ATLAS Results on Higgs Boson Couplings

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on behalf of ATLAS Collaboration

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

cnrs dépasser les frontières IN2P3 Les deux infinis

Higgs Boson Property Measurements

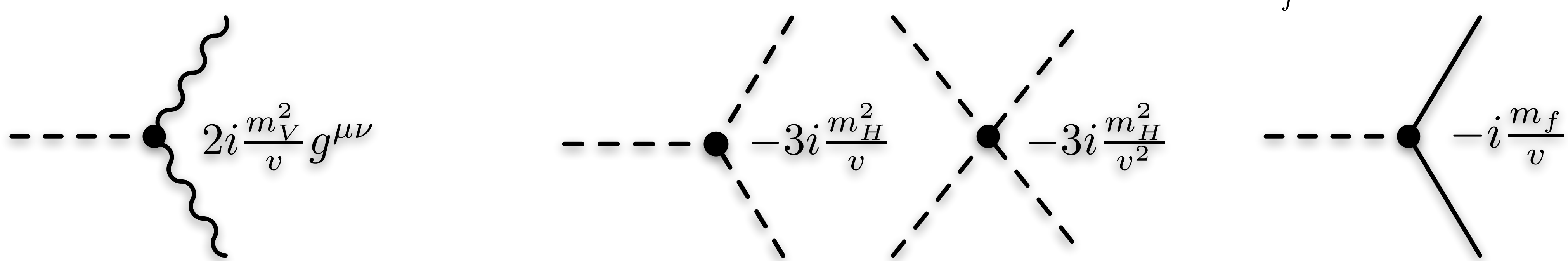
K. Cranmer

1. Higgs boson mass (M_H) & decay width (Γ_H) ⇨ talk by L. Fayard
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	Higgs self-couplings	Couplings to fermions
$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$



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

Higgs Boson Property Measurements

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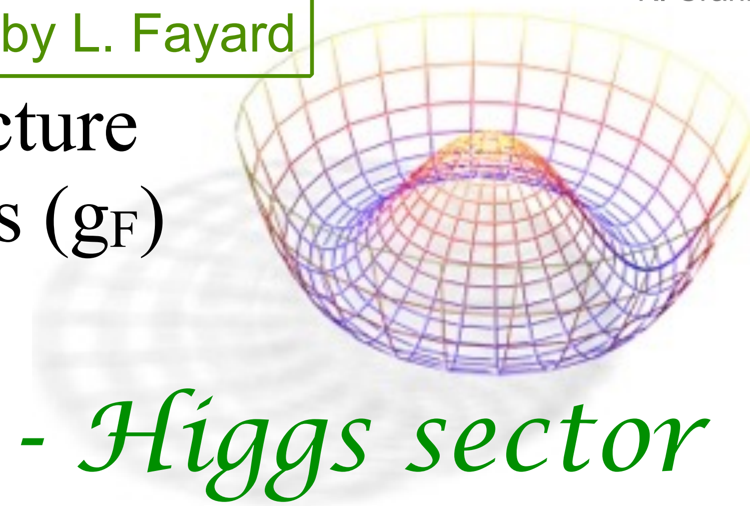

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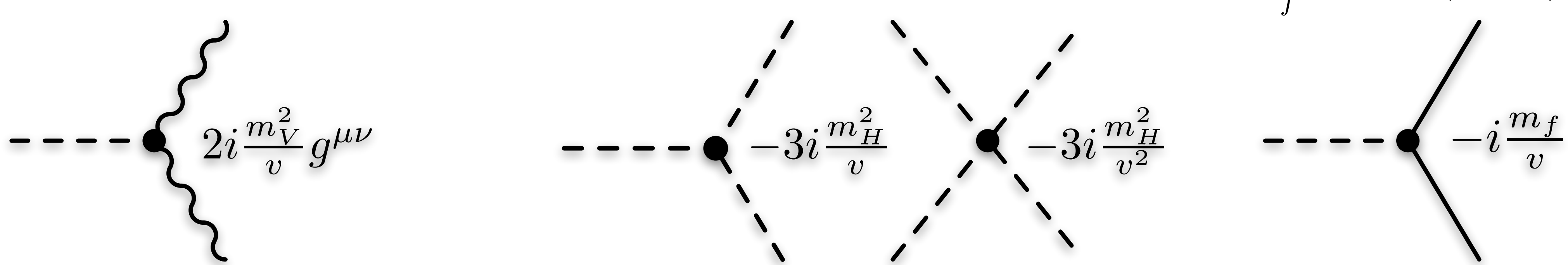

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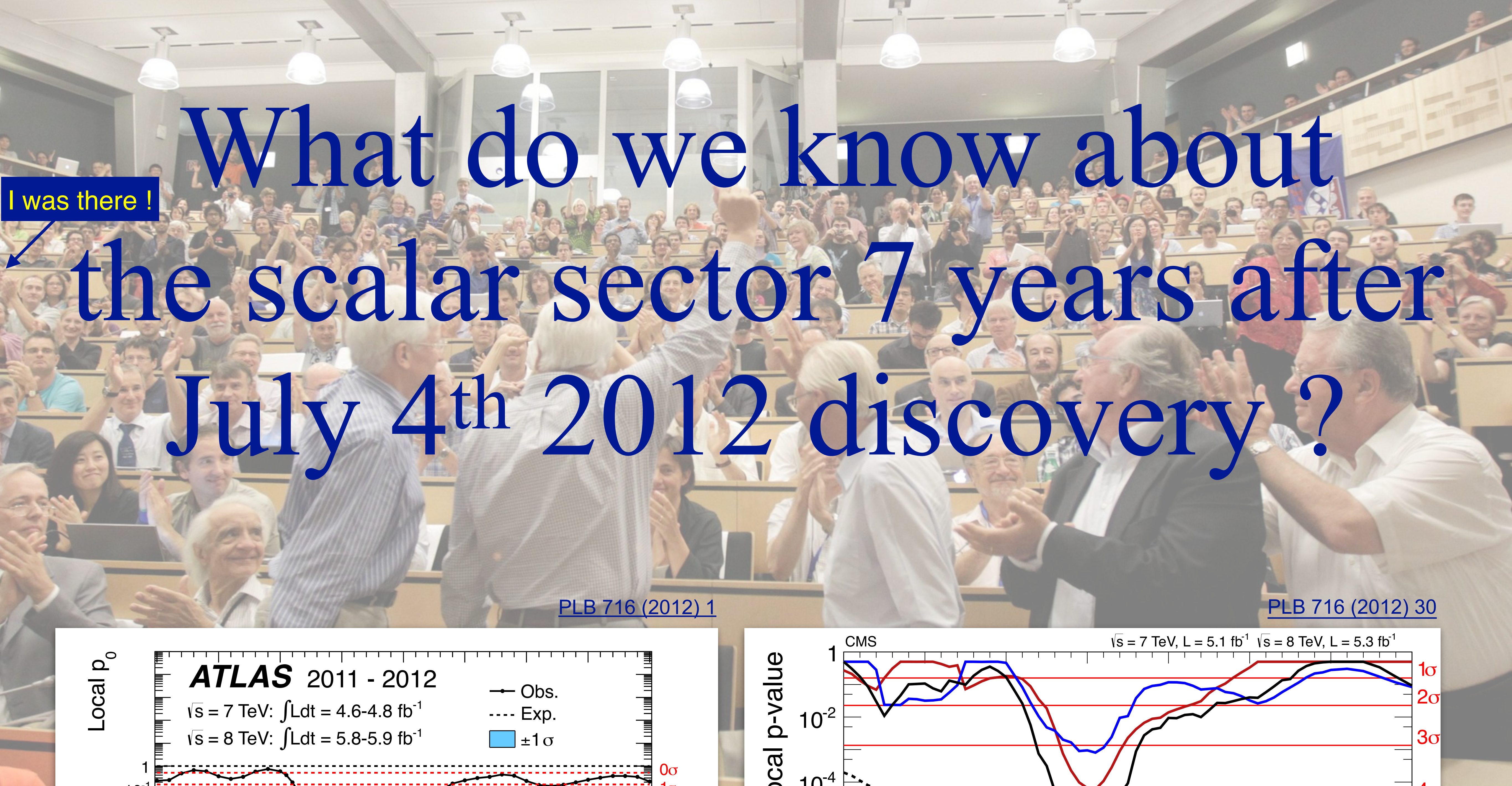
The ultimate goal of particle physics of today is to test the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).

What do we know about the scalar sector 7 years after July 4th 2012 discovery ?



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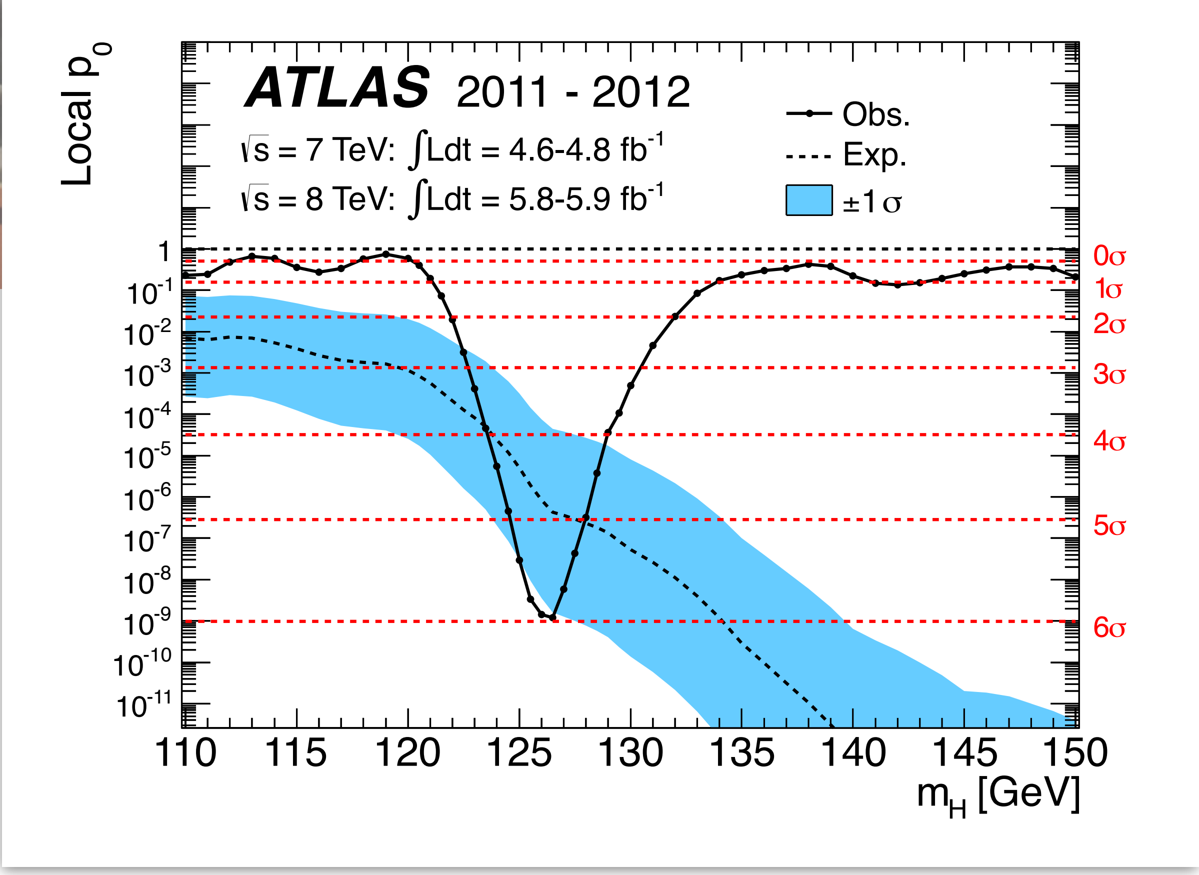

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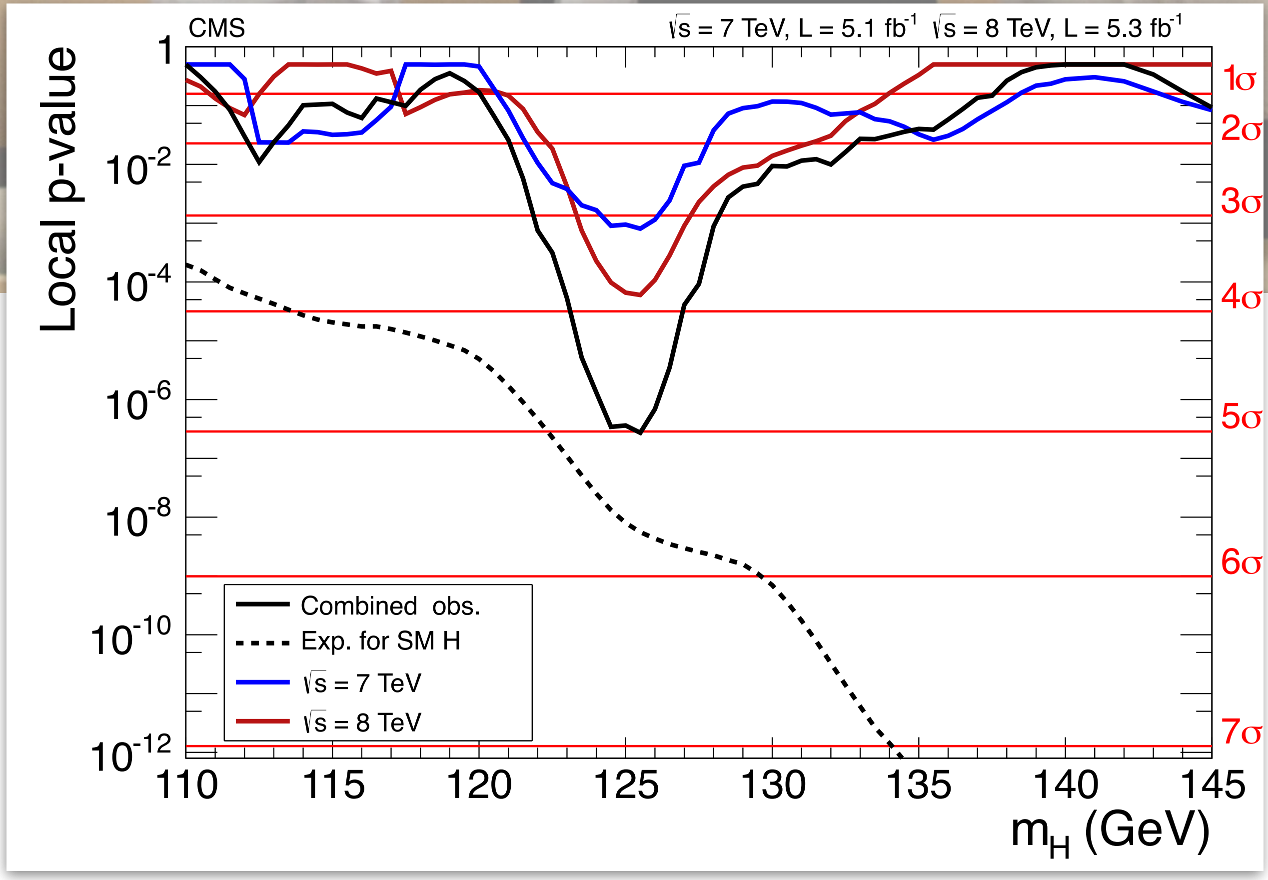
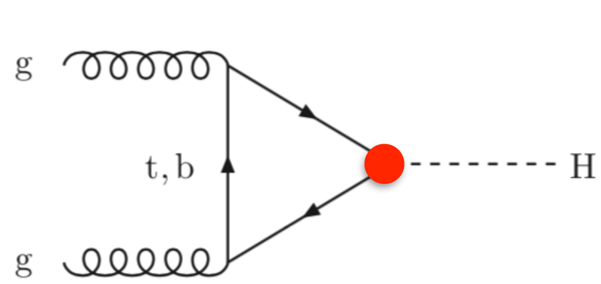
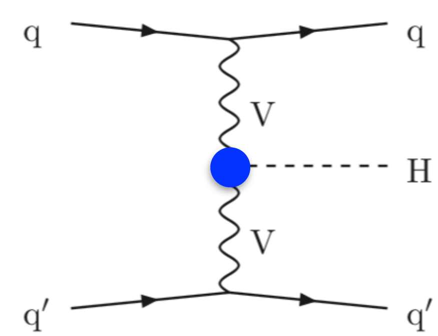


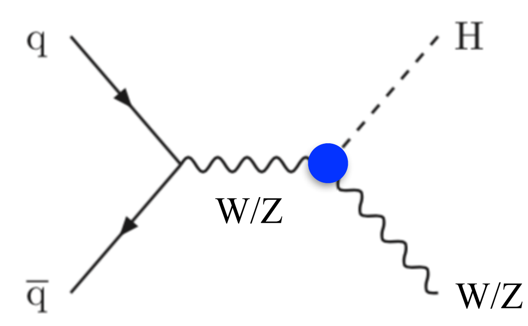
1. Higgs Boson Production and Decay at LHC

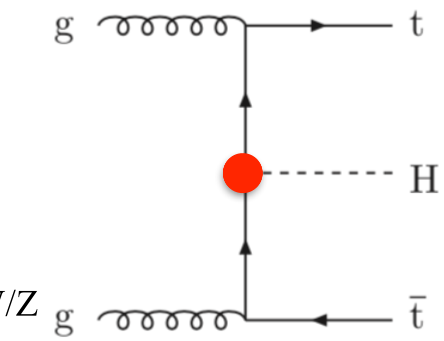
Data Analysed for Higgs Coupling Study in ATLAS

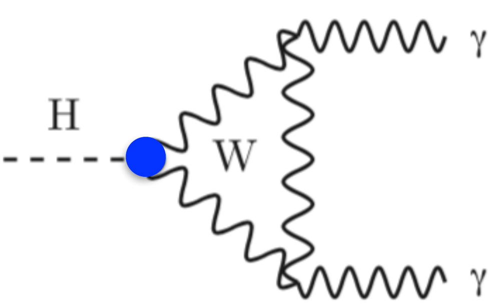
- Higgs Gauge Boson Coupling HVV
- Higgs Yukawa Coupling Hff

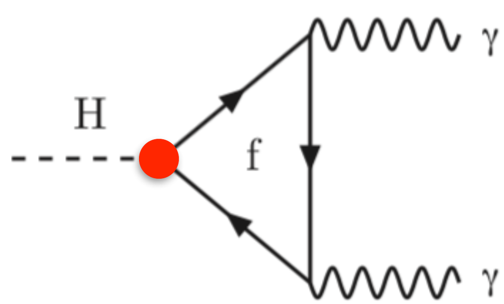


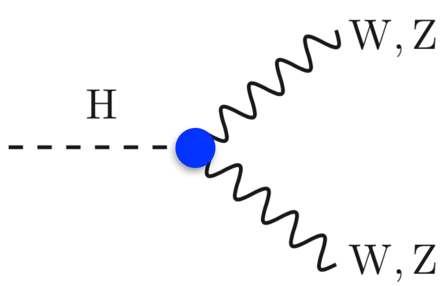


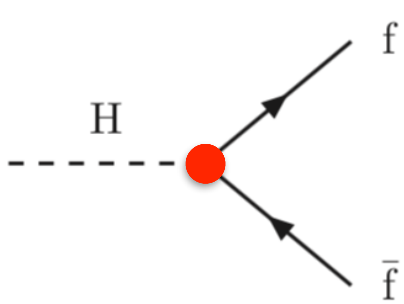












Decay \ Production	ggF	VBF	VH	ttH
γγ	√	√	√	√
ZZ	√	√	√	√
WW	√	√	√	√
bb	√	√/√	√	√
ττ	√	√	-	√
μμ	√	√	√	√

⇨ talk by P. Francavilla on statistical combination method

$\sqrt{s} = 13$ TeV
$\int L dt = 24.5 - 79.8$ fb^{-1}

√ Analysed but not included in the combination
√/√ Used in a subset of combined results
+ H→invisible decay, on-shell/off-shell width measurement results

Higgs signal-strength

LHC Higgs XS WG CERN Report 3

LO κ-framework

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

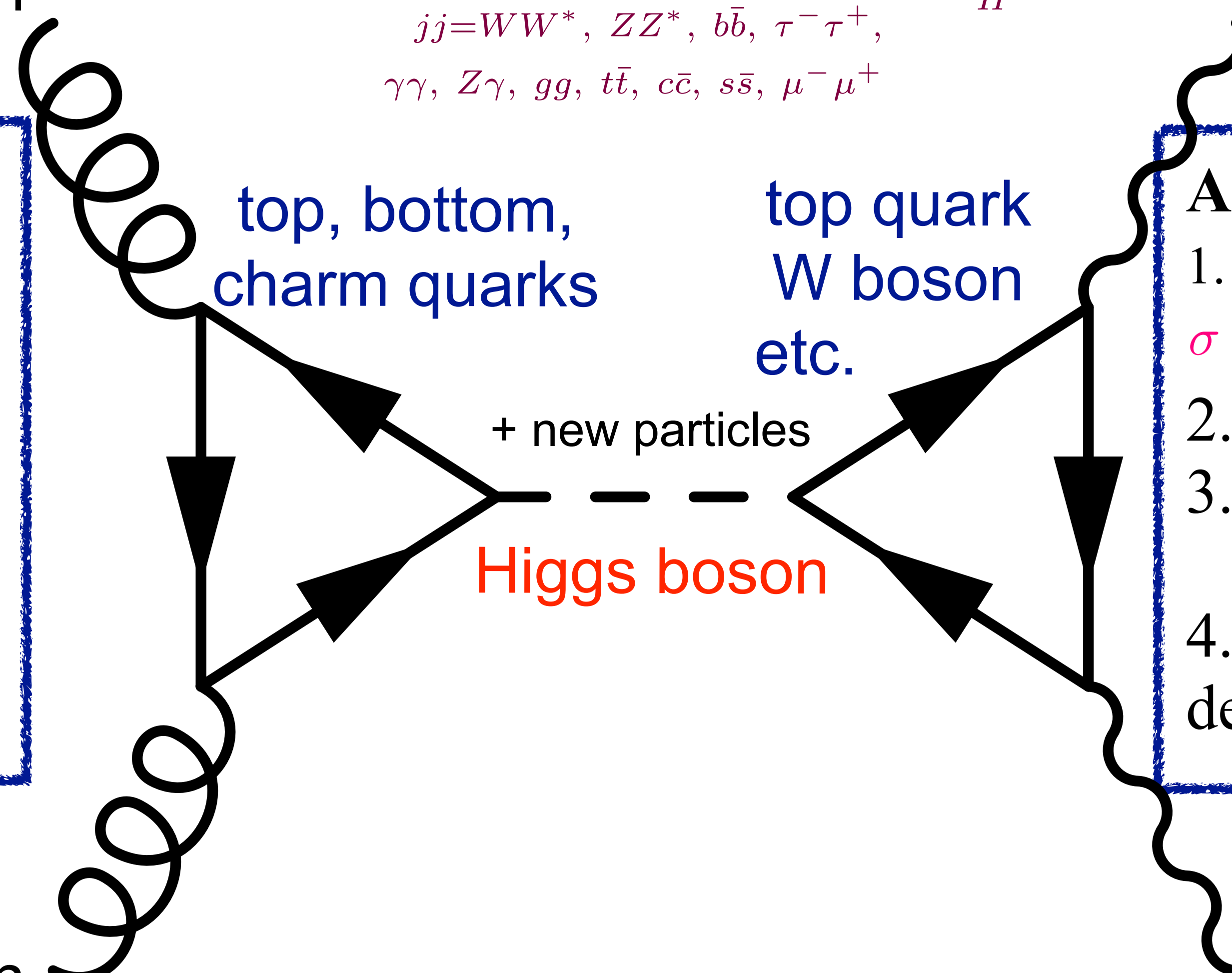
$$\mu = \frac{(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma)}{\{\sigma(gg \to \mathrm{H}) \cdot \mathrm{BR}(\mathrm{H} \to \gamma\gamma)\}_{\mathrm{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

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

- 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.

$$\sigma \cdot \mathbf{BR}\ (\mathbf{ii} \to \mathbf{H} \to \mathbf{ff}) = \frac{\sigma_{\mathbf{ii}} \cdot \mathbf{\Gamma_{ff}}}{\mathbf{\Gamma_H}}$$

