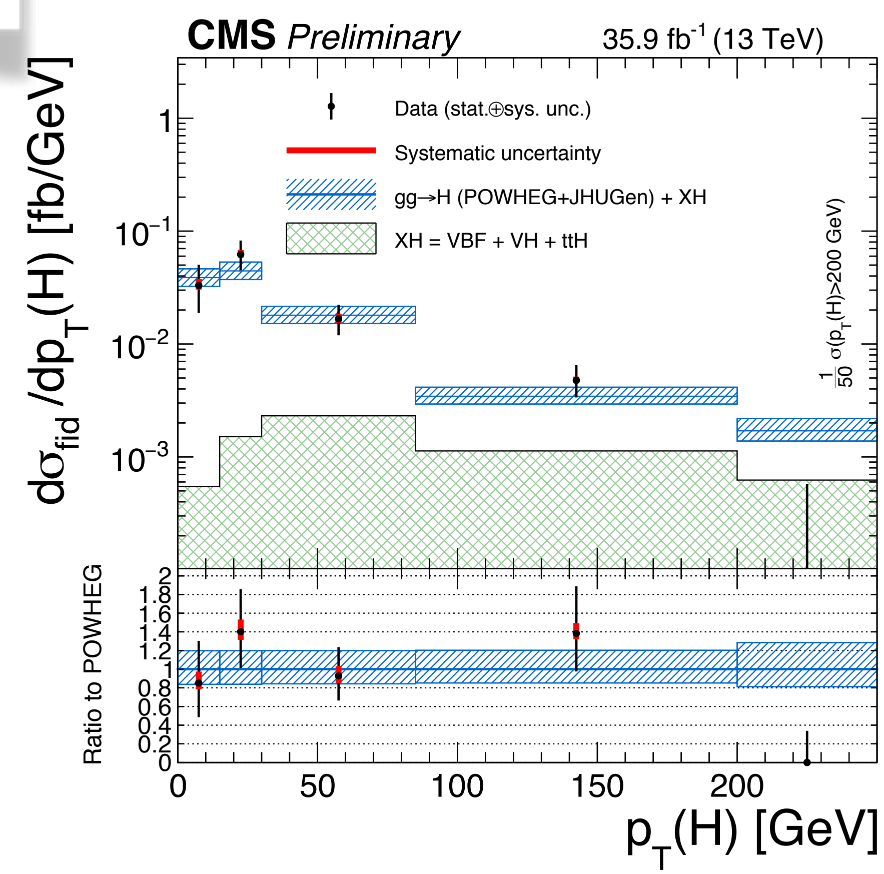


New

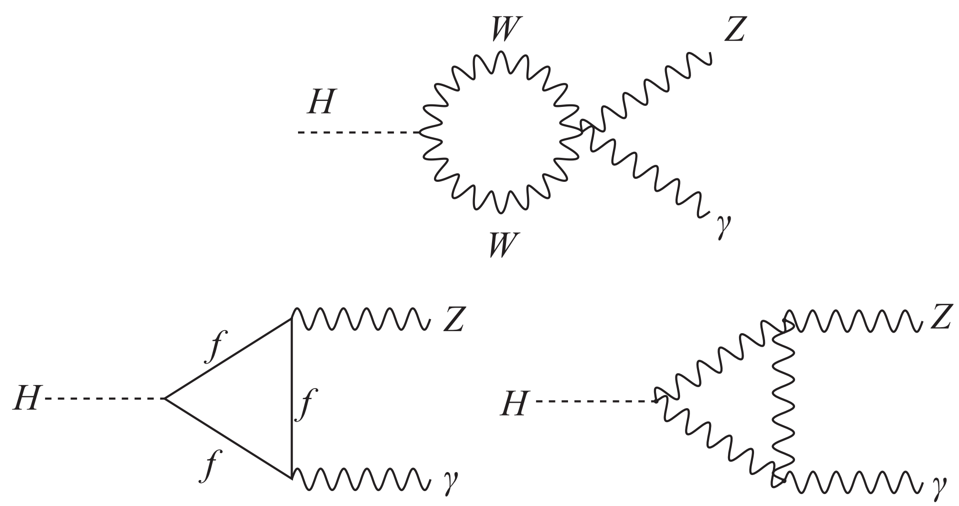
CMS-PAS-HIG-16-041



BSM physics may reveal in high pT regime.
Very important to treat finite top-quark mass effect.

Higgs Dalitz decay H→Zγ

RUN-1



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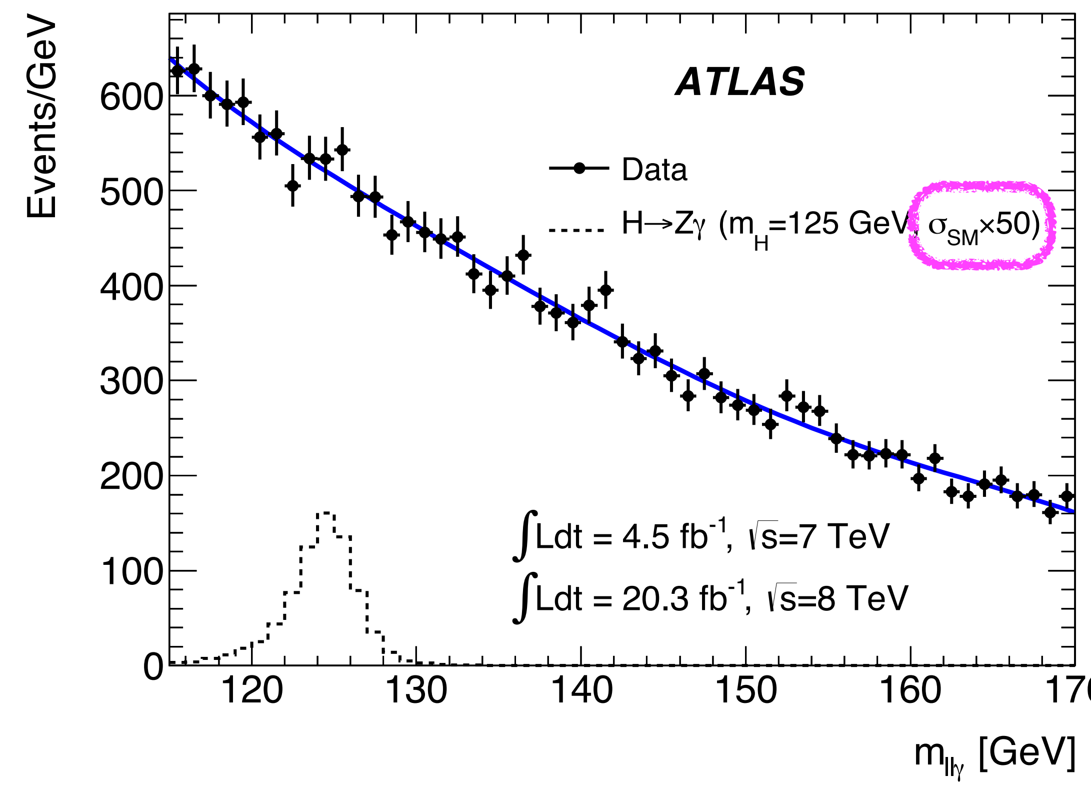
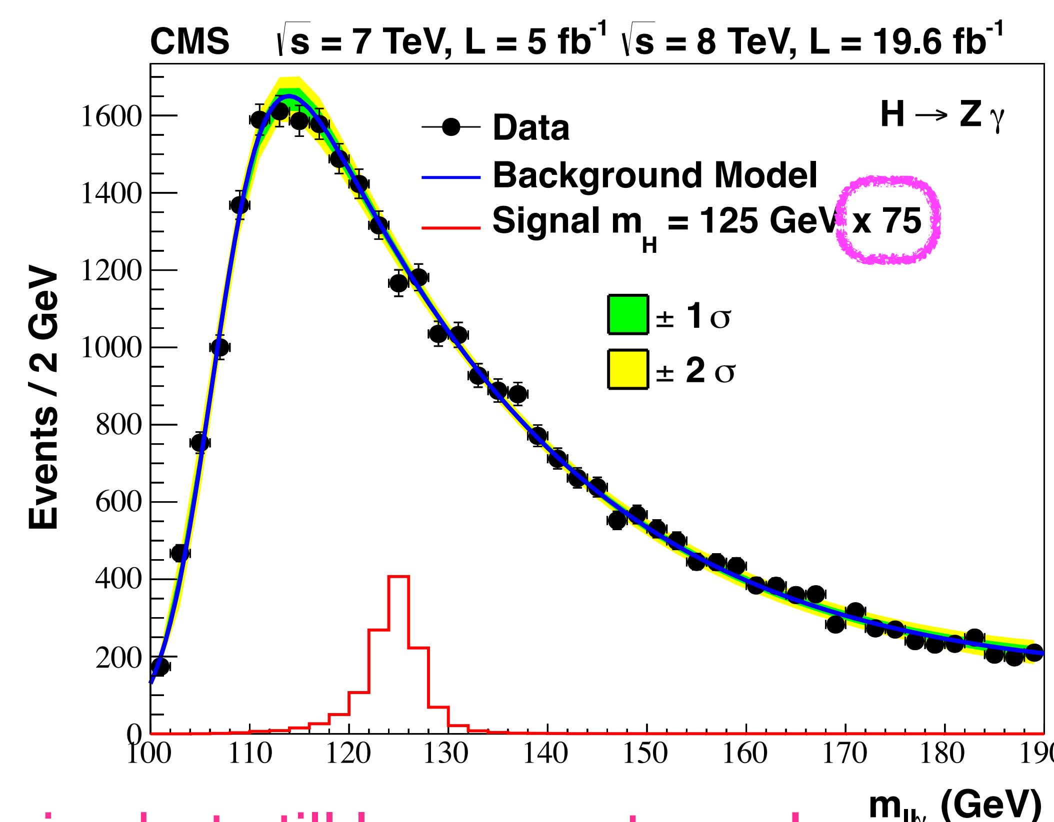


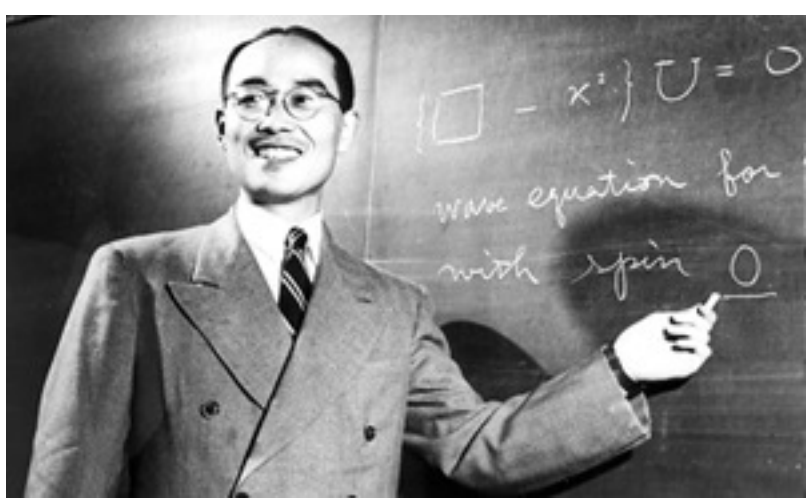
PLB 726 (2013) 587



1. Categorization should be like
   1. H → γγ
   2. H → Z*/γ*+γ → ffbar+γ
   3. H → ffbar
   4. H → Z*+γ* → ffbar + f'f'bar
2. We should call process 2 as Higgs Dalitz decay.
3. We need to come to possible agreement with CMS on signal definition with (di-lepton) invariant mass cut to put in PDG.

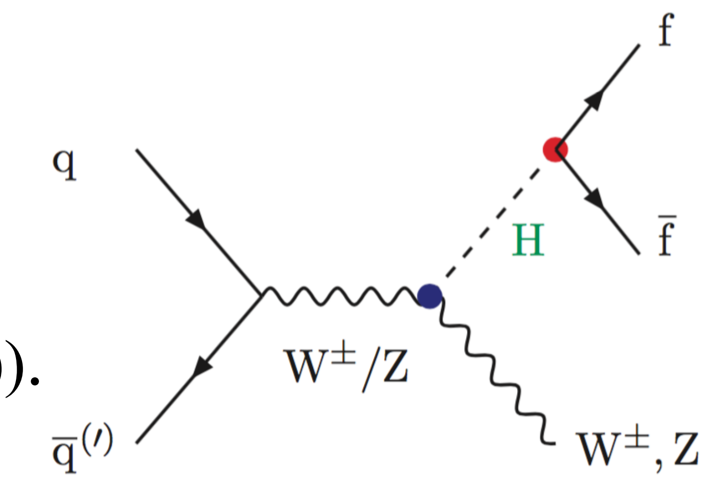
Very important channel for BSM physics but still long way to go !

4. Higgs Boson
Yukawa Coupling



湯川秀樹 (1949)

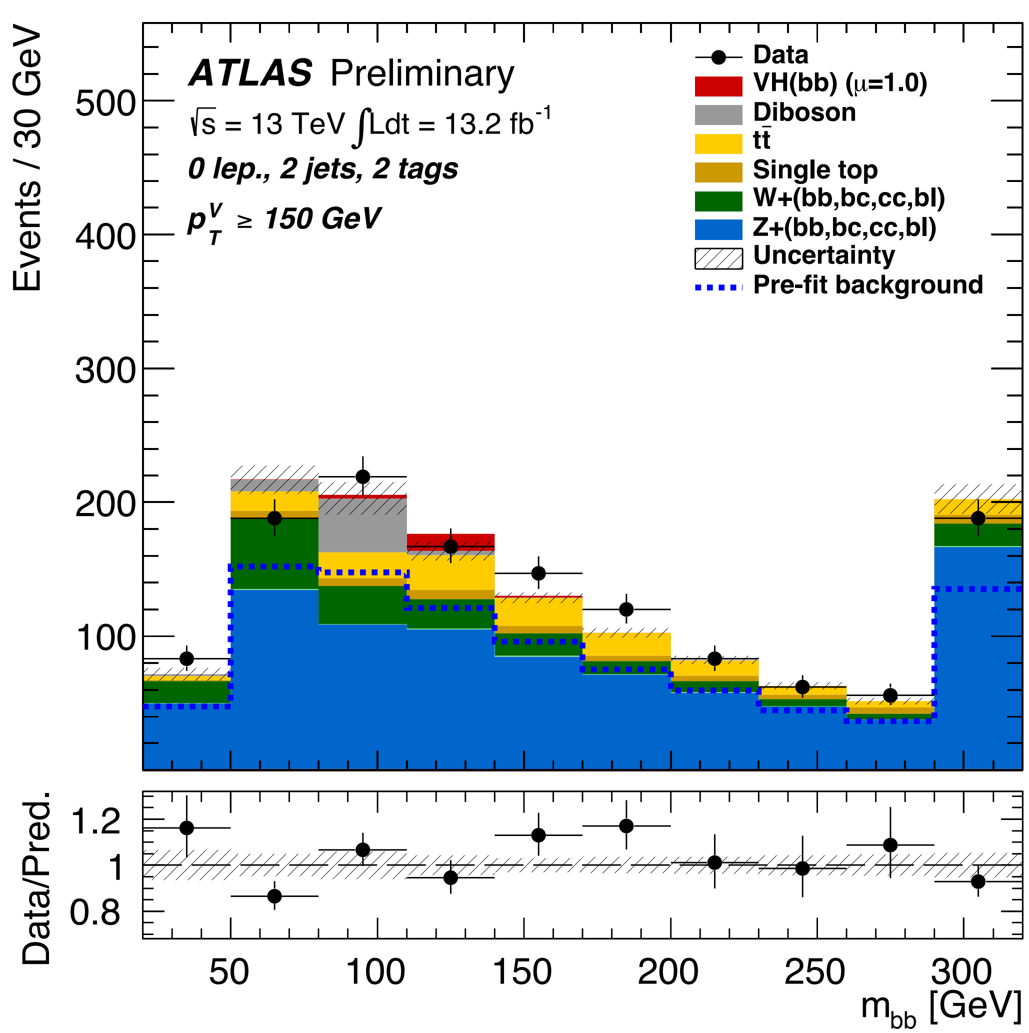
Hbb Yukawa in VH(H→bb)



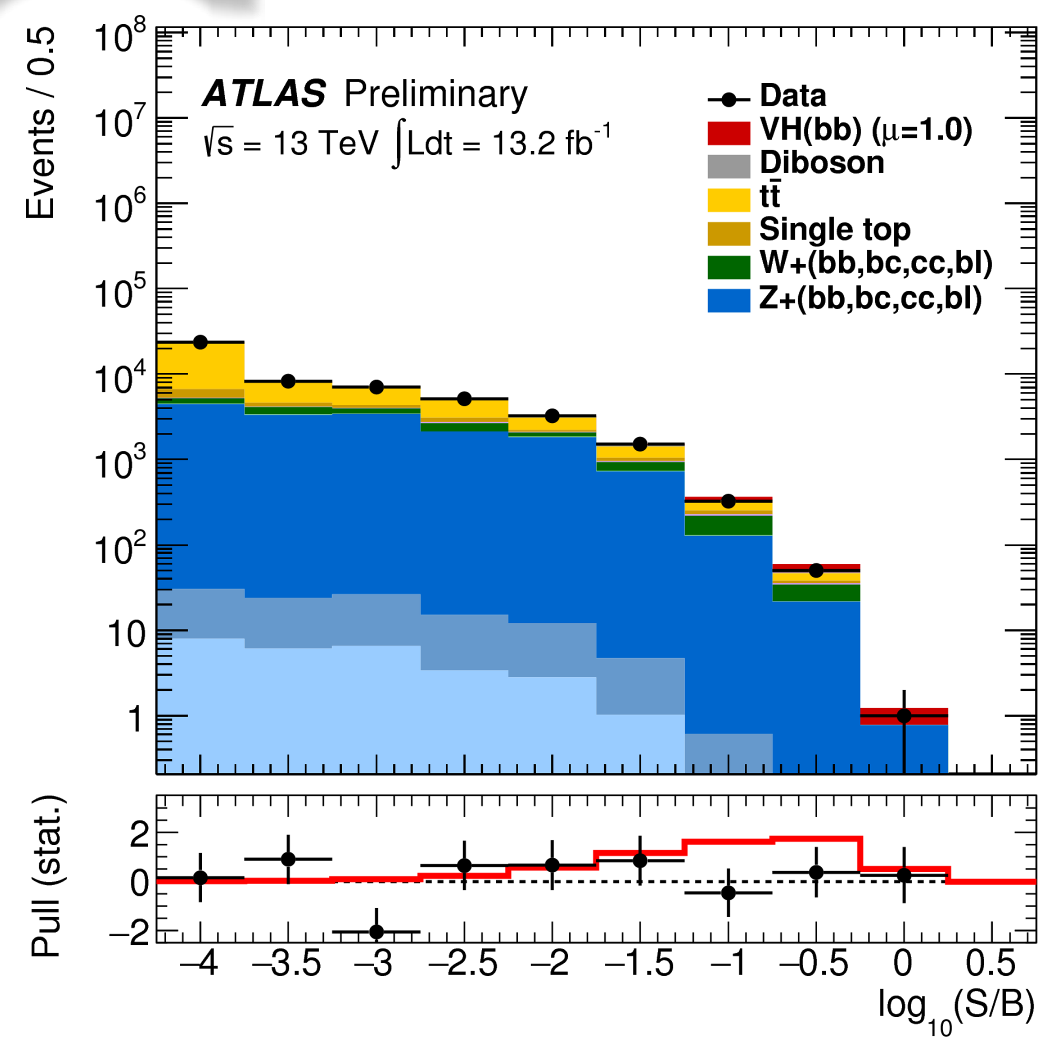
- Most sensitive to Hbb Yukawa coupling (along with ttH(H→bb)).
- Search in channels with 0,1,2 leptons (e/μ) with V→νν,lν,ll.
- Large variety of the SM backgrounds from V+HF(Zbb etc.), VV, ttbar.
- Aggressive use of BDT & profile likelihood fits to isolate signal and measure background parameters from data in control region.

