# The LHC Higgs Cross Section Working Group


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On behalf of the LHC Higgs (Cross Section) Working Group

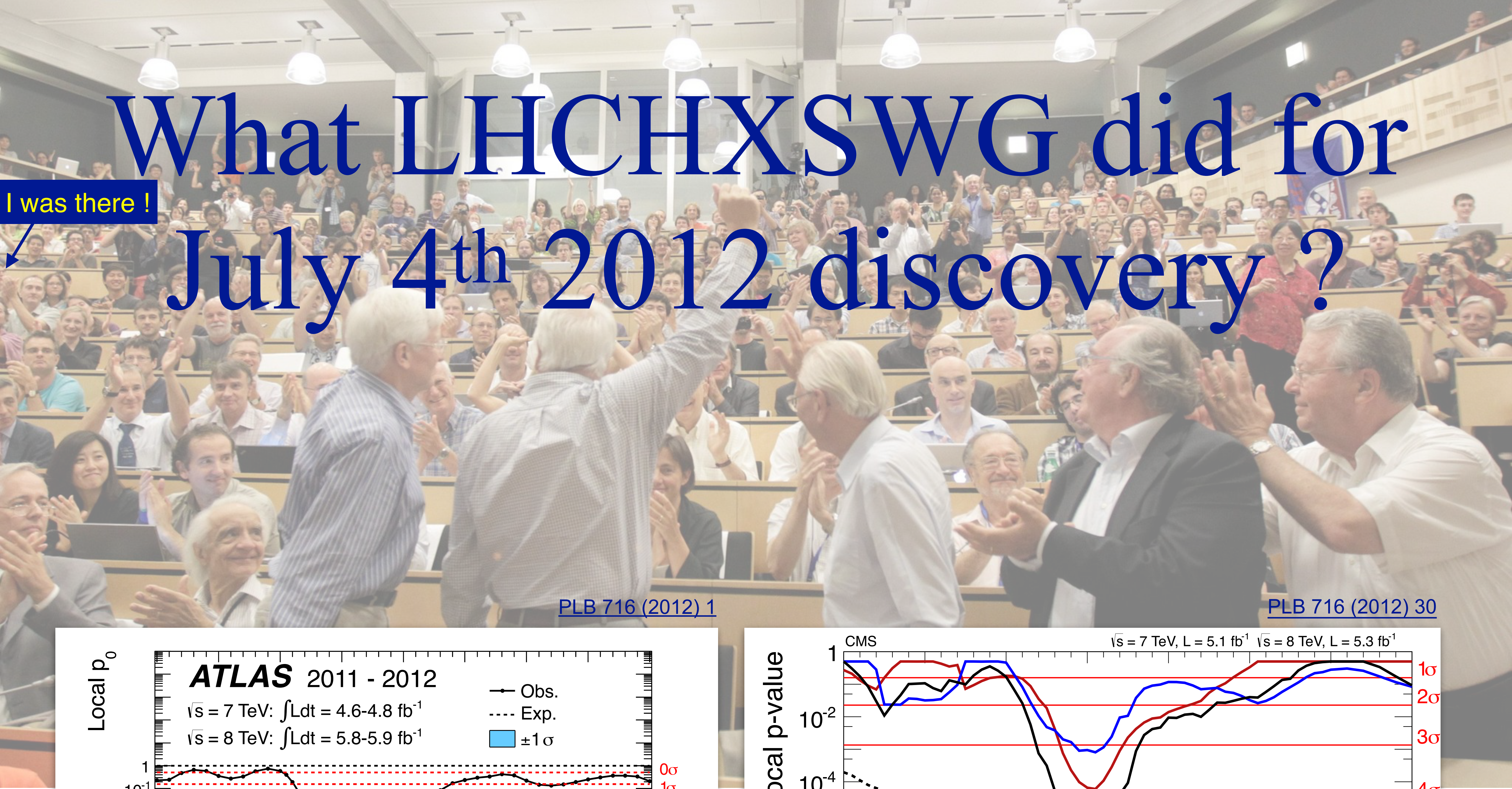

- Special thanks to colleagues from Theory, ATLAS and CMS -

HiggsDiscovery@10 Symposium,
June 30th 2022, Birmingham

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs dépasser les frontières IN2P3 Les deux infinis

# What LHCHXSWG did for July 4th 2012 discovery ?

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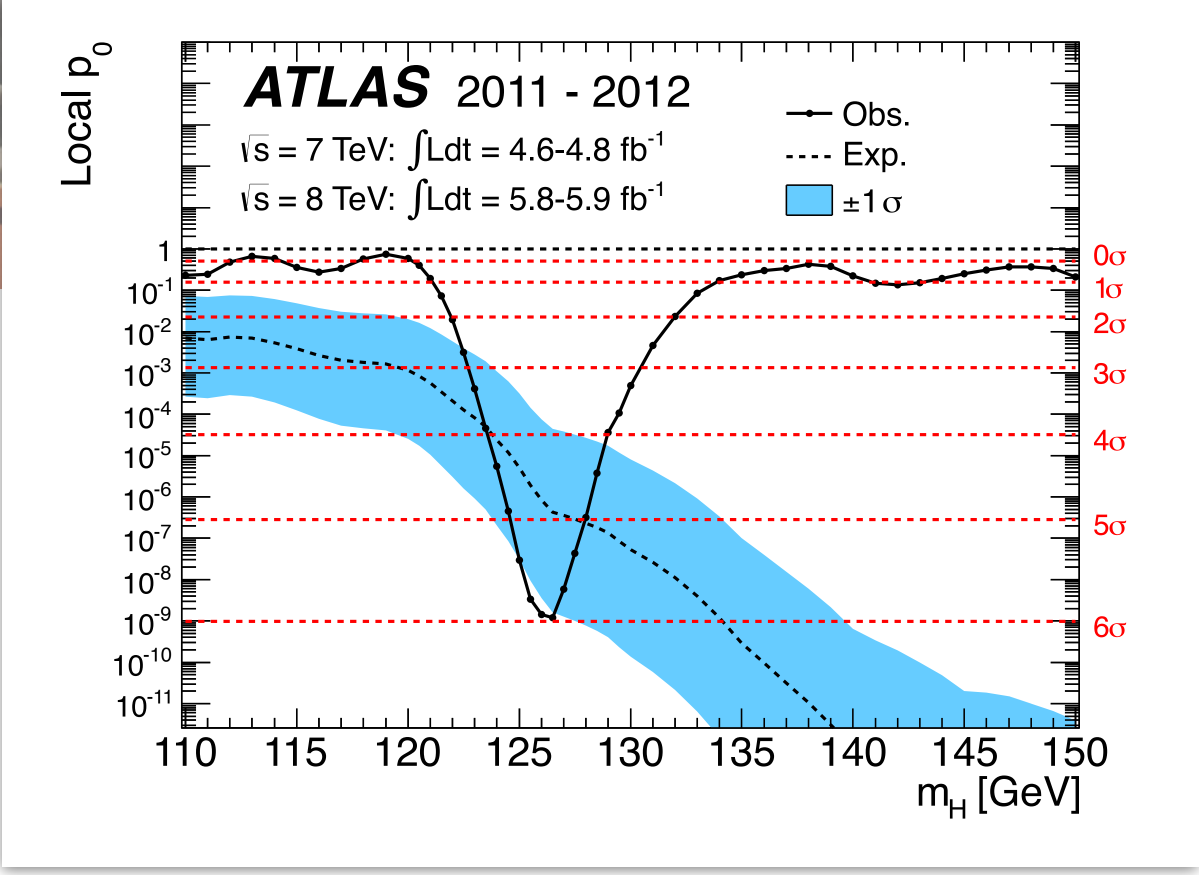


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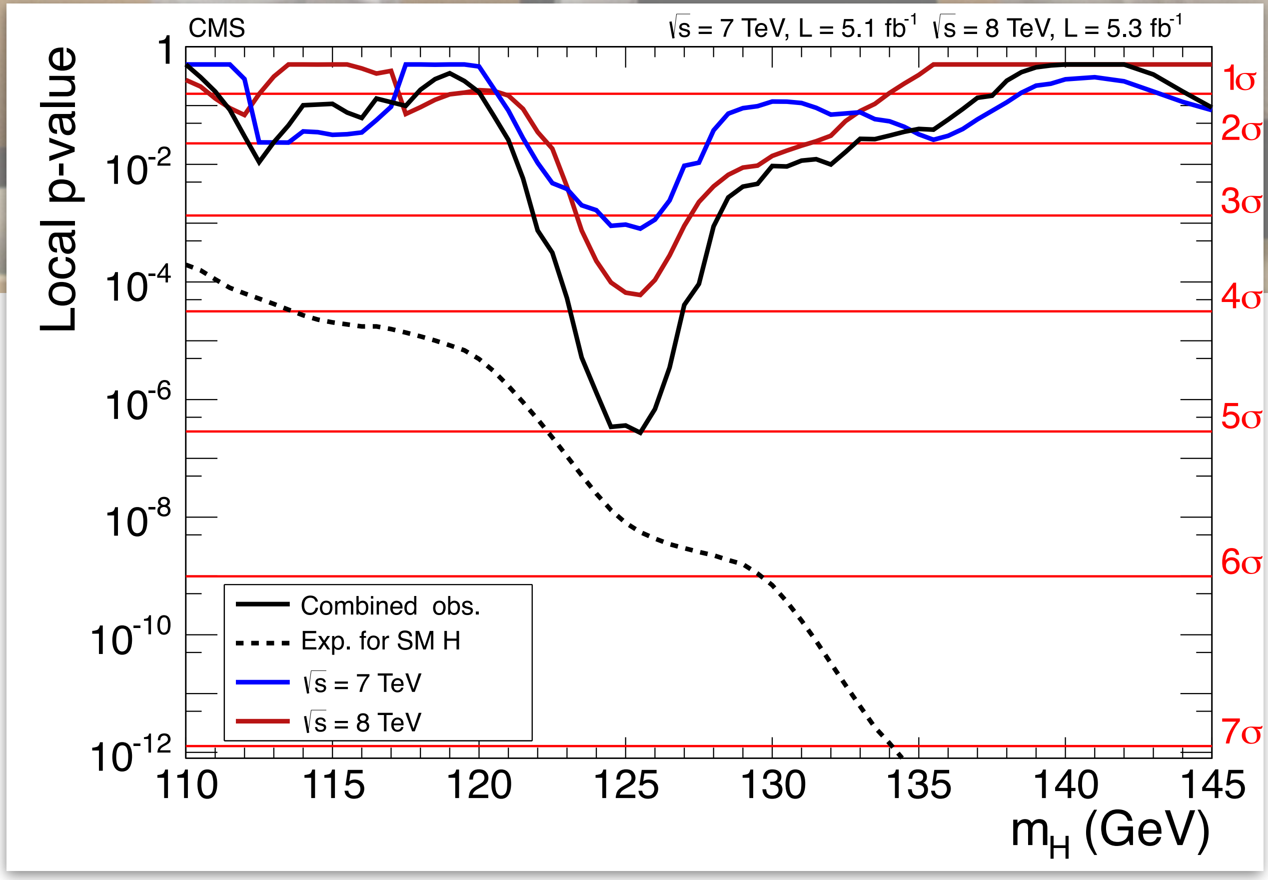
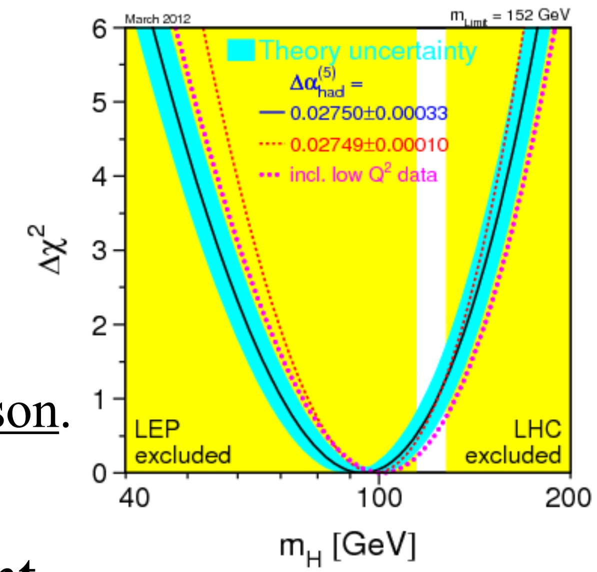


