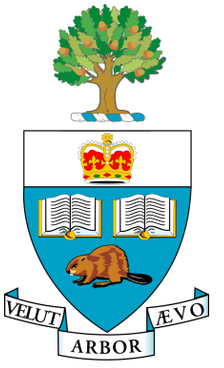


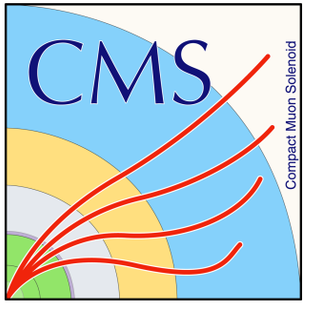
Status of the LHC Higgs Cross Section Working Group

Pierre Savard

University of Toronto and TRIUMF

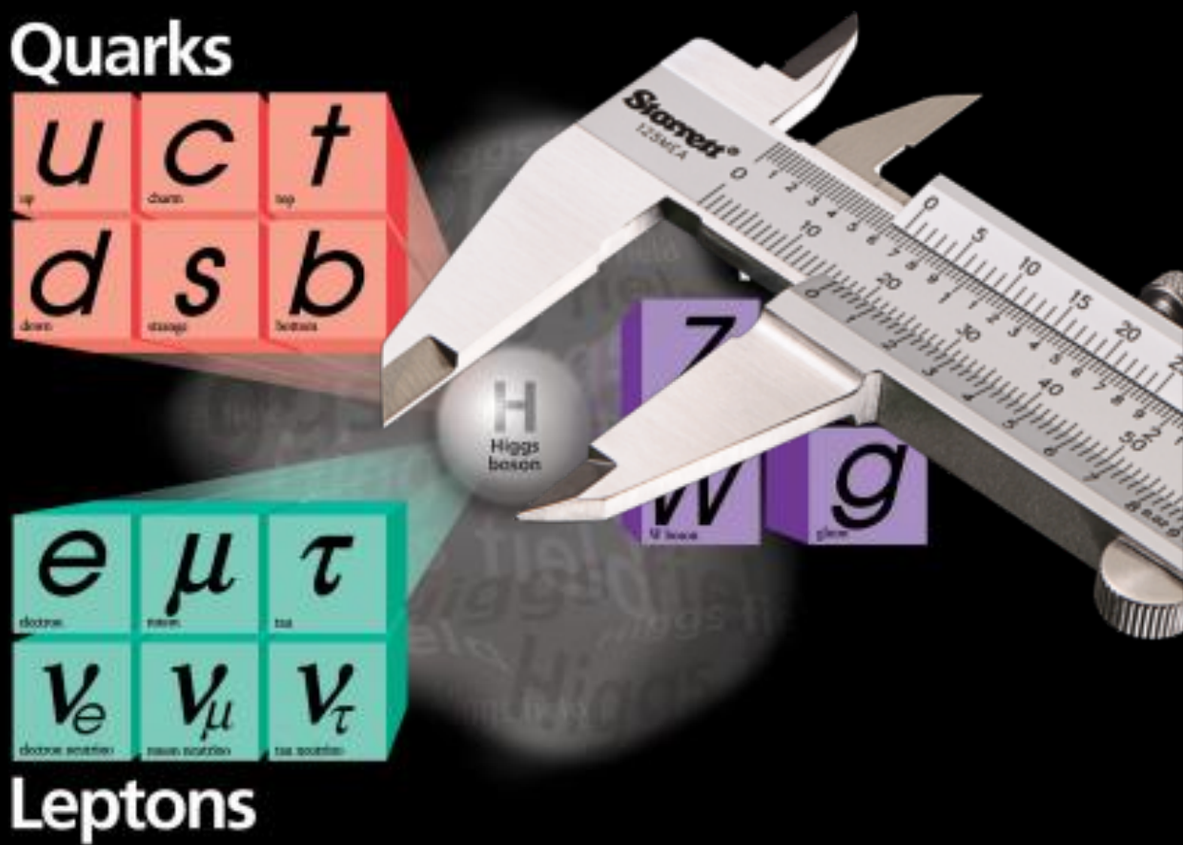
Higgs Days is Santander

19 September 2016



Outline

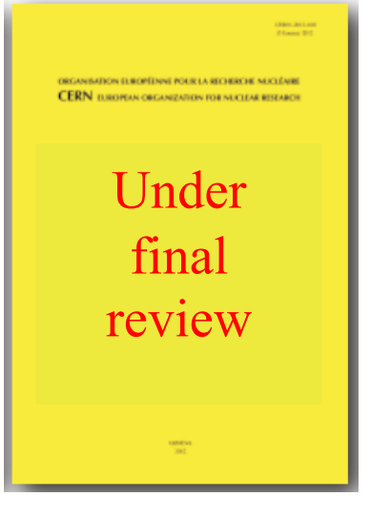
- Introduction
- Summary of YR4
  - Inputs
  - PDFs
  - Branching Ratios
  - ggF
  - VBF/VH
  - TTH/TH
  - Properties, POs, EFTs
  - BSM
- Next Steps
- Conclusions



Introduction

Yellow Report 4 “Deciphering the Nature of the Higgs Sector” is under final review