RUN-2

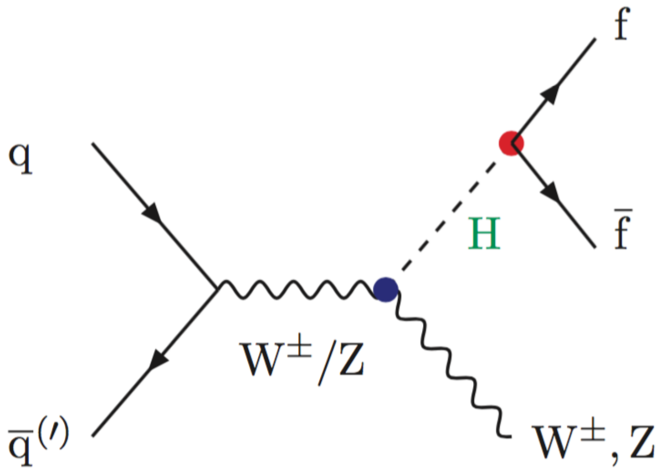
ATLAS-CONF-2016-091



ATLAS-CONF-2016-091



Hbb Yukawa in VH(H→bb)



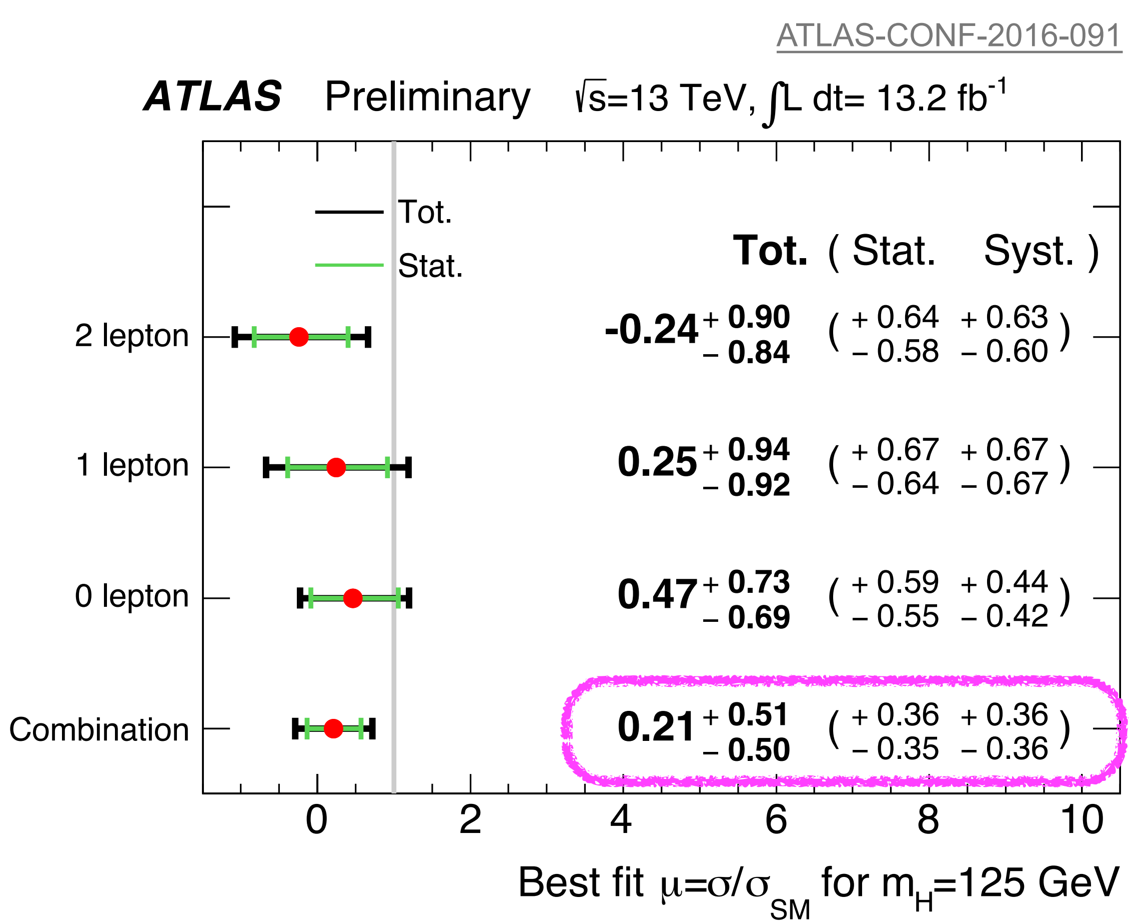
- Statistical and systematic uncertainties are the same !
- Will arrive 3σ discovery with more data, but understanding the background is crucial.
- Dominant systematic uncertainties: b&c-jet tagging efficiency, Z/W+heavy flavor, ttbar normalization.

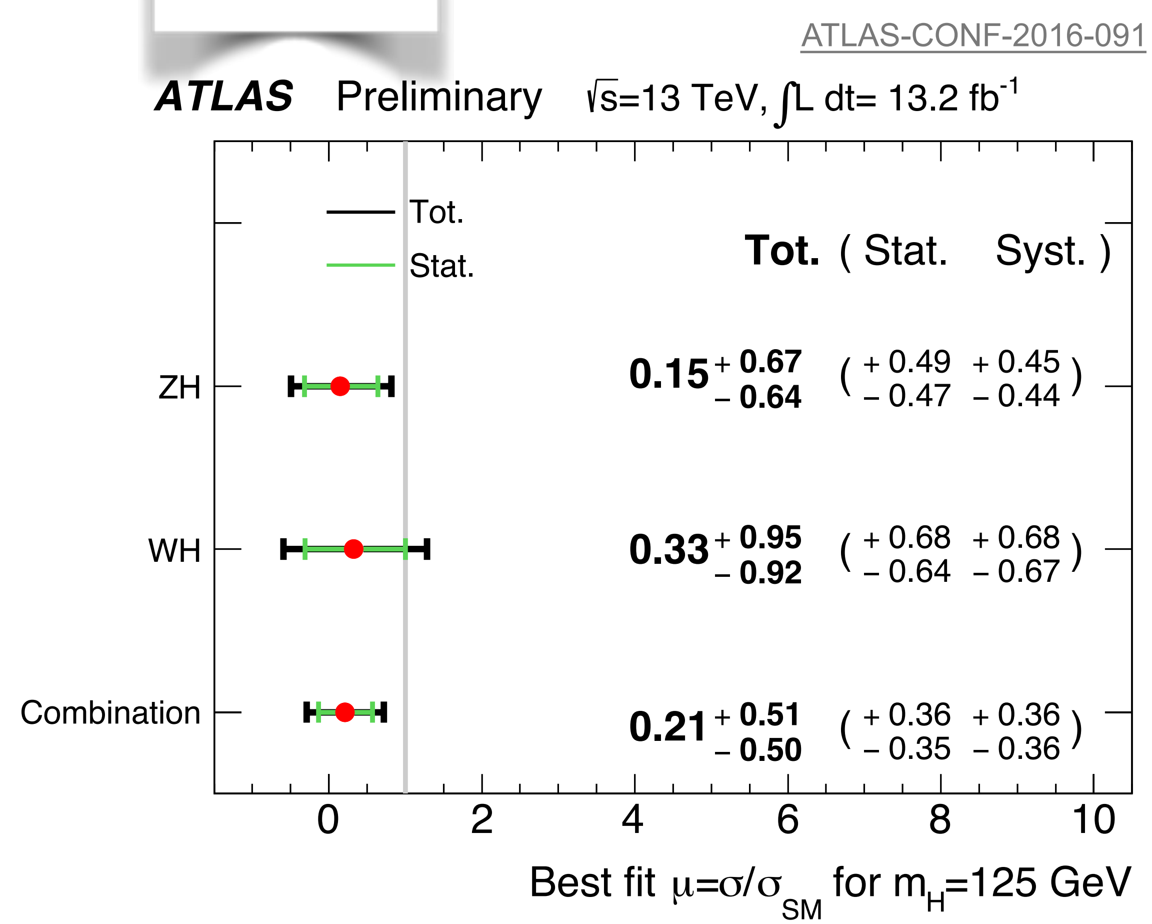
Sample	Scale factor
$t\bar{t}$ 0+1-lepton	0.86 ± 0.13
$t\bar{t}$ 2-lepton	0.94 ± 0.09
W + HF	1.59 ± 0.39
Z + HF	1.04 ± 0.11

H→bb significance: 0.42σ (1.94σ expected)
Evidence for (W/Z)Z, Z→bb: 3.0σ (3.2σ expected)

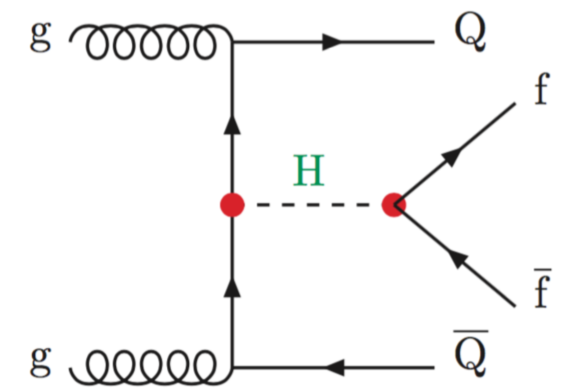
$$\mu_{\text{diboson}} = 0.91 \pm 0.17\,(\text{stat})\ {}^{+0.32}_{-0.27}\,(\text{syst})$$

RUN-2





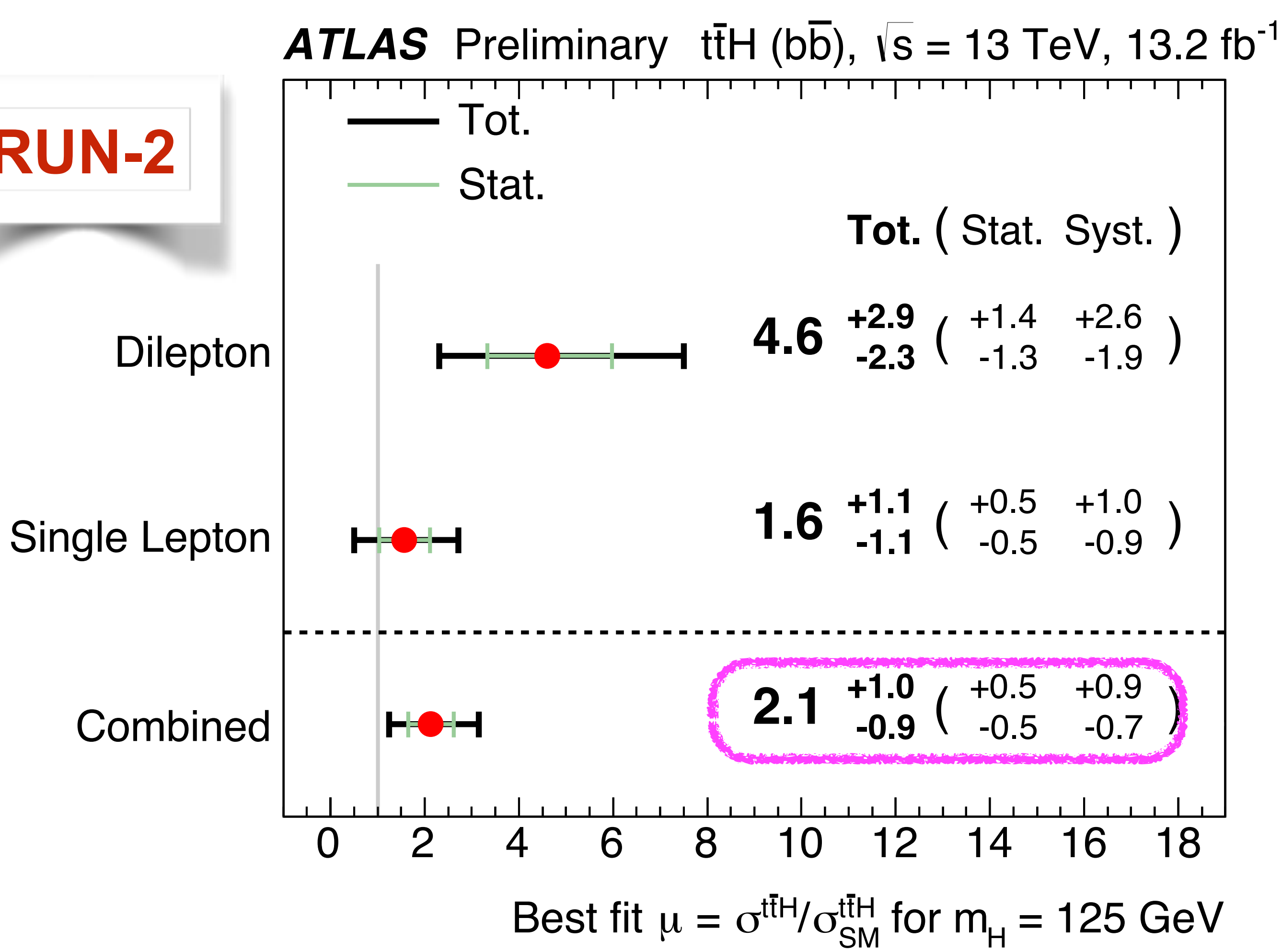
Htt/Hbb Yukawa in ttH(H→bb)



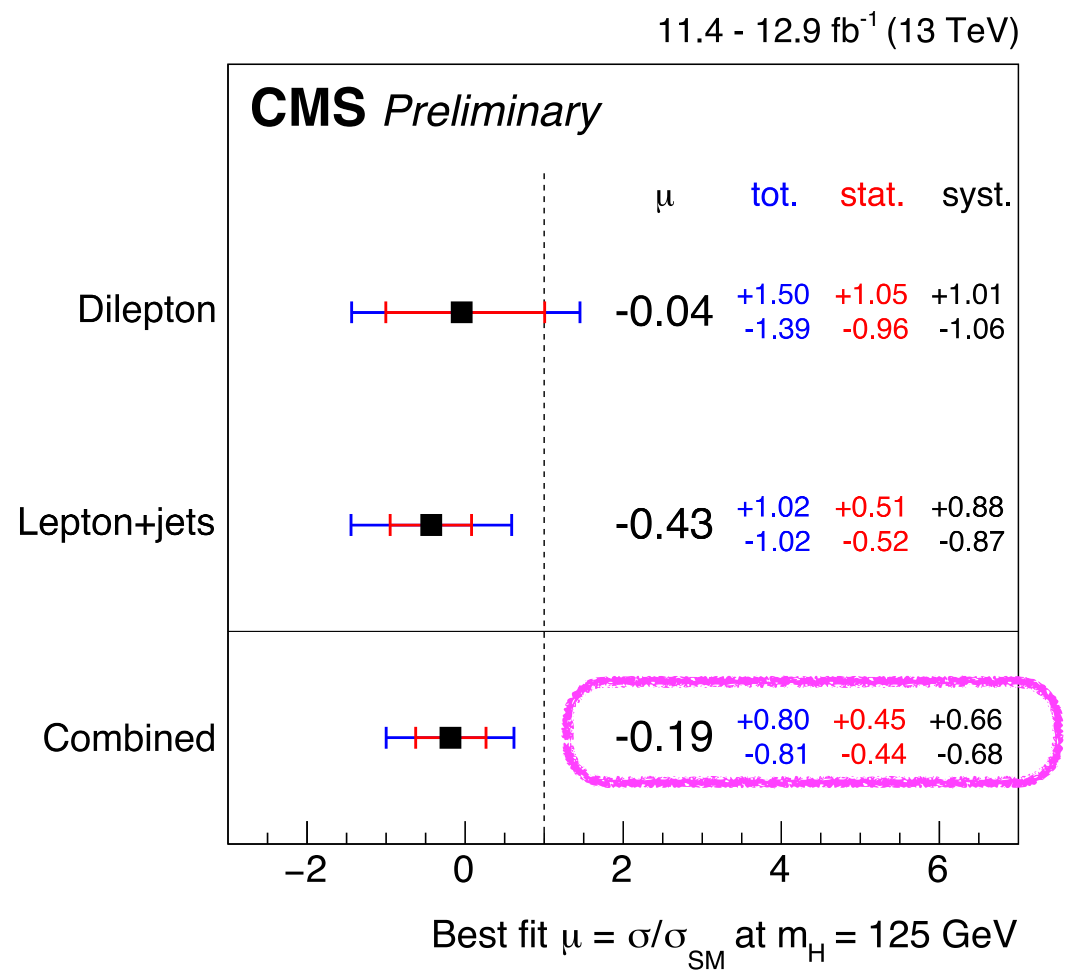
- Associated Higgs boson production with ttbar
  - Best channel to probe ttH Yukawa coupling directly (ggF in indirect way).
  - Different Higgs boson decay channels are studied in H→γγ, ZZ*(→4l), WW*, ττ and bb.
- H→bb
  - Very complicated final state (4 b-jets), large backgrounds from ttbar+V/HF.
  - High event yield but large backgrounds from ttbb, ttbar+jets, etc.
  - Complex combinatorial in bottom-quark paring. ➪ Fully BDT or ME driven analysis.