2. only 1 SM-like Higgs
3. SM tensor structure (spin 0, CP-even)
4. on-shell production and decay

Global Signal Strength & Production Cross Section

- ATLAS Combined γγ, ZZ, WW, ττ, μμ, bb with **80fb[-1] data at √s=13TeV**

ATLAS-CONF-2019-005

RUN-2 ATLAS

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.})\,\pm 0.03\,(\text{bkg. th.})$$

JHEP 08 (2016) 045

RUN-1 ATLAS+CMS

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

√s=7TeV 5fb[-1]
√s=8TeV 20fb[-1]

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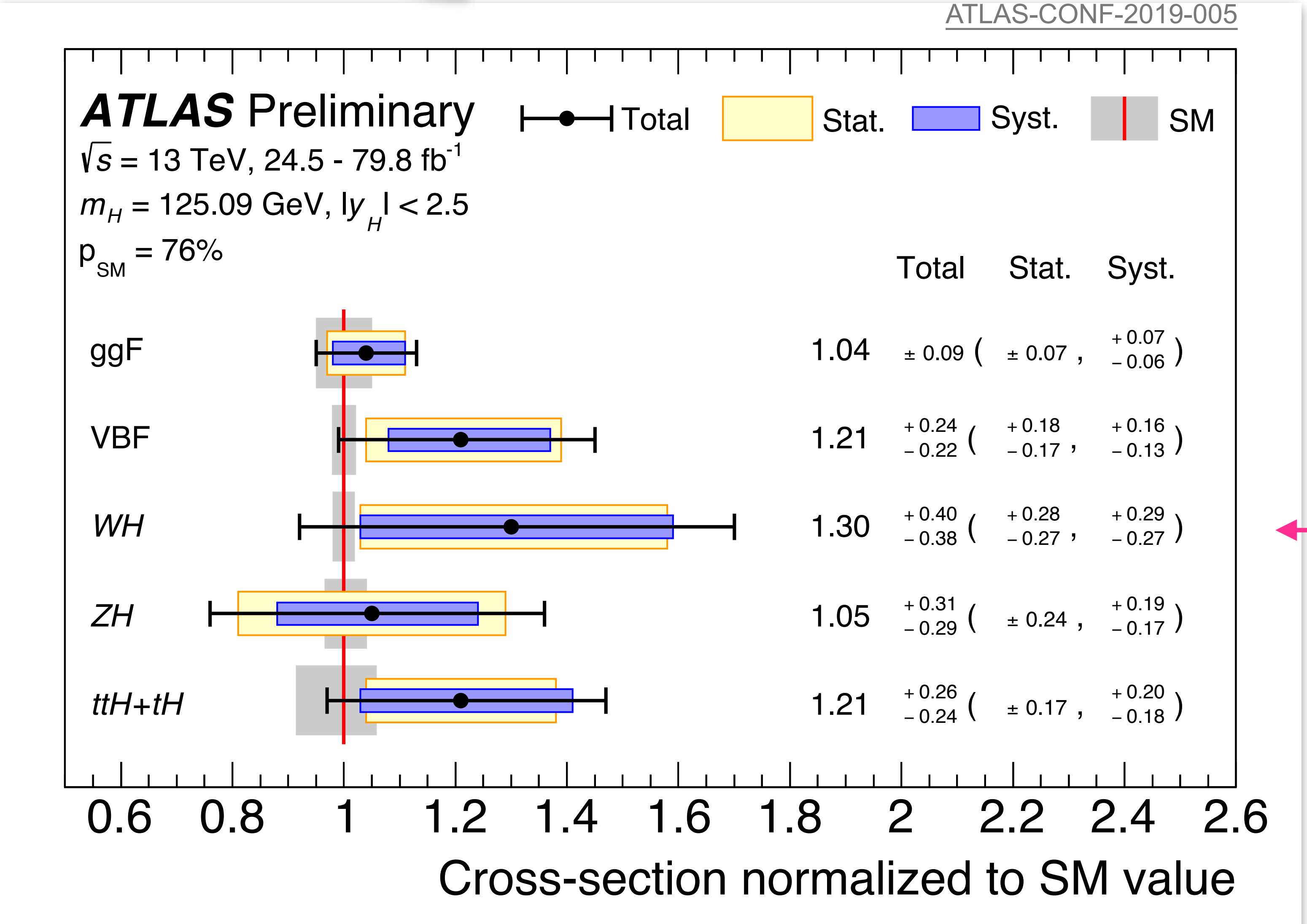

RUN-2

Major TH uncertainty due to ggF QCD scale

Large theory uncertainties in VBF, VH and ttH channels due to ggF contamination,UE/PS uncertainty etc.

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

Higgs Boson Decay Width and Branching Ratio

- Various Higgs-boson decay channels at $M_H = 125$GeV
- Narrow Higgs-boson decay width $\Gamma_H = 4.1$ MeV
- Dominated by H→bb decay (BR=58%)

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

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

RUN-2

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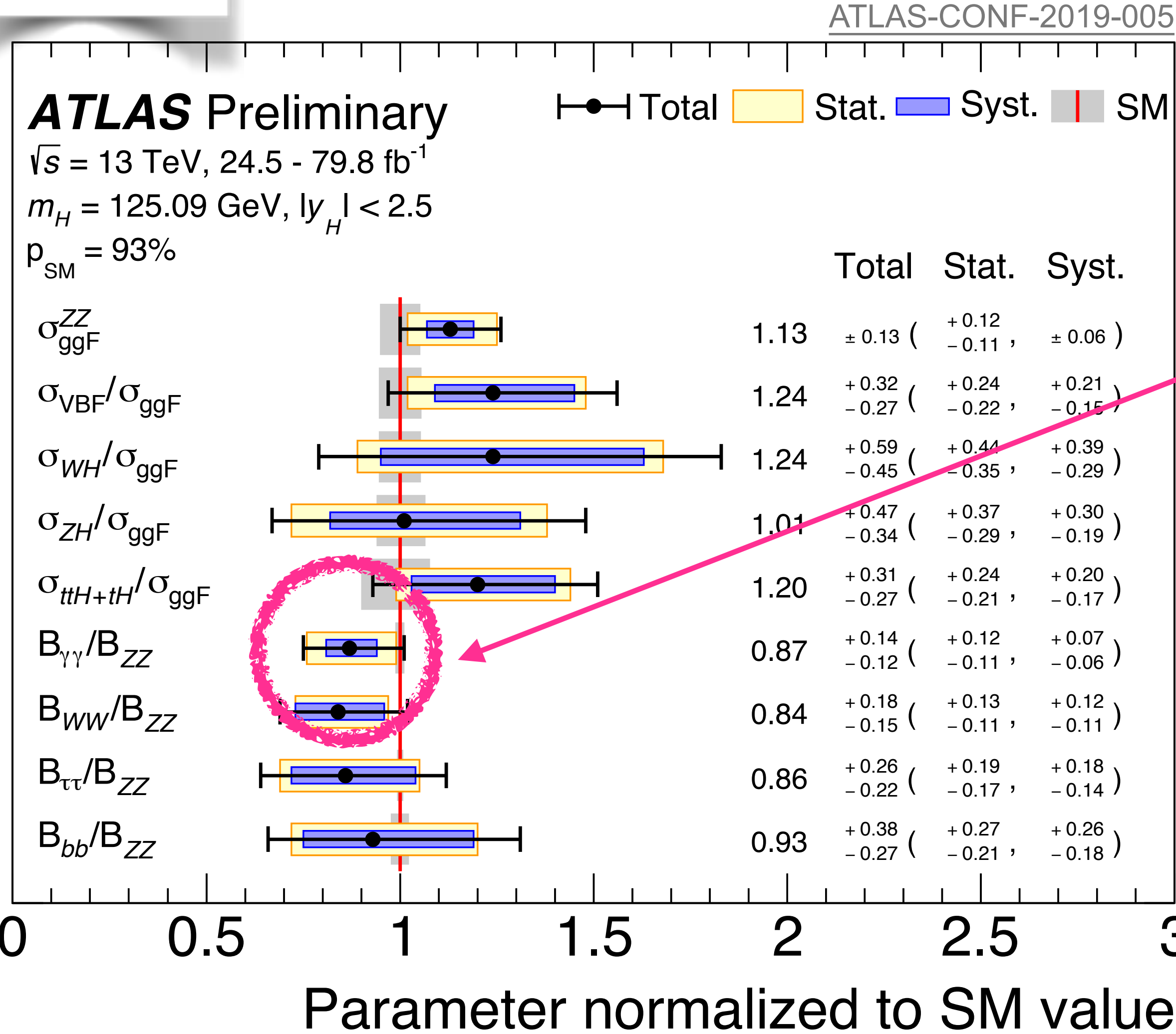
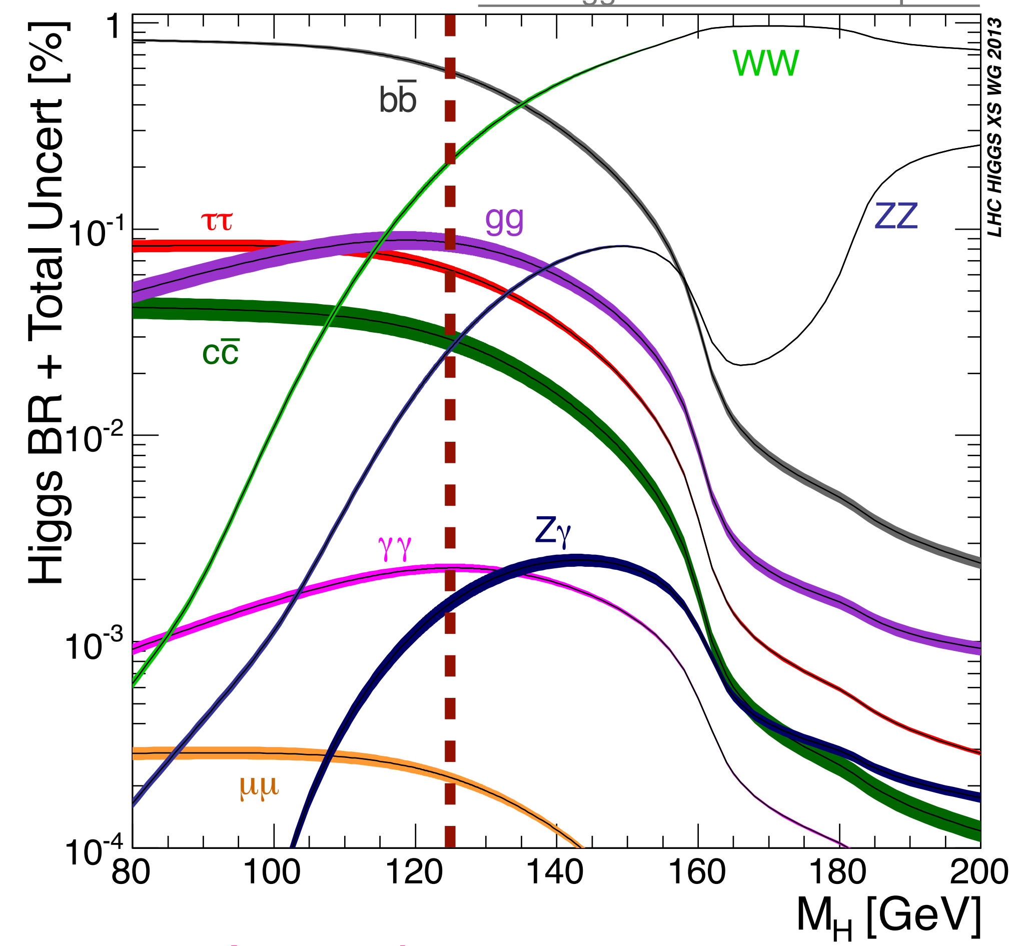


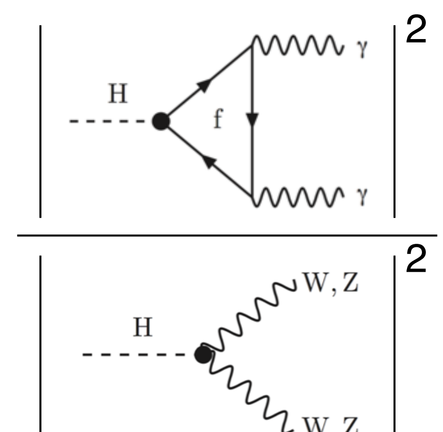
LHC Higgs XS WG CERN Report 4



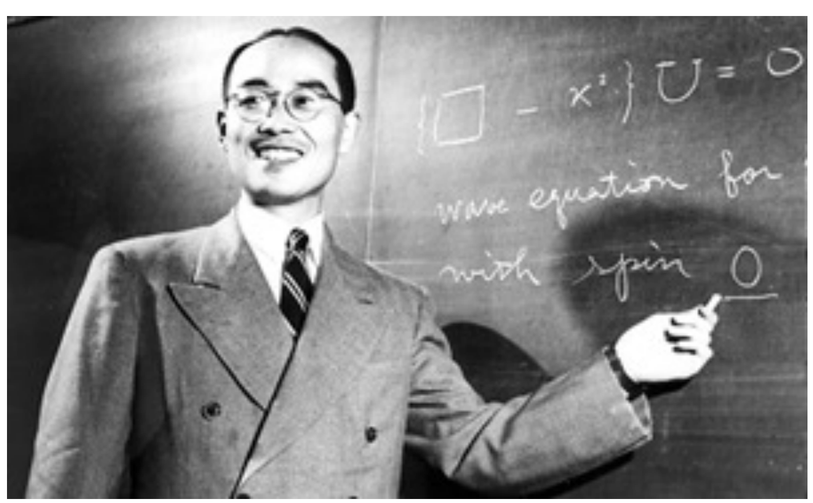
Interesting quantity $\Gamma_{\gamma\gamma}/\Gamma_{ZZ}$:
sensitive to new physics via loop in $\gamma\gamma$

➪ Theory uncertainty is ±1.1% (+ΔM_H) !
But current EXP error is ±20%. Long way to go…

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{ZZ}} =$$

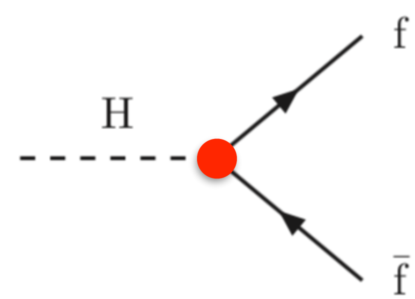


2. Higgs Boson Yukawa Coupling



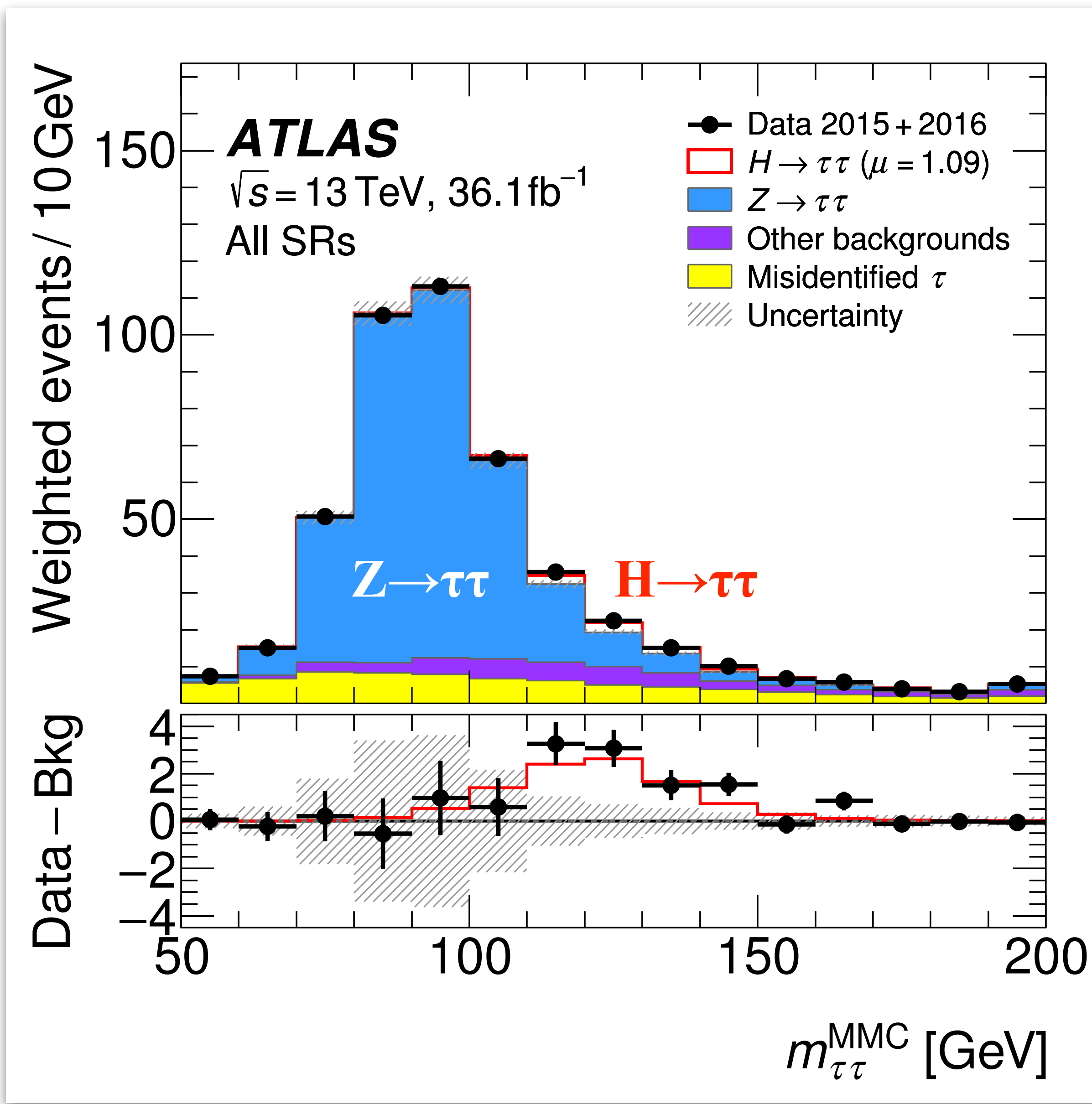
湯川秀樹 (1949)

Hττ Yukawa in H→ττ

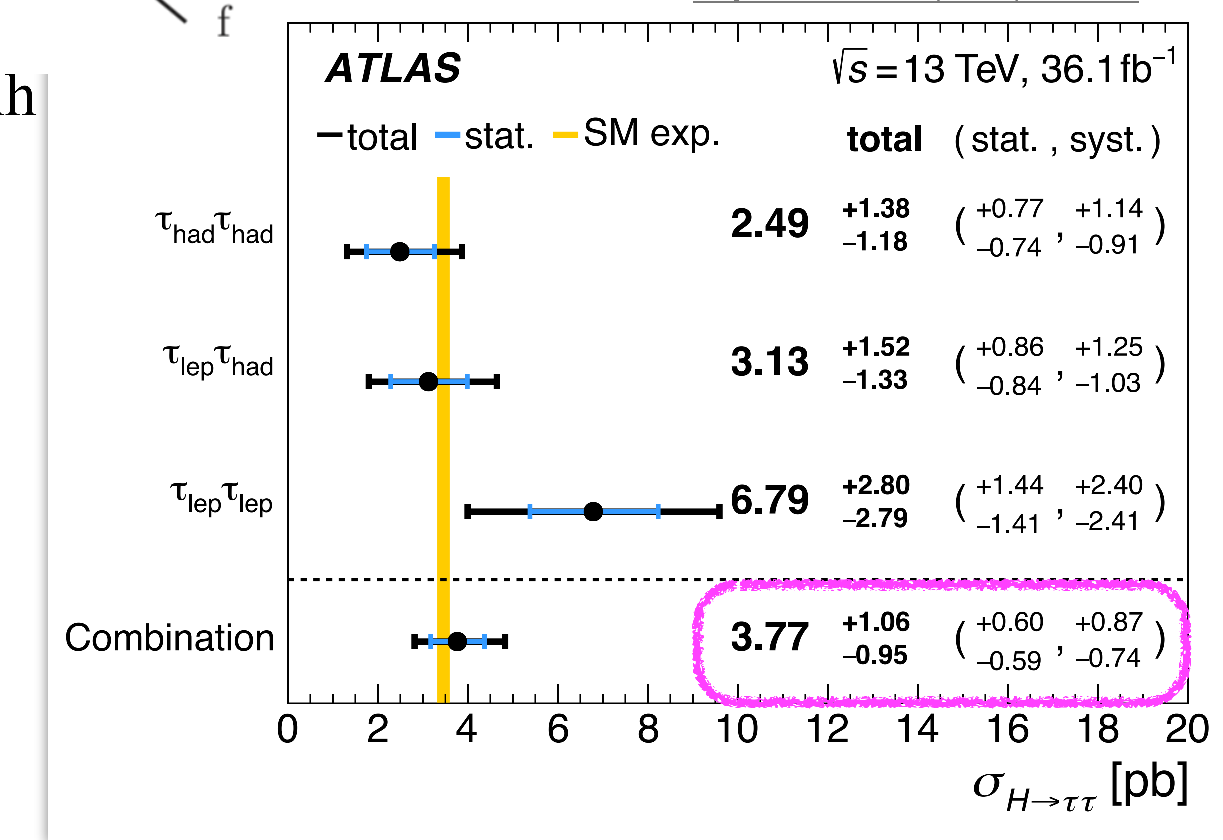


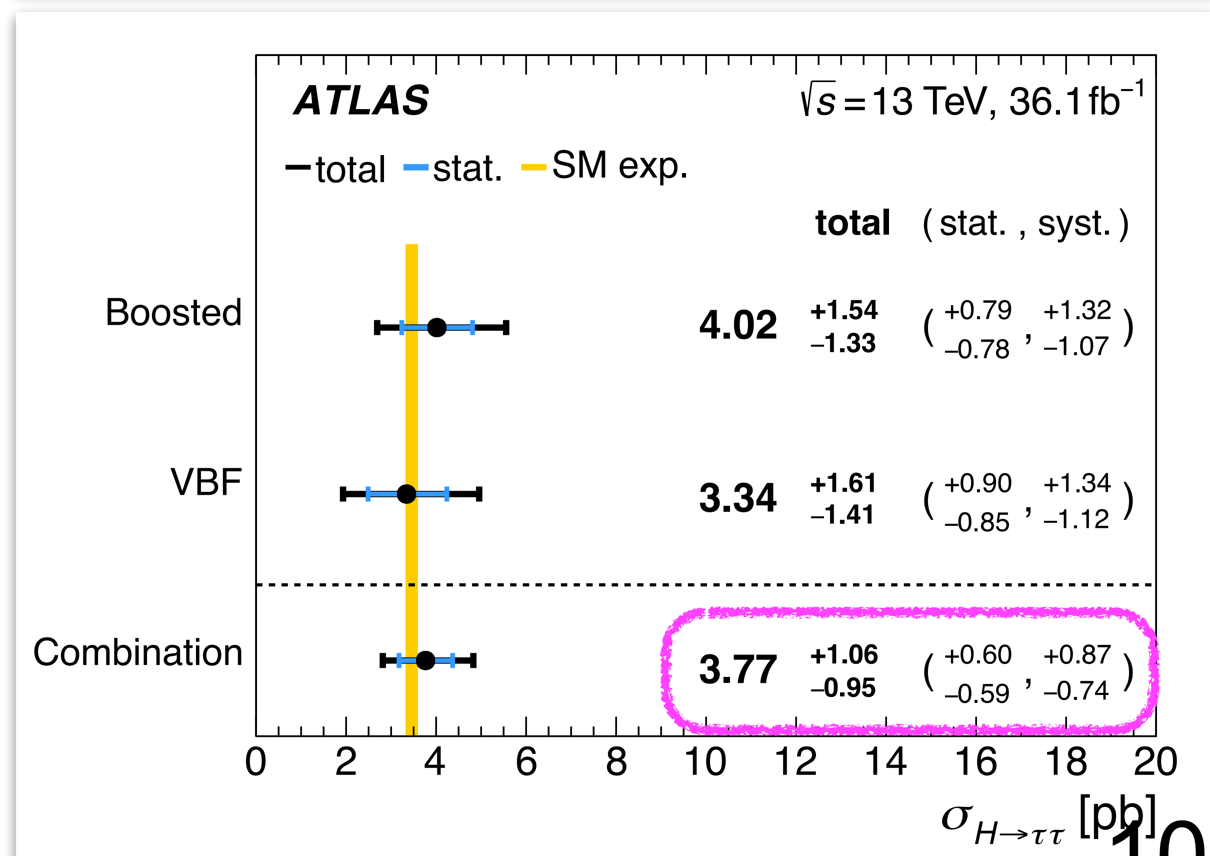
RUN-2

- Boosted ggF and VBF topologies in ττ→ll, lh and hh channels
- Large Z→ττ backgrounds
- Observation of H→ττ decay process:
  - 6.4σ significance (5.4σ expected) with Run 1+2 data