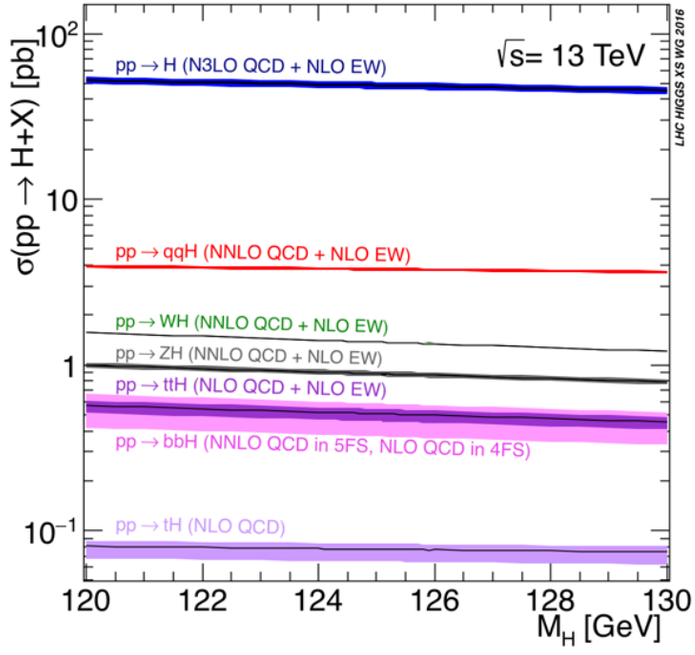
- A big effort:
  - Covers:
    - SM production and decays
    - Higgs properties
    - BSM Higgs
  - 3 years after YR3
  - 869 pages, 248 tables, 292 figures, 1636 citations
  - Please read and post comments:
    - Link: https://cds.cern.ch/record/2215893
    - Deadline: Friday Sept 30th
- Previous Yellow Reports
  - Inclusive Observables (2011, ~150pp)
  - Differential Distributions (2012, ~275pp)
  - Higgs Properties (2013, ~400pp)

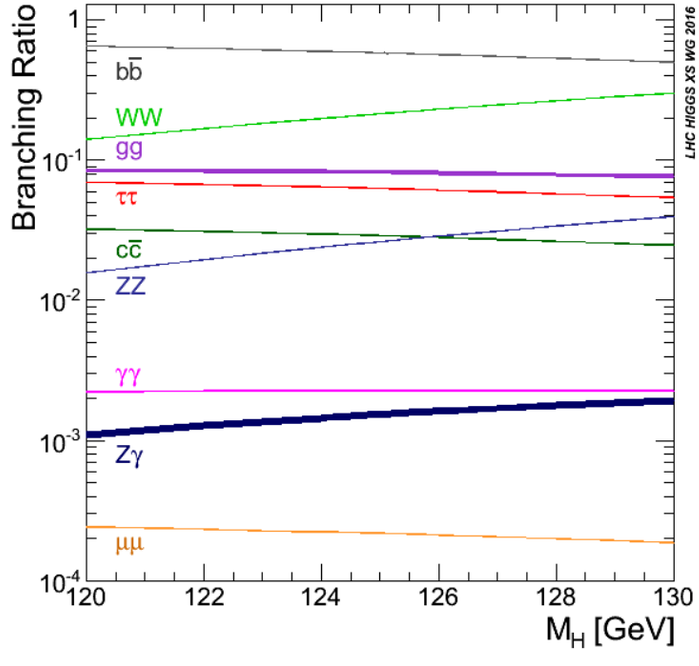


Introduction

The LHC Higgs XS WG undergoing an important transition:

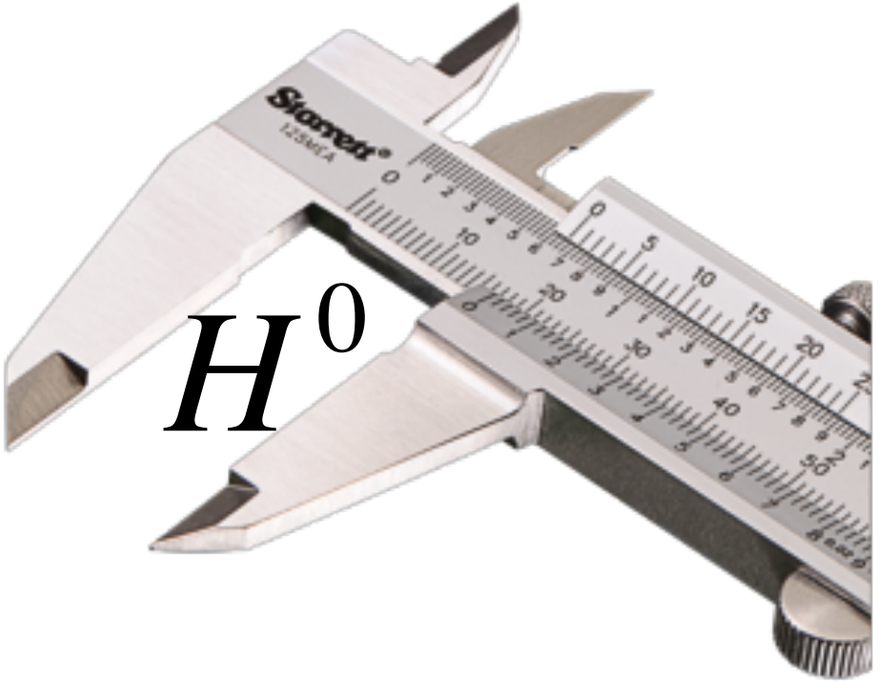
- Yellow Report 4 is going out. Solid foundation for first "high stats" Run 2 papers
- Run 2 is off to a good start:
  - We will have ~35 fb-1 of data at 13 TeV this year
  - By the end of Run 2 (in 2 years, we should have ~>120 fb-1
- First papers with full 2016 dataset will be coming out in Spring and Summer
  - Focus the group on shorter term tasks to address issues associated with 2016 dataset papers
  - Plan for the medium term: determine what we need to best exploit the full Run 2 dataset
  - Plan for the long term: Run 3 and HL-LHC





SM Higgs boson Physics

SM and interpretations under WG1 and WG2



- Main inputs for couplings (σ*BR):
  - Main production modes
    - ggH, WH, ZH, VBF, ttH
  - Main decay modes:
    - $\gamma\gamma$, WW, ZZ, tt, bb
- Fiducial and differential measurements
- Interpret measurements above
  - Kappa framework, CP-mixing, EFT
- Rare production modes:
  - tH, hh, bbH
- Rare Decay modes:
  - $\mu\mu$, $Z\gamma$, $J/\psi\ \gamma$
- Width
  - Direct, off-shell couplings, interference, lifetime
- Precision mass measurements

YR4 Inputs (and Outputs)

SM input parameters:

e	μ	τ
0.510998928(11) MeV	105.6583715(35) MeV	1776.82(16) MeV
u	c	t
100 MeV	0.986 ± 0.026 GeV	172.5 ± 1.0 GeV
d	s	b
100 MeV	100 MeV	4.18 ± 0.03 GeV

$$\alpha_s(m_Z) = 0.118 \pm 0.0015$$

W	M_W	Γ_W
	80.385(15) GeV	2.085(42) GeV
Z	M_Z	Γ_Z
	91.1876(21) GeV	2.4952(23) GeV

a. The top-quark mass is on-shell top-quark mass M_t^{OS}. Corresponding MS-bar mass is $M_t^{MS}(M_t)$=162.7±1.0 GeV.

b. The bottom-quark mass is MS-bar bottom-quark mass $M_b^{MS}(M_b)$. Corresponding on-shell mass is M_b^{OS}=4.92±0.13 GeV.

c. The charm-quark mass is evaluated at M_c(3 GeV). On-shell charm-quark mass is M_c^{OS}=1.51±0.13 GeV.