ATLAS-CONF-2016-080

RUN-2

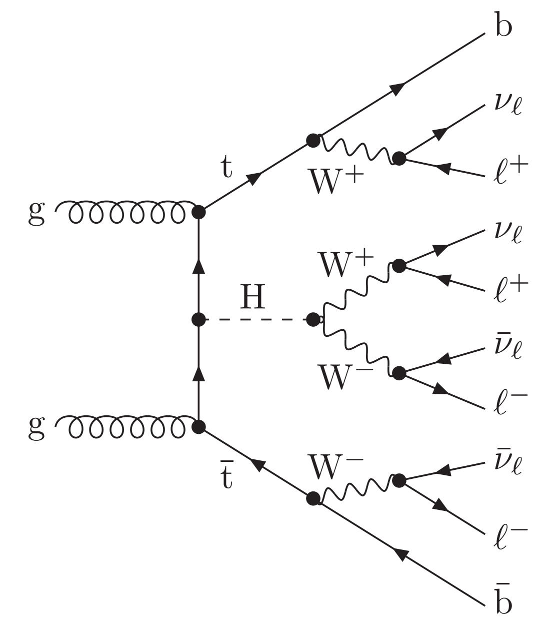


CMS-PAS-HIG-16-038



Htt Yukawa in ttH(multi-lepton)

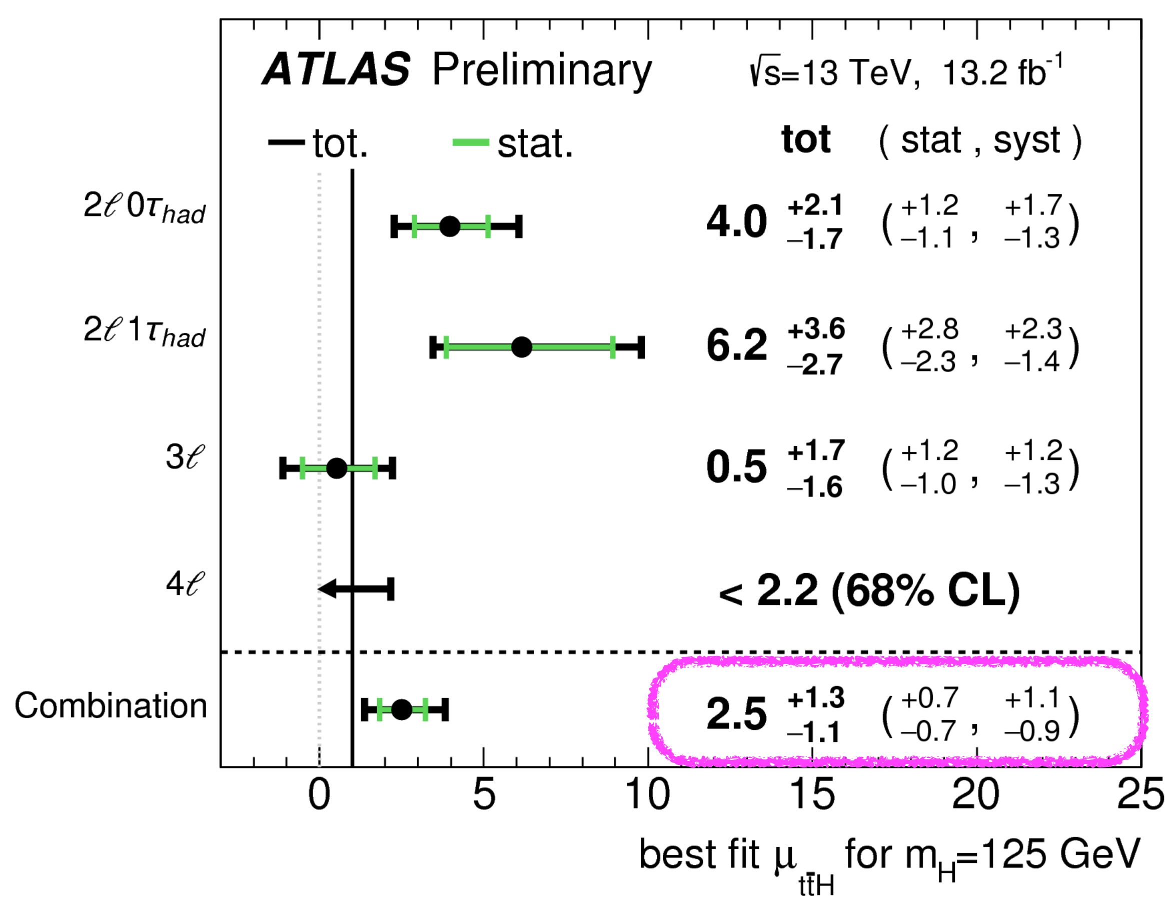
- ttH (multi-lepton)
  - Clean signal.



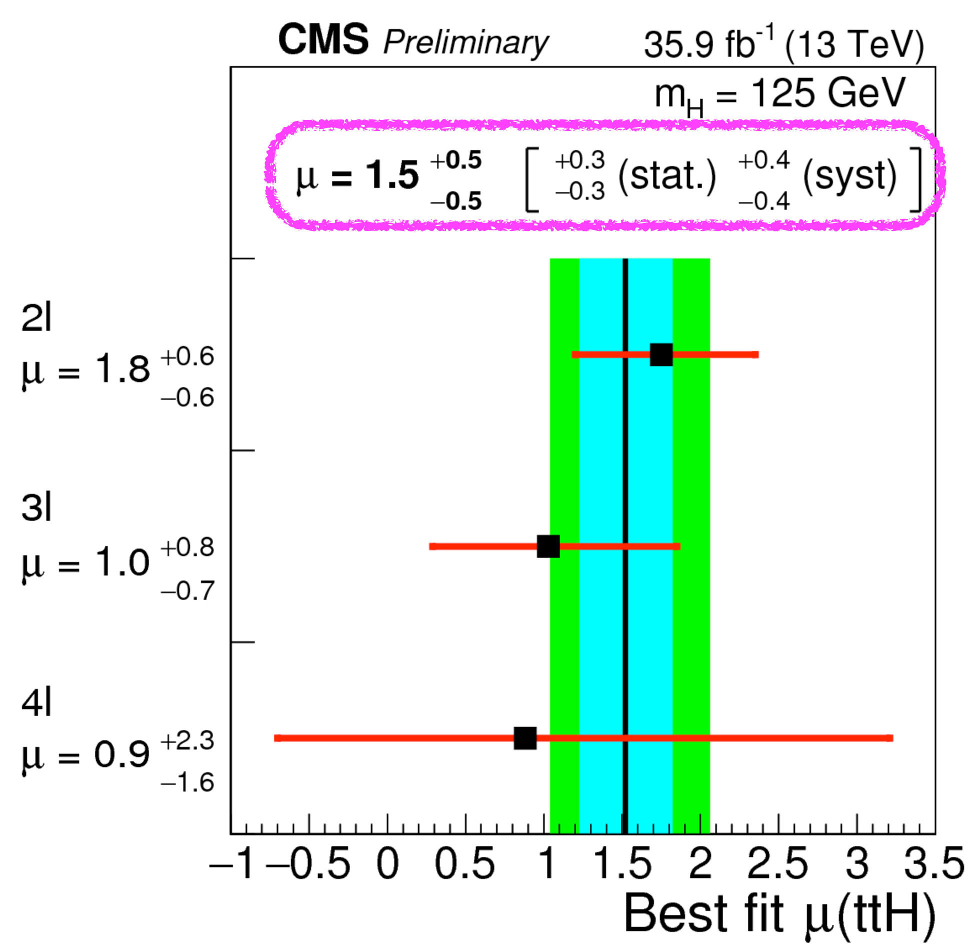
RUN-2

New

ATLAS-CONF-2016-058

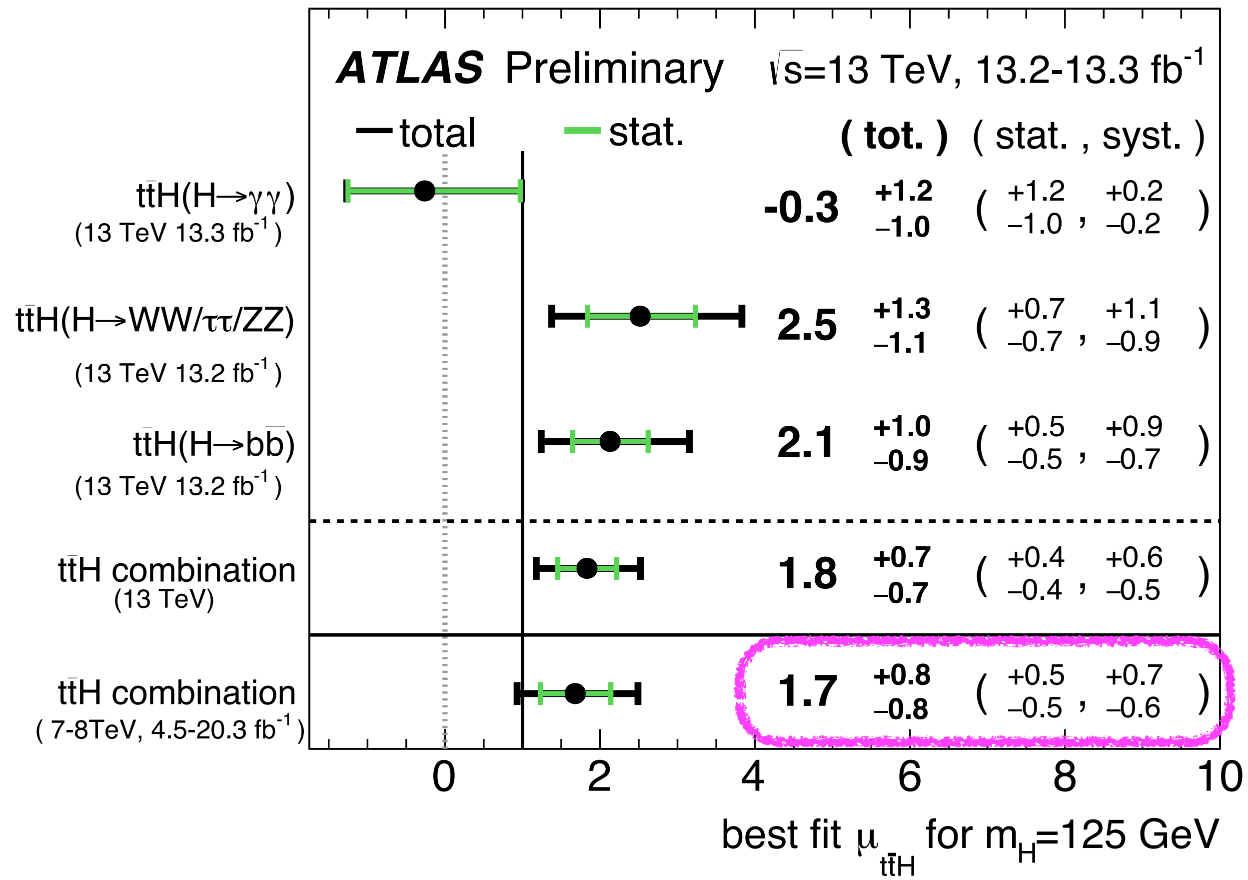


CMS-PAS-HIG-17-004



Htt/Hbb Yukawa in ttH Combined Results

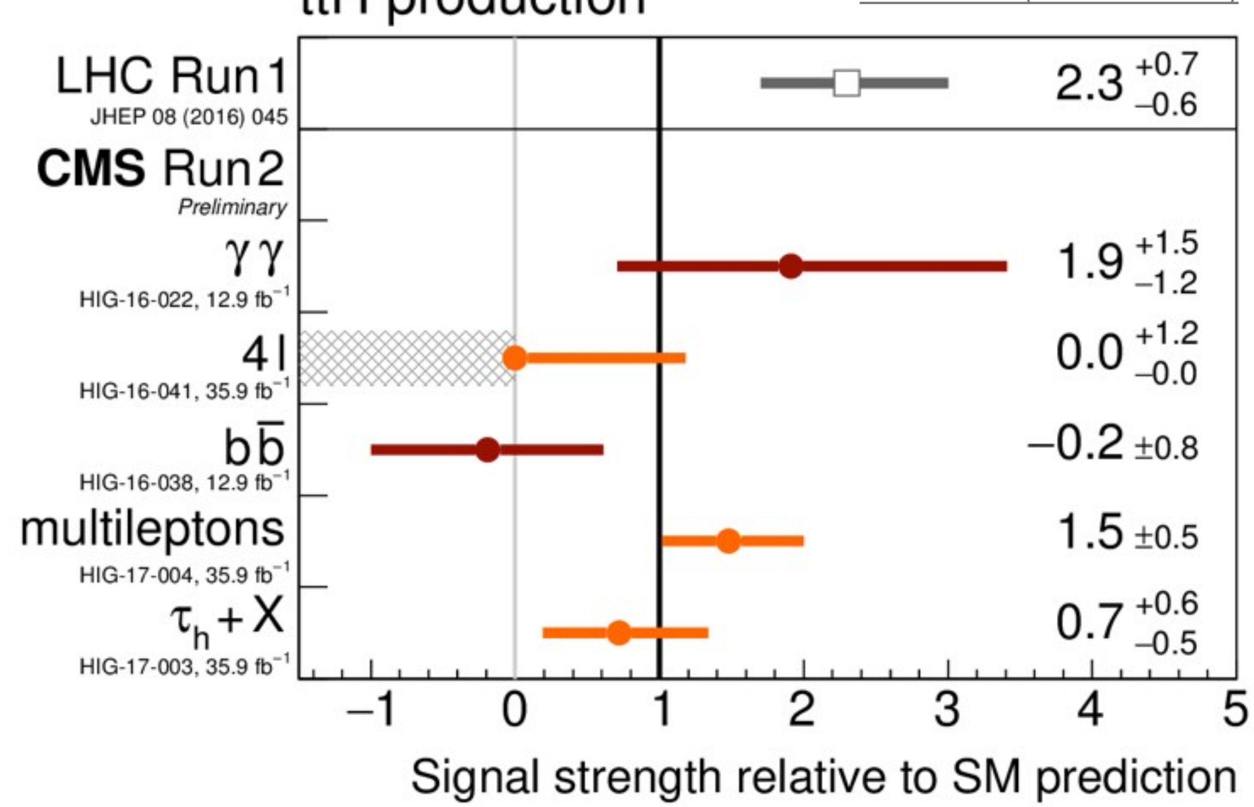
ATLAS-CONF-2016-068

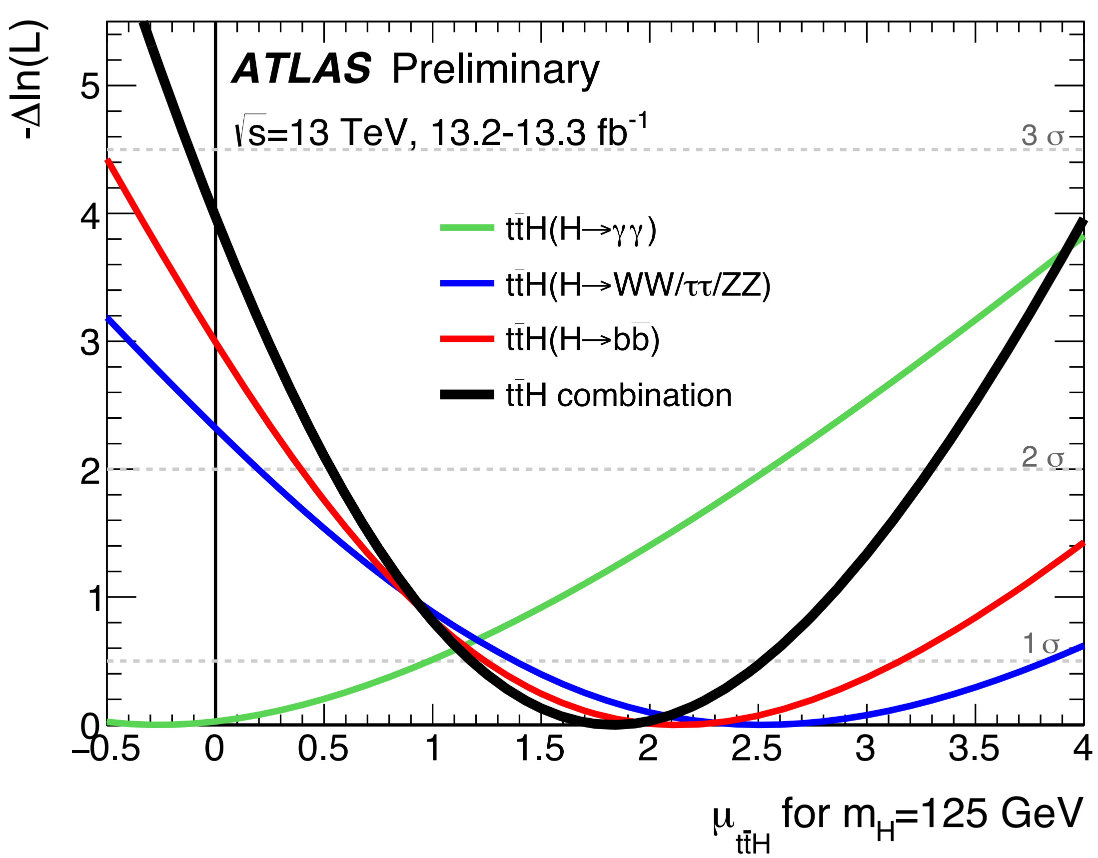


RUN-2

New

N. Chanon (Moriond QCD)





ATLAS Preliminary

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

Direct evidence on Htt&Hbb Yukawa couplings are still to come !

Yukawa sector: Search for $H \rightarrow \mu^+\mu^-$, e^+e^-, cc, etc.