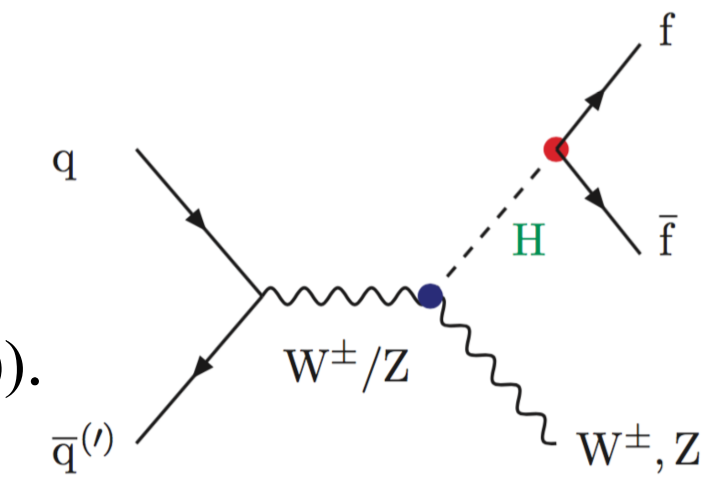


Phys. Rev. D 99 (2019) 072001

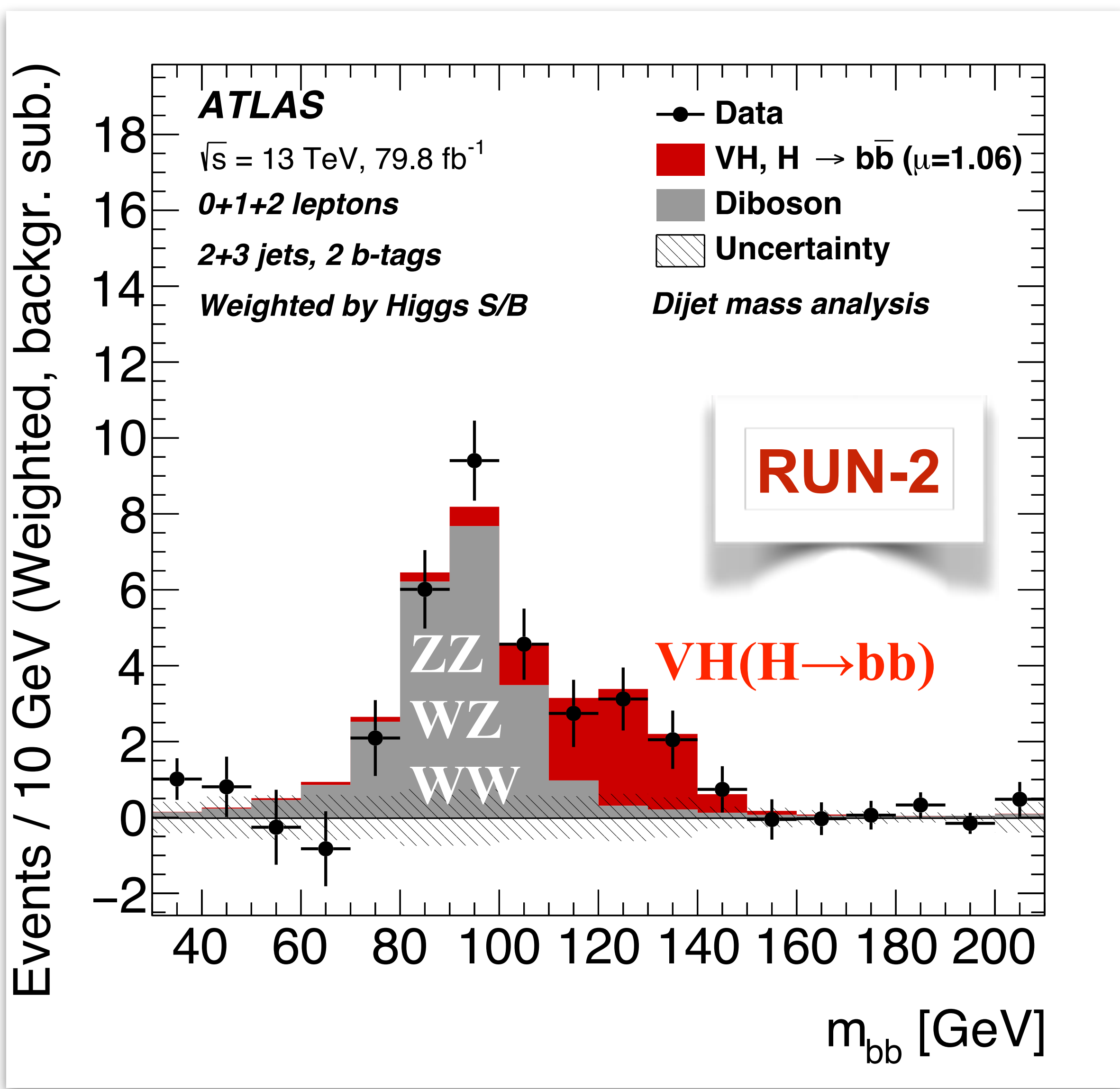




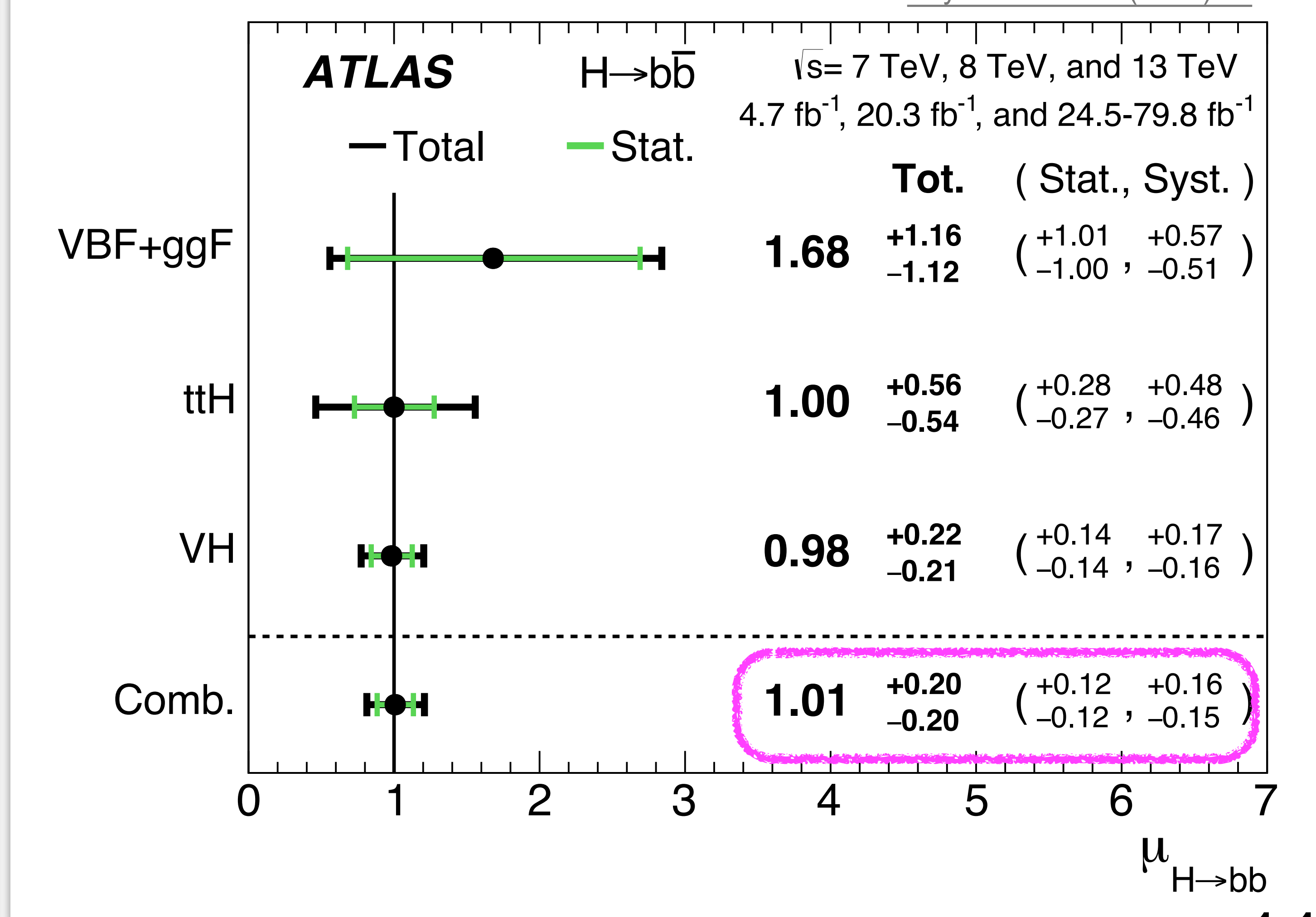
Hbb Yukawa in VH(H→bb)



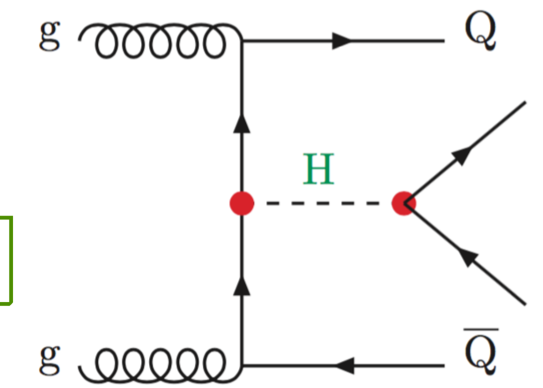
- Most sensitive to Hbb Yukawa coupling (along with ttH(H→bb)).
- Search in channels with 0,1,2 leptons (e/μ) with V→νν,lν,ll.
  - Large variety of the SM backgrounds from V+HF(Zbb etc.), VV, ttbar.
  - Use of BDT & profile likelihood fits to isolate signal and measure background parameters from data in control region.
- Observation of VH production process: 5.4σ significance (5.5σ expected) with Run 1+2 data



ATLAS: Phys. Lett. B786 (2018) 59



Htt/Hbb Yukawa in ttH(H→bb)

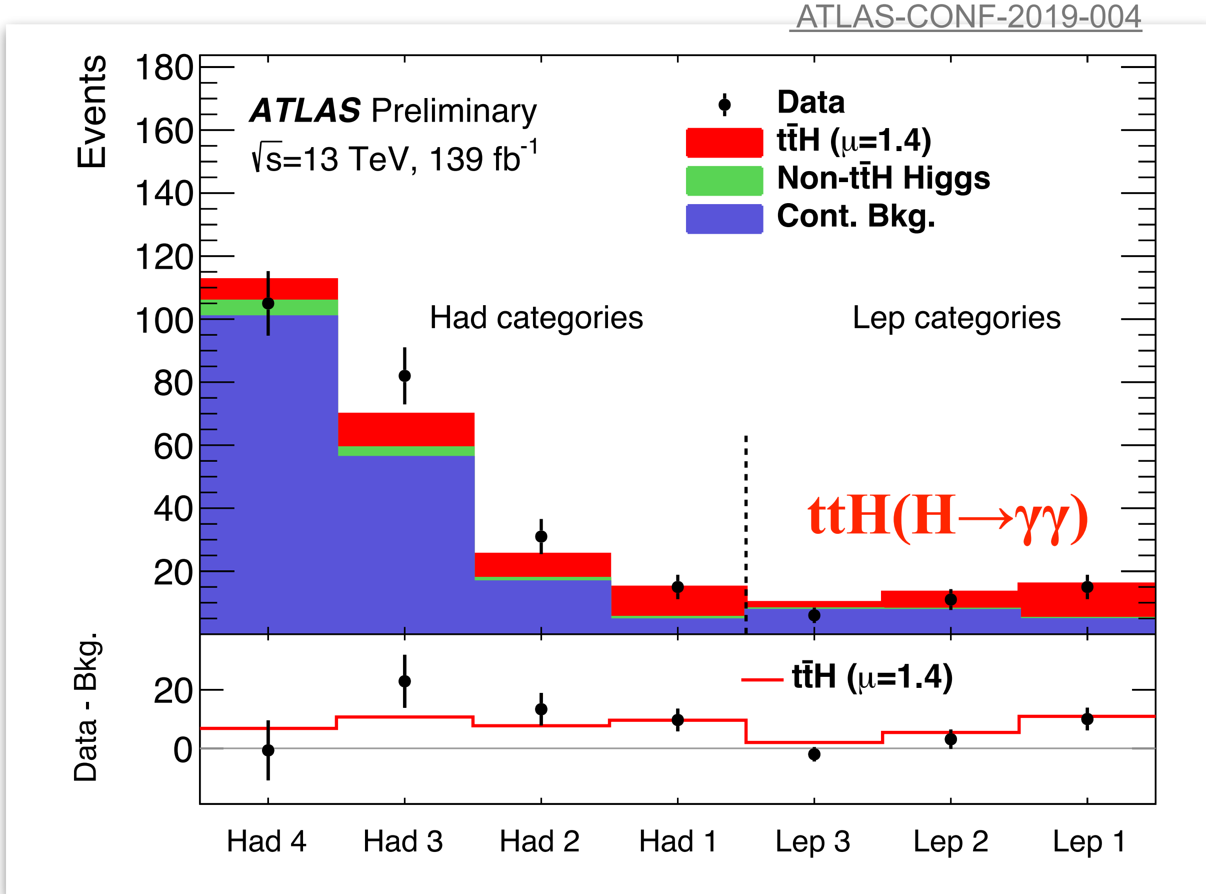


⇨ talk by B. Stelzer

- Associated Higgs boson production with ttbar
  - 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→γγ: despite very small BR(2.3×10^{-3}), clean signature. Statistical error dominated.
- H→bb: very complicated final state (4 b-jets), large backgrounds from ttbar+V/HF (ttbb etc.)
- Observation of ttH production process: 6.3σ significance (5.1σ expected) with Run 1+2 data

H→γγ

ATLAS-CONF-2019-004



RUN-2

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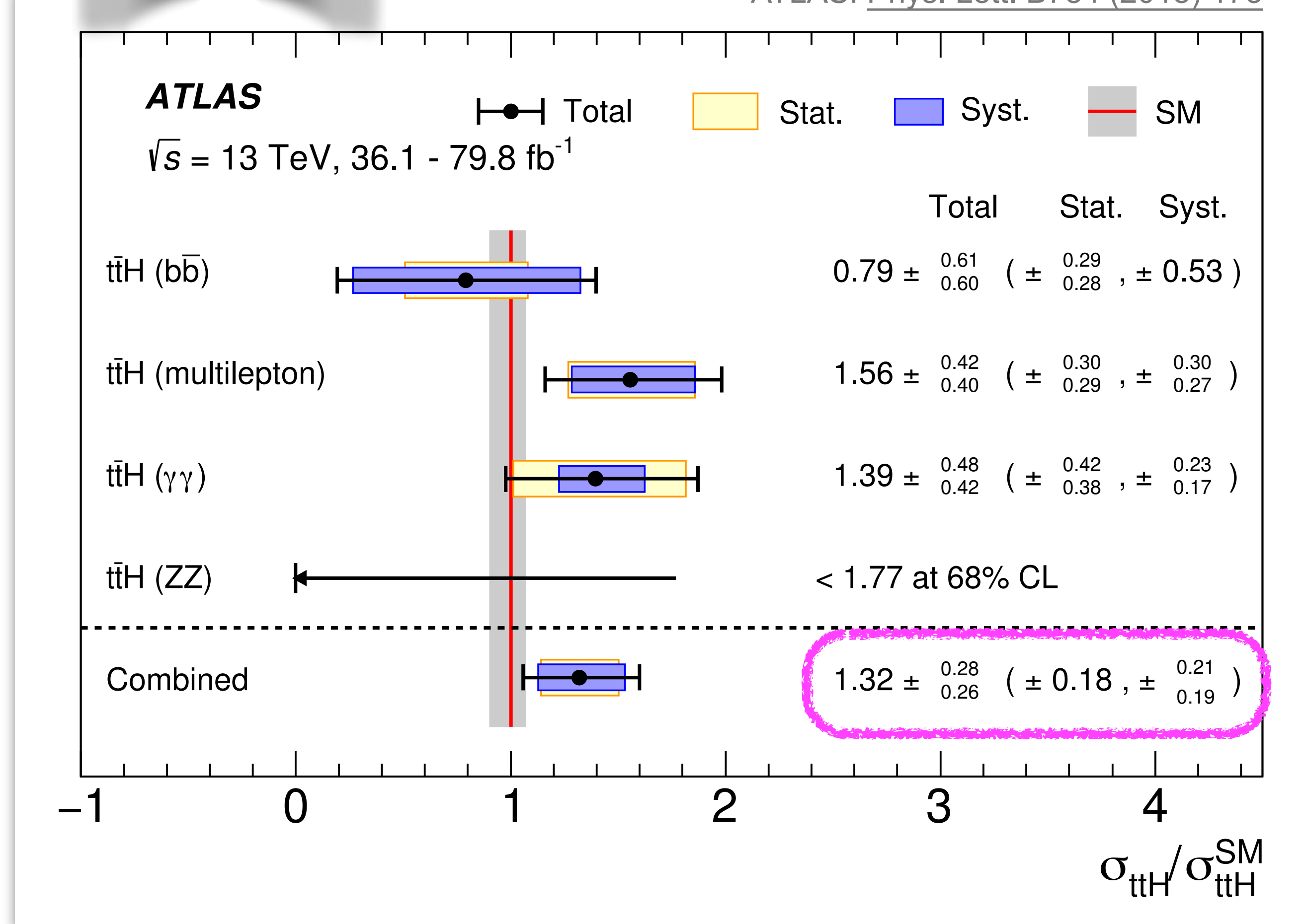
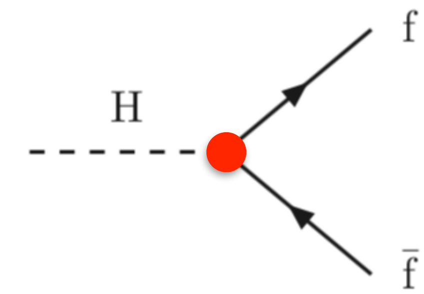


Higgs Yukawa Coupling in the 2^{nd} Generation

- **2^{nd}&1^{st} generation**: branching ratios (Yukawa) are very small
  - $BR(H \to \mu^+\mu^-) = 2.2\times10^{-4}$, $BR(H \to e^+e^-) = 4.9\times10^{-9}$ for M_H=125 GeV.
  - Higgs Dalitz decay $BR(H \to Z\gamma) = 1.5\times10^{-3}$, should be searched in $ff\gamma$.

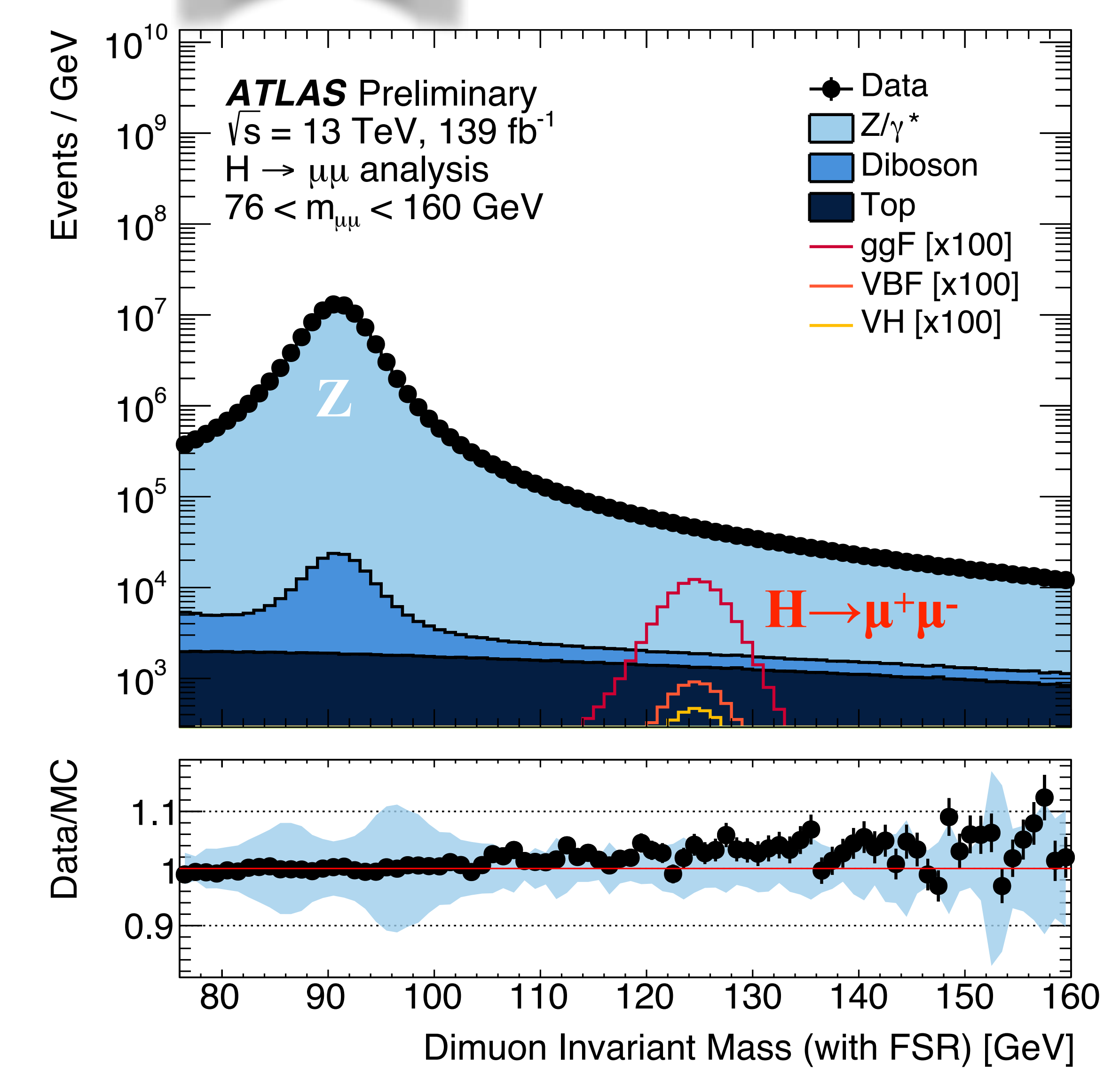


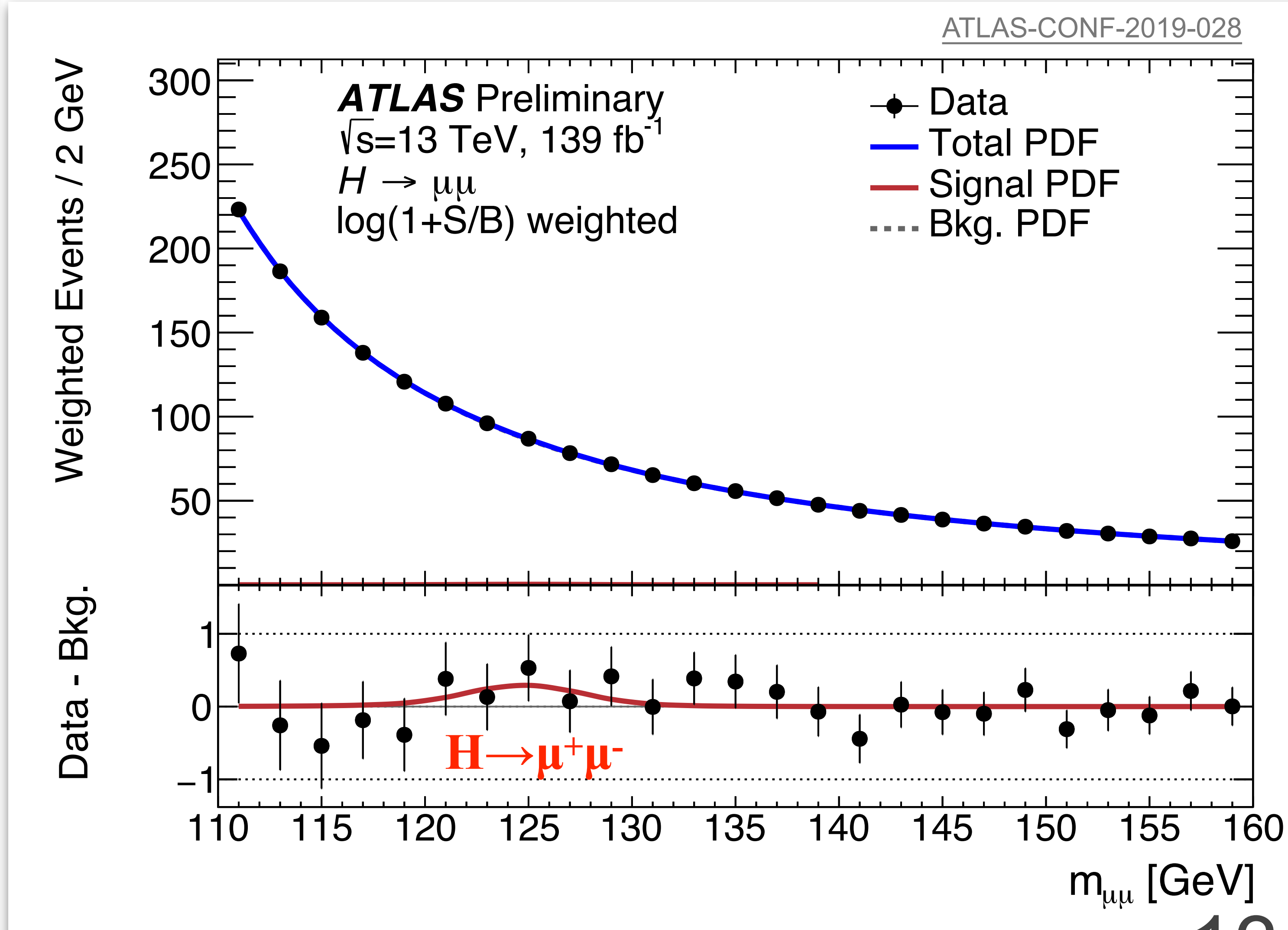
- Search for $H \to \mu^+\mu^-$ decay: very large Drell-Yan backgrounds.