# Why LHC Higgs Cross Section Working Group ?




## Preamble

- In late 2000's, a bunch of people had an idea to form TH+ATLAS+CMS forum for Higgs boson precision physics (discussions initiated by G. Passarino).
  - The Higgs boson discovery could happen earlier than expected if light Higgs boson.
  - Many theoretical progresses on Higgs physics before LHC start.
  - **Interactions between TH and EXPs for common language are very important.**
- Access to the most advanced theory predictions for Higgs Cross Sections and Branching Ratios
  - Experiments will coherently use the common XS&BR's based on the interaction with the TH community.
  - This will facilitate the comparison and the combination of the individual results. (LHC Higgs Combination Group was created later.)
  - In case of a deviation from SM prediction, precise theoretical prediction are mandatory.
- The LHC Higgs Cross Section Working Group was created in January 2010.
  - The pre-foundation meeting was held in Torino during 23-24, November, 2009 - 1st LHC collision day !
  - The first coordinators: S. Dittmaier (TH), C. Mariotti (CMS), G. Passarino (TH), R. Tanaka (ATLAS)

# LHC Higgs Cross Section Working Group

Run 1 | Run 2 | Run 3

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 20

YR1 (2011) · YR2 (2012) · YR3 (2013) · YR4 (2017)

Aug. TH&ATLAS& CMS proposal for joint forum for Higgs XS

Nov. 23-24 Torino WS @ LHC 1st pp collision

Jan. Creation LHCHXSWG

Apr. Inauguration WS in Freiburg

July 4th Higgs boson Discovery

Nov. LHC Higgs XS WG ➩ LHC Higgs WG


**WG1: Higgs XS&BR**
**WG2: Higgs Properties**
**WG3: BSM Higgs**

Annual meetings at Freiburg, Bari, BNL, LAL and CERN

Important interaction with:
- PDF4LHC, MCNet
- LHC Higgs Combination WG
- LHC EW/Top Physics WG
- LHC Effective Theory WG

*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.)

← July 4th 2012 Higgs boson Discovery

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

# LHC Higgs Cross Section Working Group

| Run 1 | Run 2 | Run 3 |
|---|---|---|

| 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

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YR1 YR2 YR3

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YR4

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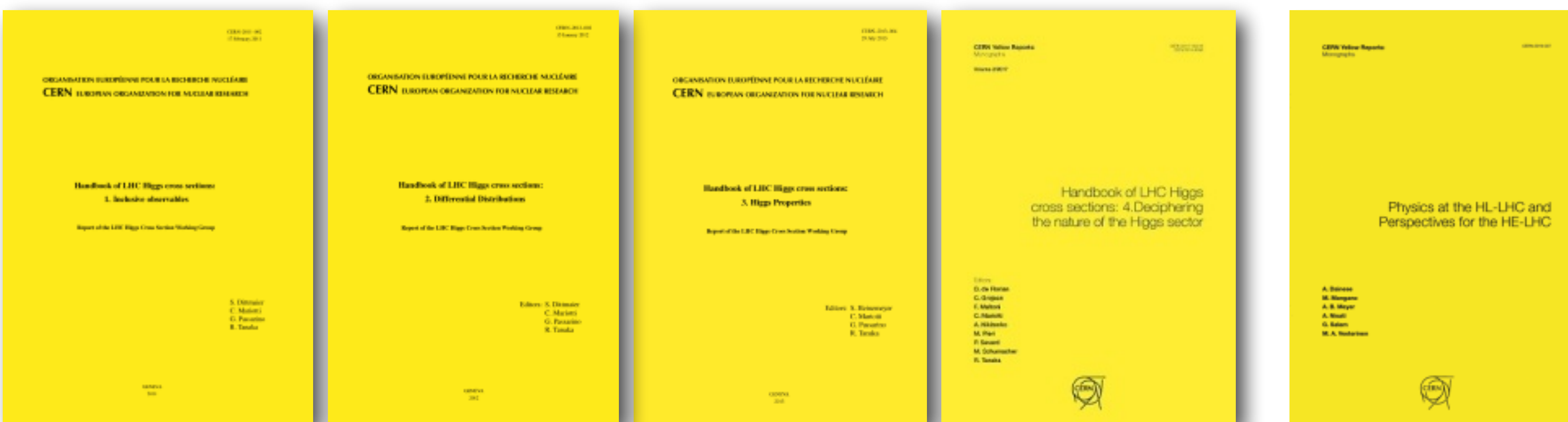


HL/HE-LHC Physics
CERN-2019-007
1418 pp.

*LHC Higgs XS WG CERN Reports*

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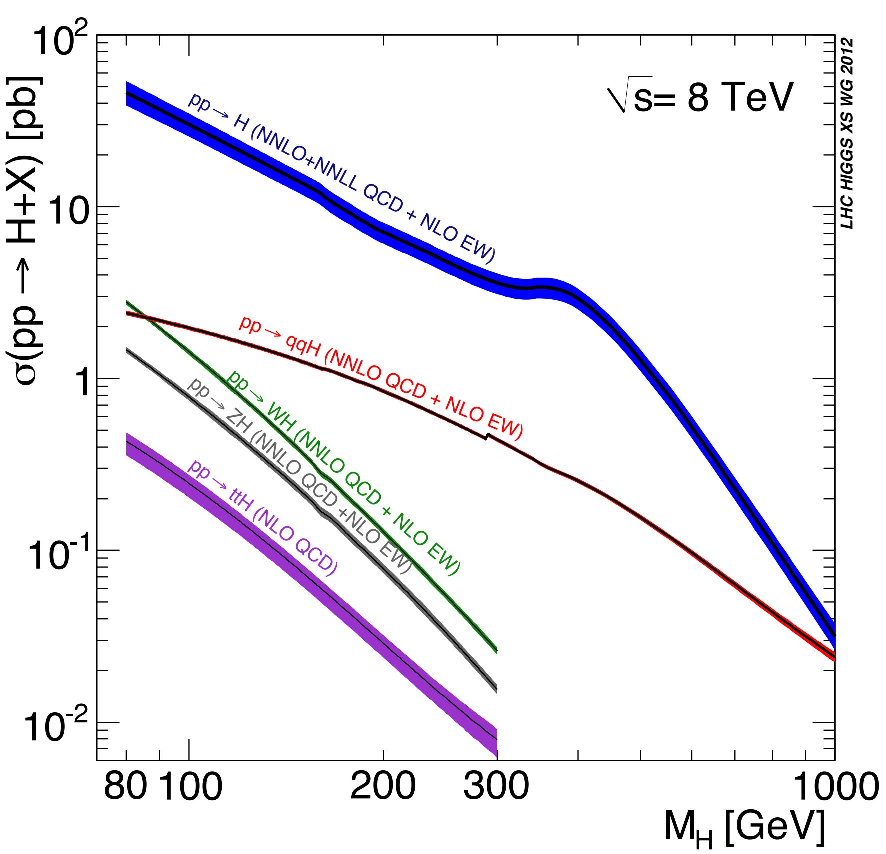
You can safely say that it (YR4) is the "heaviest Yellow Report" ever —digital versions have no weight ! (CERN Library)