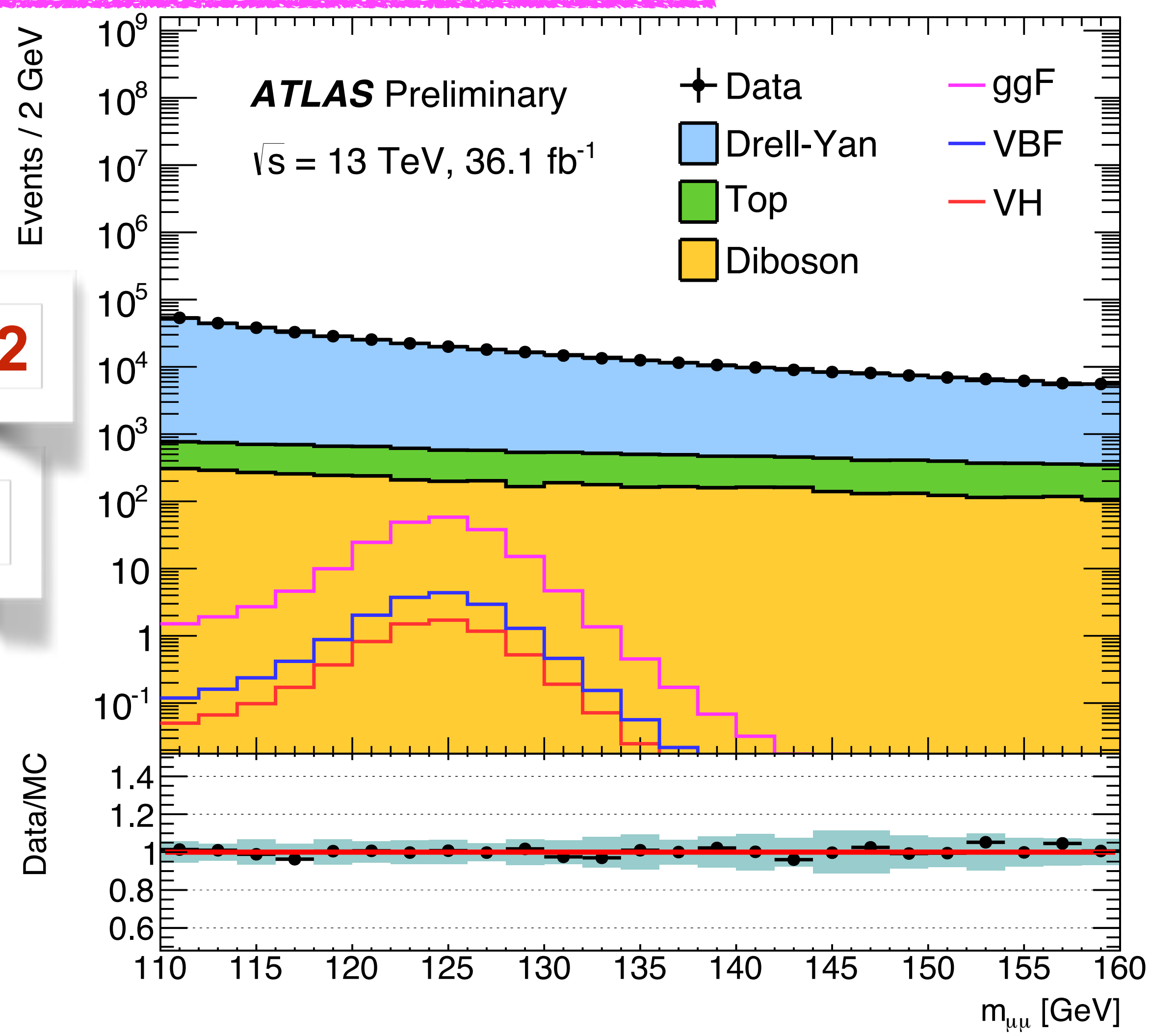
- 2nd&1st generation: branching ratios (Yukawa) are too small.
  - $BR(H \rightarrow \mu^+\mu^-) = 2.2\times10^{-4}$, $BR(H \rightarrow e^+e^-) = 4.9\times10^{-9}$ for M_H=125GeV.
  - Higgs Dalitz decay $BR(H \rightarrow Z\gamma) = 1.5\times10^{-3}$, should be searched in ffγ.
- Very difficult for H → cc, ss, gg at hadron collider (new ideas for charm via p_T).
  - Maybe accessible to charm via J/ψ+γ ($BR(H \rightarrow J/\psi+\gamma) = 2.5\times10^{-6}$).

$\mu < 3.0$ (2.1 exp) in RUN-2
$\mu < 2.7$ (2.8 exp) in RUN-1&2

ATLAS-CONF-2017-014

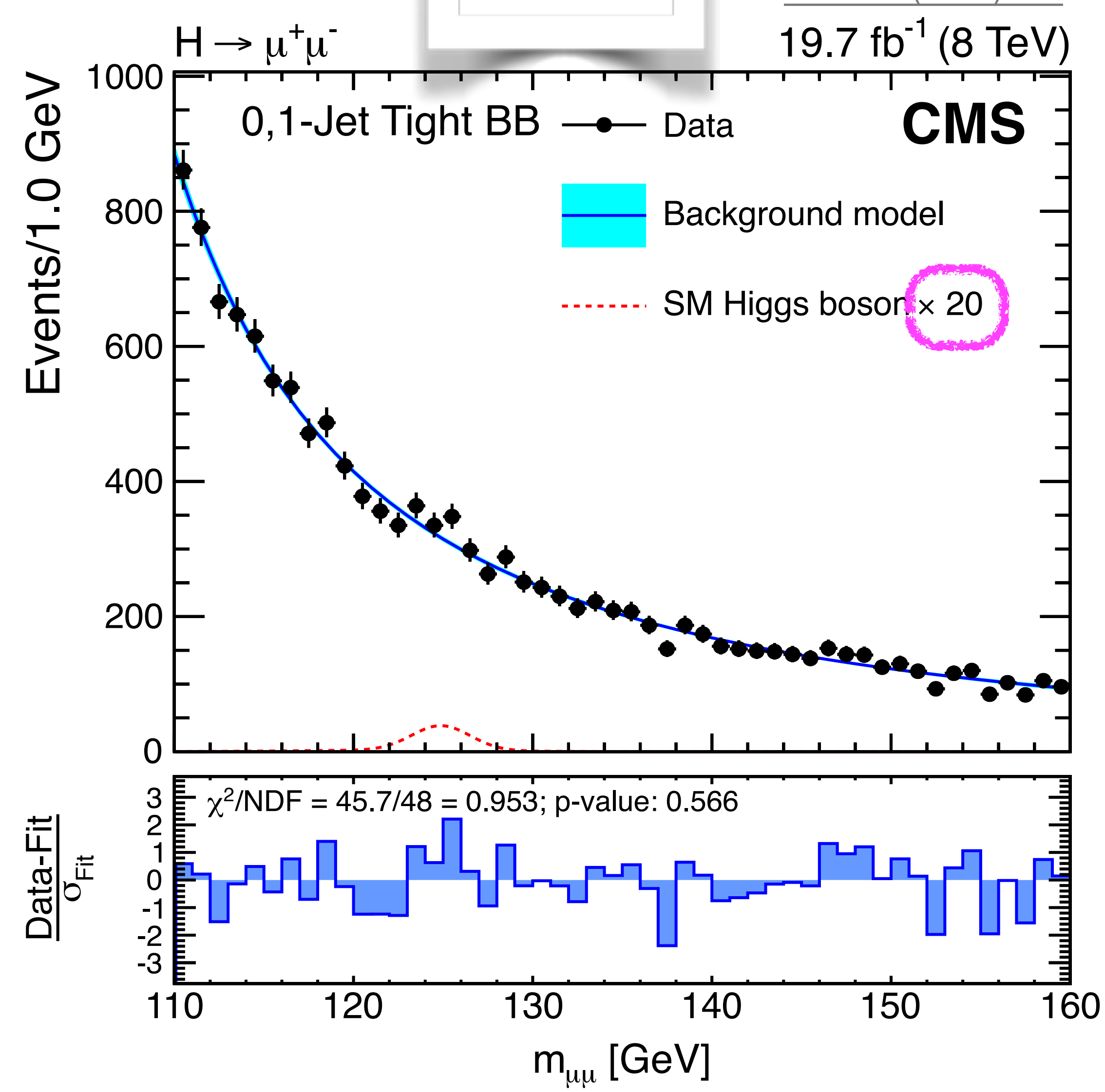
RUN-2

New



RUN-1

PLB 744 (2015) 184

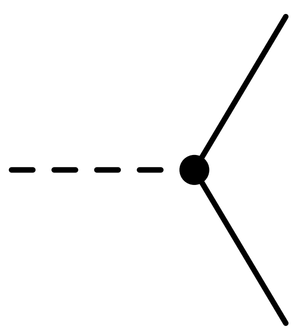


Couplings versus Mass - Higgs-gauge boson and Yukawa -

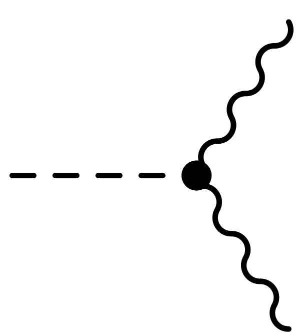
- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W/Z gage bosons and fermions and unitarity conservation below 1 TeV.
- Non-linear relation would indicate the Higgs sector is not single doublet.

JHEP 08 (2016) 045

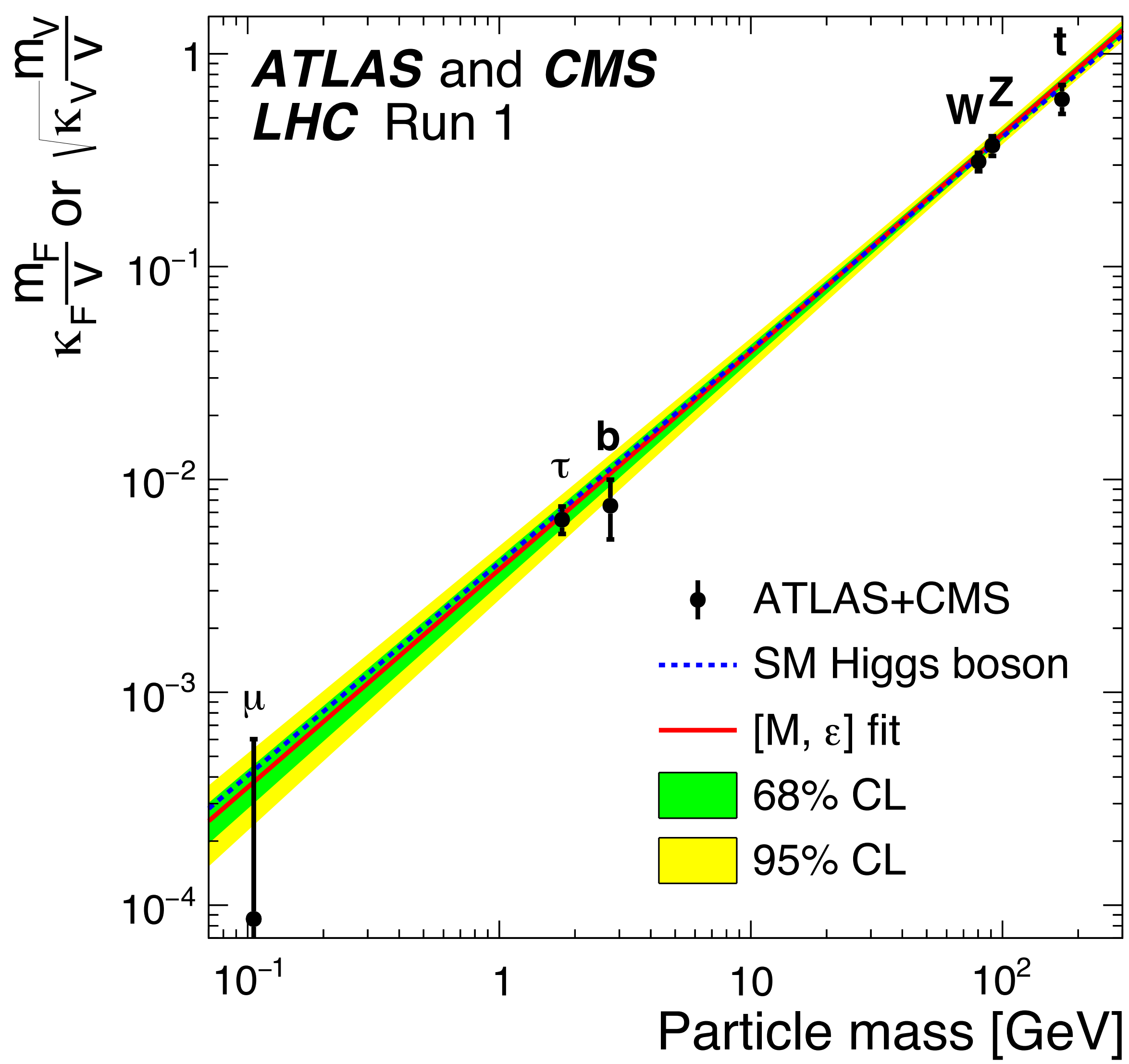
$$\begin{cases} y_F = \kappa_F \frac{m_f}{v} \\ y_V = \sqrt{\kappa_V} \frac{m_V}{v} \end{cases}$$



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



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



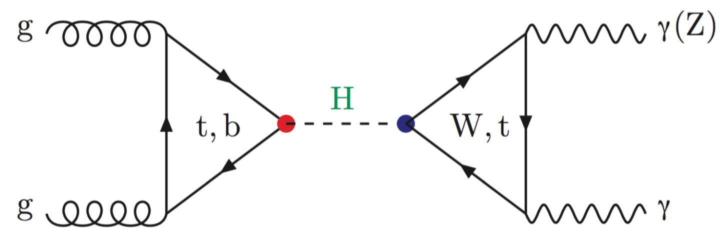
LHC wants to add Higgs self-coupling λ and fermion coupling $H \rightarrow \mu^+\mu^-$, cc, etc. (e^+e^- hopeless).

Couplings (κ_V, κ_F) in $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$

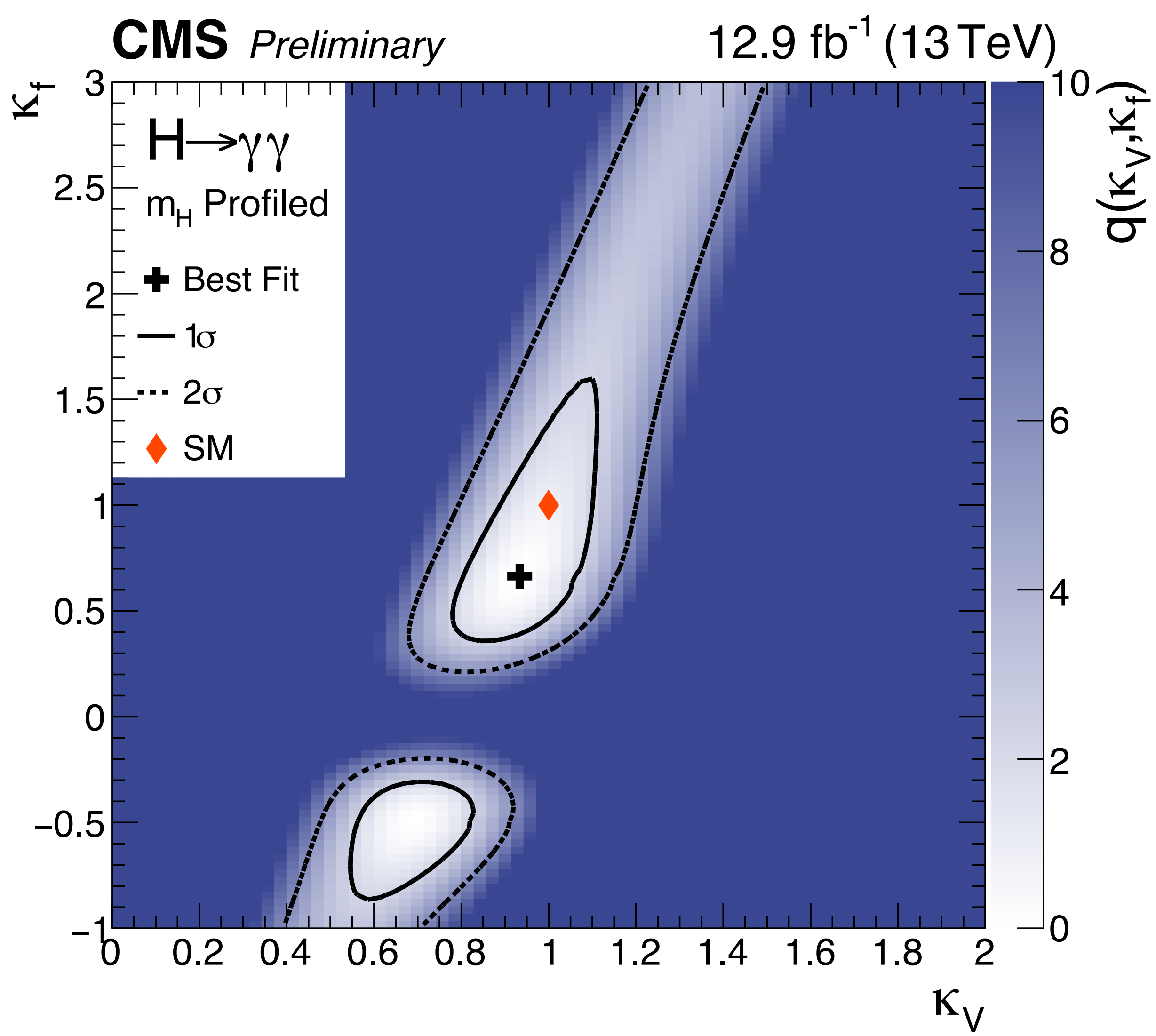
- Slope due to negative interference between top and W-boson in $H\rightarrow\gamma\gamma$ decay

$$\kappa_\gamma^2(\kappa_W,\kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