RUN-2

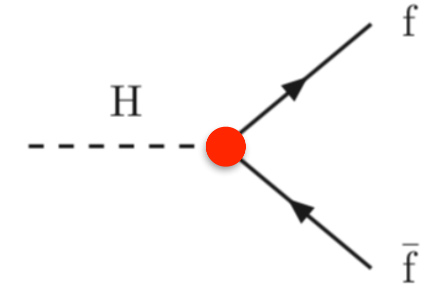
  - Observed (Expected) Upper limit: 1.7 (1.3) × σ_{SM} at 95% C.L.

$H \to \mu^+\mu^-$





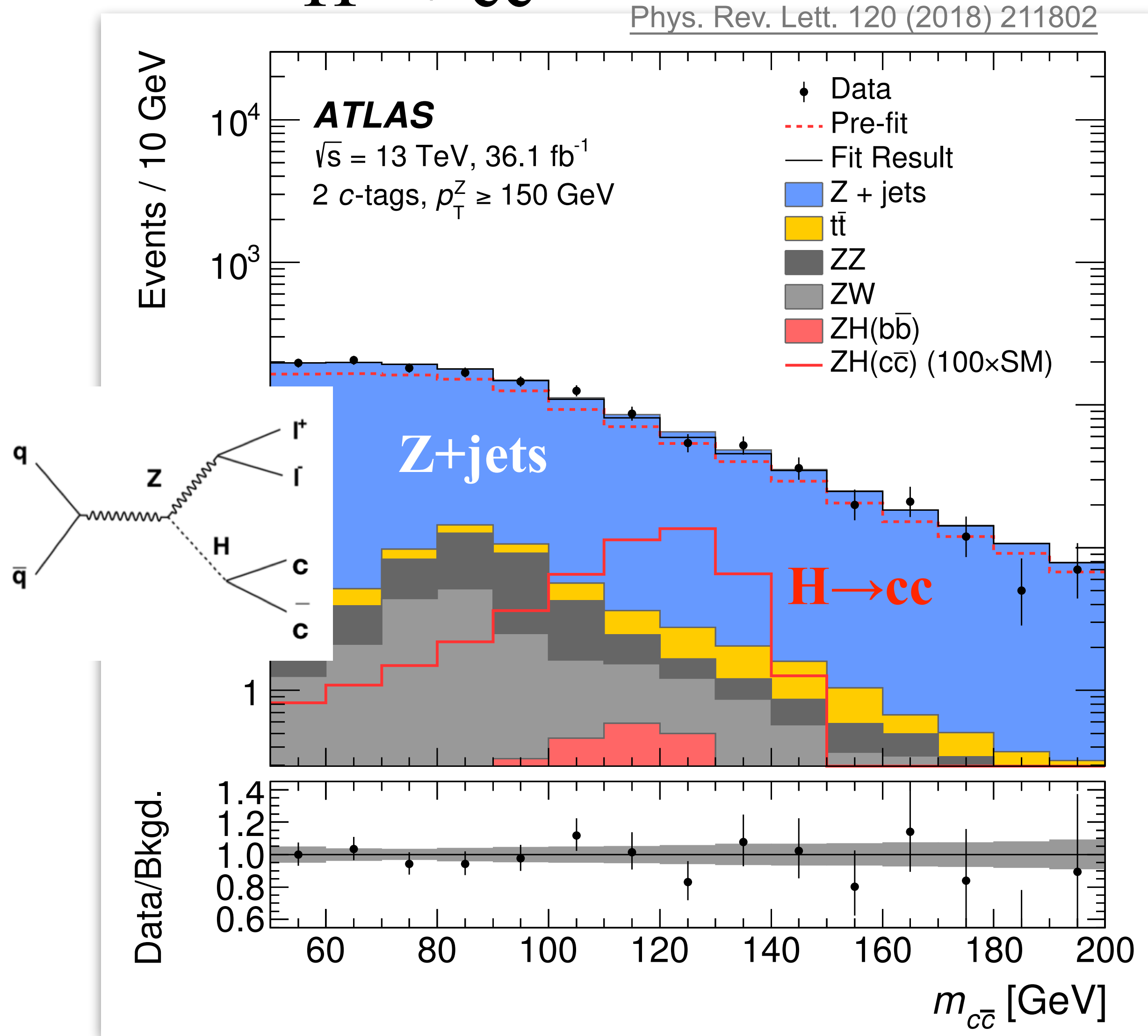
Yukawa sector: search for H→cc, e⁺e⁻



- Search performed via associated production VH(H→cc)
  Observed (expected) limit $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) = 2.7\,(3.9)$ pb at 95% C.L. (SM 26 fb)
- Charm coupling via Higgs p_T (light quark modifies Higgs spectrum at low p_T)
- Maybe accessible to charm via J/ψ+γ (BR(H→ J/ψ+γ) =2.5×10^{-6}), ϒγ, ϕγ and ργ.
  Observed limit $\mathcal{B}(H \to J/\psi + \gamma) = 3.5 \times 10^{-4}$ at 95% C.L. Phys. Lett. B 786 (2018) 134
- Search for the 1st generation Yukawa has also been performed in H → e⁺e⁻ decay.
  Observed (expected) limit $\mathcal{B}(H \to e^+e^-) = 3.6\,(3.5) \times 10^{-4}$ at 95% C.L. ($BR_{SM}=4.9\times10^{-9}$)

H → cc

Phys. Rev. Lett. 120 (2018) 211802



H → e⁺e⁻

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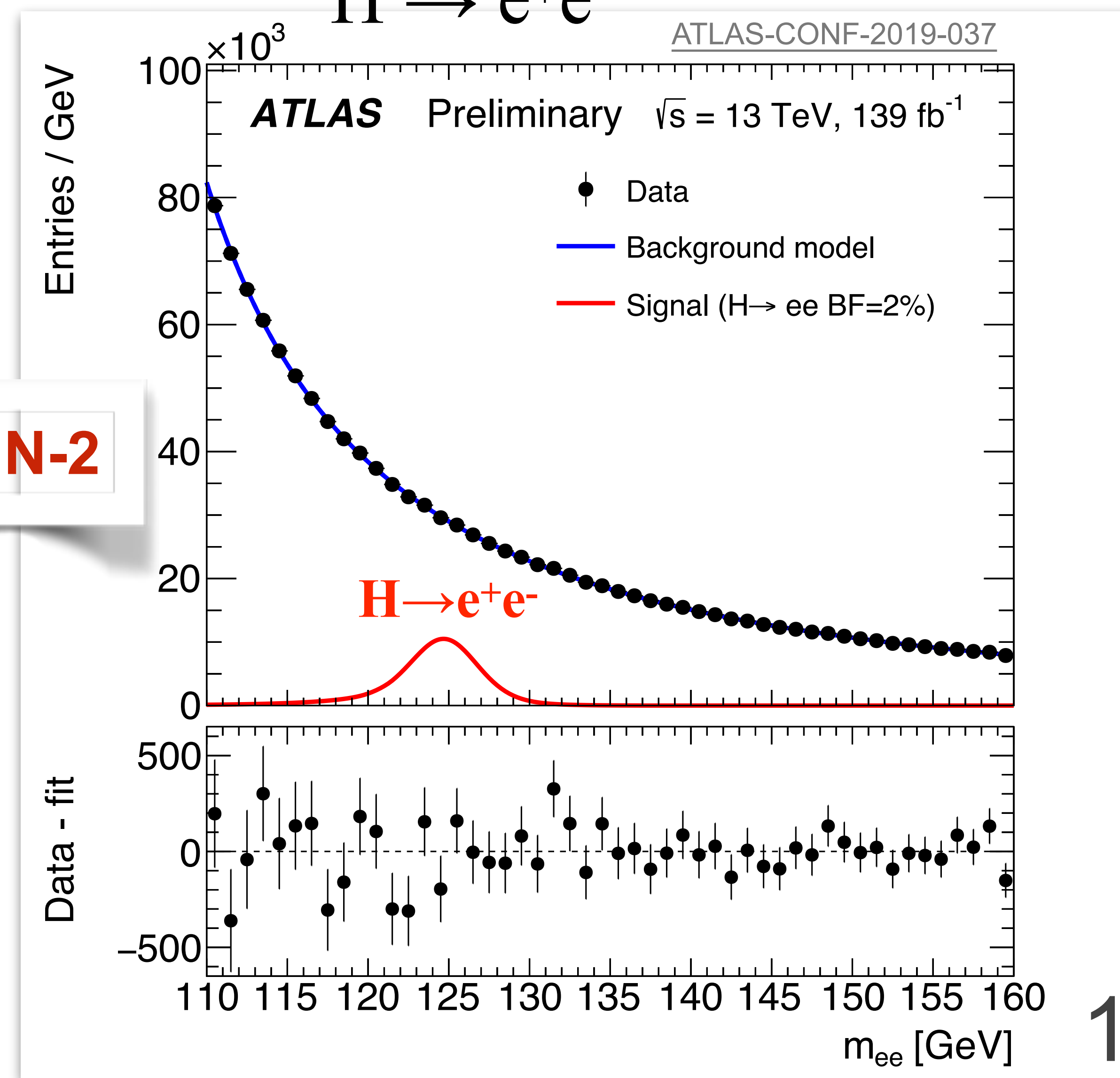


Generic κ-parametrization

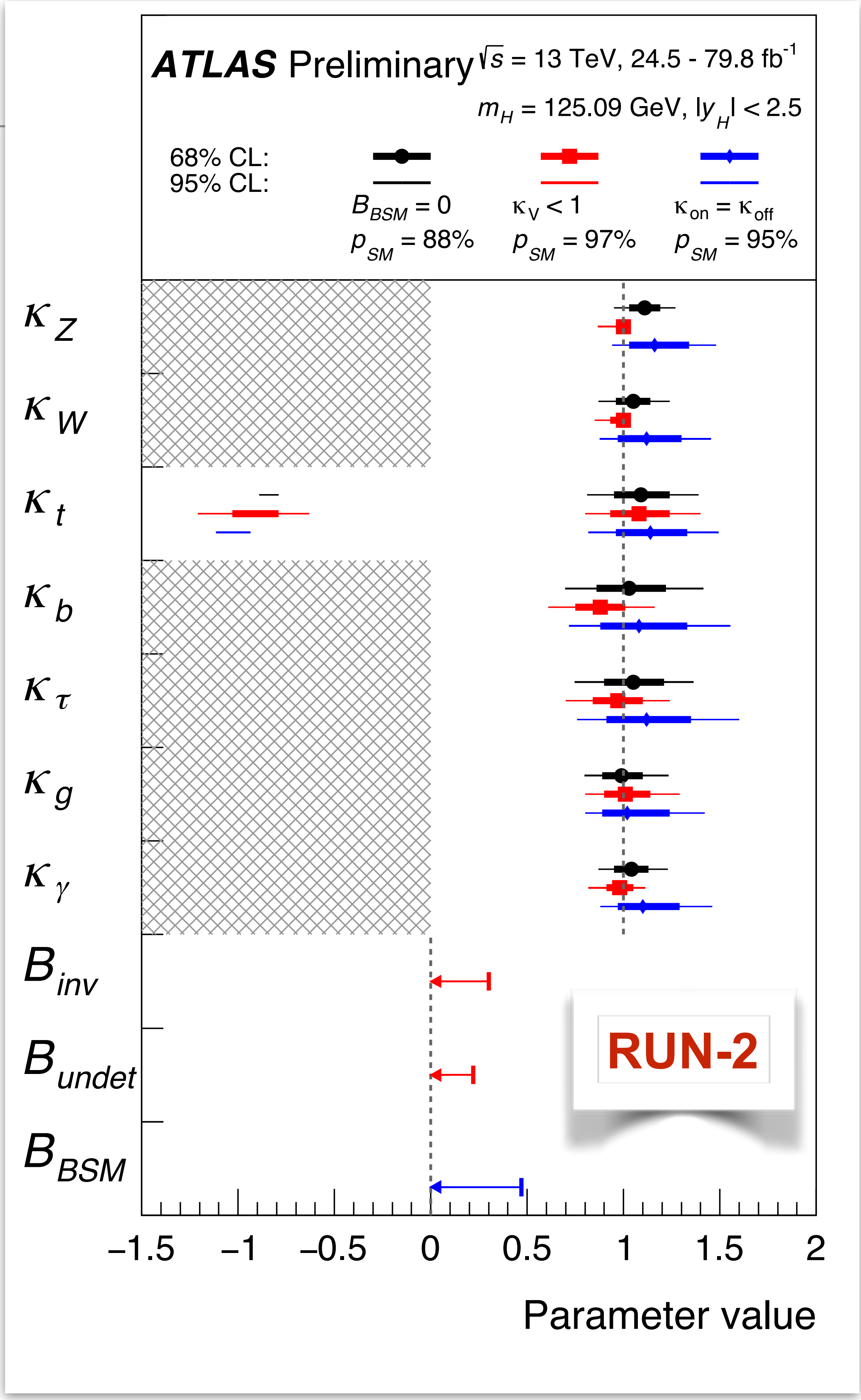
- LHC cannot measure Higgs boson total decay width
- "Coupling modifier" κ at each Higgs vertex

$$\sigma\left(i \to H \to f\right) = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^{\mathrm{SM}}}$$

- Can accommodate Higgs-boson invisible decay or undetected mode

$$\Gamma_{\mathrm{H}}\left(\kappa_i, \mathcal{B}_{\mathrm{invisible}}, \mathcal{B}_{\mathrm{undetected}}\right) = \frac{\kappa_{\mathrm{H}}^2(\kappa_i)}{1 - \mathcal{B}_{\mathrm{invisible}} - \mathcal{B}_{\mathrm{undetected}}} \Gamma_{\mathrm{H}}^{\mathrm{SM}}$$

- Many BSM models predict $\kappa_V < 1$
- In principle Higgs couplings are running, but we assume on-shell and off-shell couplings are the same.



1) Assuming $BR_{invisible} = BR_{undetected} = 0$

2) Constrain $BR_{invisible}$ and $BR_{undetected}$ using H→invisible decay analysis and κ_V<1

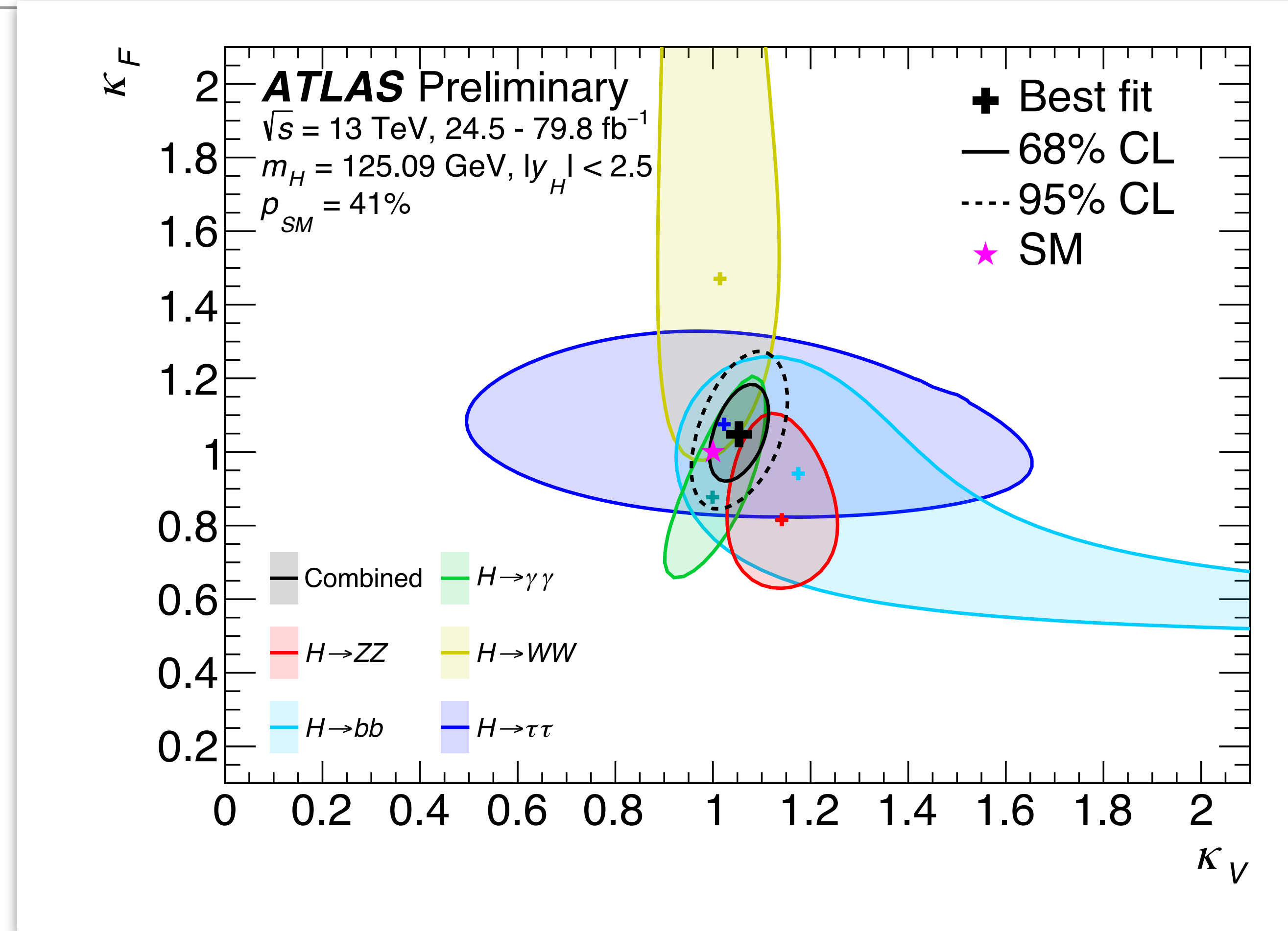
3) Constrain $BR_{BSM} = BR_{invisible} = BR_{undetected}$ using off-shell analysis and assuming $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$

Couplings (κ_V, κ_F) in κ-framework in LO

RUN-2

ATLAS-CONF-2019-005

- 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 and we need information from interference to resolve the degeneracy.
  - $\kappa_V > 0$ by convention
  - $\kappa_F < 0$ excluded by RUN-1 ATLAS+CMS

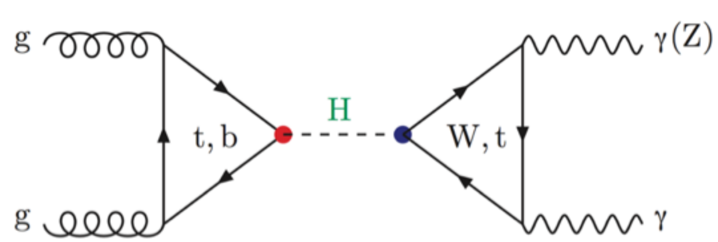


- H→γγ

Slope due to negative interference between top and W-boson in H→γγ decay

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

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

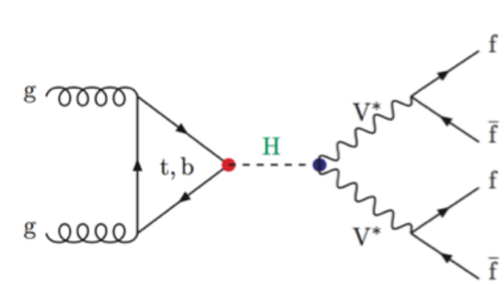


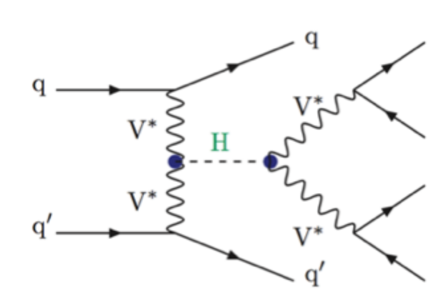
- H→ZZ/WW

Mostly sensitive to κ_V, but can constrain on κ_F with associated productions in VBF and VH. (∵ too large κ_F means small BR=Γ_{ZZ}/Γ_{tot}).