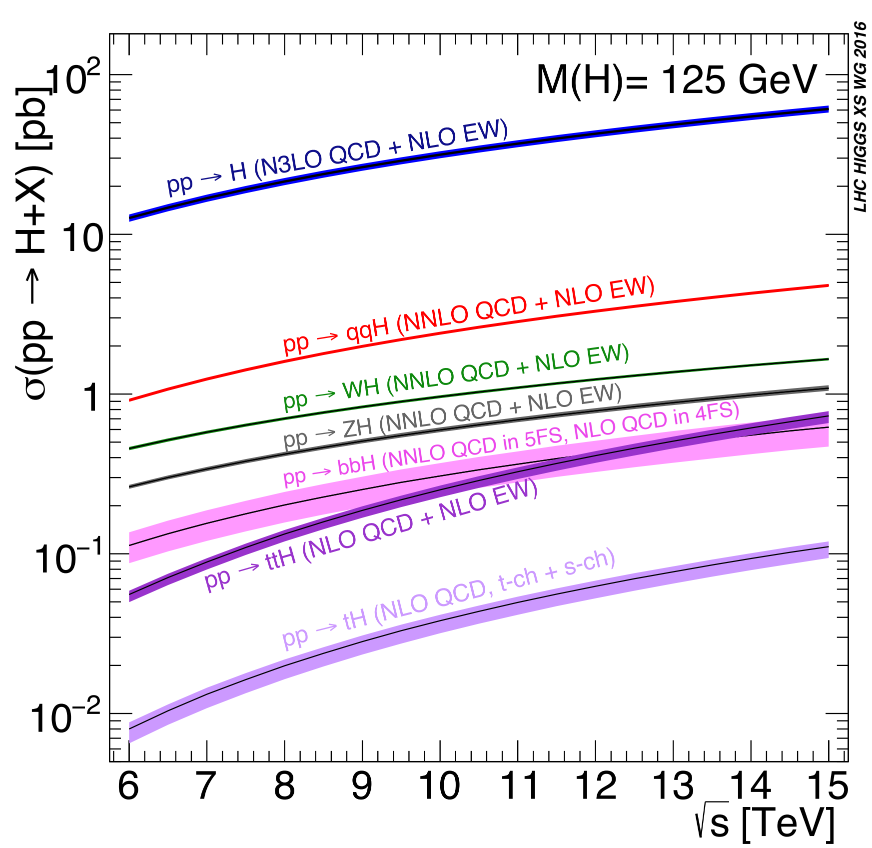
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

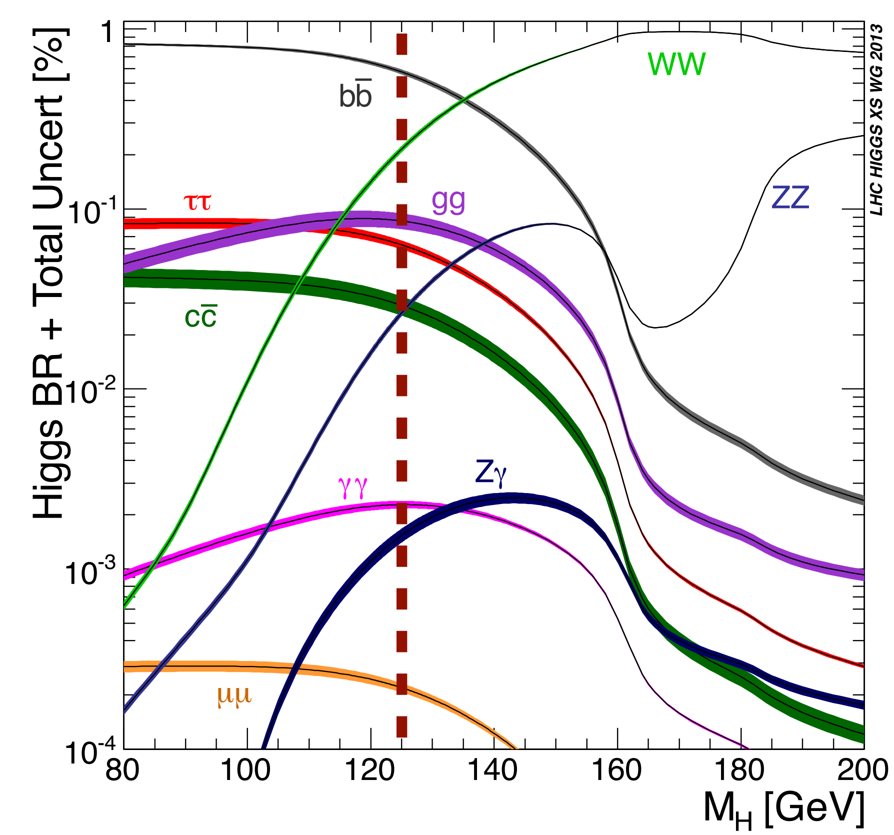
# Higgs boson production XS & decay BR

- State-of-the-art Higgs XS and BR predictions with estimated theory uncertainties
  - Common SM input parameters coordinated for calculation for different processes
  - Mostly NNLO QCD + NLO EW production cross section
    - N3LO for ggF (ATLAS and CMS adopted promptly)
  - $M_H$=125GeV was lucky to have many different decay channels

- ATLAS and CMS had common XS&BR numbers since Day-0 well before Higgs boson discovery when we did not know where it is.
- ~240k Higgs boson when Discovery, 9M in RUN-2, will produce 190M in HL-LHC (3 $ab^{-1}$)



New in CERN Report 4

# gg→H gluon-gluon fusion Cross Section

- First complete N3LO calculation at hadron collider ! [Anastasiou:2016cez]

| $\delta$(scale) | $\delta$(trunc) | $\delta$(PDF-TH) | $\delta$(EW) | $\delta(t,b,c)$ | $\delta(1/m_t)$ |
|---|---|---|---|---|---|
| $^{+0.10}_{-1.15}$ pb | ±0.18 pb | ±0.56 pb | ±0.49 pb | ±0.40 pb | ±0.49 pb |
| $^{+0.21\%}_{-2.37\%}$ | ±0.37% | ±1.16% | ±1% | ±0.83% | ±1% |

missing higher-orders; uncertainty from the soft expansion; missing N3LO PDFs; EW corrections; uncertainty from heavy-quark mass dependence; uncertainty in the 1/$m_t$ included corrections

13TeV, $M_H$=125GeV: cross section went up by +10%

$$\sigma = 48.58\,\text{pb}\,^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

- NNLO+NNLL: σ = 44.14 pb +7.6 -8.1% (QCD scale) ± 3.1% (PDF+$\alpha_s$)

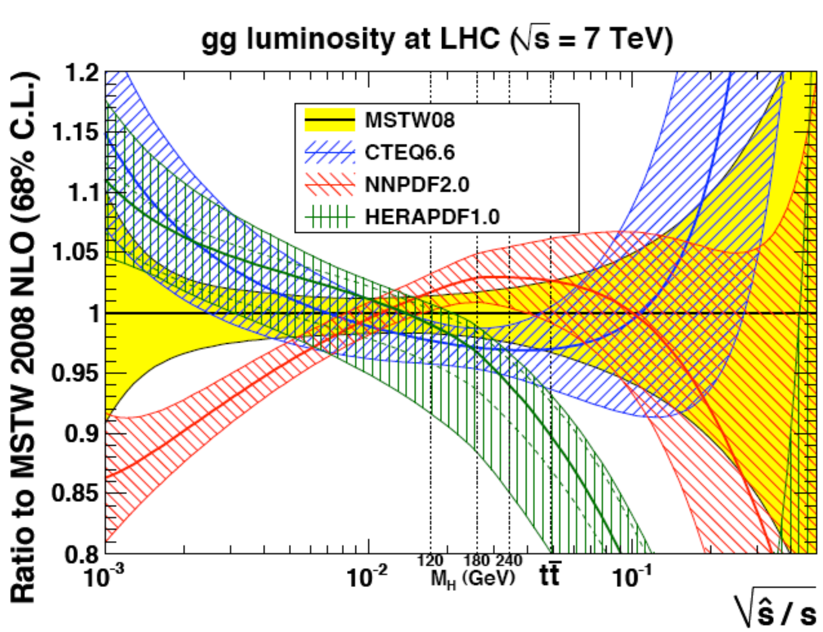
- Debates on TH QCD scale uncertainty treatment
  - **TH: use Flat uncertainty: [−6.7, +4.6]% @100% CL**
  - **EXP: use Gaussian uncertainty: max{neg,pos}/√3 = ±3.9% @67% CL**
    - Use this number for current workspace construction à la LHC-HCG prescription, "Procedure for the LHC Higgs boson search combination in Summer 2011", ATL-PHYS-PUB-2011-11 CMS NOTE-2011/005

$$\rho(\theta) = \frac{1}{\sqrt{2\pi}\ln(\kappa)} \exp\left(-\frac{(\ln(\theta/\tilde{\theta}))^2}{2(\ln\kappa)^2}\right)\frac{1}{\theta}$$