$$\text{slope}: \quad \frac{d\kappa_F}{d\kappa_V} \simeq 4.7$$



CMS-PAS-HIG-16-020



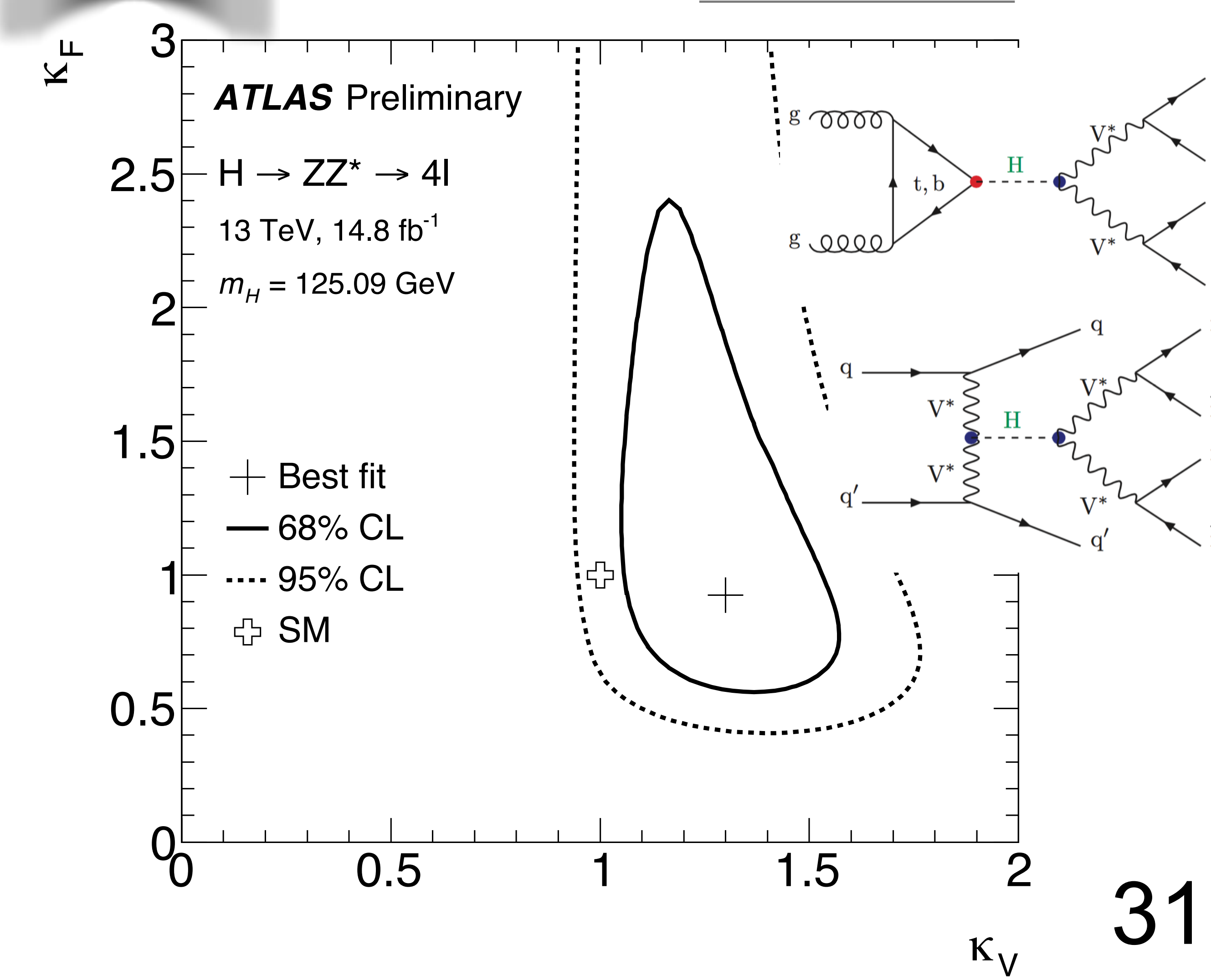
- Mostly sensitive to κ_V, but can constrain on κ_F with associated productions in VBF and VH. ($\because$ too large κ_F means small $BR=\Gamma_{ZZ}/\Gamma_{tot}$ where Γ_{tot} is dominated by $H\rightarrow bb$).

$$BR(H\rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{tot}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}}+\Gamma_{VV}}$$

$$\Gamma_{f\bar{f}} : \Gamma_{VV} \simeq 3:1 \text{ (dominated by } \Gamma_{b\bar{b}})$$

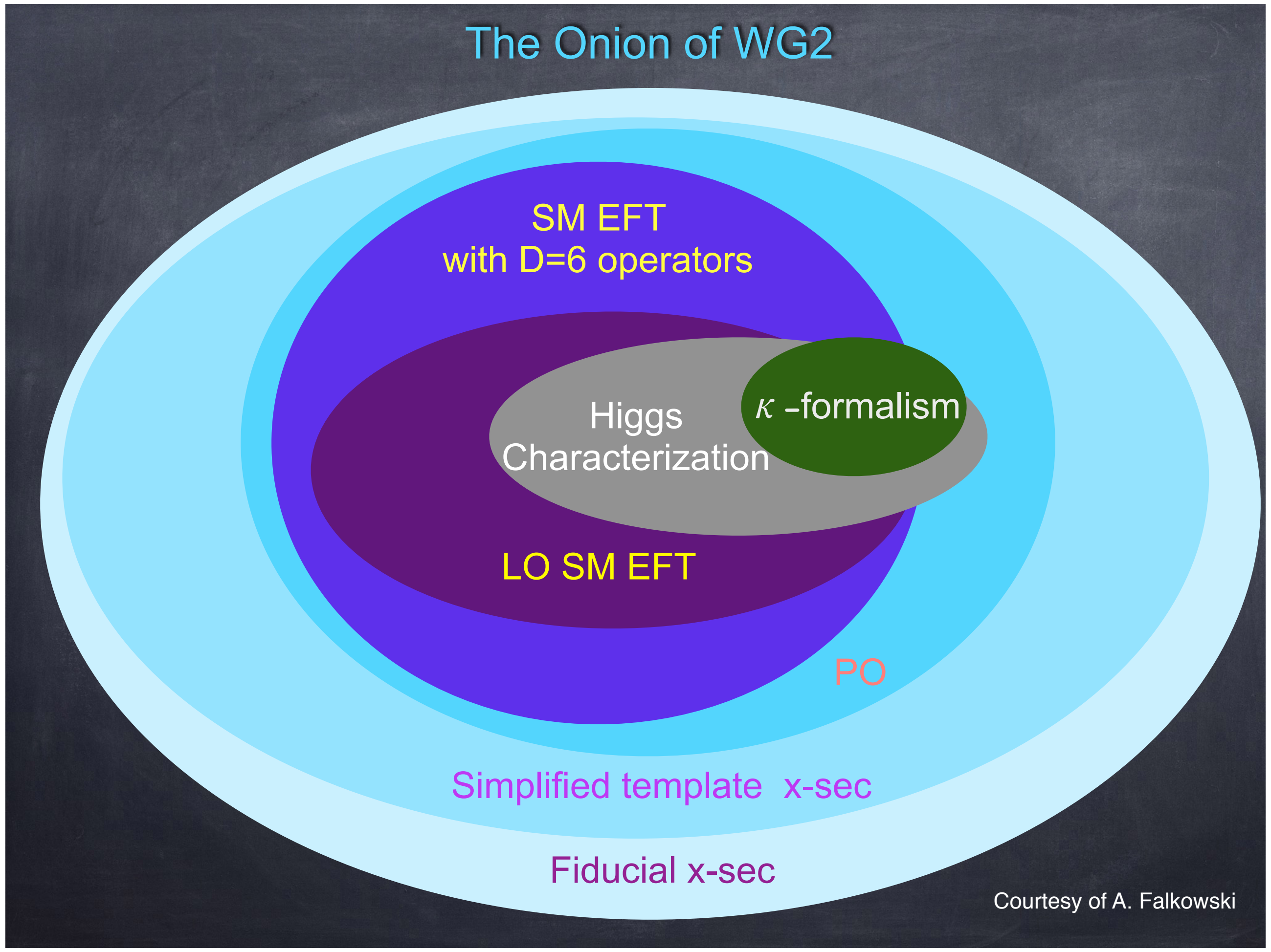
RUN-2

ATLAS-CONF-2016-079



Go beyond κ-framework

- Various frameworks exist:
  1. Fiducial Cross Section
  2. Simplified Template Cross Section
  3. Pseudo-Observables
  4. Higgs Effective Field Theory
  5. Higgs Characterization (did in RUN-1)
  6. kappa-framework (did in RUN-1)



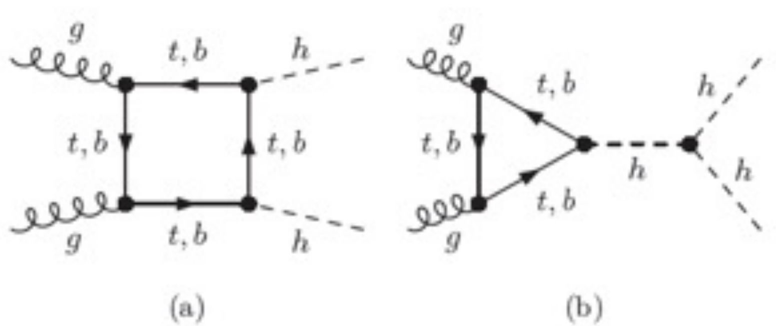
➪ κ-framework remains as an option in RUN-2
  - References [LHCHXSWG-2012-001] [CERN Yellow Report 3]
- κ-framework is aimed to "detect the deviation from the SM", not "measuring the coupling itself for precision physics".

- Extensive discussions in WG2 of the LHC Higgs Cross Section Working Group
  - Experiments provide Fiducial XS and Simplified Template XS.
  - Measurements in Pseudo-Observables
  - Interpretation in the Effective Field theory (eventual combination with EWPD)

5. Higgs Boson Self-Couplings

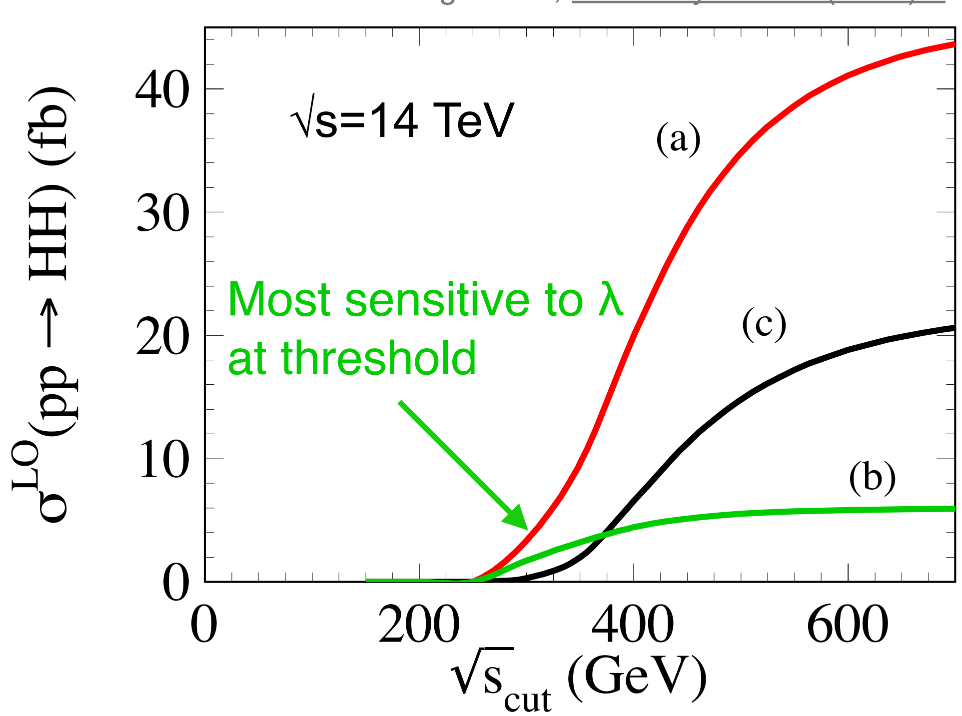
Higgs potential - Higgs self-coupling

- One of the core physics programs at HL-LHC, but very challenging in both experiment and theory.
- Is it feasible to measure Higgs self-coupling at 20-30% precision at HL-LHC ?
  - Explore all possible channels like HH→bbbb, bbγγ, bbττ, ttHH, etc.
  - New ideas like boosted Higgs analysis.
- Non-trivial interference between different diagrams.

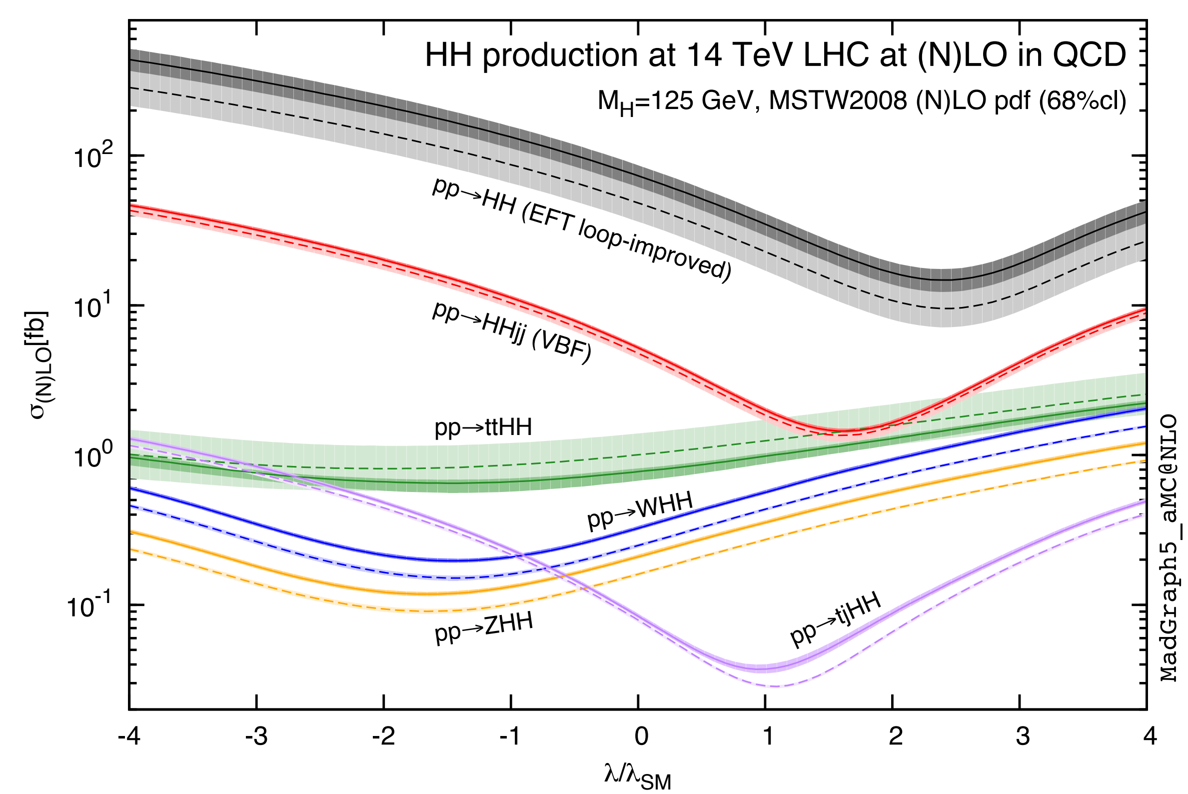


Destructive interference between box (a) and triangle (b) diagrams.