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

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

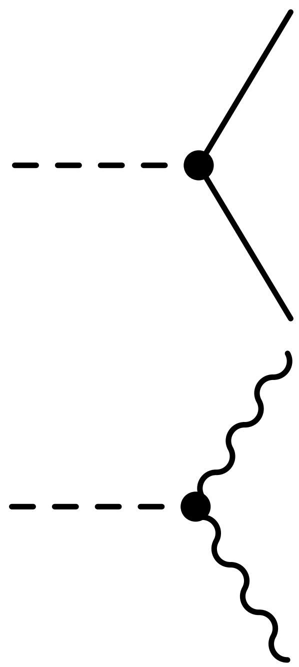




Couplings versus Mass - Higgs-gauge boson and Yukawa -

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

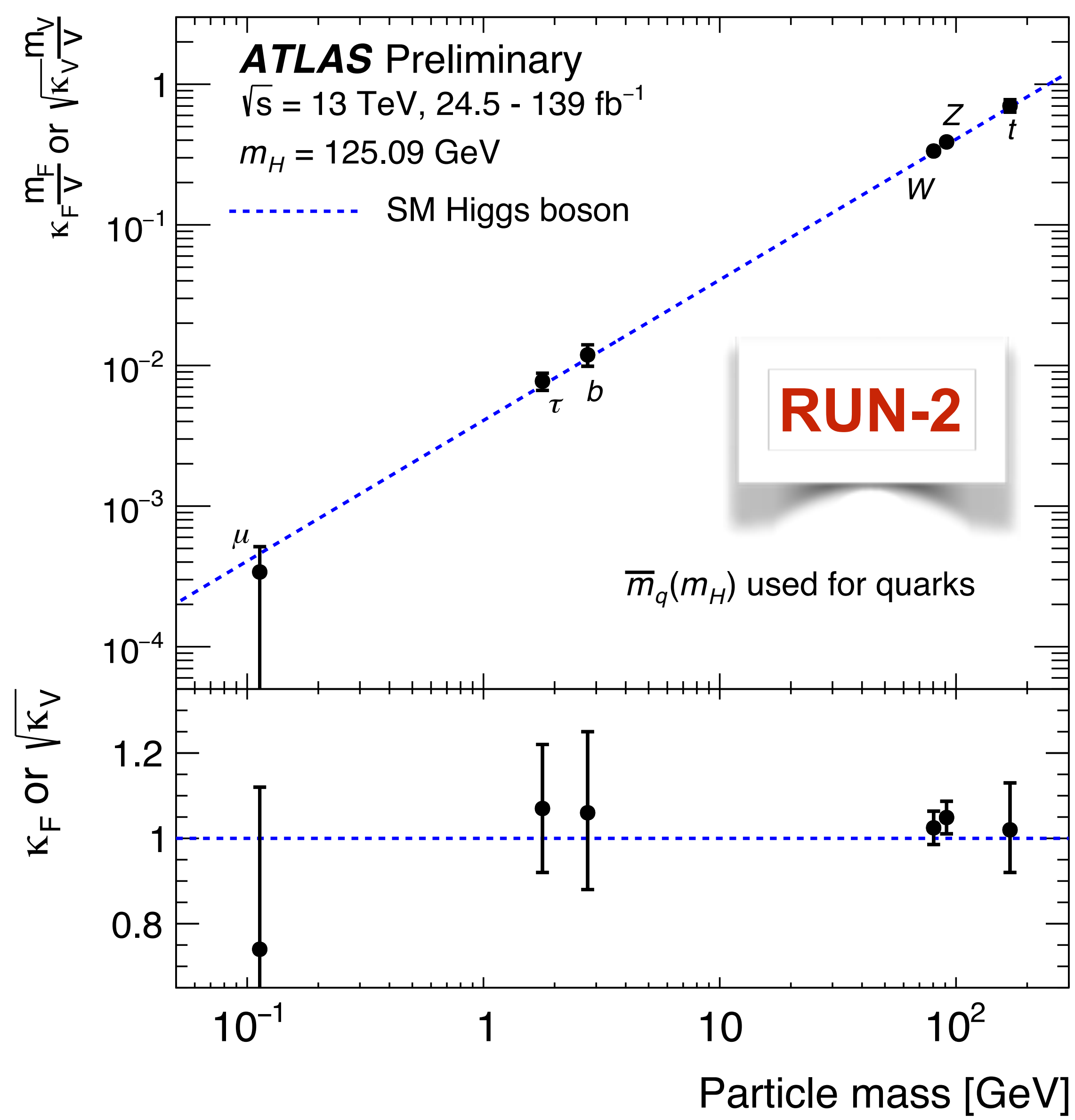
ATLAS-CONF-2019-005, ATLAS-CONF-2019-028



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

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

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

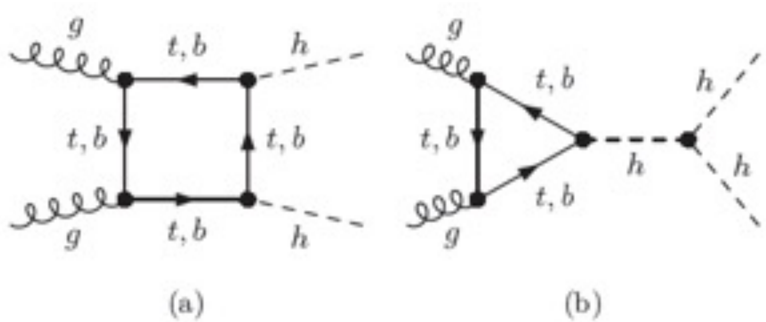


Challenges in Higgs self-coupling λ and fermion coupling $H\rightarrow\mu^+\mu^-$, cc, etc. (e^+e^- hopeless).

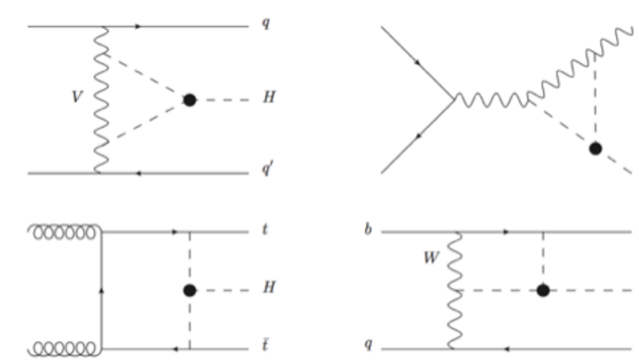
3. Higgs Boson Self-Couplings

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 HL-LHC ?
  - Explore all possible channels like HH→bbbb, bbγγ, bbττ etc.
  - New ideas like boosted Higgs analysis, via single-Higgs production (2-loop).
- Non-trivial interference between different diagrams.

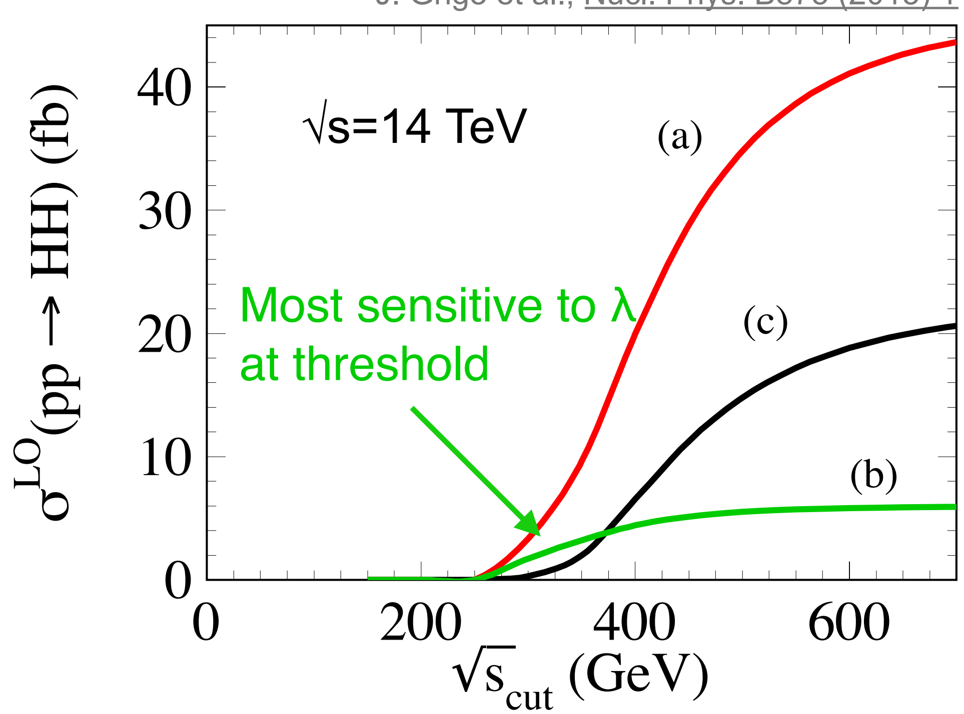


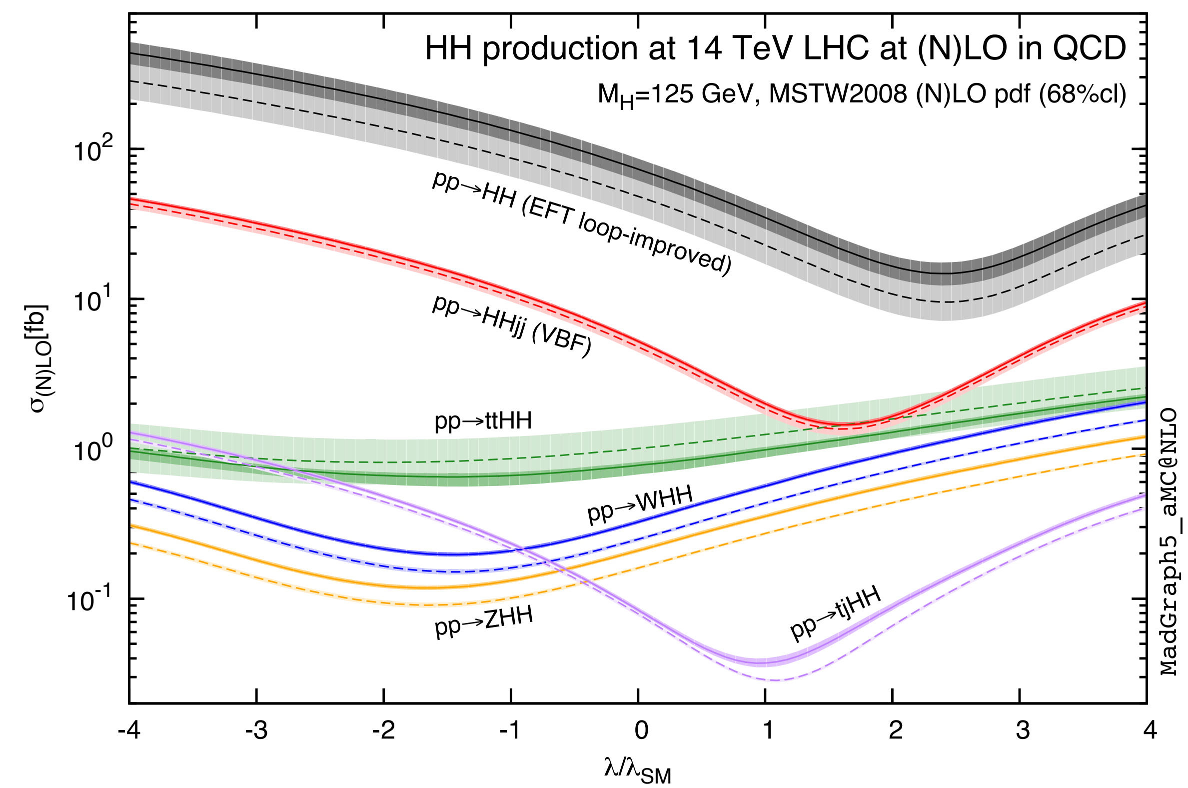
Destructive interference between box (a) and triangle (b) diagrams.



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

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



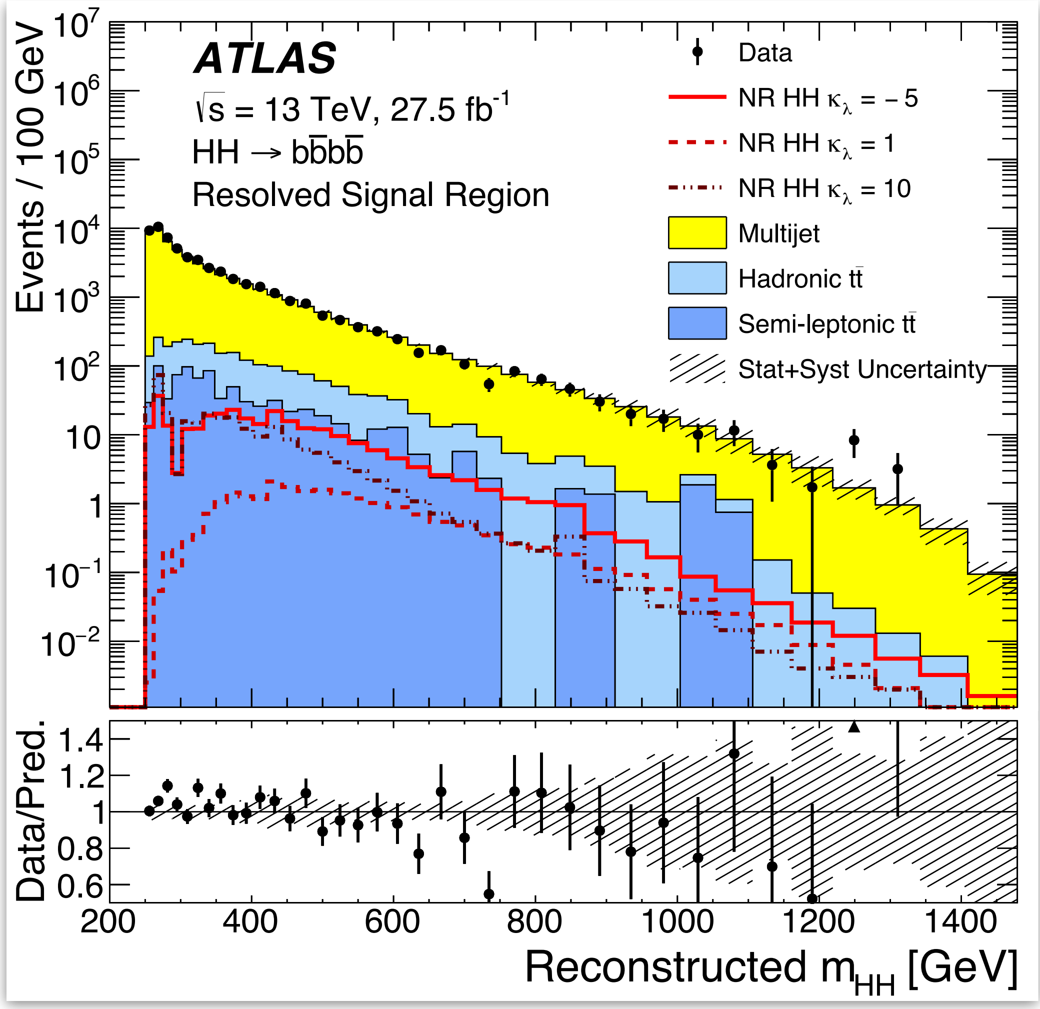


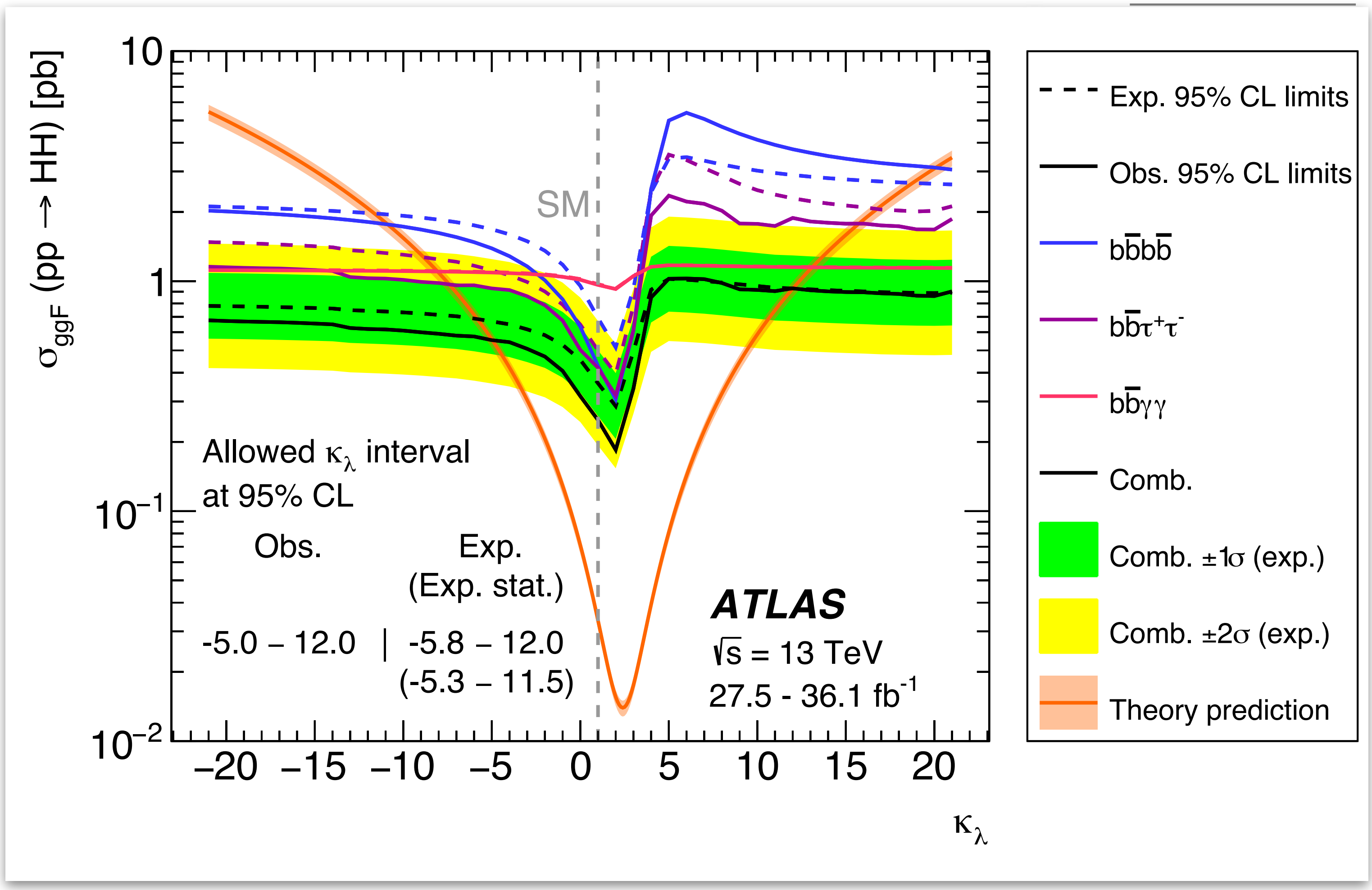
HH Production

- Higgs self-coupling modifier due to BSM scenarios: $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$
- Largest statistics in bbbb channel. Good compromise between statistics and S/B in bbγγ and bbττ channels.
- Currently at O(10)xSM sensitivity level.
  - 95% CL limit for κ_λ=1: is 6.9(10)xSM Obs(Expected)
  - 95% CL confidence level intervals: κ_λ =[-5,12] observed, [-5.8,12] expected

RUN-2

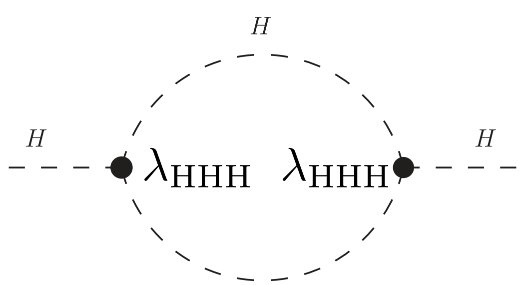
arXiv:1906.02025



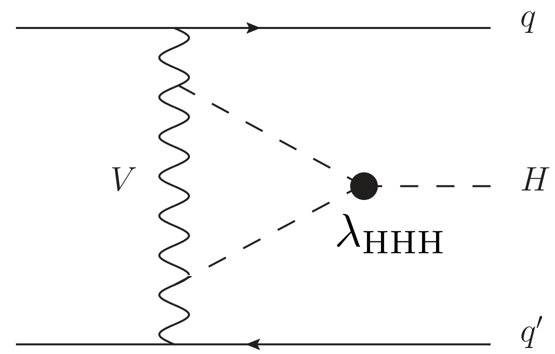


Higgs self-coupling via single production

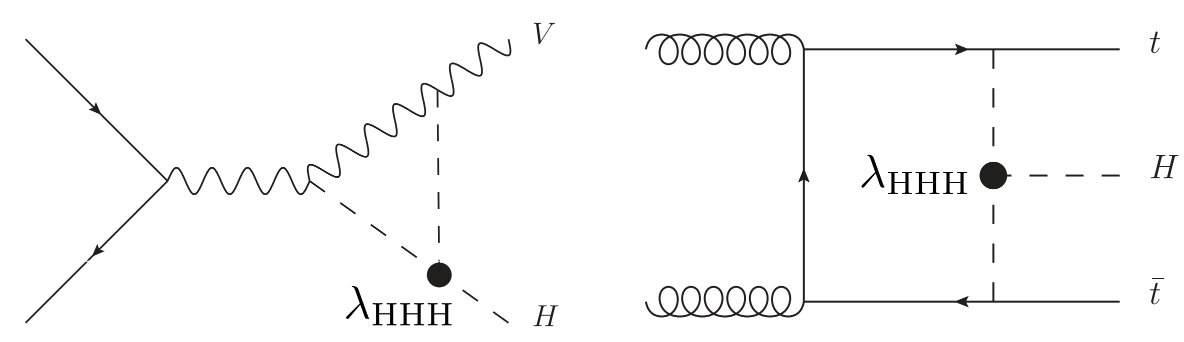
- Higgs self-coupling could occur in electroweak loops in single Higgs production.
- Assume new physics affects only to the Higgs boson self-coupling (λ_{HHH}).