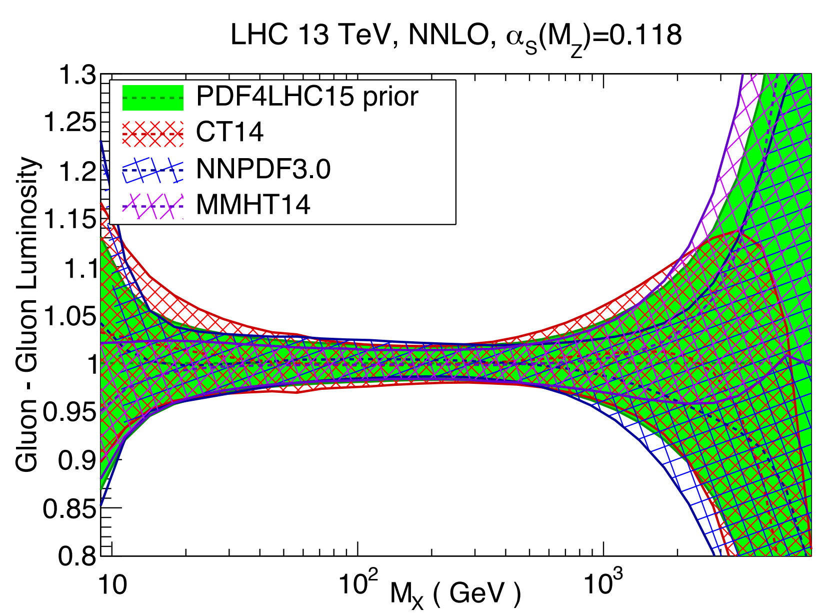
$\theta$=σ for κ=1

# Parton Distribution Functions (PDF)

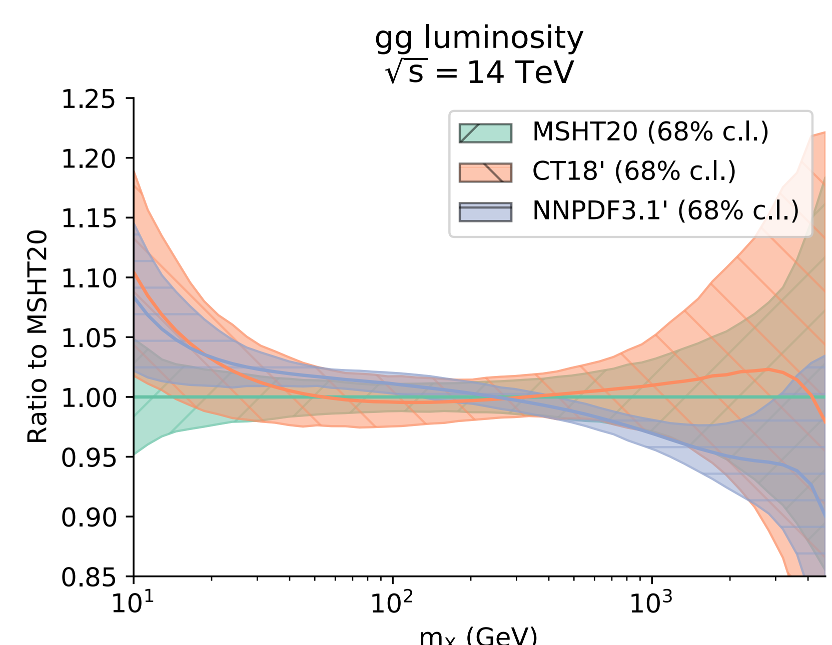
- **PDF4LHC** (arXiv:1101.0536, arXiv:1101.0538)
  - NLO PDF sets for Run-1: CT10, MSTW2008, NNPDF2.3
  - Uncertainty provided by the envelope of all three PDF sets and central prediction as mid-point.
- **PDF4LHC15** (J. Phys. G: Nucl. Part. Phys. 43 (2016) 023001)
  - NNLO PDF sets for Run-2: CT14, MMHT2014, NNPDF3.0
    - Alternative PDF sets: ABM12, CJ15, HERAPDF2.0, JR14 (richness of this field !)
  - Large improvements in PDF due to inclusion of LHC data and improvements in the fitting formalisms.
  - ggF PDF⊕$\alpha_s$ uncertainty at $\sqrt{s}$=14TeV for $M_H$=125GeV: +8-7% → ±3.2% (PDF ±1.9%, $\alpha_s$ ±2.6%)
  - Agreement in gg-parton luminosity was accidental.
- New **PDF4LHC21** (arXiv:2203.05506)
  - NNLO PDF sets for Run-3: CT18, MSHT20, NNPDF3.1
  - Good agreement between global PDF fits in both gg&qq-parton luminosities and reduction in uncertainties !




PDF4LHC (2011)




PDF4LHC15 (2015)




PDF4LHC21 (2022)

# Higgs boson decay width and branching ratio

Uncertainties in Branching Ratio (LHC-HCG)

1. Start with Higgs boson decay width
   $\Gamma_H = \Gamma^{\rm HDECAY} - \Gamma^{\rm HDECAY}_{WW} - \Gamma^{\rm HDECAY}_{ZZ} + \Gamma^{\rm Prophecy4f}_{4f}$
2. Categorize PU($\alpha_s$, $m_b$, $m_c$, $m_t$) and THU
   Separate treatment of PU($\Delta\alpha_s$, $\Delta m_q$) and THU
3. Convert to BR (correlations are taken into)
   Partial cancellation for H→bb,cc but not for gg !

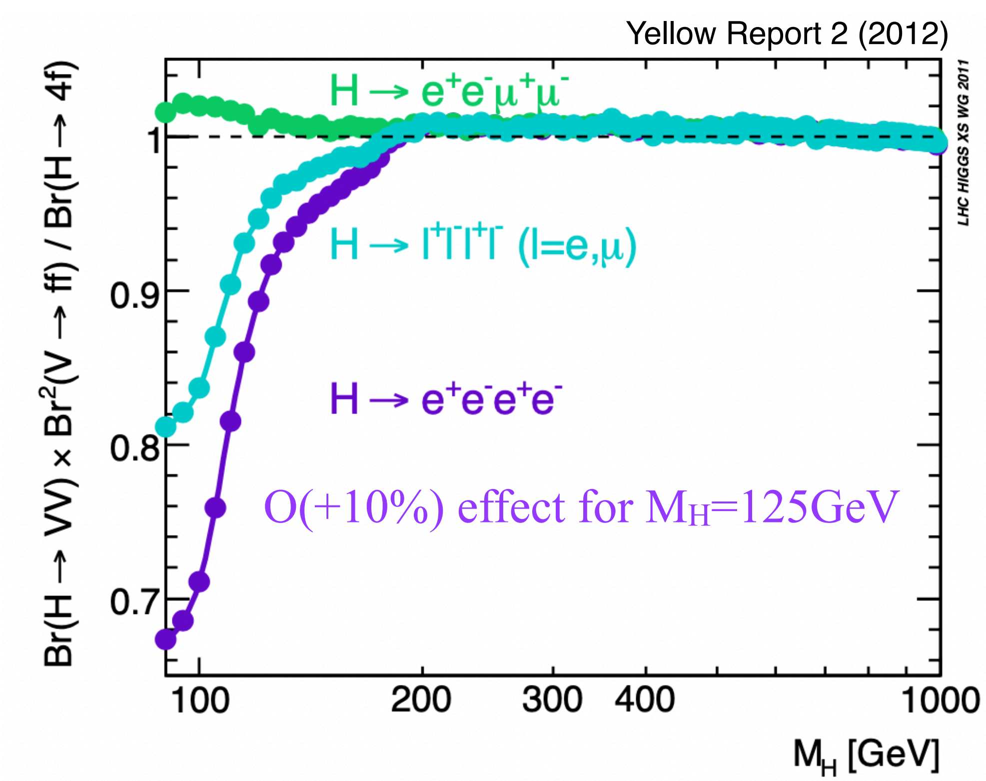
$$BR(H \to VV) = \frac{\Gamma_{VV}}{\Gamma_{\rm tot}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}} + \Gamma_{gg} + \Gamma_{VV}}$$

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

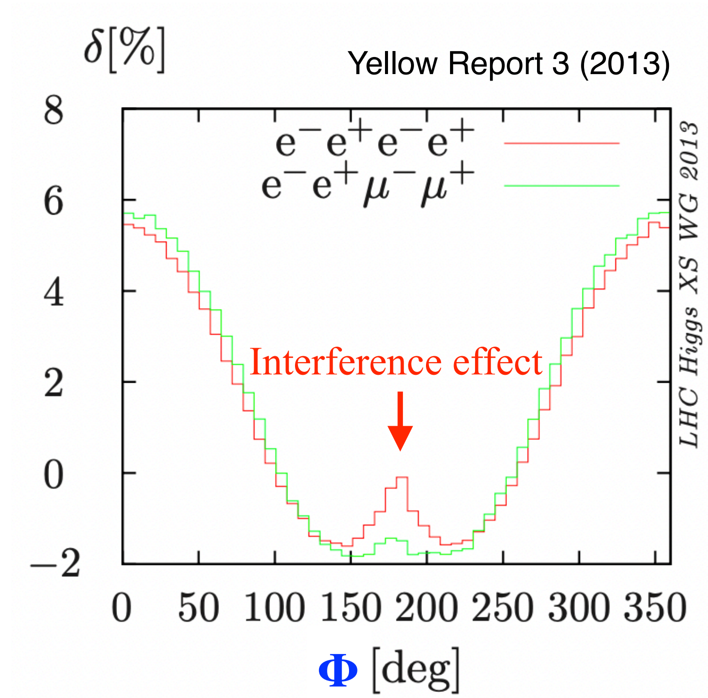
| $M_H$=126GeV | Decay width uncertainty | | | | |
|---|---|---|---|---|---|
| Decay | $\Delta\alpha_s$ | $\Delta m_b$ | $\Delta m_c$ | $\Delta m_t$ | THU |
| H→bb | ∓2.3% | ±3.3% | ±0.0% | ±0.0% | ±2.0% |
| H→cc | ∓7.1% | -0.1% | ±6.2% | ±0.1% | ±2.0% |
| H→ττ | ±0.0% | ±0.0% | ±0.0% | ±0.1% | ±2.0% |
| H→μμ | ±0.0% | ±0.0% | ±0.1% | ±0.1% | ±2.0% |
| H→gg | ±4.2% | -0.1% | ±0.0% | ∓0.2% | ±3.0% |
| H→γγ | ±0.0% | ±0.0% | ±0.0% | ±0.1% | ±1.0% |
| H→Zγ | ±0.0% | ±0.0% | ±0.1% | ±0.1% | ±5.0% |
| H→WW | ±0.0% | ±0.0% | ±0.0% | ±0.0% | ±0.5% |
| H→ZZ | ±0.0% | ±0.0% | ±0.0% | ±0.0% | ±0.5% |

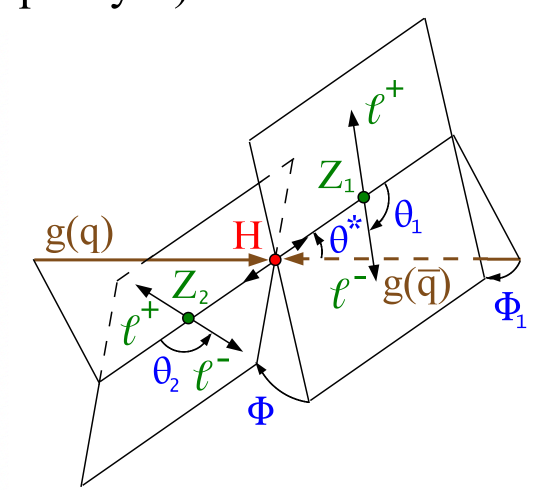
Precise H→4f BR estimation and Monte Carlo at NLO EW