J. Grigo et al., Nucl. Phys. B875 (2013) 1

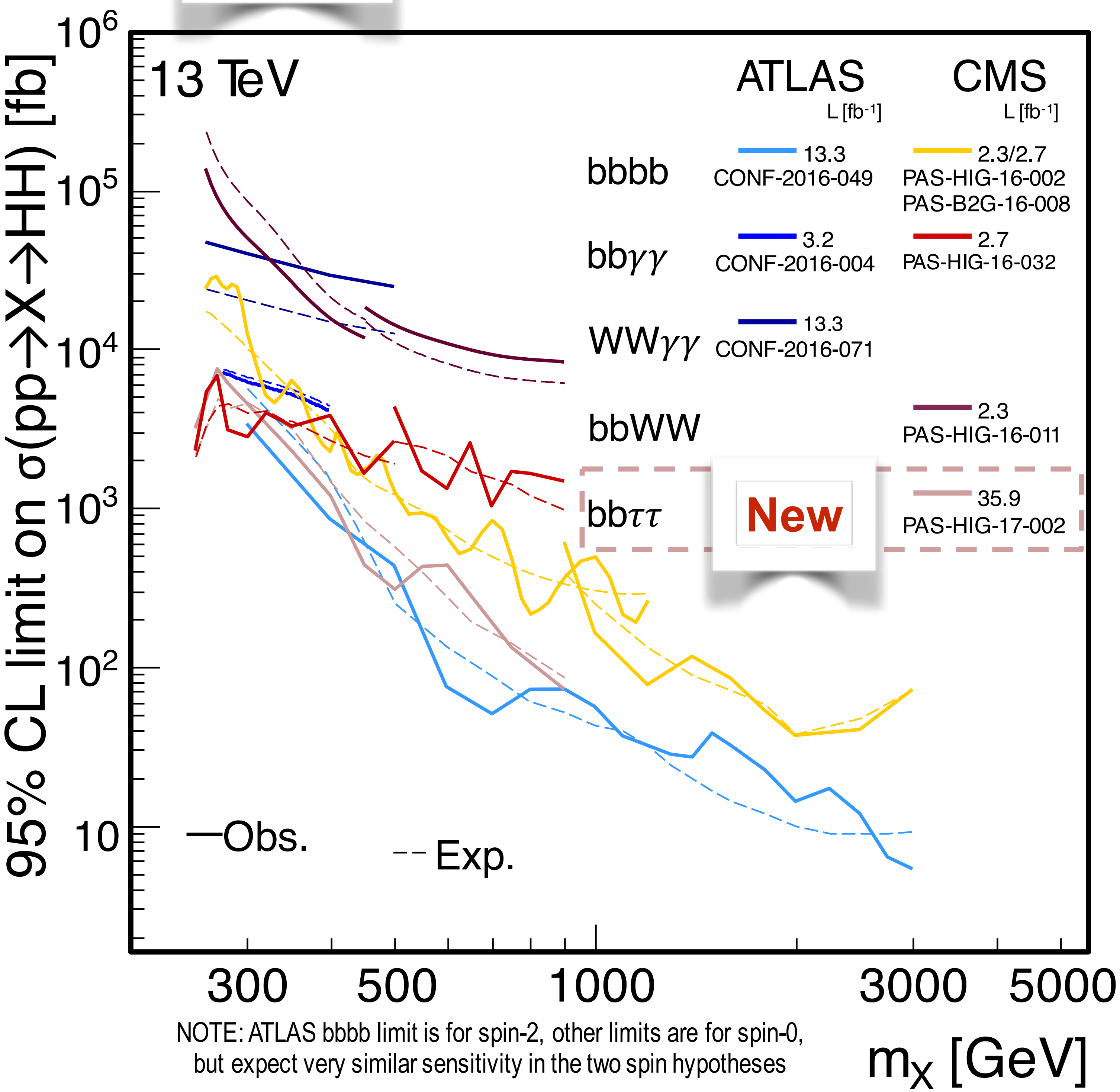


R. Frederix et al., PLB 732 (2014) 142



HH Overview for Results in RUN-1&2

RUN-2



NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

Make use of "resolved" and "boosted" techniques

L. Cadamuro (Moriond EW)

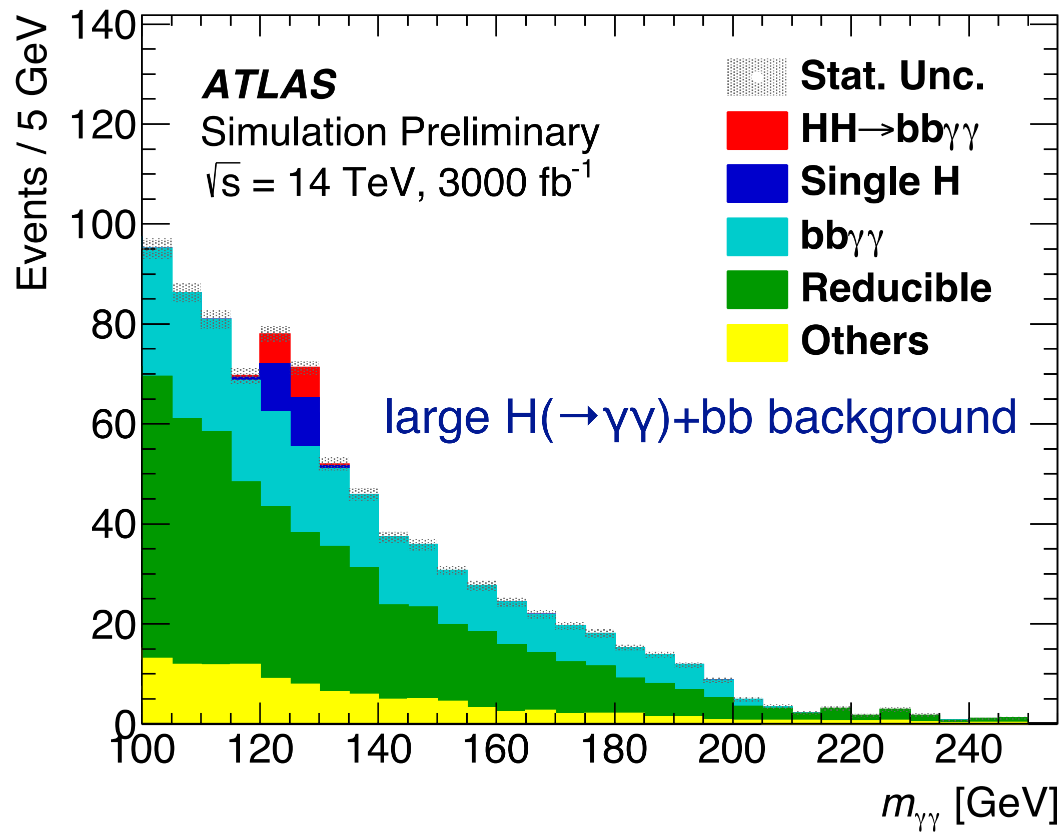
Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227)
bbττ	-	28 (25)
bbγγ	117 (161)	91 (90)
WWγγ	747 (386)	-

2.3-3.2 fb^{-1}	13.3 fb^{-1}	35.9 fb^{-1}

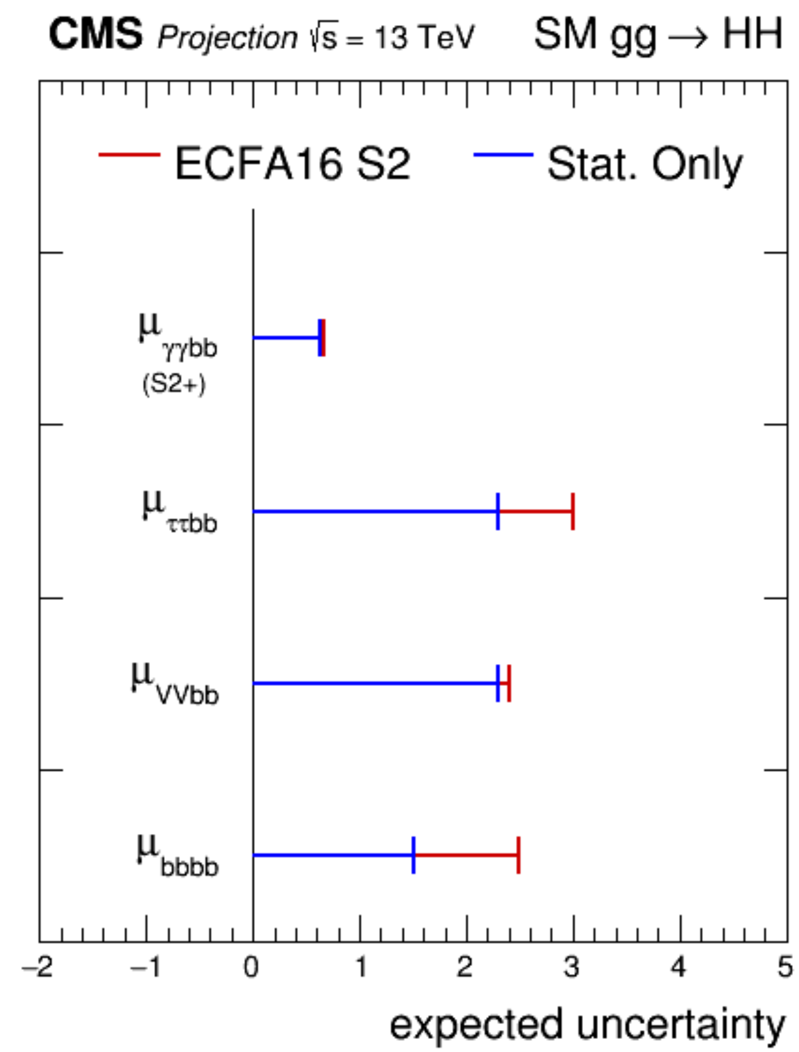
HH Prospects in HL-LHC

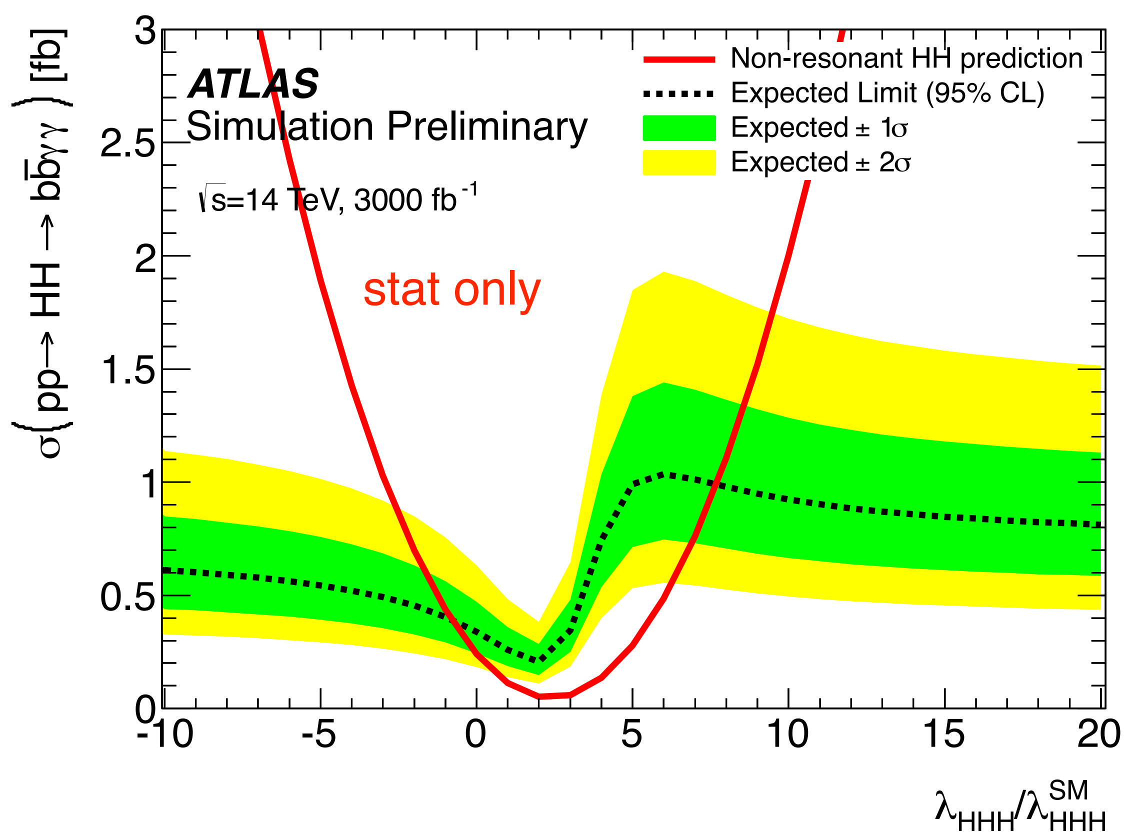
CMS-DP-2016-064

ATL-PHYS-PUB-2017-001



HL-LHC





Certainly we need to study many channels as much as possible and eventually combine ATLAS+CMS to observe HH production.

6. BSM Higgs Sector
More doublet(s) ?

Two Higgs Doublet Model (2HDM)

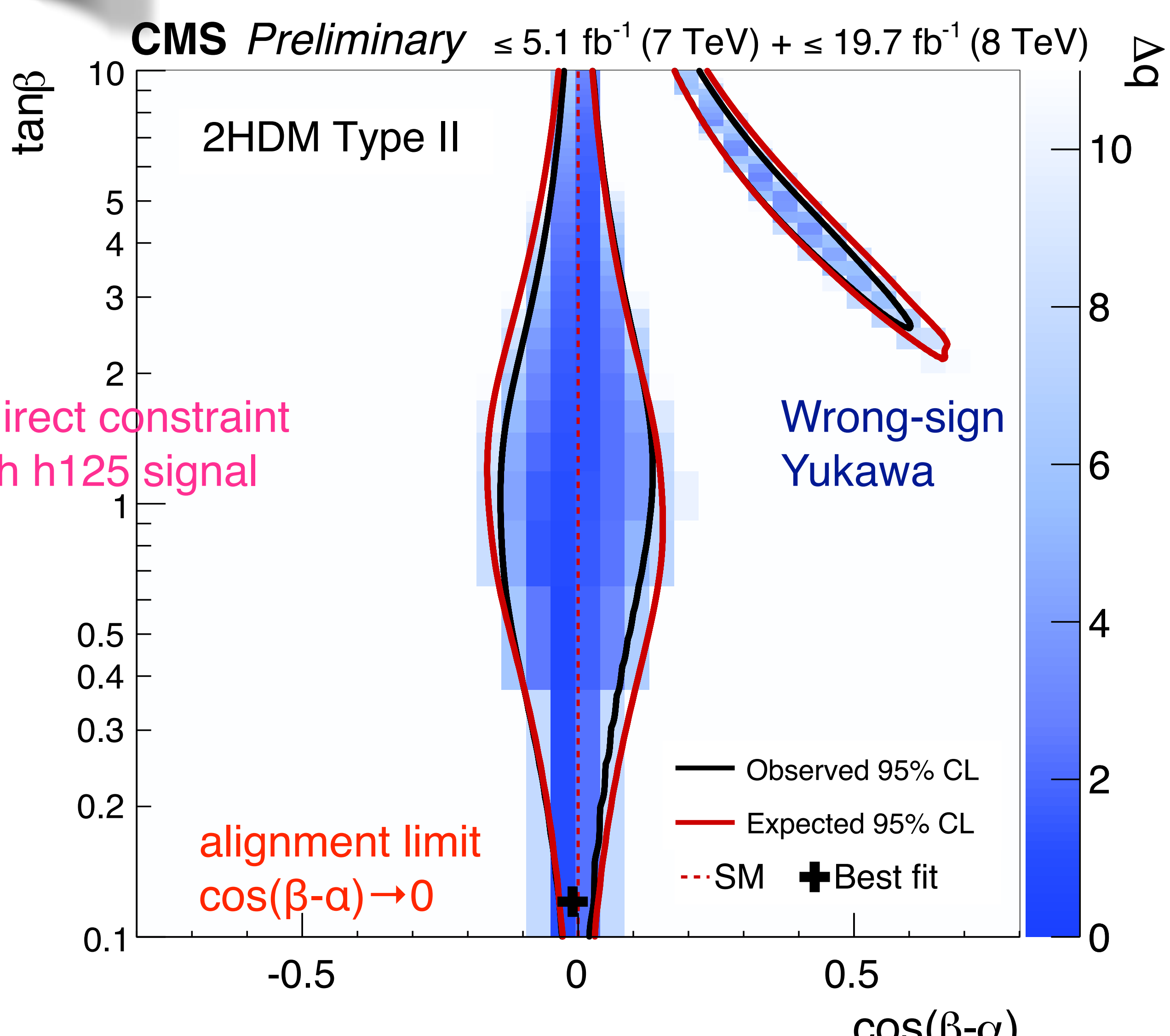
- 2HDM predicts the existence of 3 neutral Higgs bosons (h/H/A) and 2 charged Higgs ($H^{\pm}$). MSSM is Type-II 2HDM.
- 2HDM scalar potential

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v_1\end{pmatrix},\ \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v_2\end{pmatrix}$$

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \ldots$$

RUN-1

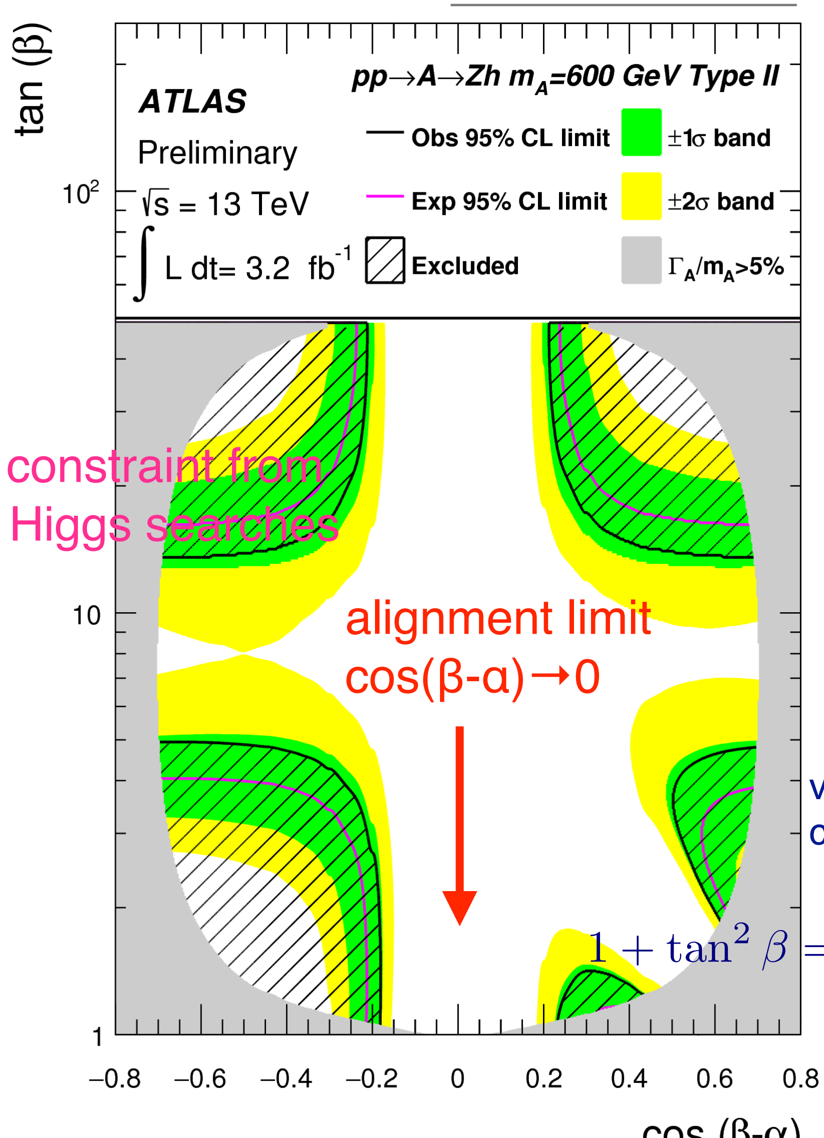
CMS-PAS-HIG-16-007



Indirect constraint with h125 signal

alignment limit cos(β-α)→0

ATLAS-CONF-2016-015



Direct constraint from heavy Higgs searches

vanishing h→bb coupling

$$1+\tan^2\beta = \frac{1}{\cos^2(\beta-\alpha)}$$

MSSM $h \to \tau^+\tau^-$

Talk by Johannes Brandstetter on SM $Z/H \to \tau^+\tau^-$

- Above 3σ significance in RUN-1 for both ATLAS and CMS for SM $h \to \tau^+\tau^-$.
  - 5.5σ evidence for $h \to \tau^+\tau^-$ decay when ATLAS&CMS are combined.
- Interpretation in MSSM for m_h^{mod}, hMSSM scenario, etc.
  - large $\tan\beta$ region with heavy A allowed, but pointing to the decoupling limit…