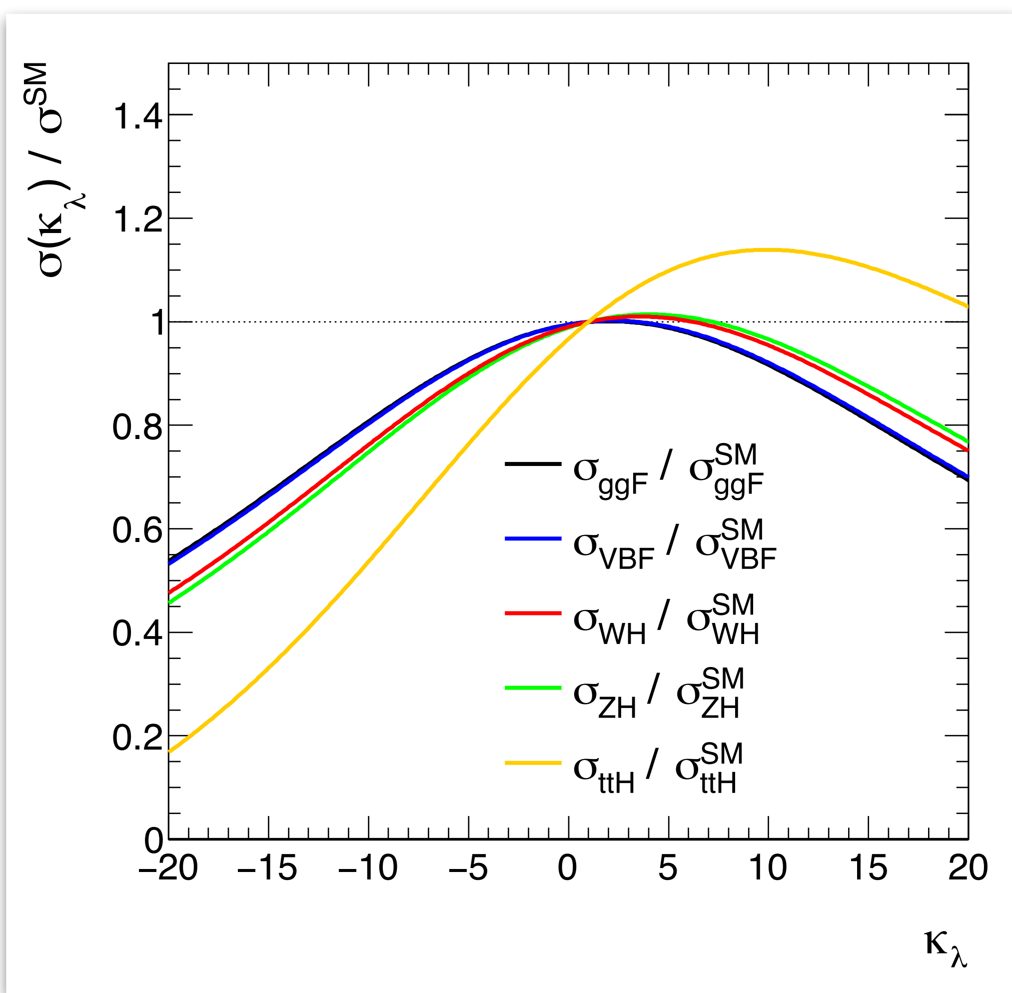
Higgs self-energy contributing to the ggF Higgs production



Vector Boson Fusion



Higgs boson Associated Production



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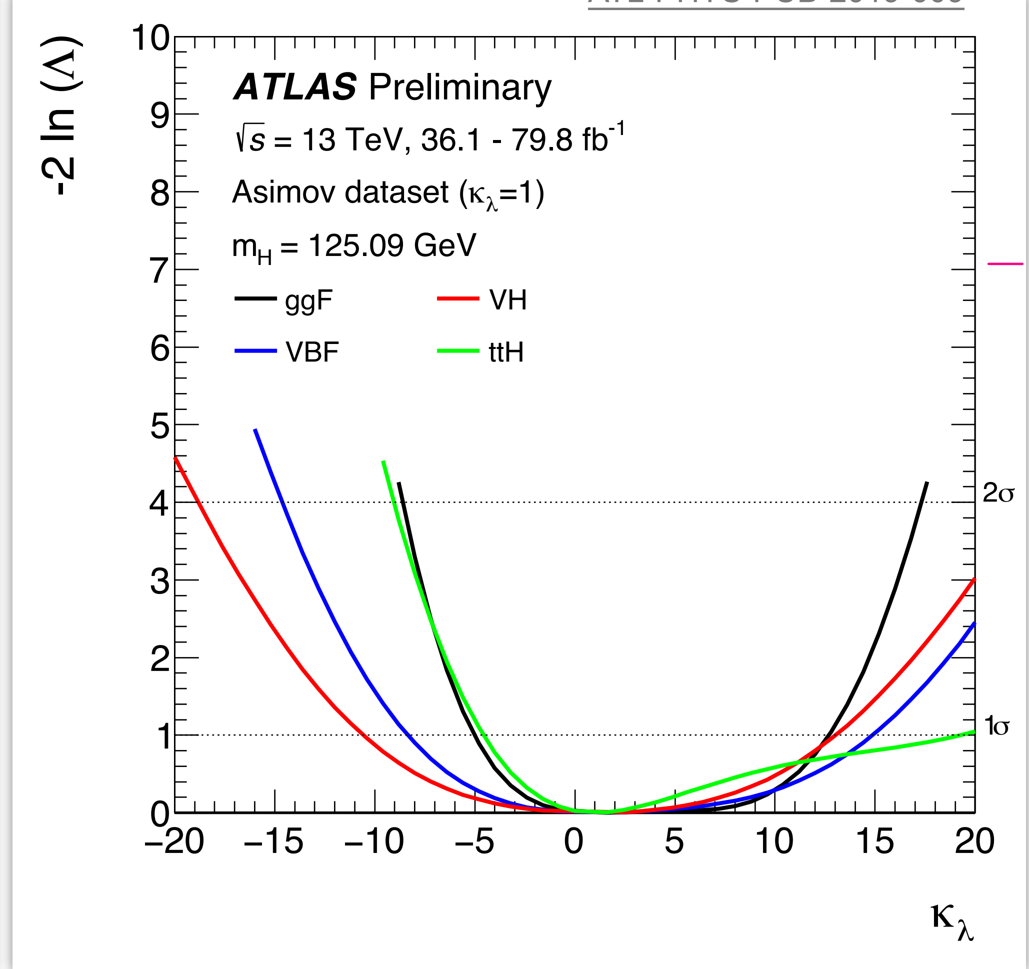


RUN-2

$$-3.2 < \frac{\lambda_{HHH}(\text{obs})}{\lambda_{HHH}(\text{SM})} < 11.9$$

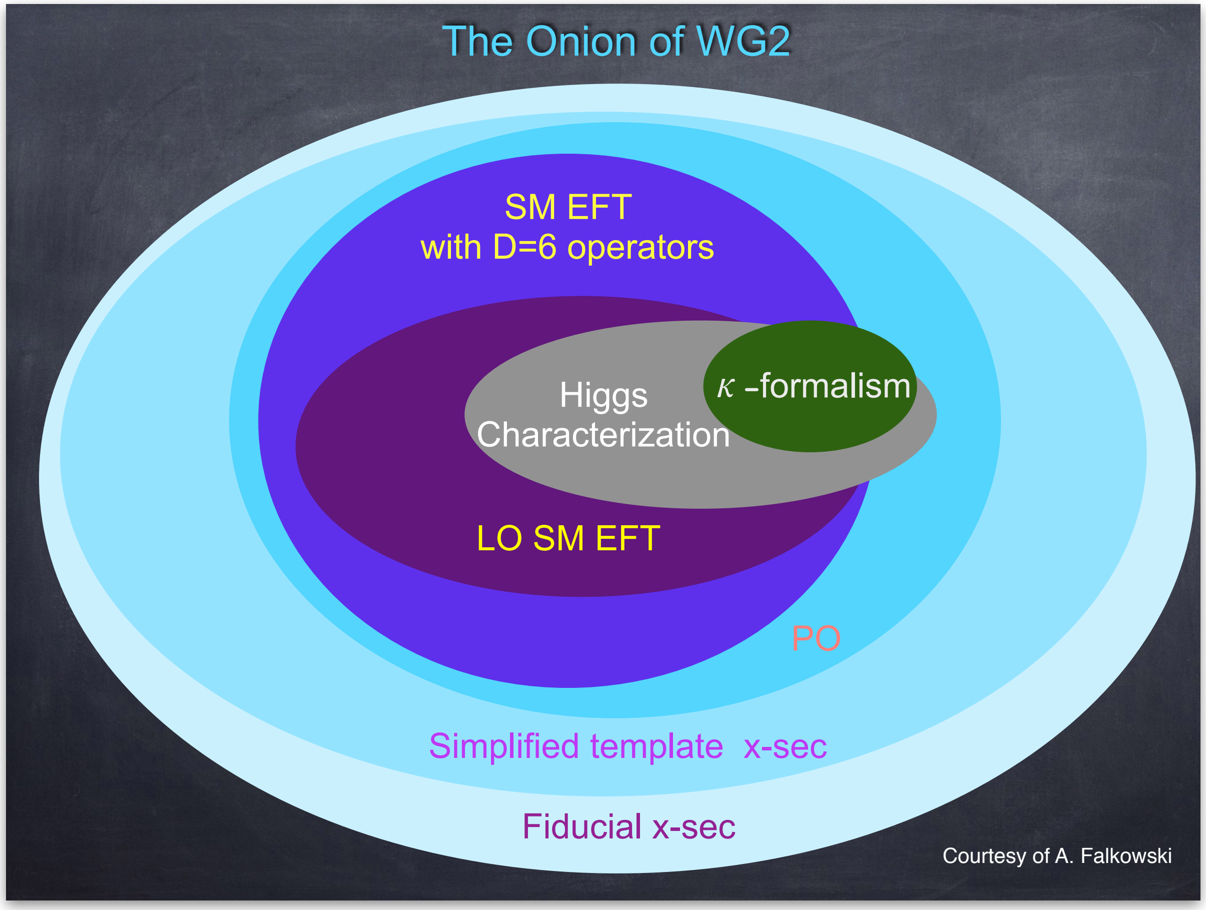
Complete 2-loop NLO EW correction calculation desired.

4. Higgs Couplings via Effective Field Theory

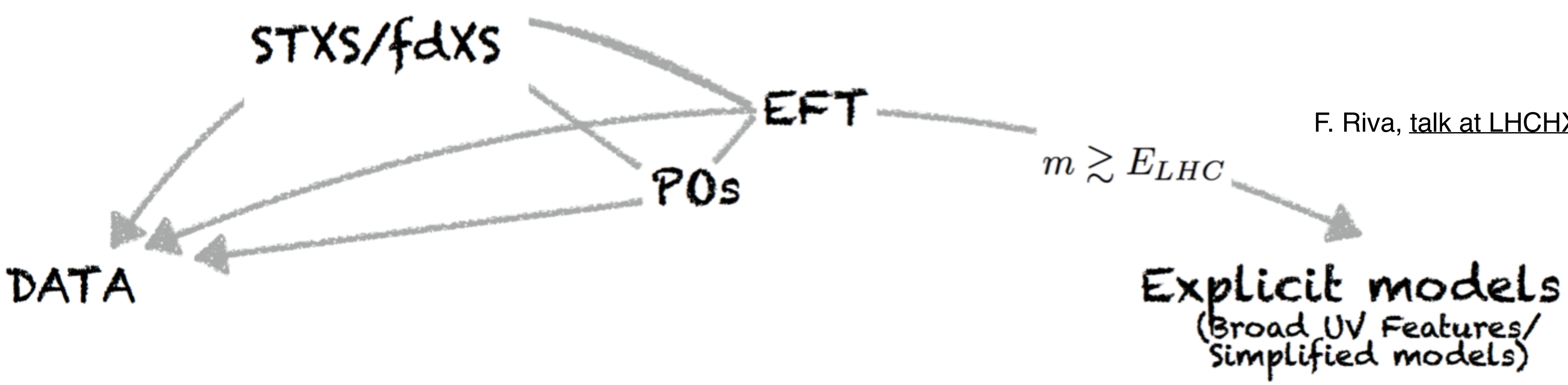
Higgs Effective Field Theory - go beyond κ-framework

- κ-framework aimed to "detect the deviation from the SM" at O(5-10%)
  - It is only at lowest-order (LO) and does not incorporate differential distributions which are sensitive to BSM.
- Model independent framework exists, *i.e.* the Effective Field Theory (EFT)

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



  - Neglecting dimension-5 operator, dimension-6 consists of 59 operators.
  - Search for BSM physics indirectly via precision Higgs coupling measurements.
  - Capable to combine EWPD, aTGC, Higgs and Top data with common Lagrangian.

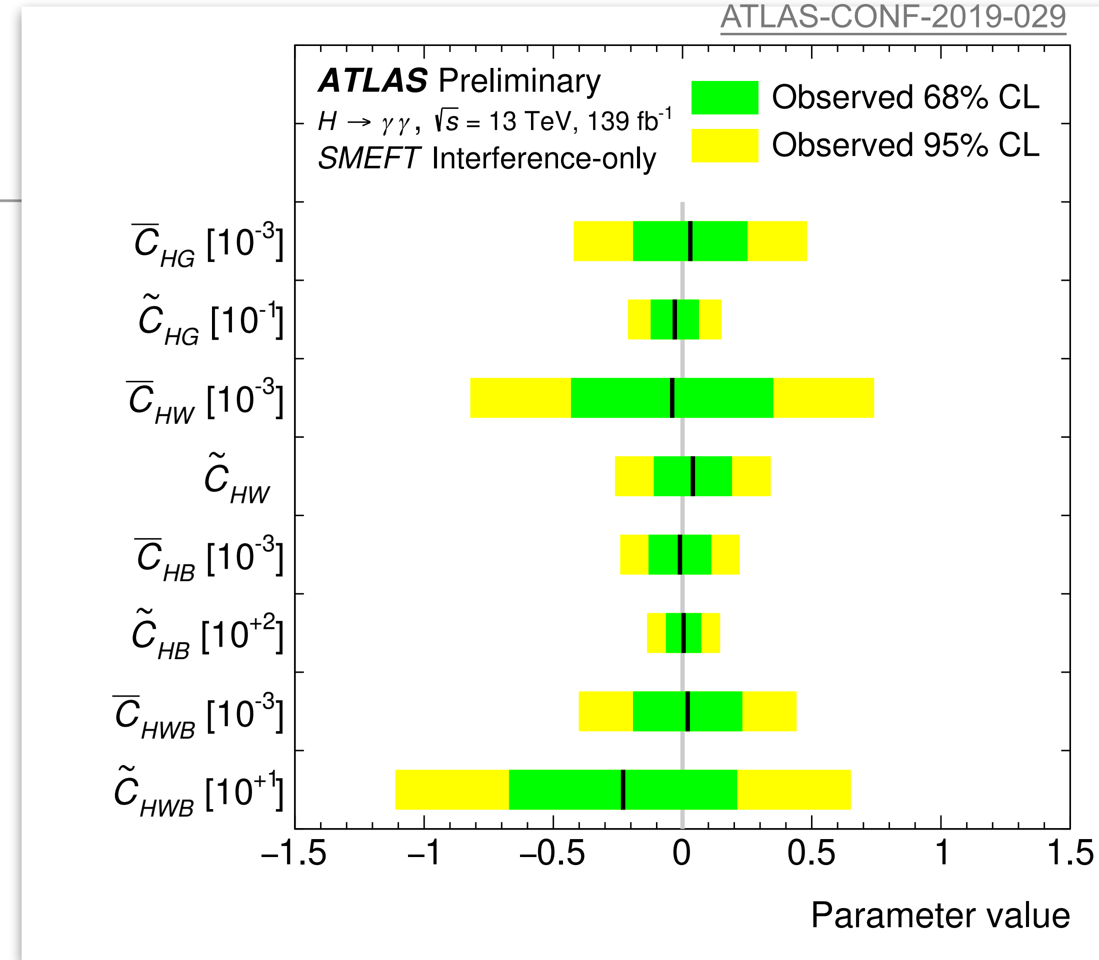


F. Riva, talk at LHCHXSWG general meeting

Higgs EFT Analysis H→γγ

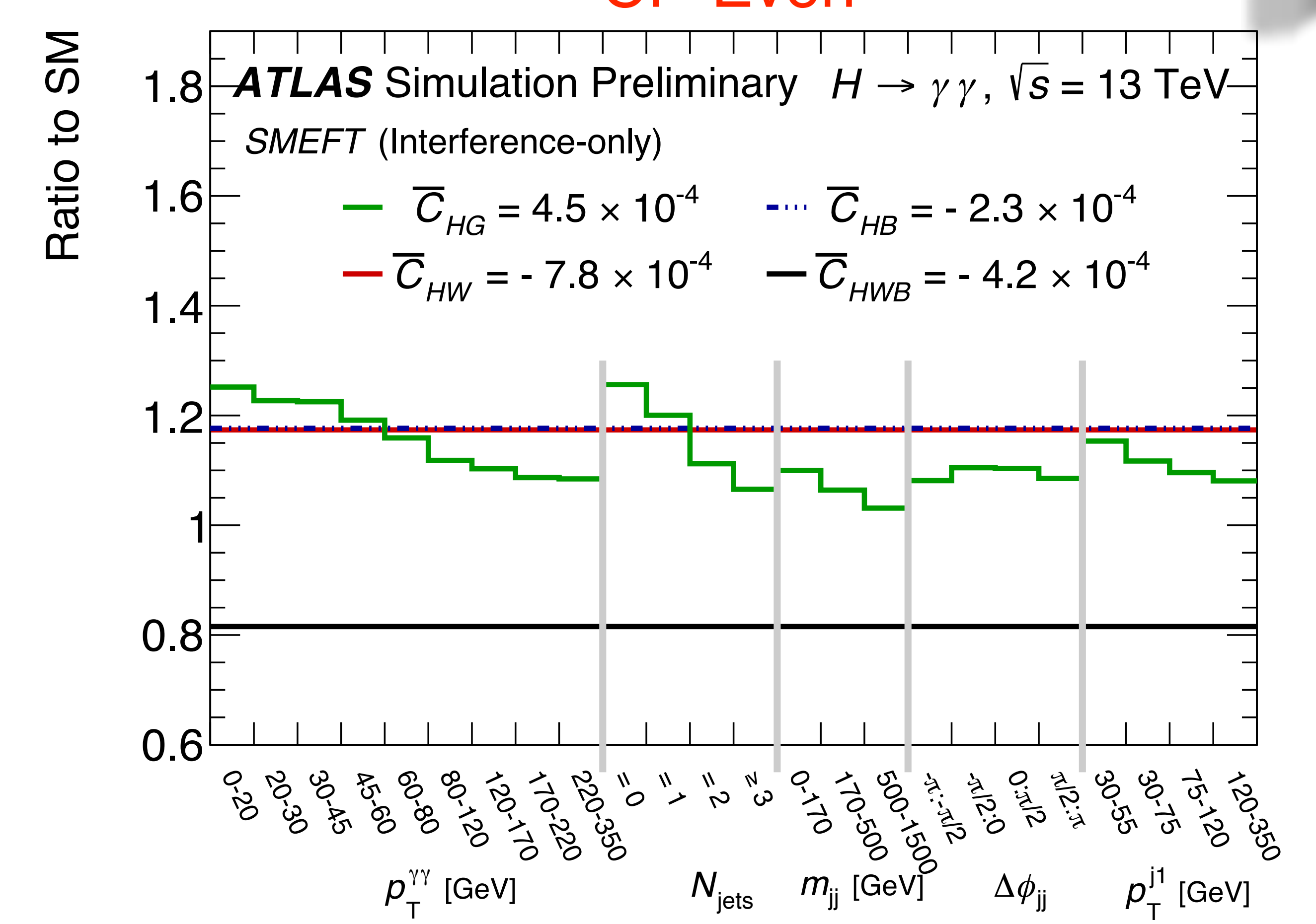
- EFT analysis in H→γγ decay with 5 differential distributions
- CP-even Wilson coefficients(C_{HG}, C_{HW}, C_{HB}, C_{HWB})
  - C_{HG}: ggF
  - C_{HW}, C_{HB}, C_{HWB}:VBF, VH, H→γγ
  - EWPD constraints: C_{HWB} (S), C_{HD} (T)