Interference effect in H→ZZ*→$e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$




Precise H→4f Monte Carlo (Prophecy4f) at NLO EW




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

# Challenges beyond Yellow Report 4 - selected topics

## ggF

- N3LO differential distributions
- Reduction of ggF in VBF category
- Boosted Higgs XS

## STXS & Fiducial/Differential XS

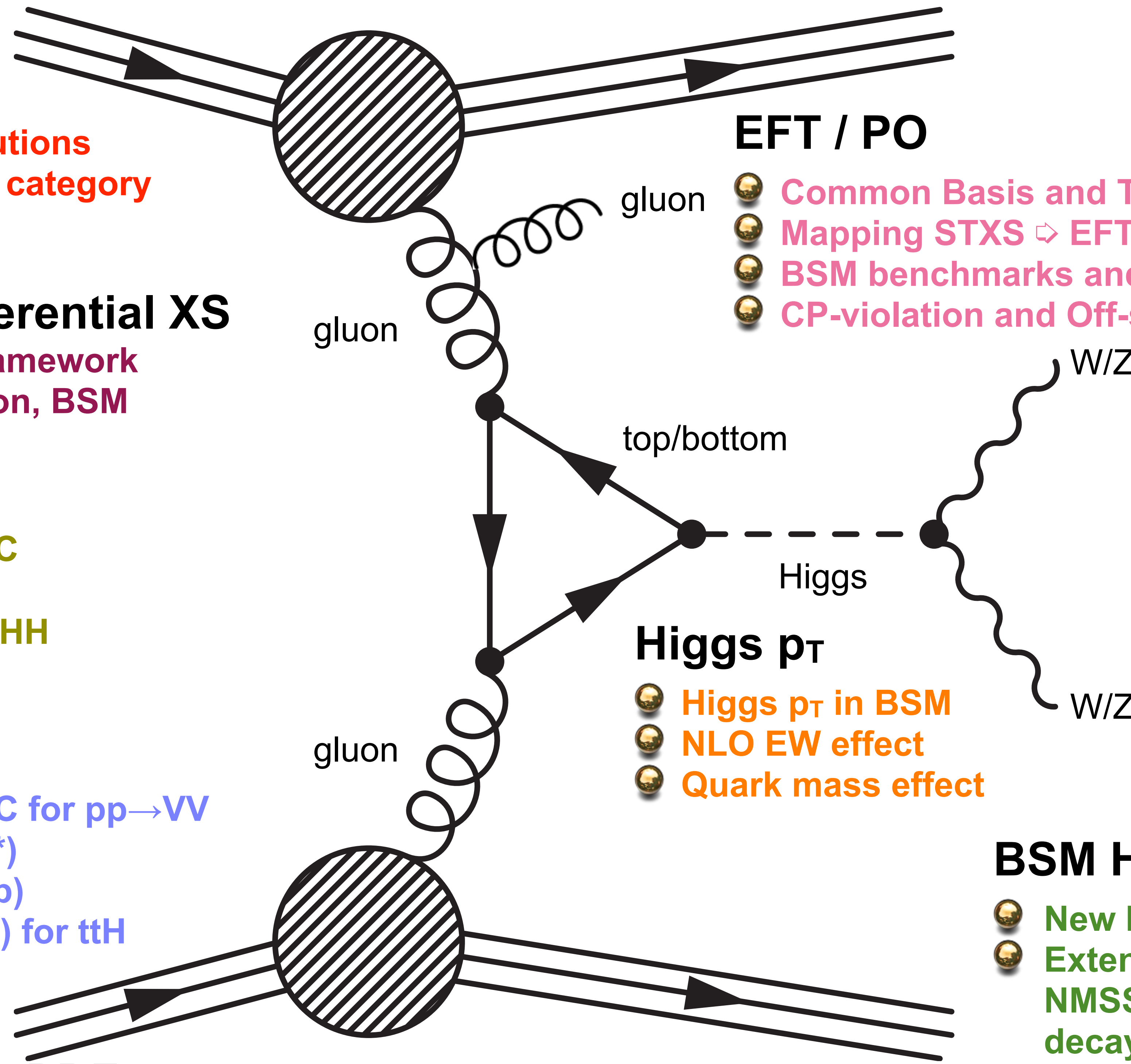
- Uncertainties in STXS framework
- STXS bins for CP-violation, BSM

## (N)NLO MC

- NNLO QCD + NLO EW MC
- $\Delta\phi_{jj}$ in H+2-jets MC
- NLO MC for gg→VV, ZH, HH
- PS Uncertainties

## SM Backgrounds

- NNLO QCD + NLO EW MC for pp→VV (include off-shell, ex Z*Z*)
- V+HF modeling for VH(bb)
- ttbar+V/HF+jets (ttbb, ttV) for ttH




## EFT / PO

- Common Basis and Tools development
- Mapping STXS ➪ EFT
- BSM benchmarks and interpretation
- CP-violation and Off-shell Higgs interpret.

## Higgs $p_T$

- Higgs $p_T$ in BSM
- NLO EW effect
- Quark mass effect

## BSM Higgs

- New benchmark scenario
- Extended Higgs, MSSM, NMSSM, Exotic Higgs decays, bbH/bH

## PDF

- N3LO PDF set for N3LO, missing higher-order correction
- Reduction of PDF (small/large-x) and $\alpha_s$ uncertainties
- Inclusion of EW corrections

# *Higgs signal-strength*

## LO κ-framework

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

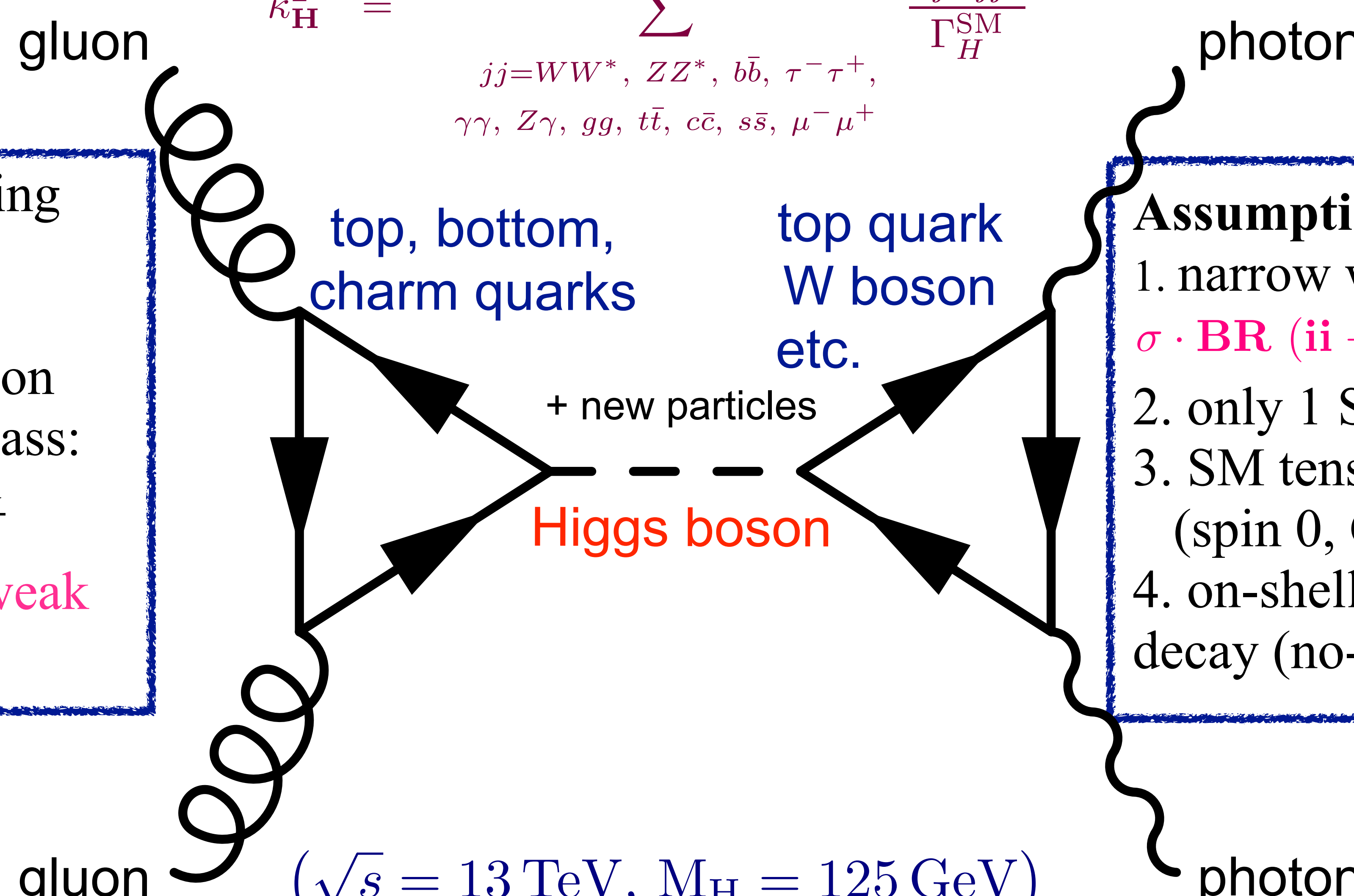
$$\mu = \frac{(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma)}{\{\sigma(gg \to \mathrm{H}) \cdot \mathrm{BR}(\mathrm{H} \to \gamma\gamma)\}_{\mathrm{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_\mathrm{H}^2}$$

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

- Measure with coupling scale factors $\kappa_i$.
- 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%).