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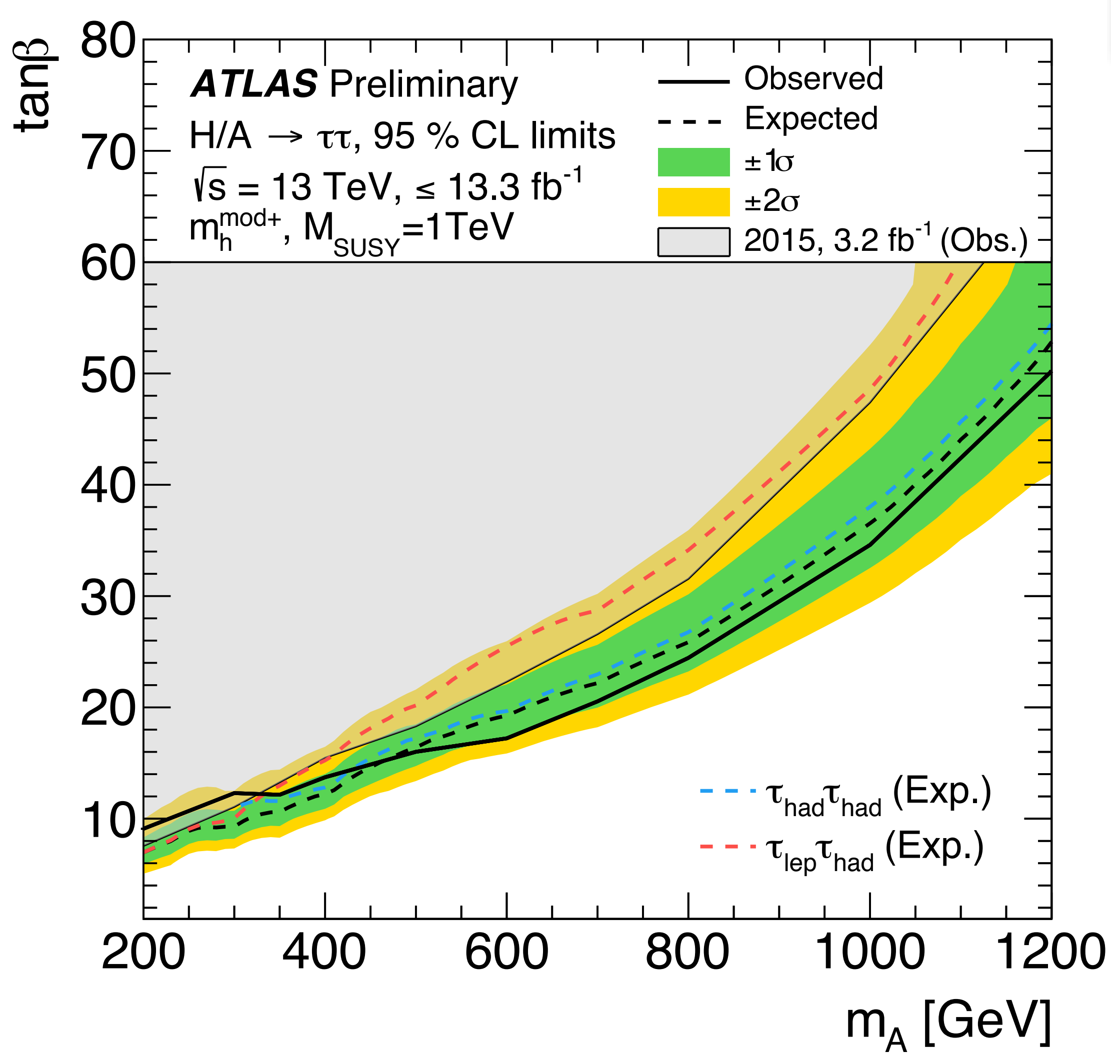
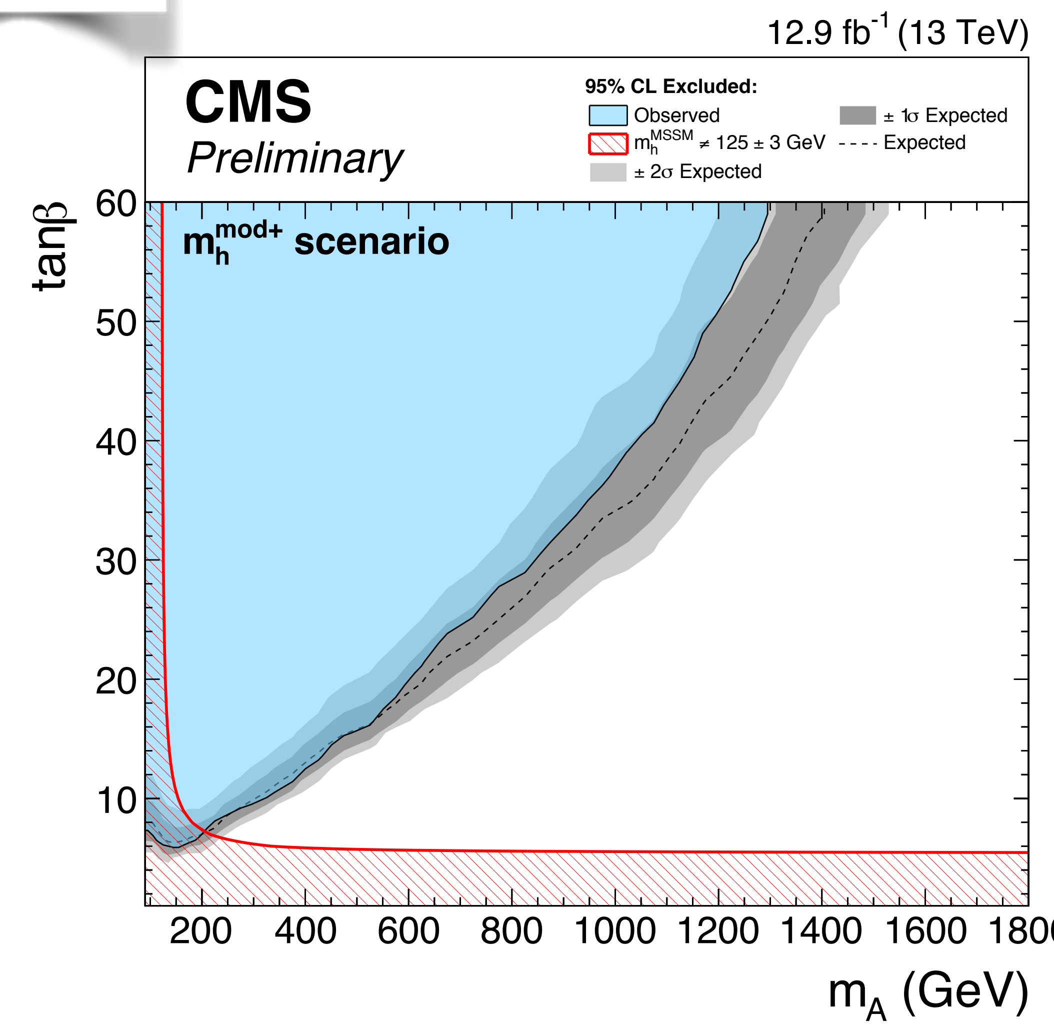
RUN-2

ATLAS-CONF-2016-085

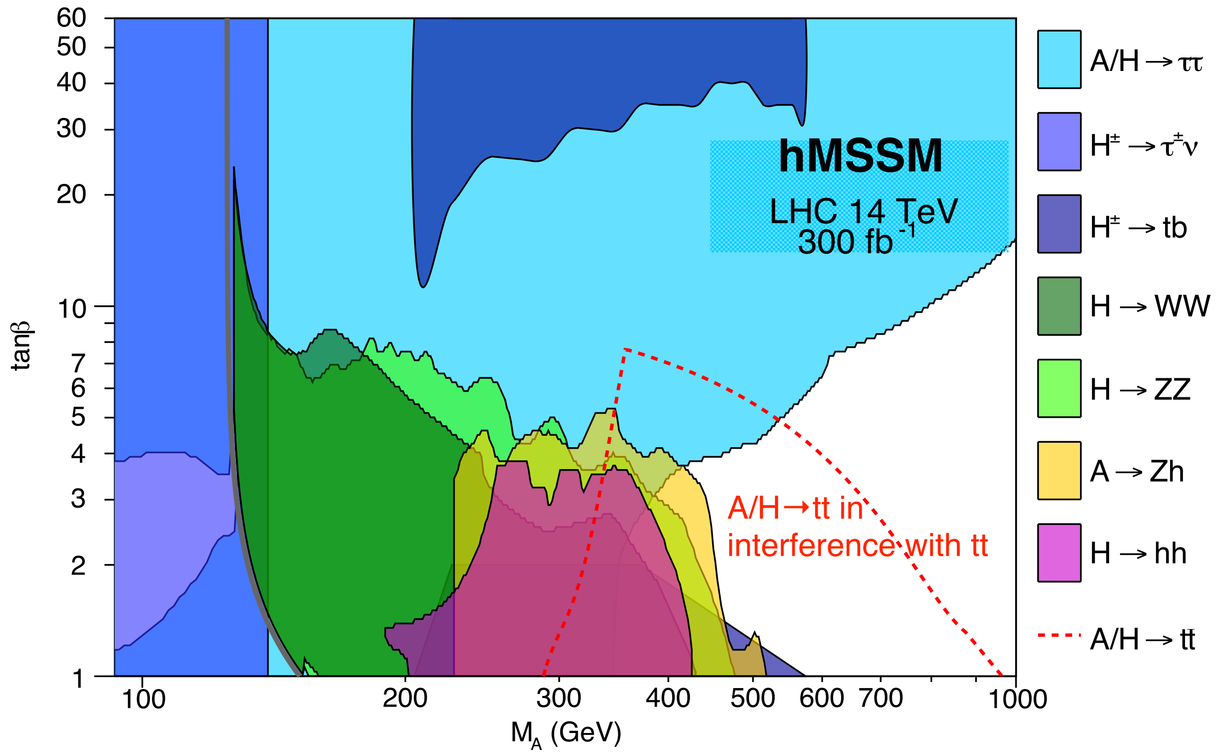


CMS-PAS-HIG-16-037

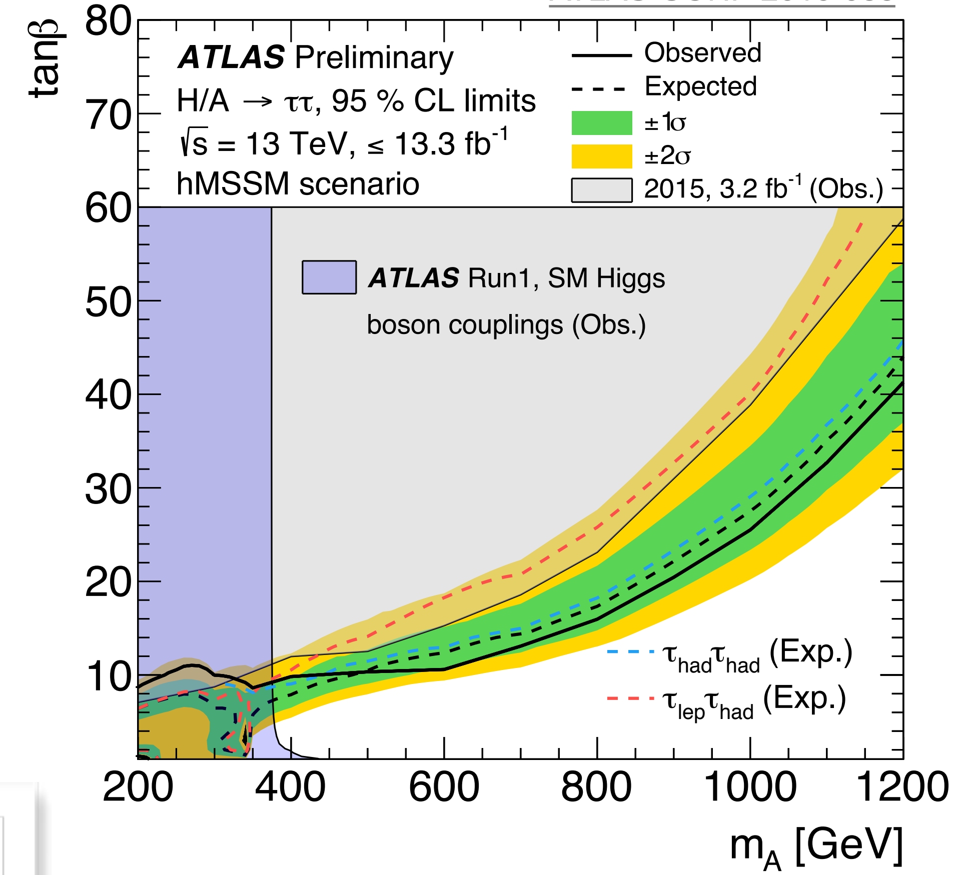


Simplified MSSM: hMSSM scenario

A. Djouadi et al., JHEP 06 (2015) 168



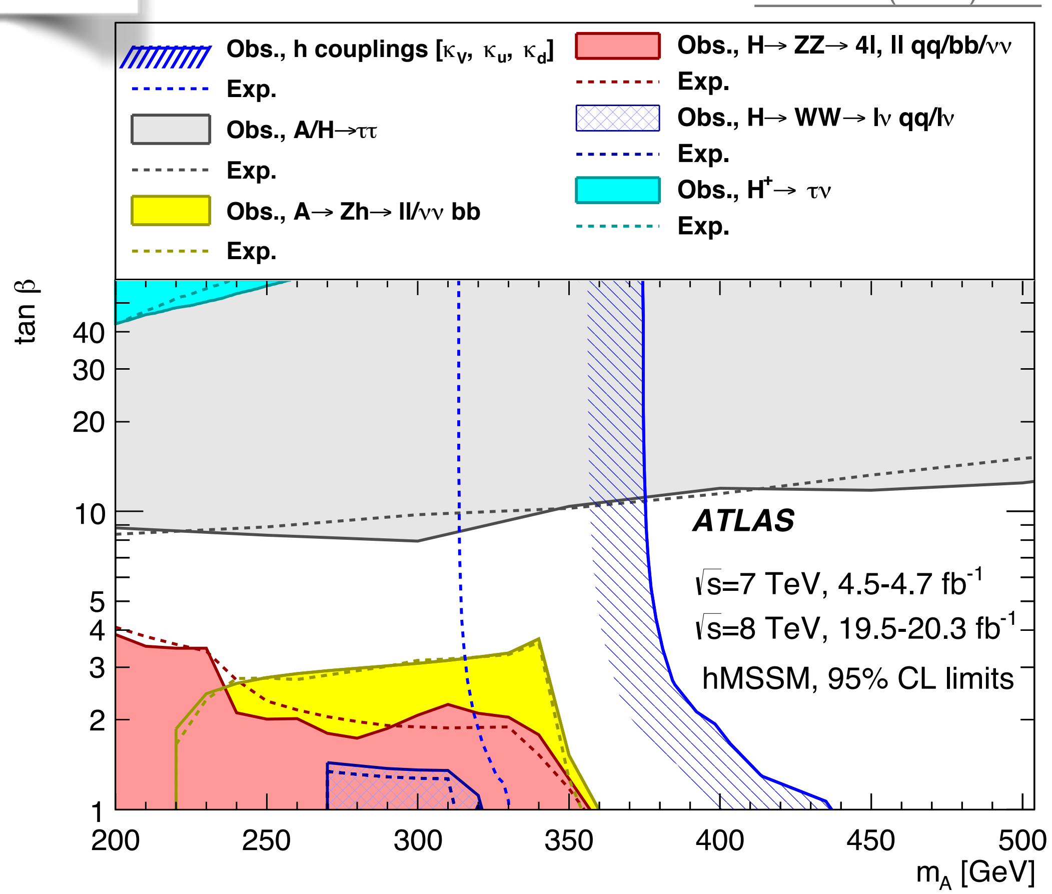
ATLAS-CONF-2016-085



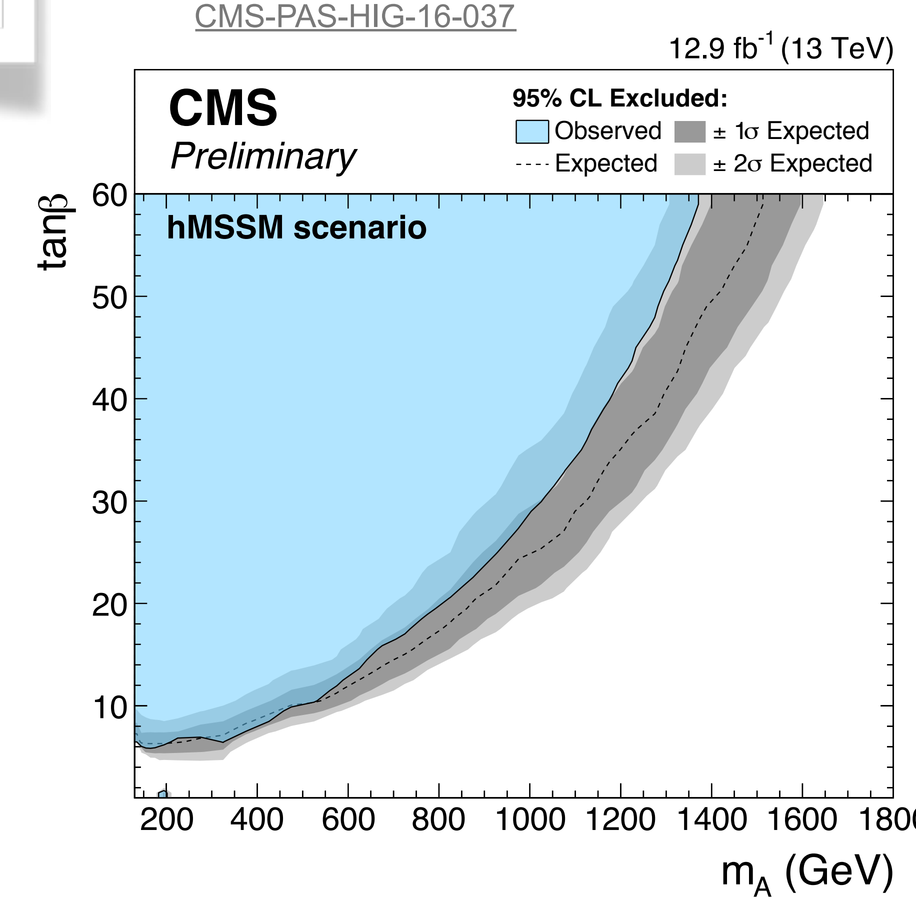
RUN-1

RUN-2

JHEP 11 (2015) 206



CMS-PAS-HIG-16-037



Summary: Status of Scalar Sector

- Higgs boson mass (M_H) & decay width (Γ_H)
  $\hookrightarrow$ M_H measured at 2-3 per mille precision. No sign of BSM in Γ_H, BR_{inv}.
- Higgs couplings to gauge bosons (g_V) and fermions (g_F)
  $\hookrightarrow$ Consistent with the SM prediction, $g_V \propto m_V^2$, $g_F \propto m_f$. Next, study in $d\sigma/dX$.
- Higgs boson quantum numbers J^{PC} and tensor structure
  $\hookrightarrow$ Evidence for scalar nature of 0^+. No evidence for CP-mixture/violation.
- Higgs potential - Higgs self-coupling λ
  $\hookrightarrow$ Remains as an important territory to conquer in HL-LHC.
- Beyond the Standard Model Higgs (2HDM/MSSM, etc.)
  $\hookrightarrow$ No evidence, but keep looking for BSM Higgs(es) and exotic Higgs decays.