ATLAS-CONF-2019-029

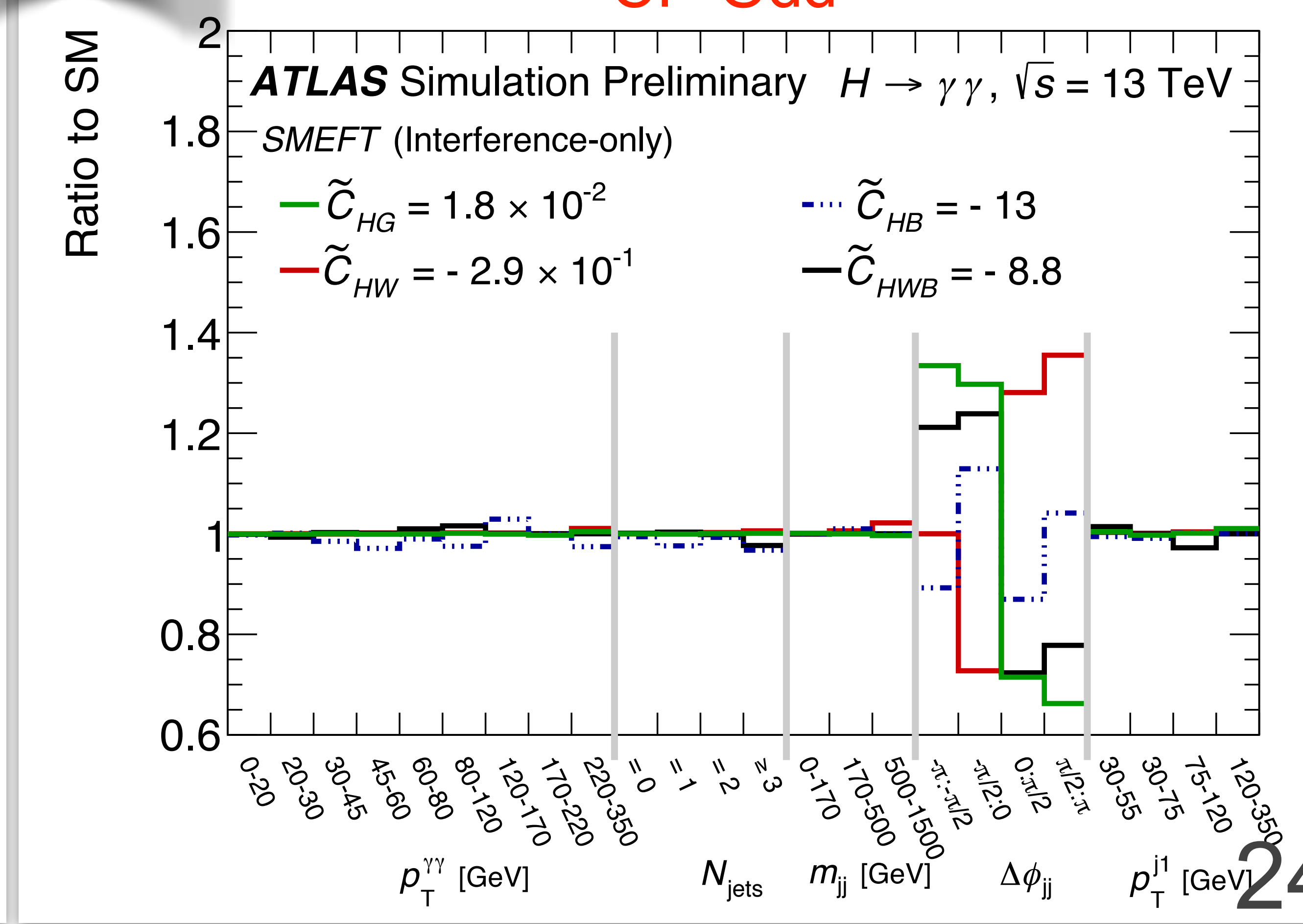


RUN-2

CP-Even



CP-Odd

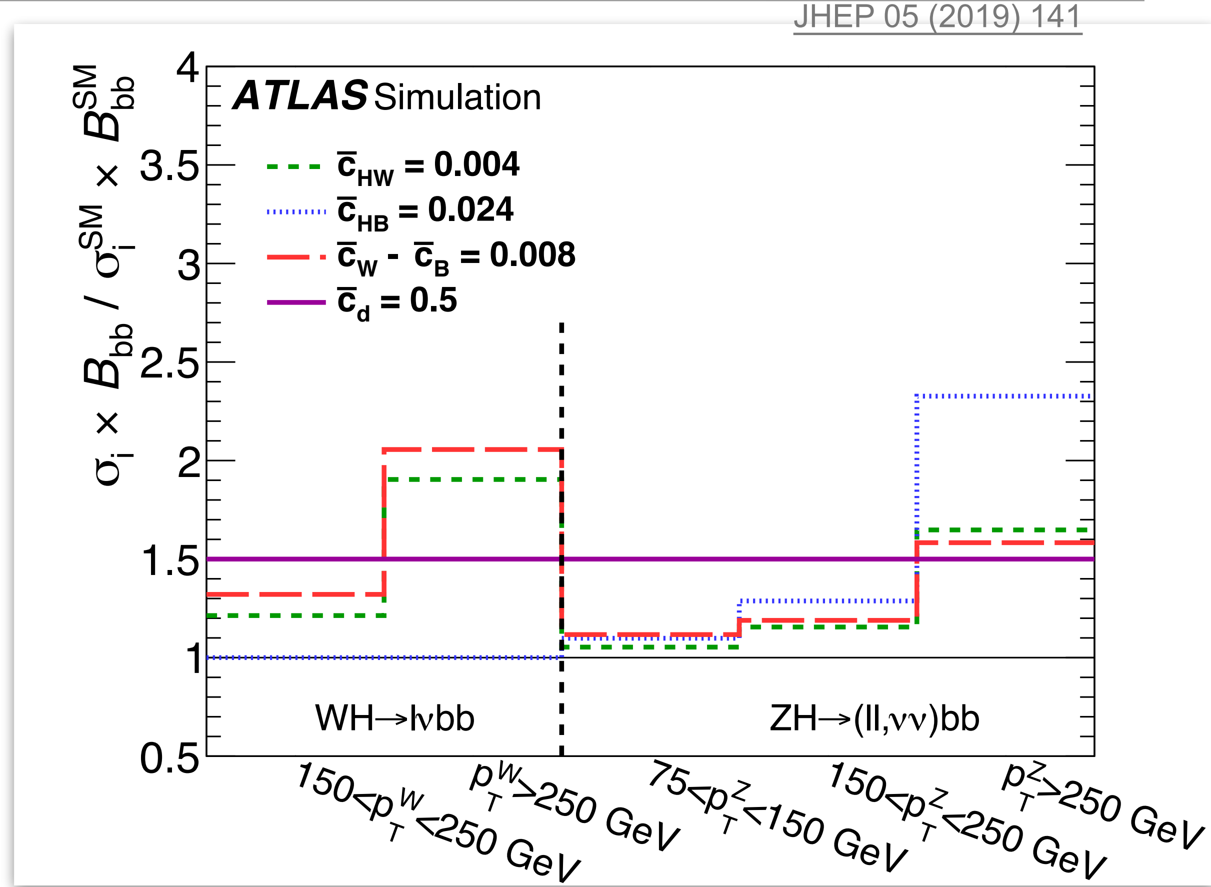


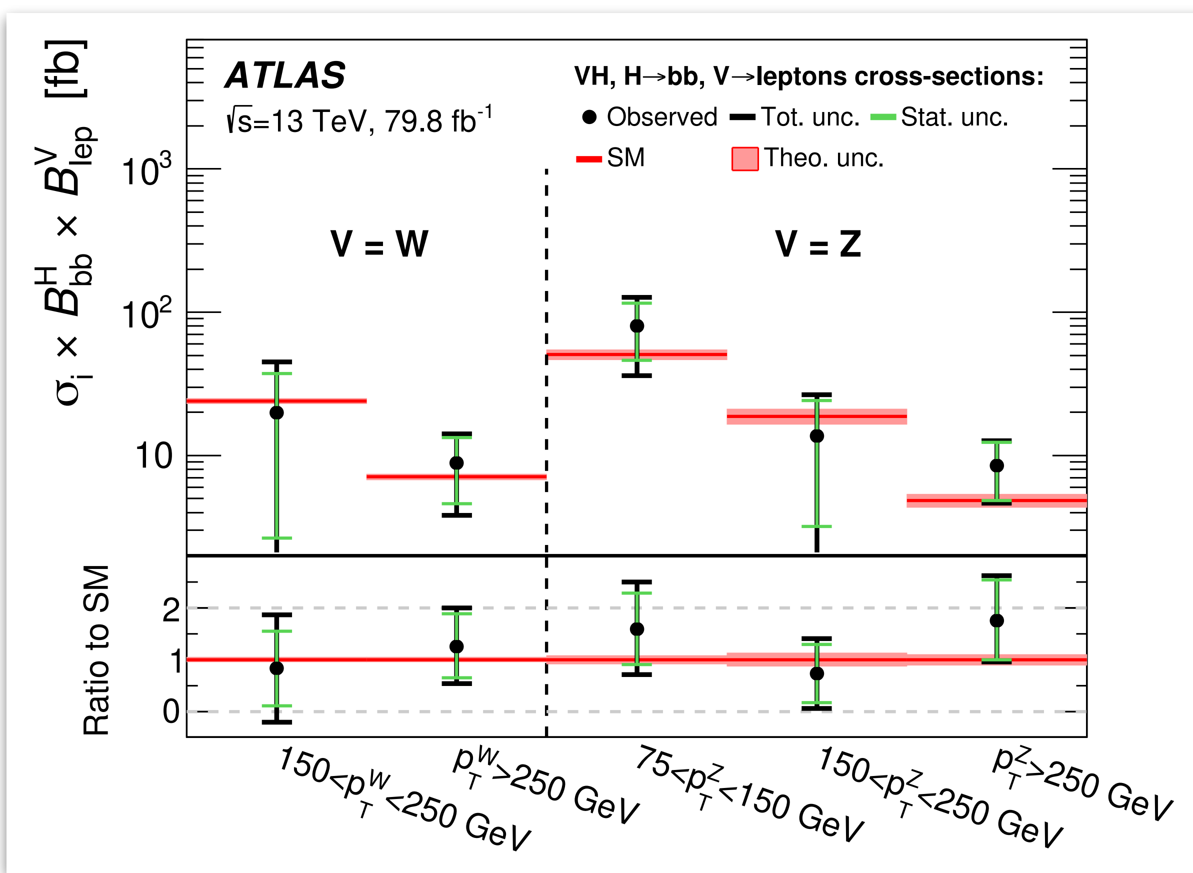
Higgs EFT Analysis in VH(H→bb)

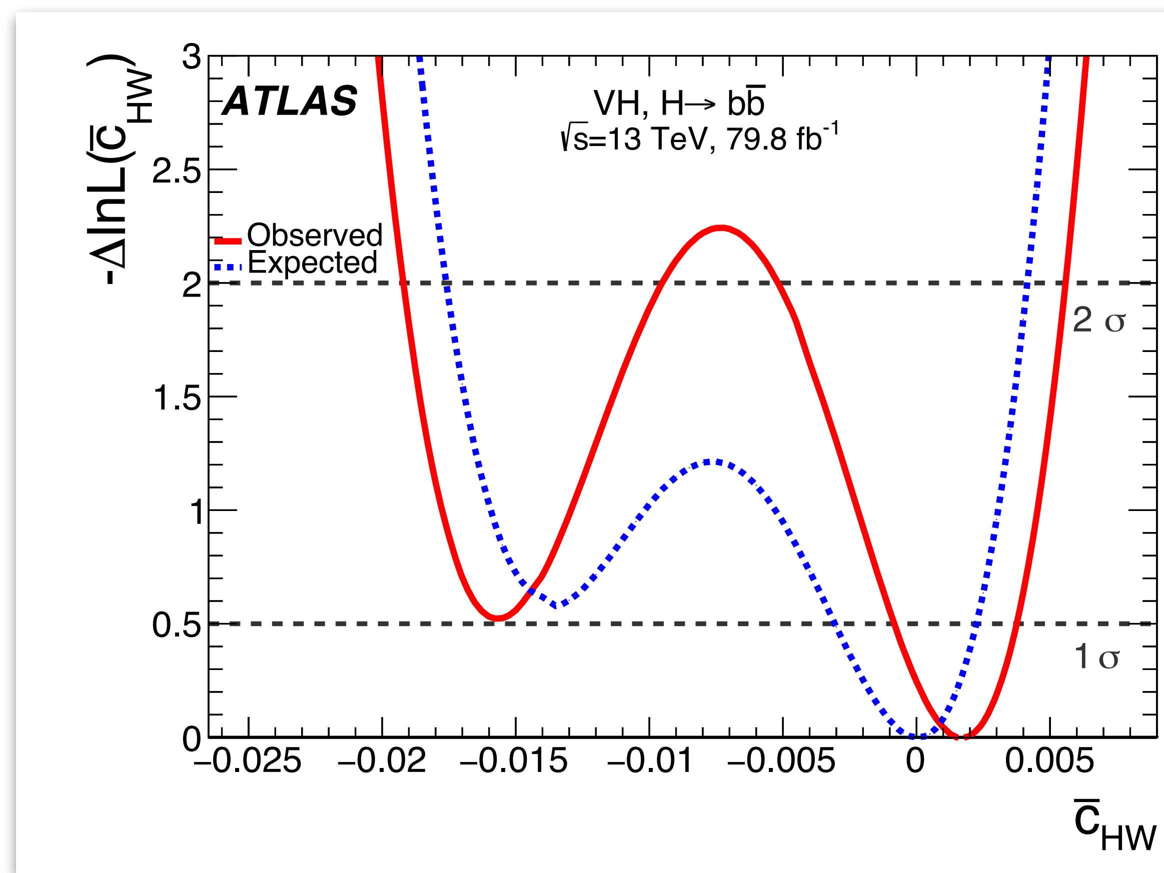
RUN-2

JHEP 05 (2019) 141

- EFT analysis in VH production with H→bb decay
  - via template cross section in vector boson p_T
- Constraints on Wilson coefficients (C_{HW}, C_{HB})







5. Higgs Boson Spin CP

CP Violation in Higgs Sector

- CP violation: immediate sign of BSM physics.
- One of the 3 Sakharov conditions for EW Baryogenesis,

  i) B number violation, ii) C or CP violation and iii) out-of-equilibrium or CPT violation
- CP violations for quark and neutrino sector, but totally unknown for Higgs sector.
- Many BSM models (ex. 2HDM, SUSY) predict CP violation
  - MSSM: no Born level CP violation, CP-violation is loop-induced.
  - NMSSM: CP-violating phase at Born level.
  - 2HDM: the effects on Higgs couplings to gauge bosons are suppressed, hence CP-violation studies often in Yukawa sector, ex. $\tau\tau$, ttH, etc.
- Strong constraints on CP- violation via Electric Dipole Moment (EDM)
  - Λ_{CP} ~1 TeV, comparable to LHC reach !

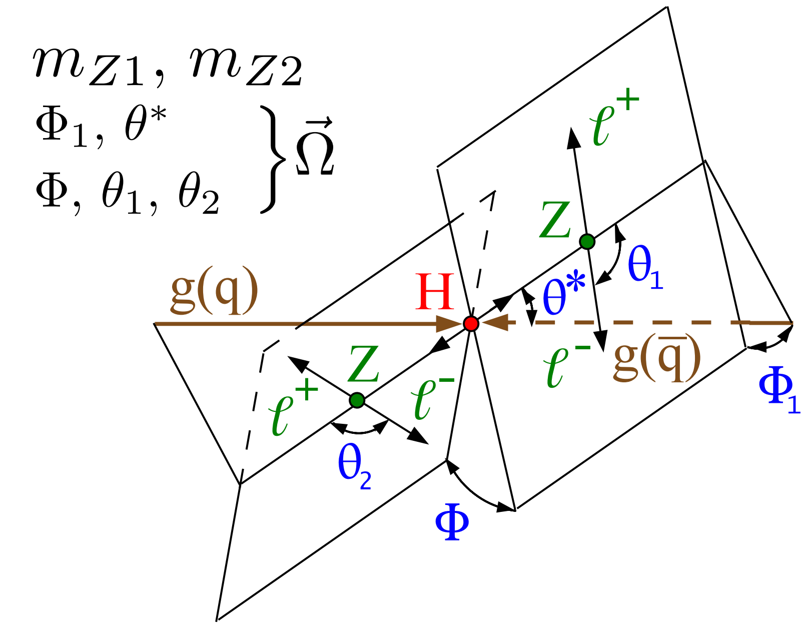
$$|d| < 10^{-25} e \times \text{cm} \to d \sim 10^{-2} \times \frac{1\,\text{MeV}}{\Lambda^2_{\text{CP}}}$$

Higgs Spin-$\mathcal{CP}$

PLB 726 (2013) 120

- Probed $\mathcal{CP}$ nature in Higgs boson decay into 4-leptons
  - No event yield information (cross section) was used but shape only in the analyses.
- Excluded pure $J^P=0^-$, $1^\pm$, 2^+ (minimal coupling) at more than 99% C.L. in RUN-1.
- Large $\mathcal{CP}$-mixing/violation is still possible.

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

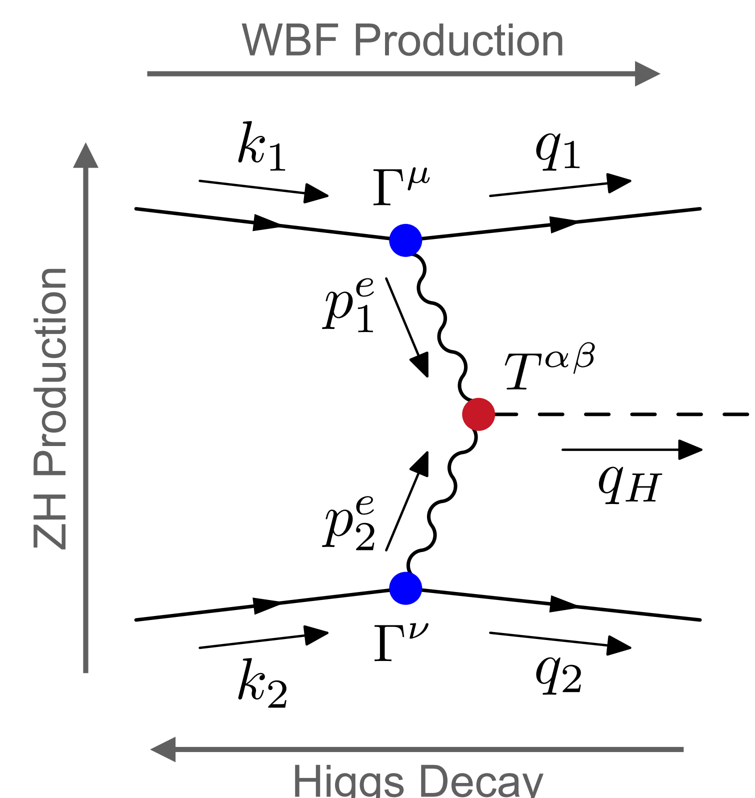


in analogy to $\pi^0 \to e^+e^-e^+e^-$

- $\mathcal{CP}$-information Geometry

Phys. Rev. D 97, 095017

  - VBF provides the best reach. But its initial state is not $\mathcal{CP}$ eigenstate. Important kinematical variable like $\Delta\phi_{jj}$ in VBF
  - ZH associated production is less model-dependent. Initial state is $\mathcal{CP}$ eigenstate.
  - $H \to ZZ^* \to 4$ leptons is clean signal but limited sensitivity due to small momentum transfer M_H^2



$\mathcal{CP}$ Violation in H→ττ Decay

RUN-1

- Vector Boson Fusion (VBF) channel to probe HVV couplings
- CP-odd Optimal Observable

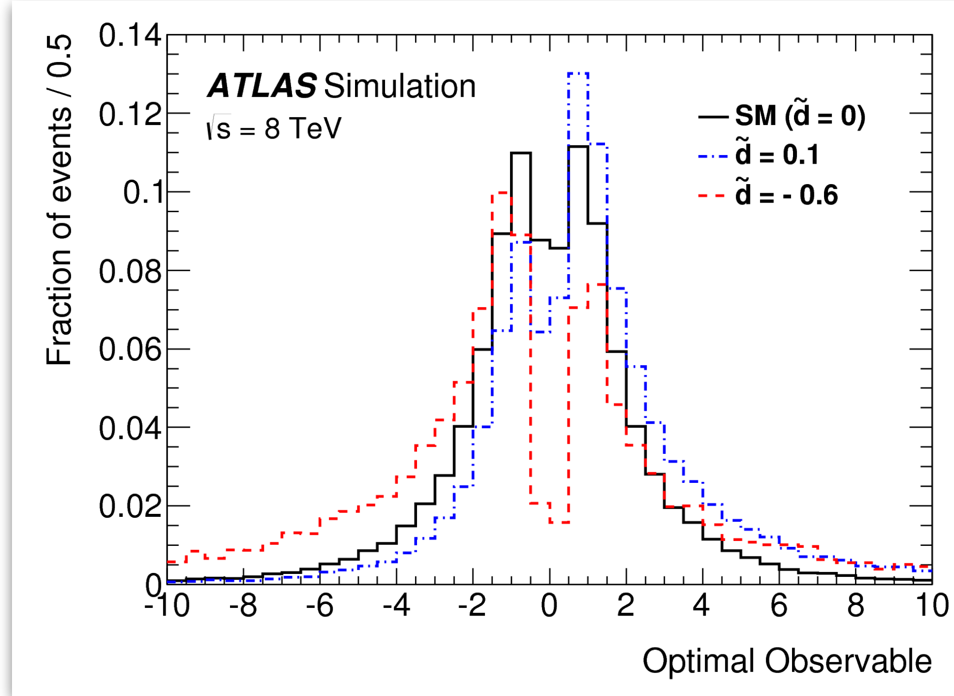
$$\mathcal{OO} = \frac{2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

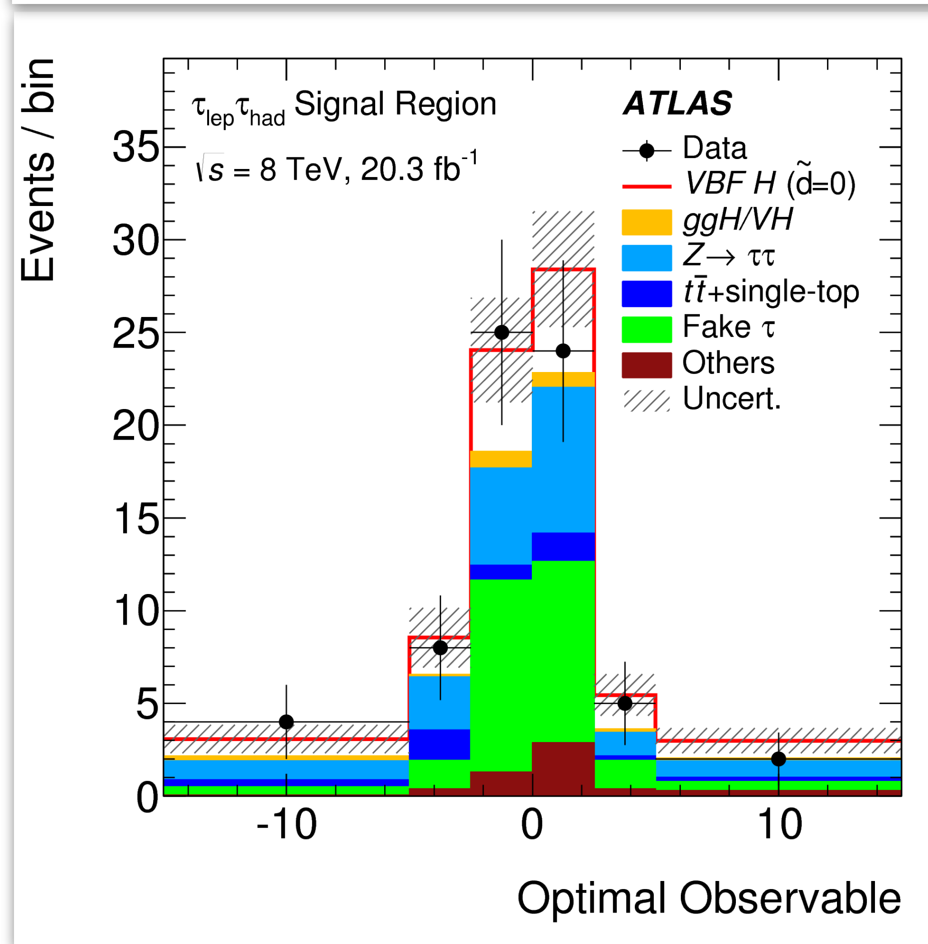
  - $\mathcal{OO}$ is CP-odd → < $\mathcal{OO}$ > ≠ 0 is an indication of CP-violation
  - Matrix element

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{\mathrm{d}} \cdot \mathcal{M}_{\mathrm{CP-odd}}$$

- CP- mixing parameter $\tilde{d}$ in h→ττ decay
  - Constrained in the interval [-0.11,+0.05] at 68%CL
  - Consistent with SM prediction $\tilde{d} = 0$

Eur. Phys. J. C76 (2016) 658

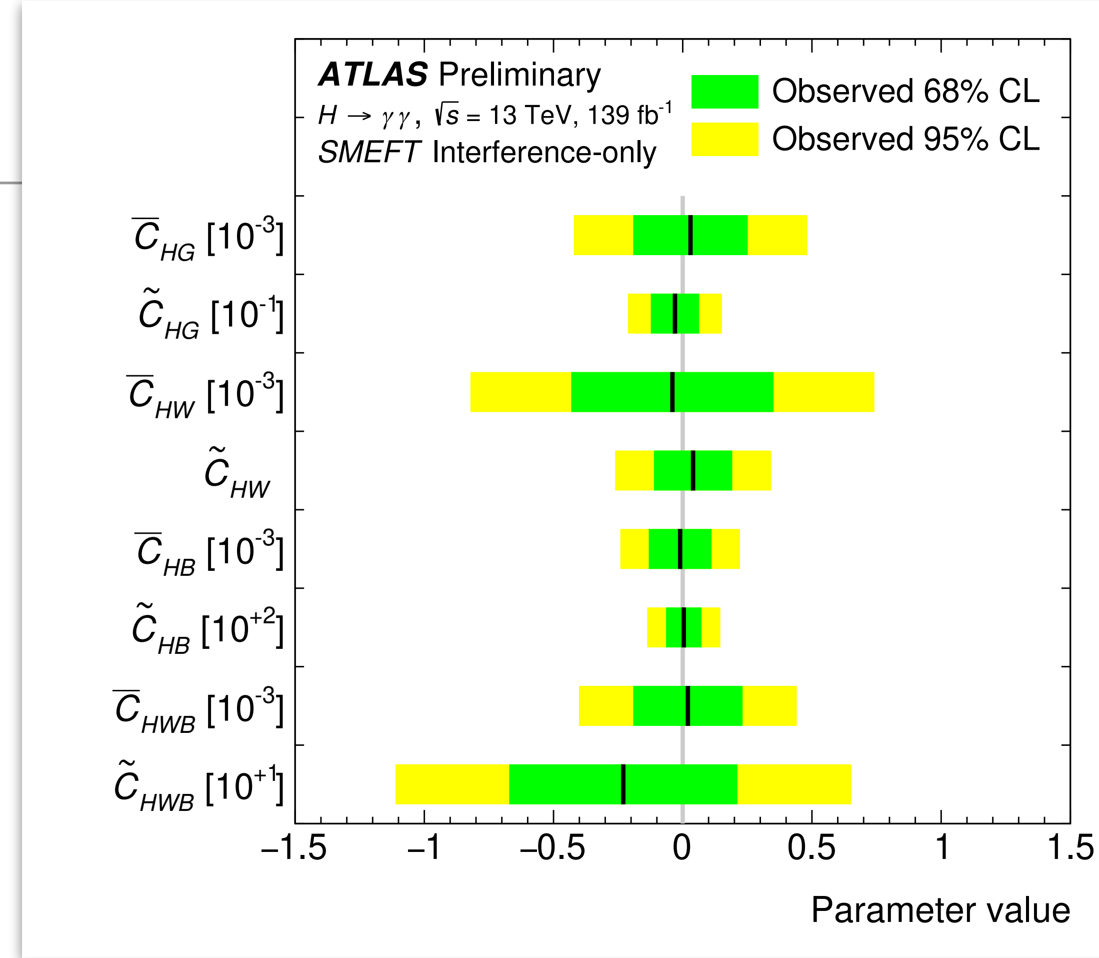




ATLAS-CONF-2019-029

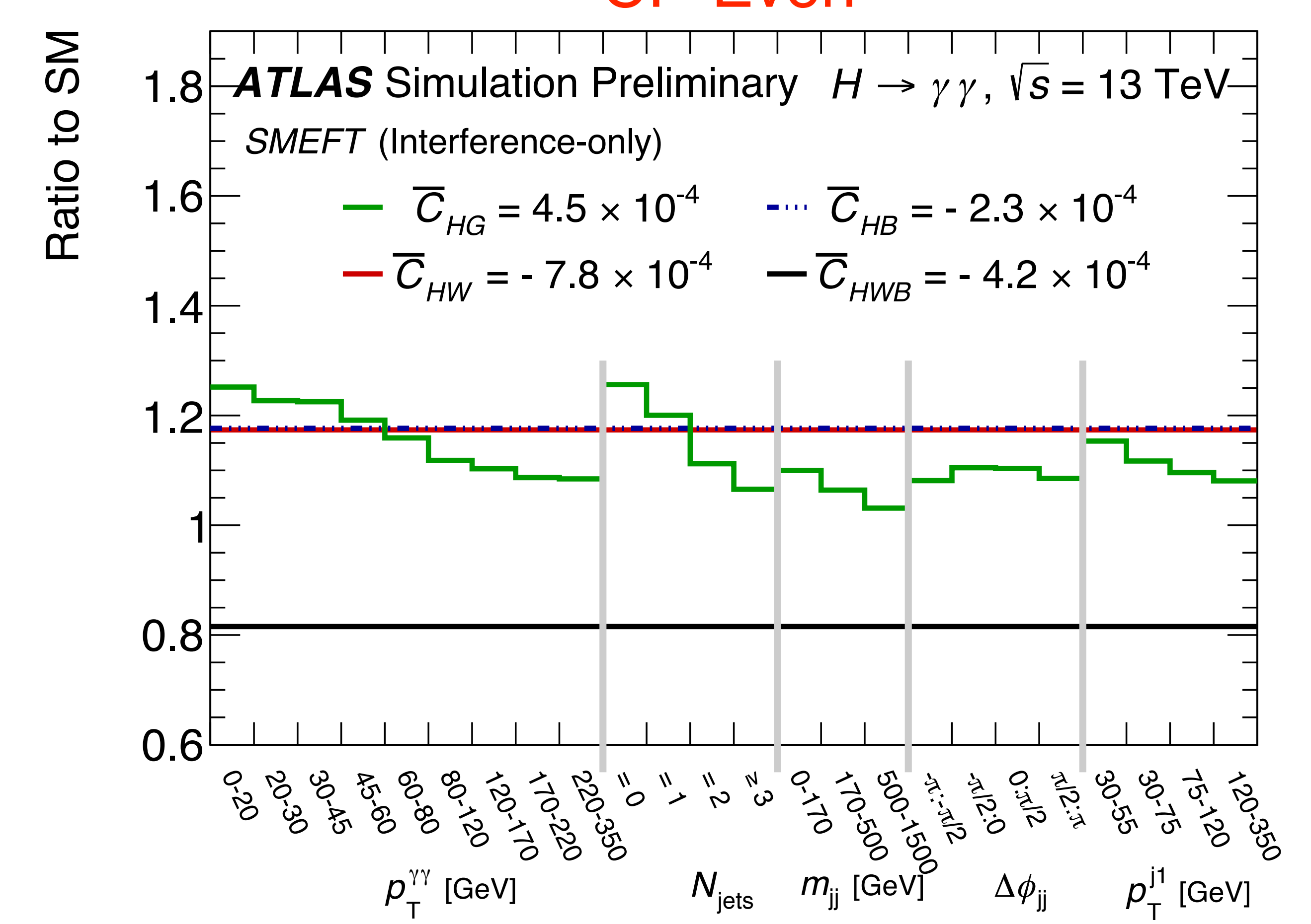
Higgs EFT Analysis H→γγ

- EFT analysis in H→γγ decay with 5 differential distributions
- CP-odd Wilson coefficients($\tilde{C}_{HG}$, $\tilde{C}_{HW}$, $\tilde{C}_{HB}$, $\tilde{C}_{HWB}$)
- Sensitivity for CP-violation in $\Delta\phi_{jj}$ (opening angle in r-ϕ plane between two forward jets in Vector Boson Fusion process)