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

**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).

$$\kappa_g^2(\kappa_t, \kappa_b, \kappa_c) = 1.040\kappa_t^2 + 0.002\kappa_b^2 + 0.00002\kappa_c^2 - 0.038\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0004\kappa_b\kappa_c$$

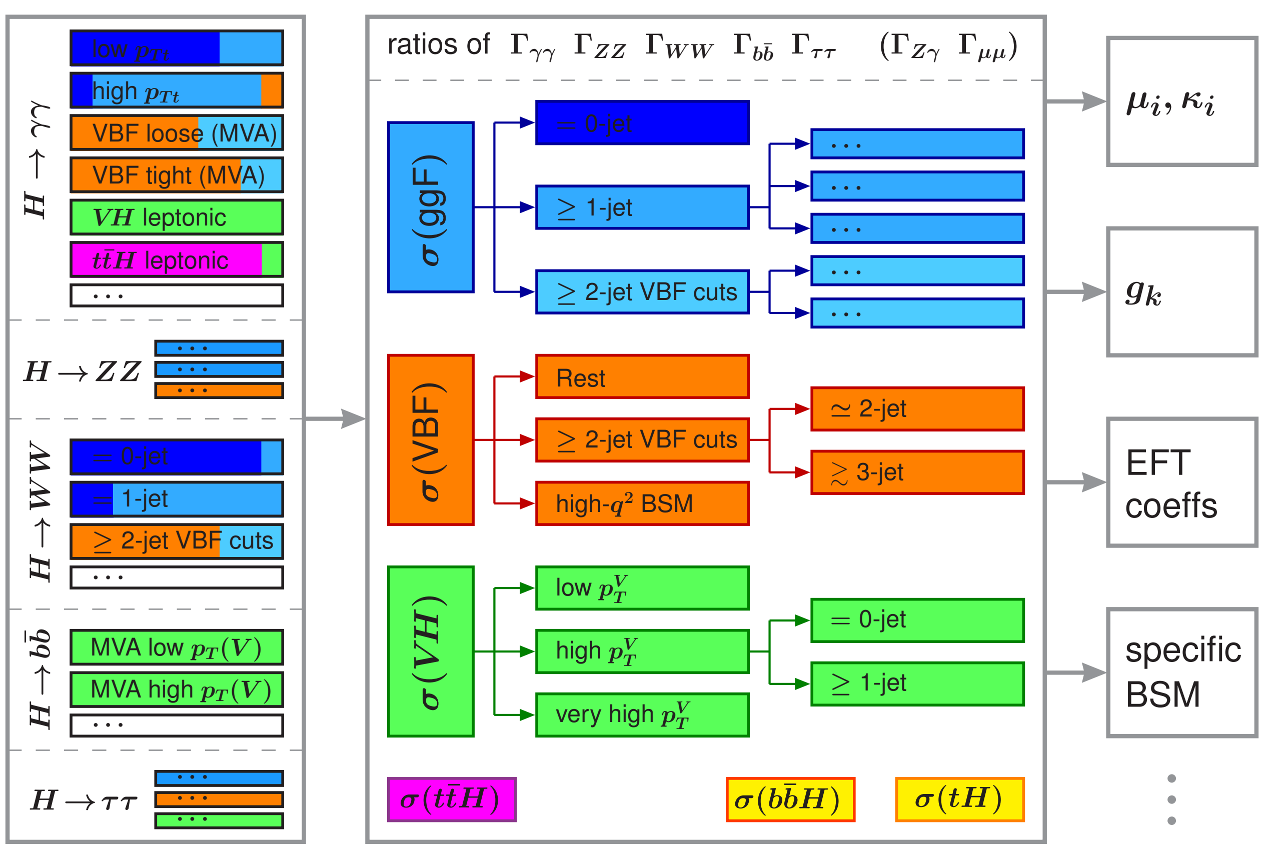
$$\kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

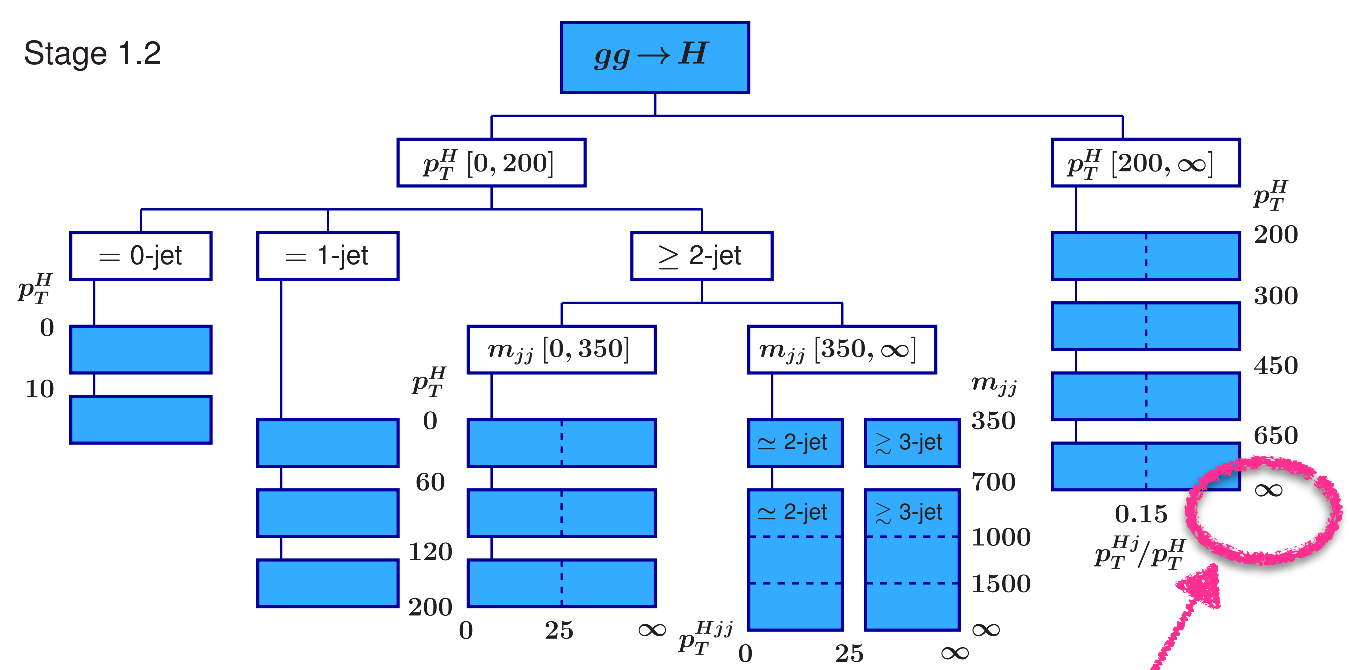
**Destructive interference in both gg→H (top-bottom) and H→γγ (W-top) loops.**

# Simplified Template Cross Section (STXS)

- Divide phase space into simplified "bins"
  - Maximise the measurement precision and the sensitivity to BSM contributions
  - Production cross sections times BR measured in mutually exclusive phase space regions
  - Based on production properties → allows combination of various decay modes
- Facilitates to compare/combine ATLAS+CMS results and to interpret theory models.
- Interpretation via Effective Field Theory (EFT)

- Fiducial Cross Section measurements in model-independent way.



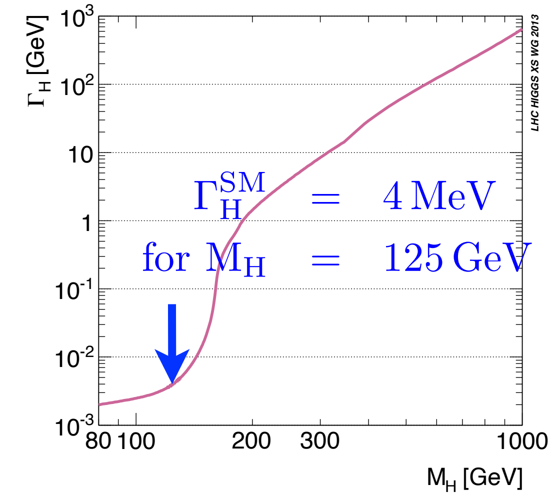

New physics might manifest itself in high pT bin.
Precise theory prediction needed.

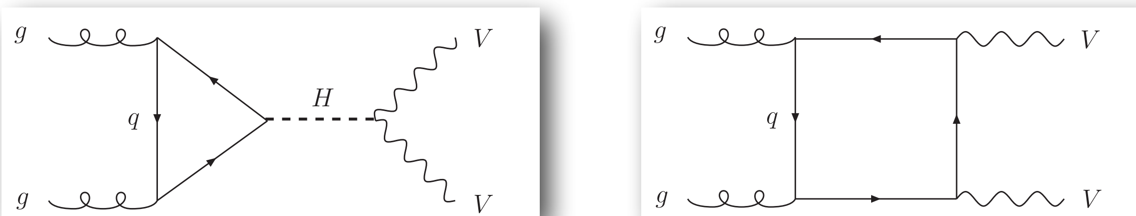
# Off-shell Higgs Boson Production and Interference

- Kauer-Passarino-Caola-Melnikov Effect
- Total gg→H→VV* receives an O(10%) off-shell correction
  - On-shell signal cross section is proportional to $1/\Gamma_H$
  - Off-shell signal cross section is independent of $\Gamma_H$
  - $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$ gives the information on $\Gamma_H$ !
- Negative signal-background interference effect