- We have observed the first elementary particle of scalar - Higgs boson.
  - Brout-Englert-Higgs mechanism: what an incredible purely theoretical idea !!!
  - Experimentalists will make every endeavor for BSM physics discovery !!
- LHC - hadron collider now enters in precision measurement era !

What do we know about the scalar sector 5 years after July 4th 2012 discovery ?

We know M_H, Γ_H, spin/CP and couplings but not much yet for direct Yukawa, Higgs potential and BSM sector !

Backup

References

- ATLAS Public Higgs Results Page
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- CMS Public Higgs Results Page
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- LHC Higgs Cross Section Working Group
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
  - CERN Report 4: **Handbook of LHC Higgs Cross Sections**
  - Deciphering the nature of the Higgs sector (CERN–2017–002-M, 869 pp)
  - https://arxiv.org/abs/1610.07922

Electroweak Symmetry Breaking Mechanism

- Higgs as the origin of Electroweak Symmetry Breaking
  - Original idea on spontaneous symmetry breaking by Y. Nambu (1960).

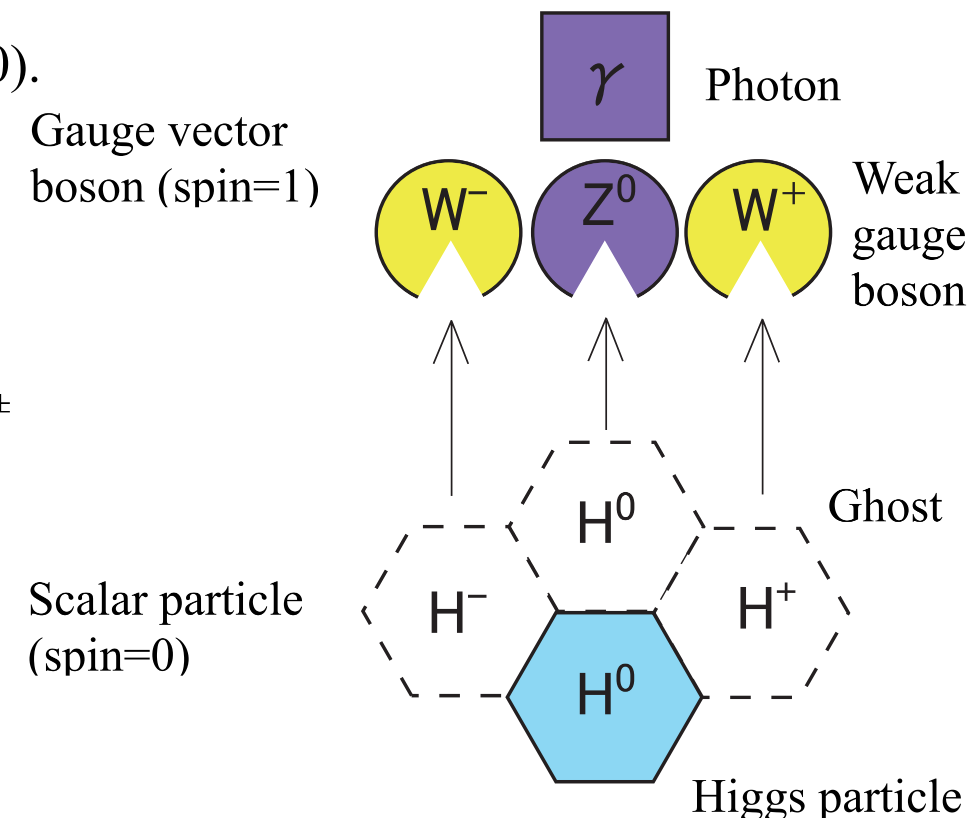
    ➪ Application to relativistic gauge theory by P. W. Higgs, F. Englert and R. Brout (1964), Brout-Englert-Higgs (BEH) mechanism.
    - SU(2) doublet of complex scalar fields → vev of 246 GeV
    - $SU(2)_L \times U(1)_Y$ symmetry spontaneously broken
    - 3 of 4 degree of freedom of doublet scalar field - "eaten" by $W^{\pm}$ and Z^0 → massive gauge bosons.
  - Fermions acquire masses via Yukawa-interaction.

- Higgs boson
  - Unique scalar elementary particle of $J^P=0^+$
  - The SM does not explain why the Higgs field developed a vacuum expectation value. The dynamics behind the EWSB unknown. Is it weakly interacting or strongly interacting?

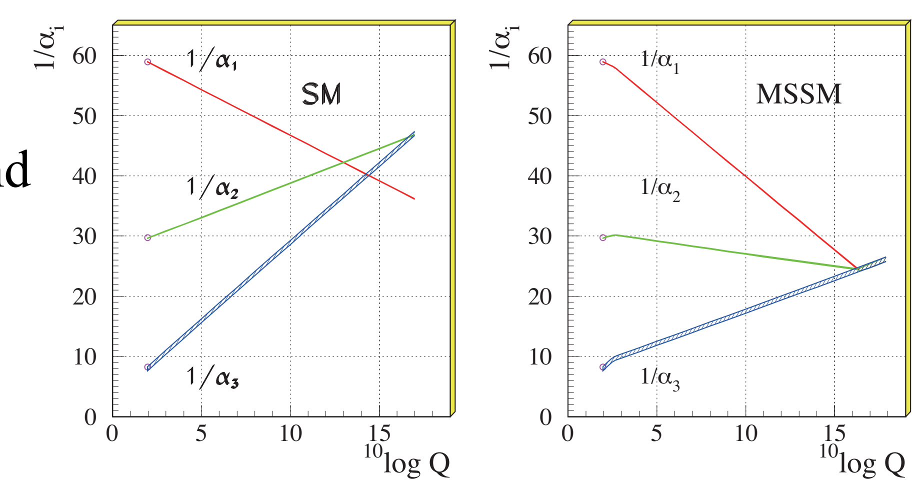
- Only one Higgs doublet?
  - Fine tuning problem, naturalness ... ➪ New physics may exist around electroweak energy scale (accessible by LHC) !
  - Most popular benchmark scenario ➪ SUSY-MSSM: Smoking-gun signature in 1991.
    SUSY is still escaping from our detection.
  - But there are many other models: like Extra-Dimension, Little Higgs, Composite Higgs or Twin Higgs, etc.

    ➪ Rich phenomenology.

G. 't Hooft, Scientific American **242** 6 (1980) 104-138.



U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)



U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)

$\alpha_1, \alpha_2, \alpha_3$ coupling constants of electromagnetic –, weak–, and strong interactions

$1/\alpha_i \propto \log Q^2$ due to radiative corrections (LO)

Higgs couplings to gauge bosons and fermions

- Assume all fermion couplings scale as κ_F while all vector boson couplings scale as κ_V.
- Assume no BSM contributions to Γ_H.

- Quad-fold ambiguity in sign of κ_F and κ_V.
  - One relative sign is physical.
  - Take $\kappa_V > 0$ as convention and look for $\pm\,\kappa_F$.
  - $\kappa_F < 0$ means sign of new physics.
  - Almost degenerate minima in the likelihood: one for $\kappa_F > 0$ and the other for $\kappa_F < 0$.
  - $H \to \gamma\gamma$ excess prefers $-\kappa_F$ but $\kappa_F > 0$ for global fit.
  - Electroweak precision data constrain $\kappa_F > 0$. ($\because$ with $\kappa_F < 0$, κ_V is further away from 1)

RUN-1

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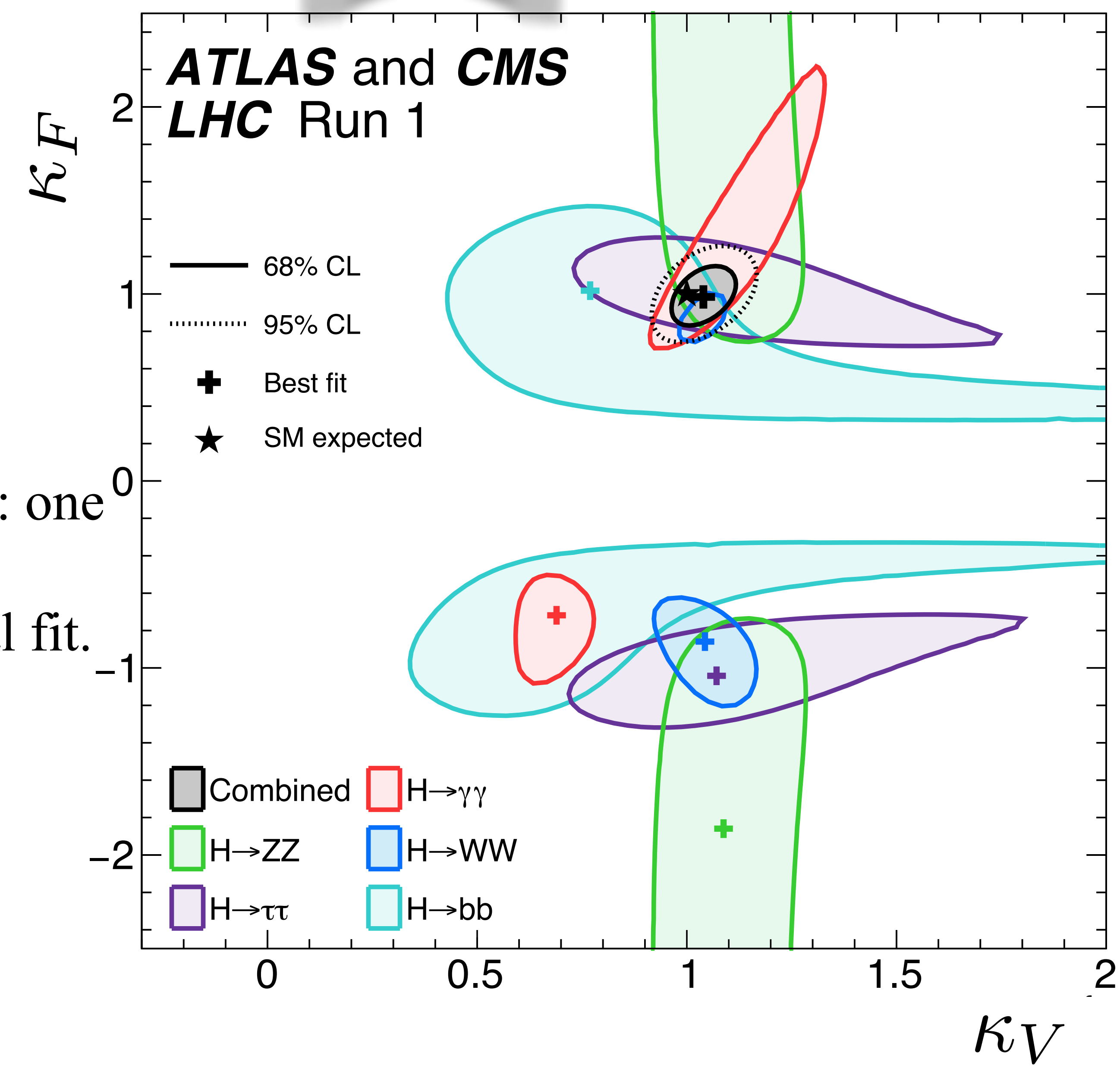


Data are compatible with SM predictions at 10-20% accuracy.

Higgs Effective Field Theory

- Model-independent framework - HEFT
- Effective Lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

where c_i is the Wilson coefficient and Λ is the cutoff scale.

- Neglecting dimension-5 operator, consider dimension-6 ($d_i=6$) basis.
- Complete basis of dimension-6 consists of 59 operators for one family.
  - Assuming observed Higgs is spin-0, CP-even, part of a SU(2) doublet, narrow and no overlapping resonances, SM local symmetry and global symmetry with L and B number conservation.
  - With more than one family, number of operators depends on the flavor assumption.
  - Projection of operators onto physical observables is basis-chosen dependent.
- Capable to combine EWPD, aTGC and Higgs data with common Lagrangian.
  - Discussion with LHC-EW WG (VV subgroup for aTGC).
- Connection with BSM Higgs Lagrangian.
  - Possible effects of heavy BSM particles encoded in higher-dimensional operators.
  - Parametrization of BSM for Higgs physics: ex. 8 parameters $\{\kappa_g, \kappa_\gamma, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau, \kappa_{Z\gamma}, \kappa_{h^3}\}$.
  - Assumes the scale of new physics Λ is heavy, *i.e.* there is no undiscovered low energy particle.
  - Capable of dealing with off-shell effects.

Clickable Link

Tools for Higgs Analysis

ggF
- HIGLU (NNLO QCD+NLO EW)
- iHixs (NNLO QCD+NLO EW)
- FeHiPro (NNLO QCD+NLO EW)
- HNNLO, HRes (NNLO+NNLL QCD)
- SusHi (NNLO QCD)
- RGHiggs (NNLO+NNNLL QCD)
- ggHiggs (approx. NNNLO QCD)

VBF
- VV2H (NLO QCD)
- VBFNLO (NLO QCD)
- HAWK (NLO QCD+EW)
- VBF@NNLO (NNLO QCD)

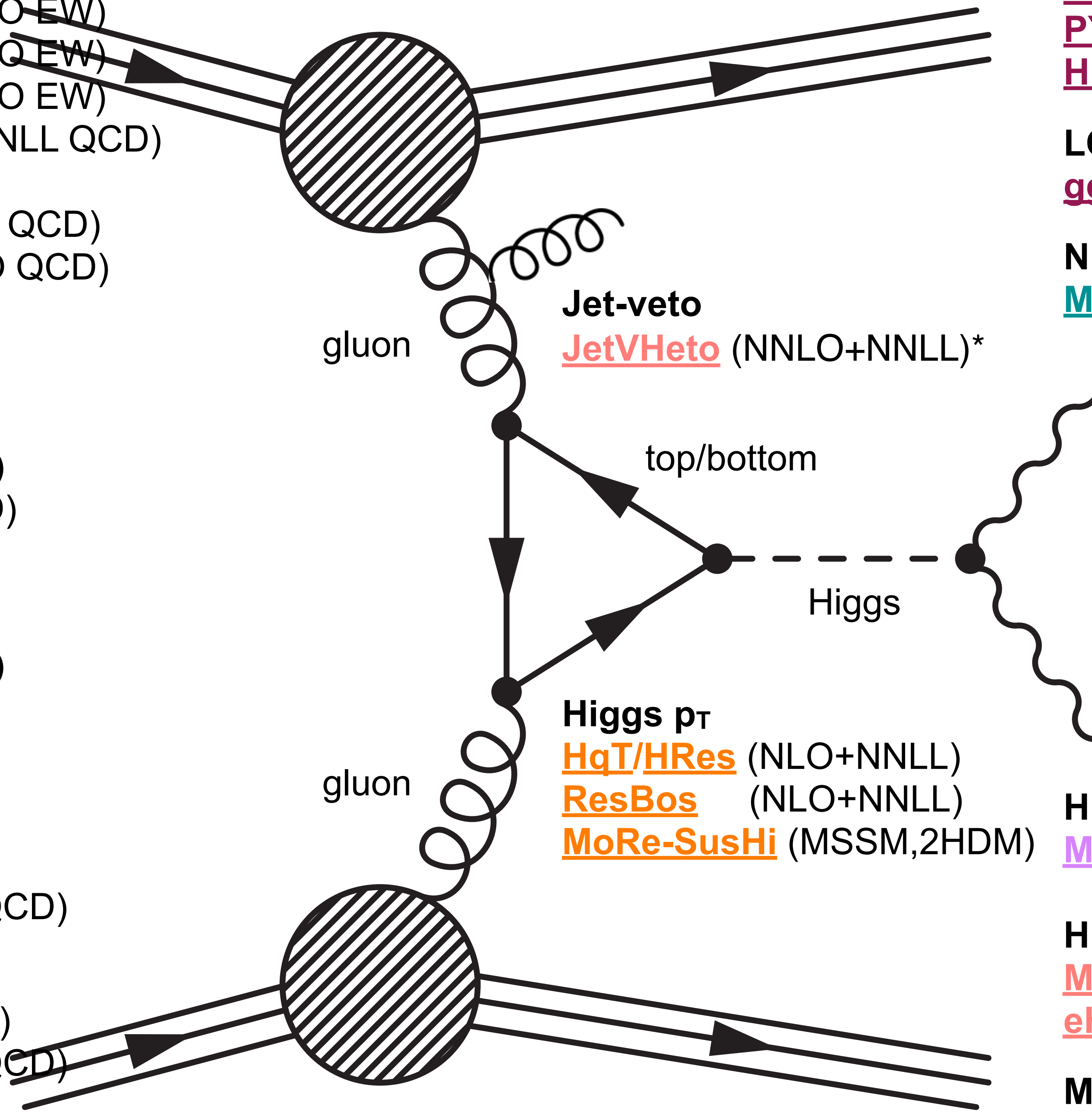
WH/ZH
- V2HV (NLO QCD)
- HAWK (NLO QCD+EW)
- VH@NNLO (NNLO)

ttH
- HQQ (LO QCD)
- POWHEL (NLO QCD)
- MG5_aMC@NLO (NLO QCD)

bbH
- bbh@NNLO (NNLO QCD)
- MG5_aMC@NLO (NLO QCD)

HH
- HPAIR (NLO QCD)
- MG5_aMC@NLO (NLO QCD)

+ private codes.



Jet-veto
JetVHeto (NNLO+NNLL)*

Higgs p$_T$
- HqT/HRes (NLO+NNLL)
- ResBos (NLO+NNLL)
- MoRe-SusHi (MSSM,2HDM)

PDF: MSTW/MMHT, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

* NLO+NNLL in differential

NLO MC
- POWHEG MiNLO
- MadGrapn5_aMC@NLO
- SHERPA MEPS@NLO
- PYTHIA8 UNLOPS
- HERWIG++ Matchbox

LO MC
- gg2VV

NLO ME
- MCFM, MG5_aMC@NLO

Higgs Decay
- HDECAY (NLO++)
- Prophecy4f (NLO)

Higgs Properties
- MELA/JHU, MEKD

HEFT
- MG5_aMC@NLO (SILH,HC)
- eHDECAY

MSSM/2HDM
- FeynHiggs, CPSuperH
- SusHi+2HDMC
- HIGLU+HDECAY

Compiled by R. Tanaka, Dec. 2014