Output (theory uncertainties)

- **XS ±Scale Uncertainty [%] ±THU [%] ±PU(quark-mass) [%] ±PU(α_s) [%] ±PDF Uncertainty [%]**
- **BR ±THU [%] ±PU(quark-mass) [%] ±PU(α_s) [%]**

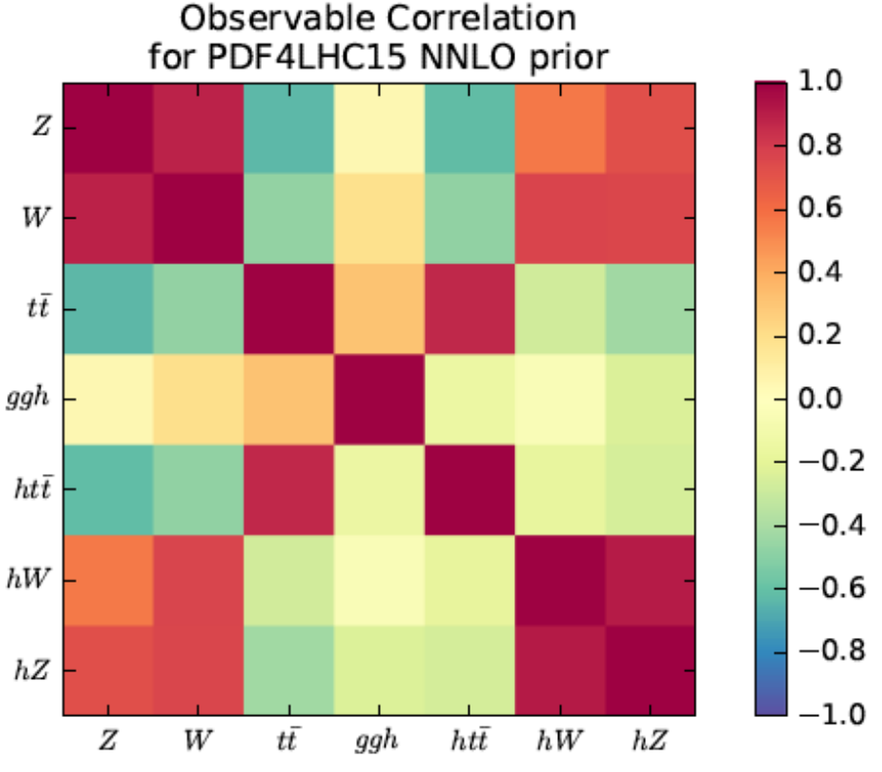
Correlate PUs between Higgs production and decays and PDFs between signal production modes and backgrounds