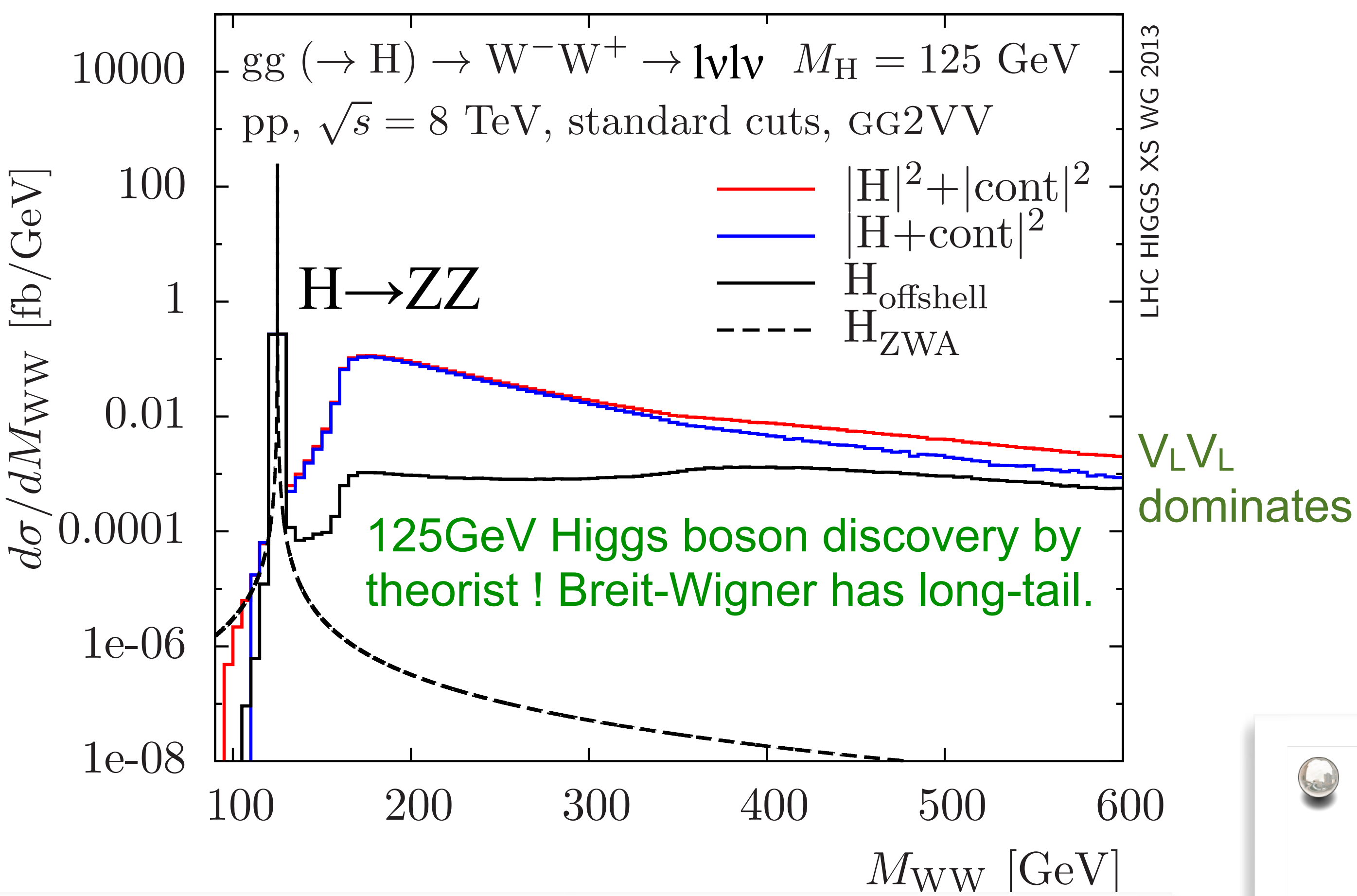
$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{Hgg}\, g^2_{HVV}}{m_H \Gamma_H}$$

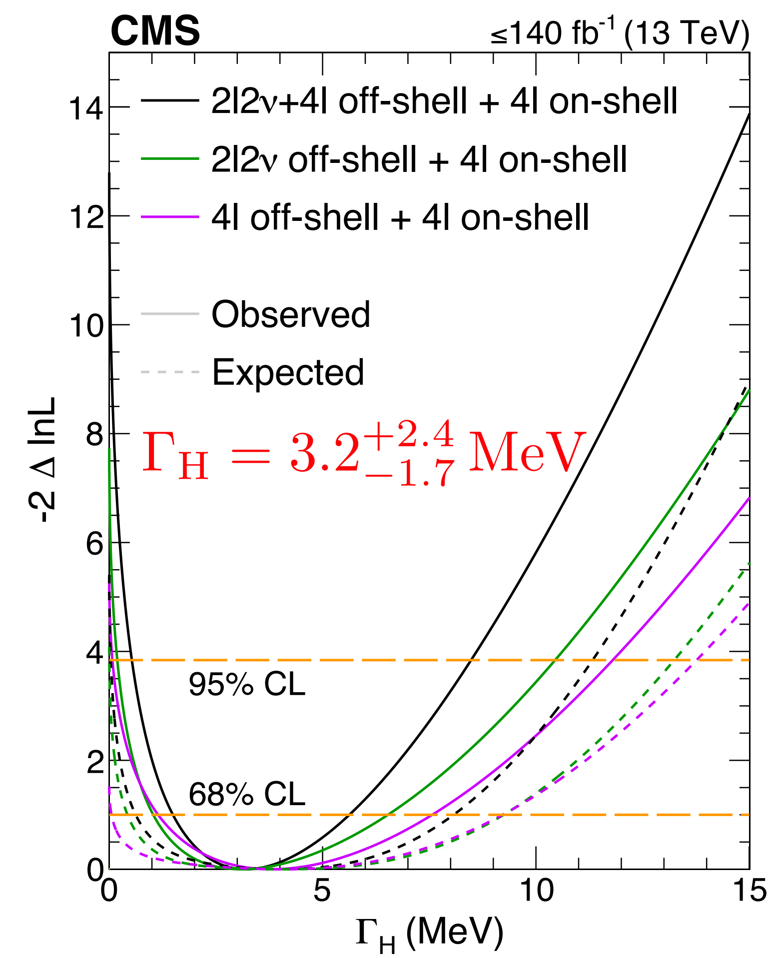
$$\sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{Hgg}\, g^2_{HVV}}{m^2_{VV}}$$




Yellow Report 3 (2013)




CMS-HIG-21-013

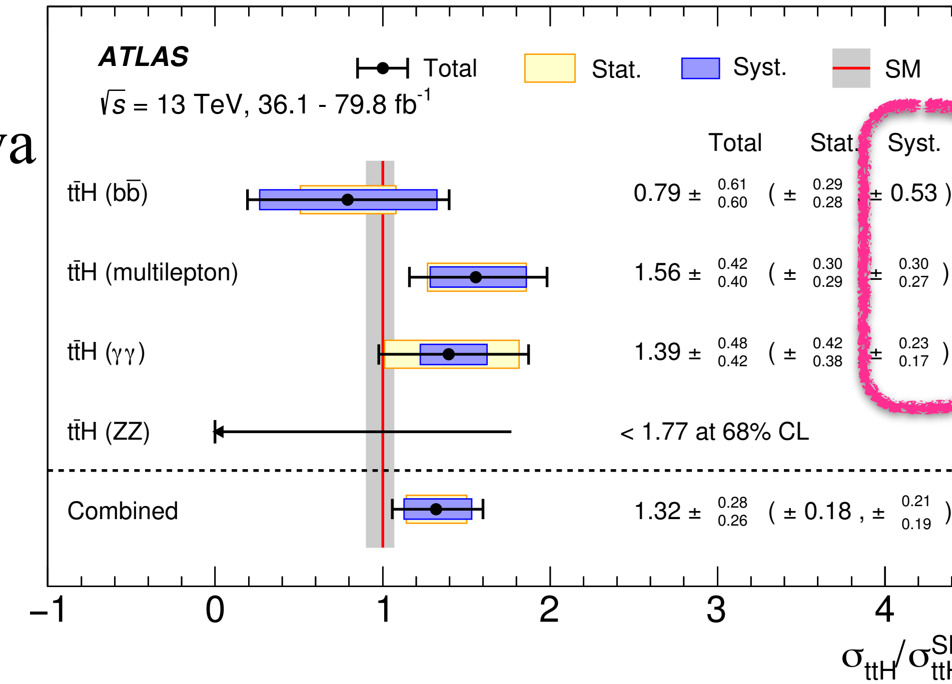
- Large theoretical uncertainties in kinematical distributions due to QCD, PDF and EW corrections of O(20-30%) at high-mass.

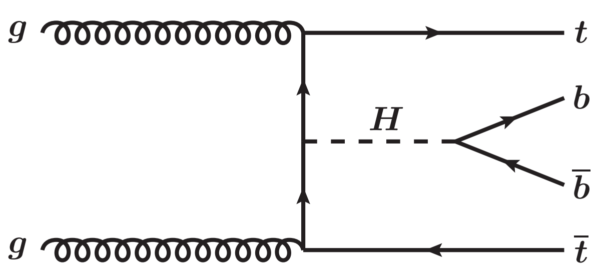
Off-shell Sensitive to new physics ⇨ EFT interpretation

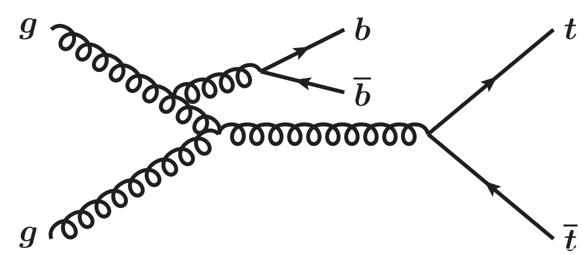
# ttH(H→bb)

- ttH is a very important channel to measure Higgs-Yukawa coupling, spin/CP
- Overwhelming and irreducible backgrounds
  - ttbb in ttH(H→bb)
  - ttW in ttH(multi-lepton)