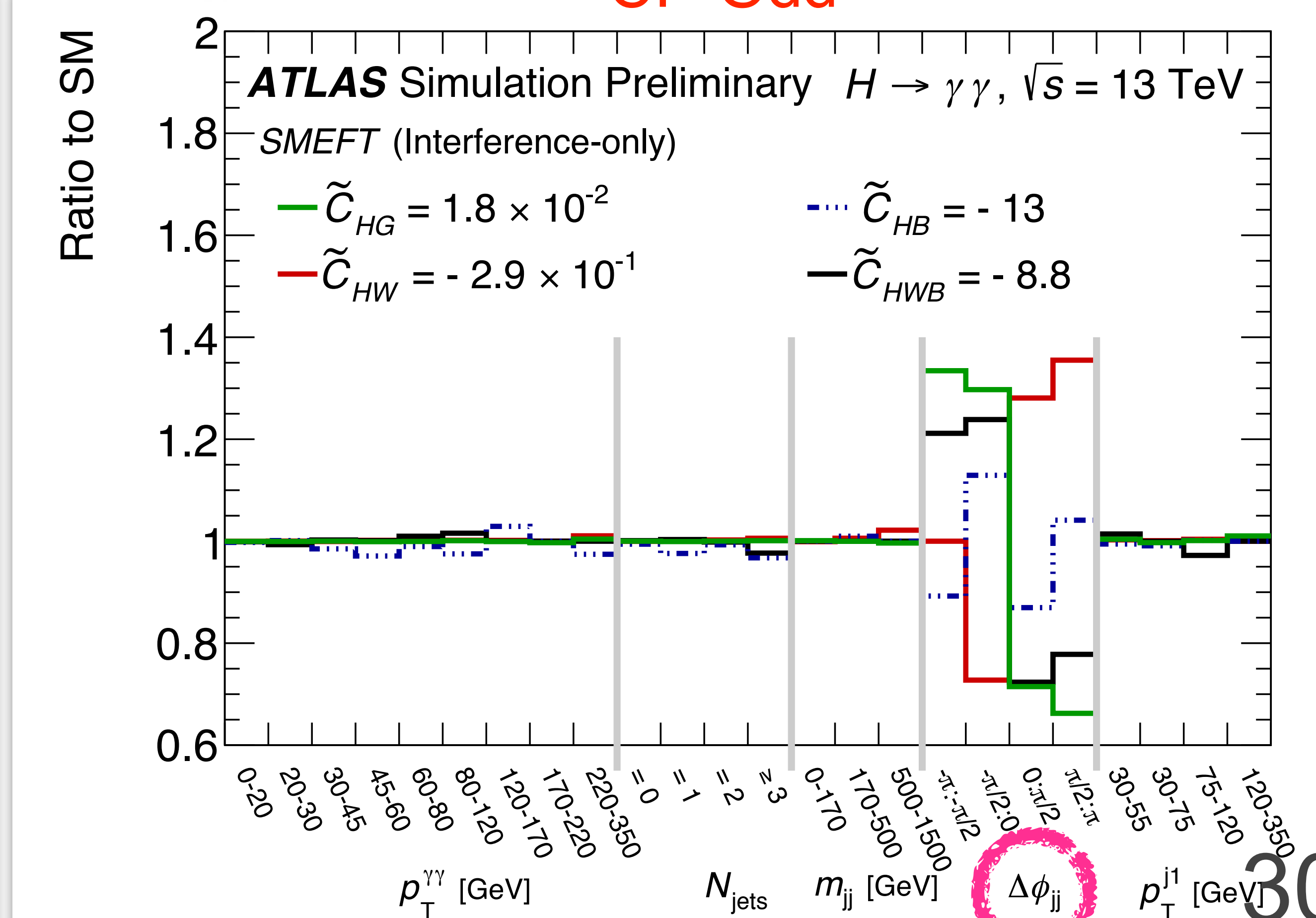


RUN-2

CP-Even

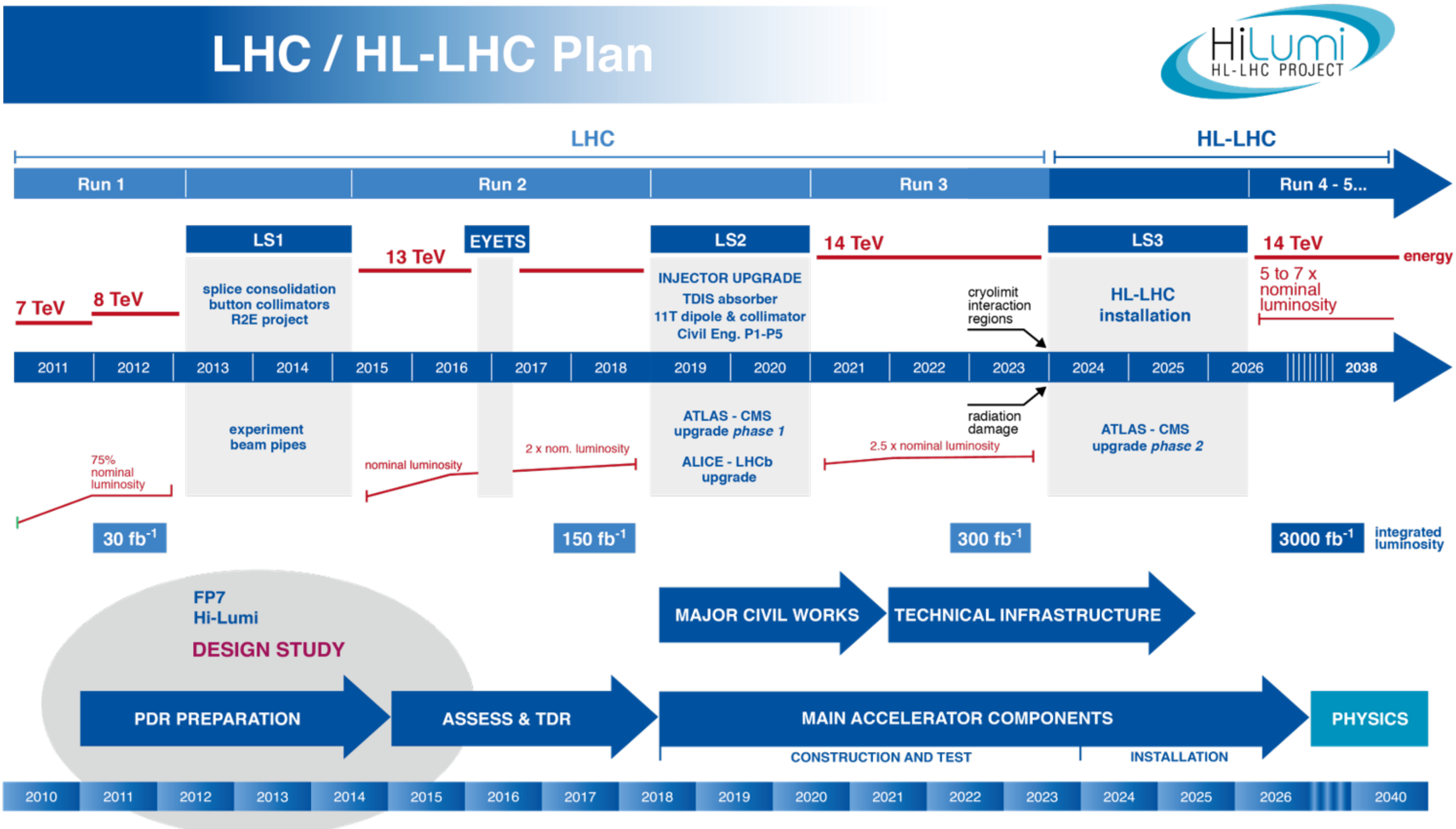


CP-Odd



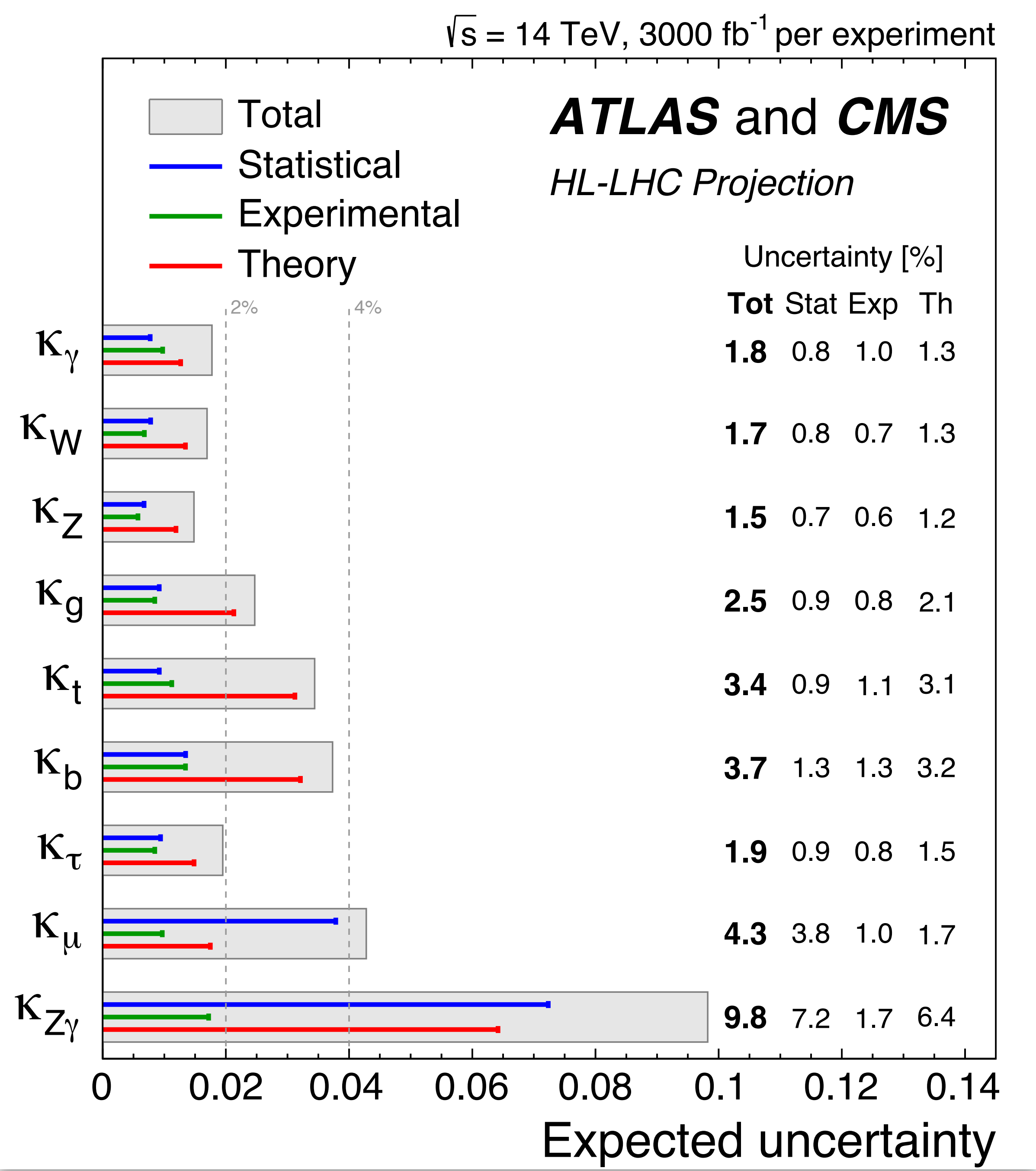
6. Prospects at HL-LHC

High-Luminosity LHC (HL-LHC)



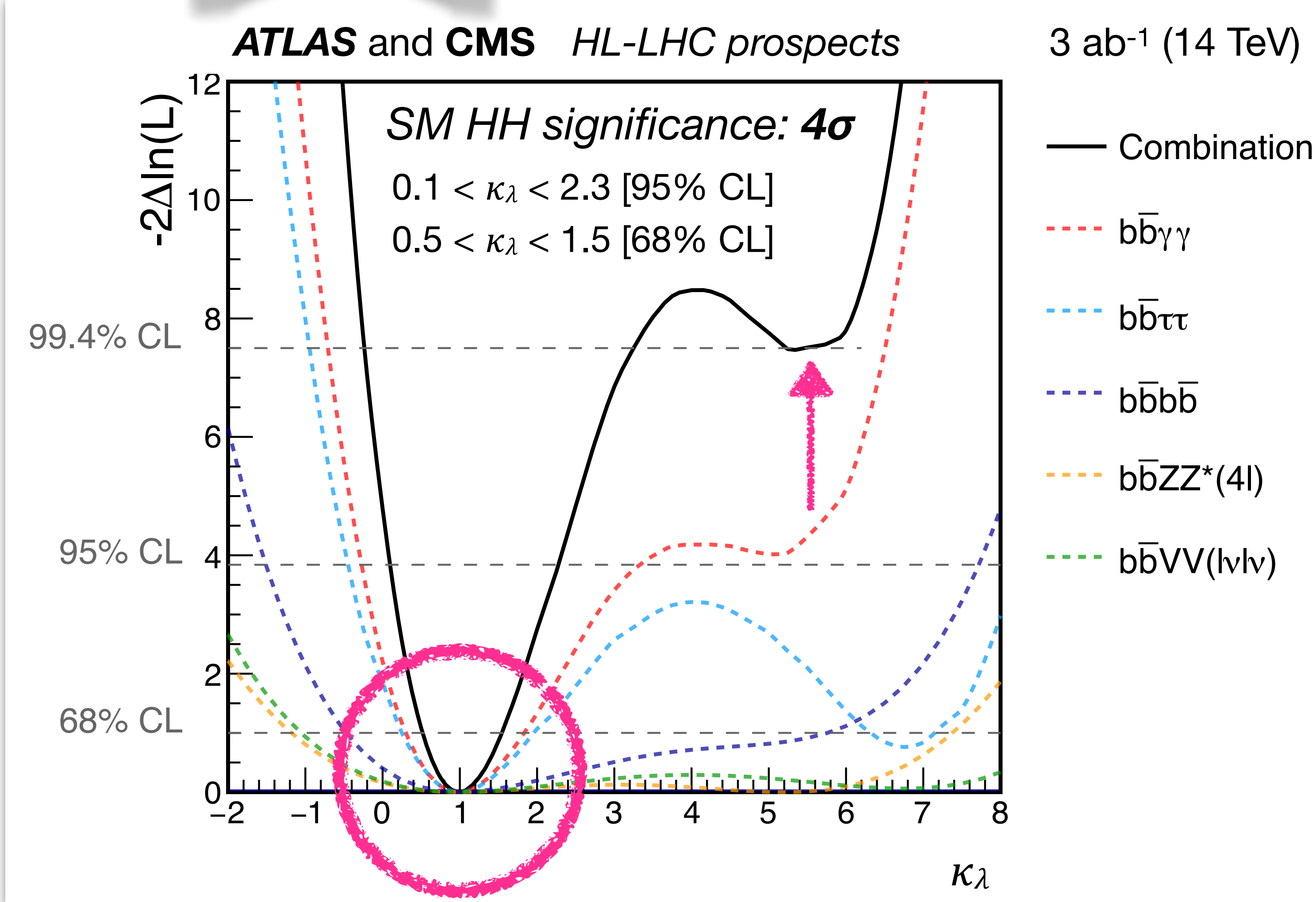
High-Luminosity LHC (HL-LHC)

- Coupling measurement at O(few%) precision
- Higgs self-coupling measurement at O(1) precision, 2nd minima excluded



HL-LHC

arXiv:1902.00134



Summary:

Higgs Boson Couplings to Bosons and Fermions

- 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)
  $\hookrightarrow$ Consistent with the SM prediction ($g_V \propto m_V^2$). Next, study in $d\sigma/dX$
- Higgs couplings to fermions (g_F)
  $\hookrightarrow$ Direct observation in the 3rd generation ($g_F \propto m_f$). Next 2nd generation
- Higgs potential - Higgs self-coupling λ
  $\hookrightarrow$ Remains as an important territory to conquer in HL-LHC and FCC
- Spin-CP
  $\hookrightarrow$ CP-violation could be possible with large mixing between CP-even&odd.

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- Spin-CP
  $\hookrightarrow$ CP-violation could be possible with large mixing between CP-even&odd.

- We have observed the first elementary scalar particle - 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 in precision measurement era like LEP !

What do we know about the scalar sector 7 years after July 4th 2012 discovery ?

What do we know about the scalar sector 7 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

Note on Coupling versus Mass relation

- Discussions on quark mass (M. Spira)

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SMInputParameter

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

1. One can define quark mass for Yukawa coupling,

$$\bar{g}_Q(M_H), \bar{g}_Q(M_Q), g_Q^{\text{pole}}$$

2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,

$$\Gamma(H \to Q\bar{Q}) = \bar{g}_Q^2(M_H) \frac{3M_H}{16\pi} \left\{ 1 + \frac{17}{3} \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\}$$

$$m_b(m_b) = 4.16\,\text{GeV}, m_b(M_H) = 2.76\,\text{GeV}$$

3. Use pole mass for top quark (172.5 GeV).

4. Use PDG values for leptons and W/Z boson masses. The universal QED corrections for leptons are small.

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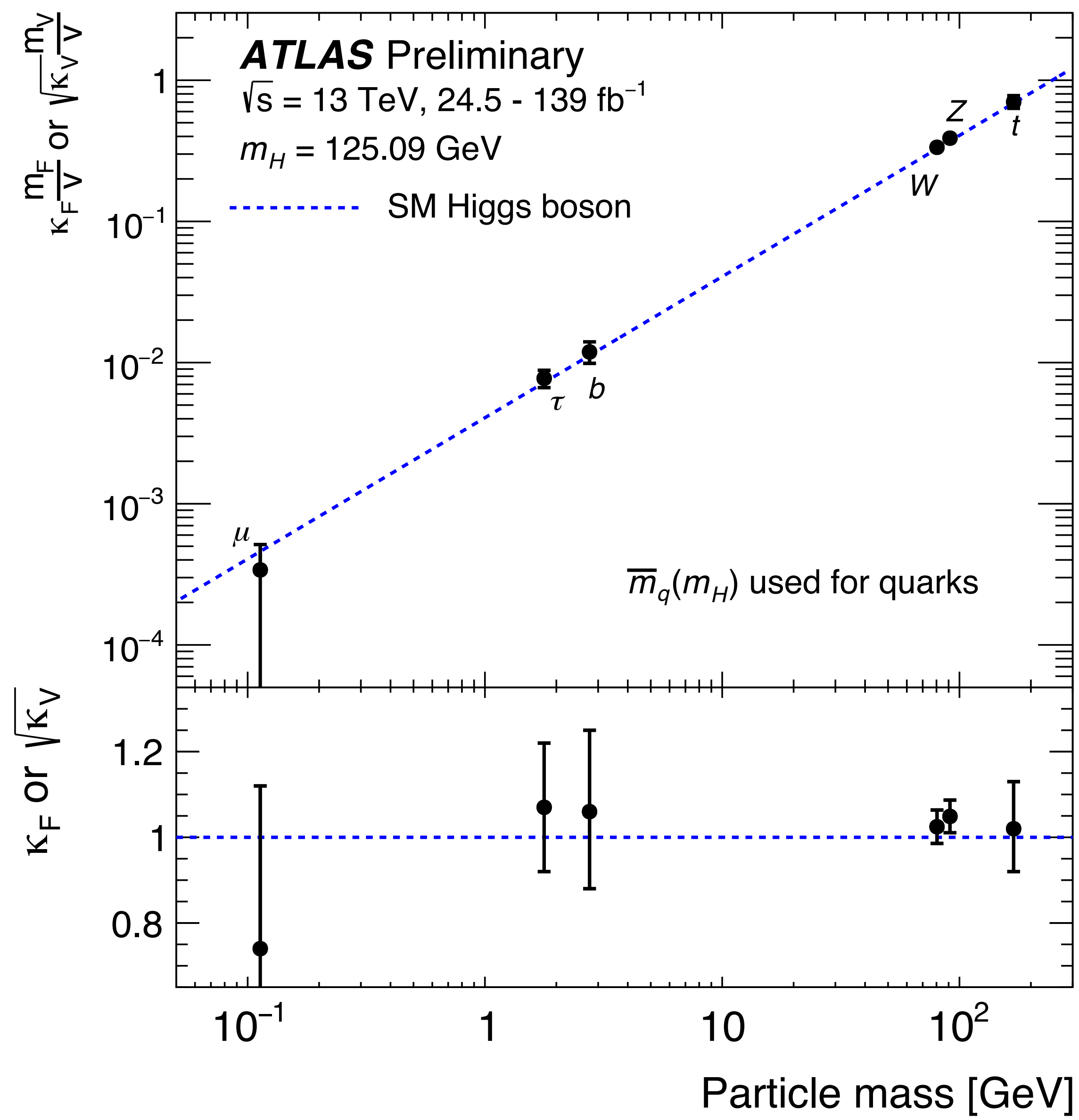

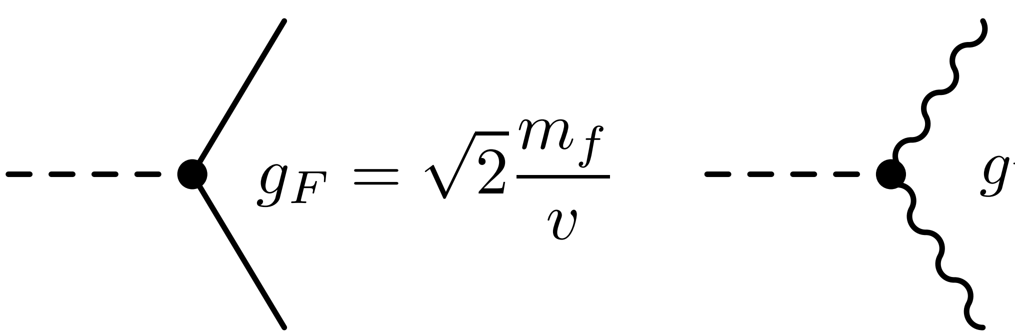

$$g_F = \sqrt{2}\frac{m_f}{v} \qquad g_V = 2\frac{m_V^2}{v}$$

$$m_c(M_H) = 0.616\,\text{GeV},\ m_b(M_H) = 2.764\,\text{GeV},\ m_t(M_H) = 169.21\,\text{GeV}$$

Higgs Effective Field Theory

- Model-independent framework - HEFT
- Effective Lagrangian:

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

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.

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