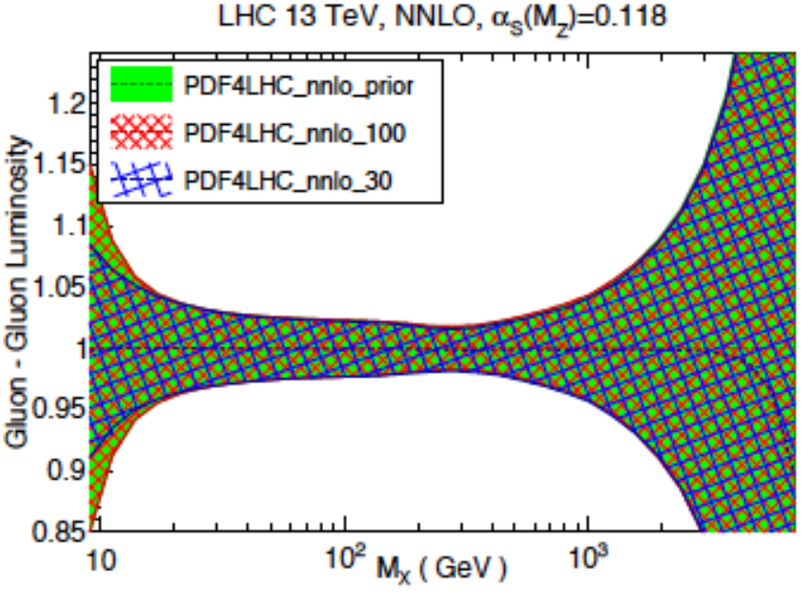
PDFs

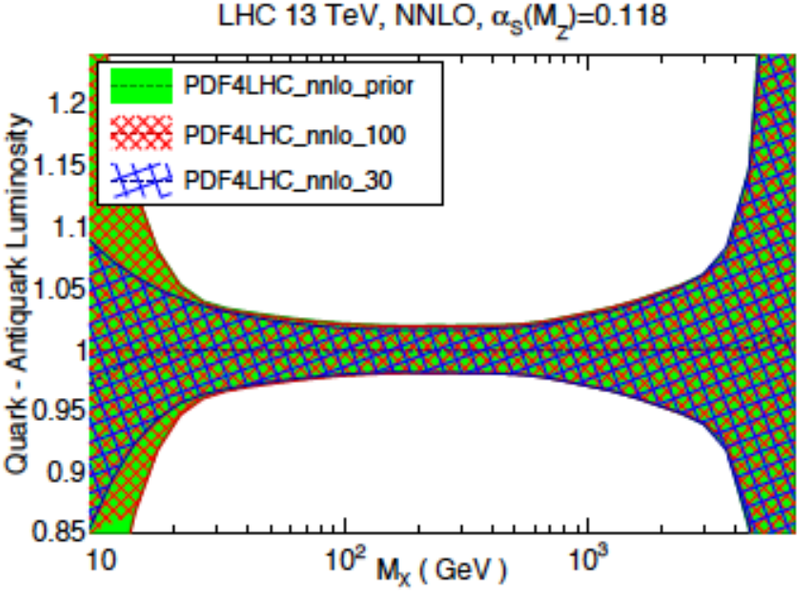
PDF4LHC recommendations:

SM Higgs PDF4LHC15_100 set
BSM Higgs PDF4LHC15_mc set

Updated correlations







From (F. Caola, Higgs Hunting)

Charting the progress

Process	~ 15 y ago	Now	What we want
ggH	towards N^3LO_{inc}	N^3LO_{inc}, NNLOPS, NNLL	N^3LO(PS) *+small details*
VBF	NLO	N^3LO_{inc}, NNLO	N^3LO
VH	NLO	NNLO	gg→VH@NLO
ttH	LO	NLO	NNLO?
Hj	NLO	NNLO	mass effects
Hjj	LO	NLO	NNLO
pp→γγ	NLO	NNLO+gg@NLO	//
pp→VV	NLO	NNLO+gg@NLO	gg@NLO massive

- Many of the desiderata require significant theory improvements
- Nevertheless, given the trend: Far From Impossible
- Quite remarkable precision Already Now

ggH

NNNLO calculation:

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

$$\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c)\text{, exact NLO}) \\
& +\ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO, } 1/m_t) \\
& +\ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& +\ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

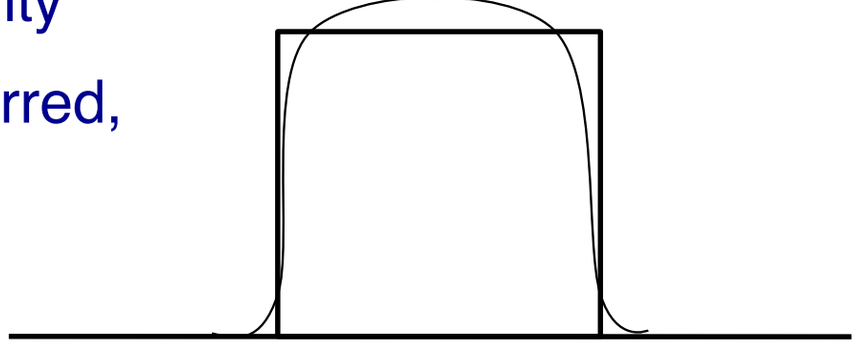
Discussion on the uncertainty, two scenarios:

F-uncertainty: $[-6.7, +4.6]\%$ corresponding to $[-3.3, +2.2]$ pb
G-uncertainty: $\pm 4.5\%$ corresponding to ± 2.2 pb