ATLAS Phys. Lett. B784 (2018) 173




ATLAS arXiv:2111.06712

| Uncertainty source | $\Delta\mu$ | |
|---|---|---|
| Process modelling | | |
| $t\bar{t}H$ modelling | +0.13 | −0.05 |
| $t\bar{t}+\geq 1b$ modelling | | |
| $t\bar{t}+\geq 1b$ NLO matching | +0.21 | −0.20 |
| $t\bar{t}+\geq 1b$ fractions | +0.12 | −0.12 |
| $t\bar{t}+\geq 1b$ FSR | +0.10 | −0.11 |
| $t\bar{t}+\geq 1b$ PS & hadronisation | +0.09 | −0.08 |
| $t\bar{t}+\geq 1b$ $p_{T}^{bb}$ shape | +0.04 | −0.04 |
| $t\bar{t}+\geq 1b$ ISR | +0.04 | −0.04 |
| $t\bar{t}+\geq 1c$ modelling | +0.03 | −0.04 |
| $t\bar{t}+$light modelling | +0.03 | −0.03 |
| $tW$ modelling | +0.08 | −0.07 |
| Background-model statistical uncertainty | +0.04 | −0.05 |
| $b$-tagging efficiency and mis-tag rates | | |
| $b$-tagging efficiency | +0.03 | −0.02 |
| $c$-mis-tag rates | +0.03 | −0.03 |
| $l$-mis-tag rates | +0.02 | −0.02 |
| Jet energy scale and resolution | | |
| $b$-jet energy scale | +0.00 | −0.01 |
| Jet energy scale (flavour) | +0.01 | −0.01 |
| Jet energy scale (pile-up) | +0.00 | −0.01 |
| Jet energy scale (remaining) | +0.01 | −0.01 |
| Jet energy resolution | +0.02 | −0.02 |
| Luminosity | +0.01 | −0.00 |
| Other sources | +0.03 | −0.03 |
| Total systematic uncertainty | +0.30 | −0.28 |
| $t\bar{t}+\geq 1b$ normalisation | +0.04 | −0.07 |
| Total statistical uncertainty | +0.20 | −0.20 |
| Total uncertainty | +0.36 | −0.34 |

- Uncertainty in tt + ≥1b modeling:
  - NLO matching, b-fractions, FSR, PS & Hadronisation, etc.
- ttbb process is theoretically challenging for correct modeling
  - Traditionally in 5FS, recently moving towards 4FS
  - Significant differences among existing theory predictions
- ATLAS+CMS joint efforts in LHC Higgs WG
  - Adopt common ttbb treatment
  - In view of a full Run 2 ttH(H→bb) combination

# *Tools for Higgs Analysis*

**ggF**
- iHixs (N3LO QCD+NLO EW)
- HIGLU (NNLO QCD+NLO EW)
- FeHiPro (NNLO QCD+NLO EW)
- HNNLO, HRes (NNLO+NNLL QCD)
- RGHiggs (NNLO+NNNLL QCD)
- SusHi, aMCSusHi (N3LO/NLO QCD)
- ggHiggs (N3LO QCD)
- TROLL (N3LL' QCD)

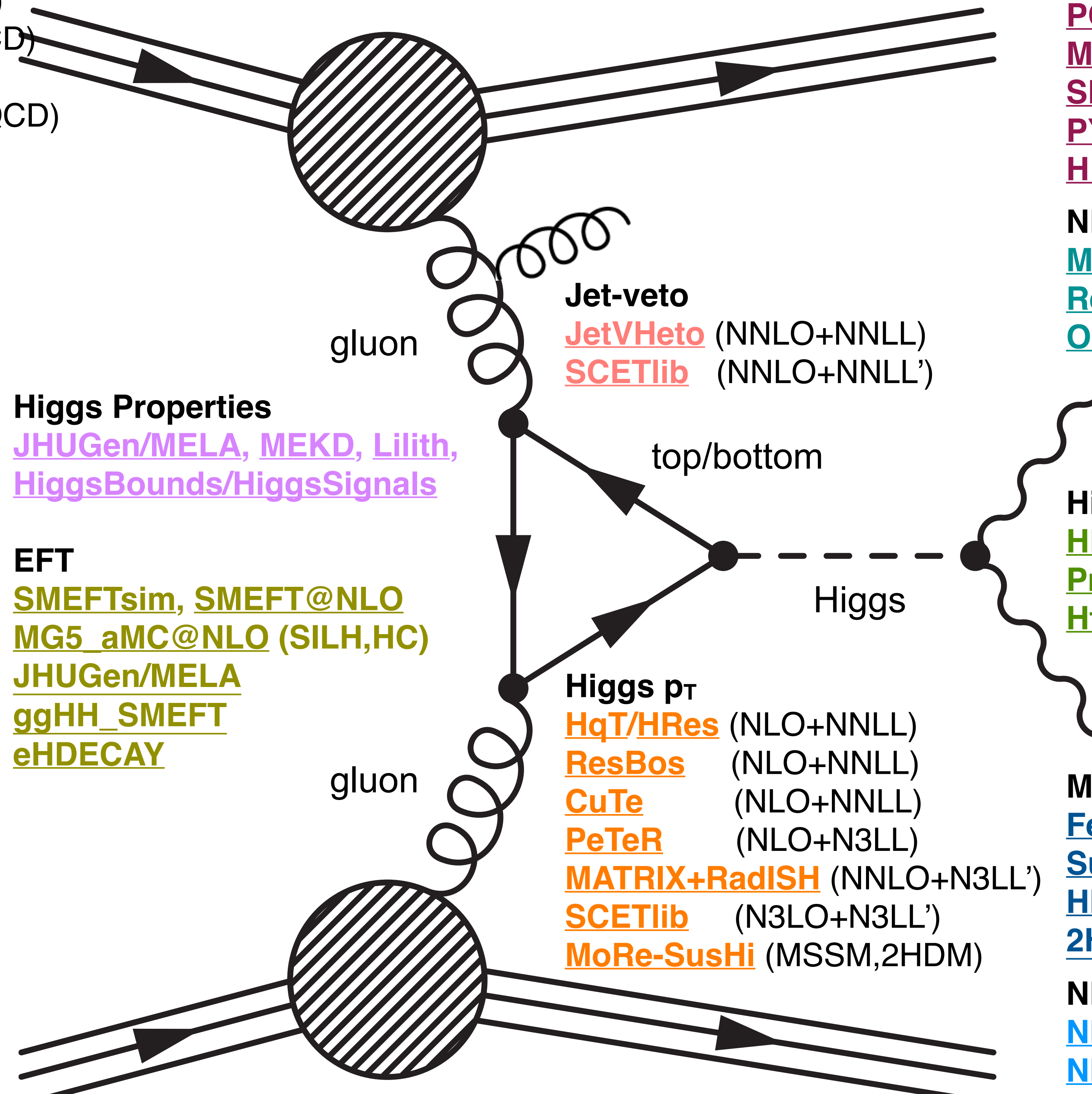
**VBF**
- VV2H (NLO QCD)
- VBFNLO (NLO QCD)
- HAWK (NLO QCD+EW)
- VBF@NNLO (NNLO QCD)
- HJets (NLO QCD)
- proVBFH (NNLO QCD)

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

**ttH**
- HQQ (LO QCD)
- POWHEL (NLO QCD)

**bbH**
- bbh@NNLO (NNLO QCD)
- bbhFONLL (NLO+NNLL QCD)
- bbX (NLO+NNLL QCD)

**HH**
- HPAIR (NLO QCD)
- ggHH (NLO QCD)
- proVBFHH (NNLO QCD)




**Jet-veto**
- JetVHeto (NNLO+NNLL)
- SCETlib (NNLO+NNLL')

**Higgs Properties**
JHUGen/MELA, MEKD, Lilith, HiggsBounds/HiggsSignals

**EFT**
- SMEFTsim, SMEFT@NLO
- MG5_aMC@NLO (SILH,HC)
- JHUGen/MELA
- ggHH_SMEFT
- eHDECAY

**Higgs $p_T$**
- HqT/HRes (NLO+NNLL)
- ResBos (NLO+NNLL)
- CuTe (NLO+NNLL)
- PeTeR (NLO+N3LL)
- MATRIX+RadISH (NNLO+N3LL')
- SCETlib (N3LO+N3LL')
- MoRe-SusHi (MSSM,2HDM)

**PDF:** MMHT/MSHT, CTEQ, NNPDF, EKO, xFitter, PDF4LHC, ... METAPDF, LHAPDF, HOPPET, APFEL

**SM:** MCFM, MATRIX. MG5_aMC@NLO, VVamp, gg2VV, DiffTop, ...

**NNLO+PS MC**
- NNLOPS (MiNLO'+reweighting)
- MiNNLO
- GenEvA

**NLO+PS MC (Multi-purpose)**
- POWHEG-BOX
- MadGraph5_aMC@NLO
- SHERPA MEPS@NLO
- PYTHIA8 UNLOPS
- HERWIG7 Matchbox

**NLO ME/Automated NLO**
MCFM, MG5_aMC@NLO, Recola, GoSam, HELAC, OpenLoops, BlackHat, etc.

**Higgs Decay**
- HDECAY (NLO++)
- Prophecy4f (NLO QCD+EW)
- Hto4l (NLO QCD+EW)

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

**NMSSM**
NMSSMCALC (EW), NMSSMTools, FlexibleSUSY, SOFTSUSY, SPheno

+ many codes for BSM physics

Clickable Link (July 4th 2022) Complaints to R. Tanaka

# Summary and Prospects

- Thee LHC Higgs Cross Section Working Group brought together the TH and EXP communities working on the Higgs physics.
  - Enabled the success for fruitful collaboration between EXP and TH.
  - The LHC Higgs Cross Section Working Group provided the state-of-the-art Higgs XS&BR since the beginning.
  - Enabled early determination of the nature of "Higgs-like" particle.
  - Attempts were made for proper theory paper citation as it is fundamental (managed by ATLAS&CMS).

The LHC Higgs Combination Group (ATLAS+CMS)
"Procedure for the LHC Higgs boson search combination in Summer 2011"
ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005

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We would like to thank the ATLAS statistics forum and CMS statistics committee for their extremely valuable and continuous feedback and for the guiding suggestions and corrections. We would like to acknowledge the role of the LHC Higgs Cross Section group that helped settle a number of non-trivial questions on correlations of theoretical errors for exclusive final states of Higgs boson production in association with jets. The prompt response of the group on the request to produce SM Higgs boson production cross sections and branching ratios for the fine grid of Higgs boson mass points needed for the combination was simply spectacular. We would also like to thank the ATLAS and CMS Higgs working groups for their close involvement in the overall effort and for preparing analysis Workspaces for performing technical exercises as reported in this document.

- Collaboration between EXP and TH is even more necessary now to find any hints for BSM physics.
  - Restarting the construction of a common language, silence of nature is only a pause.


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