Current recommendation is to use flat uncertainty

In cases where a Gaussian uncertainty is preferred,
Use 2*max(pos,neg)/sqrt(12): $\Delta_{\text{th}} = \pm 3.9\%.$

Should try to be consistent in calculations



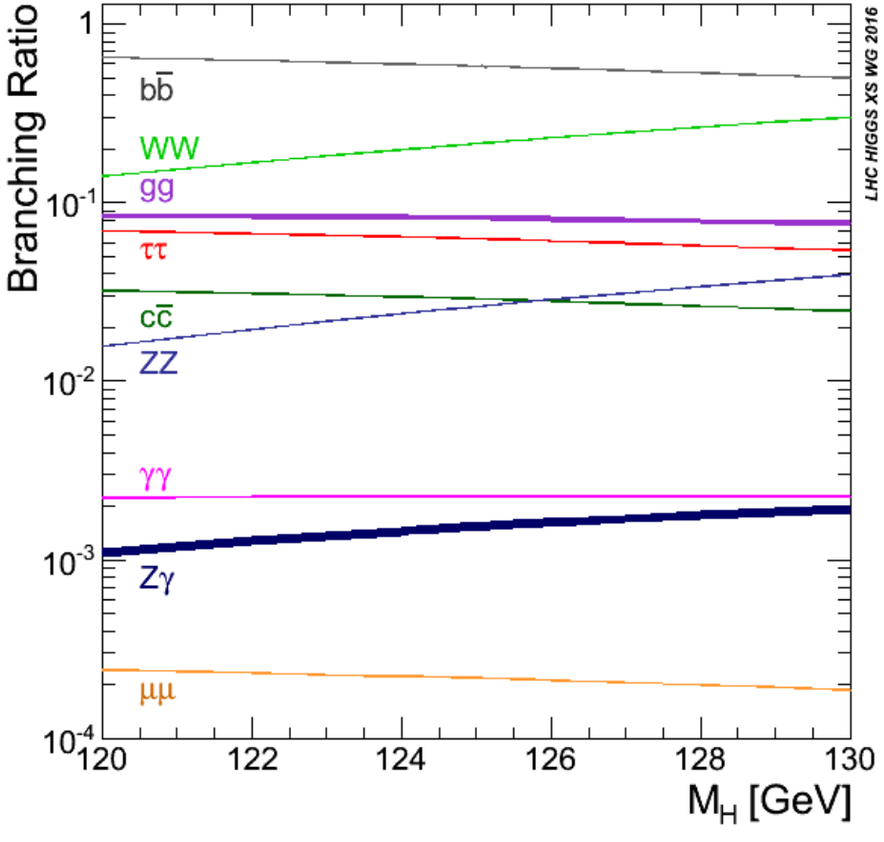
Branching Ratios

Setup unchanged: HDECAY and Prophecy4f to calculate the Higgs partial widths at the highest accuracy

$$\Gamma_H = \Gamma^{HDECAY} - \Gamma^{HDECAY}_{ZZ} - \Gamma^{HDECAY}_{WW} + \Gamma^{Prophecy4f}_{4f}$$

New in YR4:

- Improvements in HDECAY (NLO EW corrections for H→fermions, MSbar scheme for quark masses)
- Input parameters (α_S, mb, mc, mt) revisited
- Updated theoretical uncertainties



- BR central values are well within the YR3 error estimates
- Uncertainties reduced considerably

Branching Ratios

From Daniela Rebuzzi:

- Full EW NLO corrections now included in HDECAY

Old - YR3

Process	Uncertainty	Total
$H \to bb/cc$	QCD 0.1-0.2%	1-2%
	EW 1-2% for $M_H \leq 135$ GeV	
$H \to \tau\tau$	EW 1-2%	1-2%
$H \to WW/ZZ \to 4f$	EW 0.5% for M_H <500 GeV	0.5-15%
	$\sim 0.17 \cdot (M_H/1\ \text{TeV})^4$ for $M_H > 500$ GeV	
$H \to t\bar{t}$	QCD $\leq$ 5% (only NLO mass effects)	5-10%
	EW $\sim$ 2% for $M_H < 500$ GeV	
	$\sim 0.1 \cdot (M_H/1\ \text{TeV})^4$ for $M_H > 500$ GeV	
$H \to gg$	QCD $\sim$ 10% (only NNLO included in HDECAY)	$\sim$ 10%
	EW $\sim$ 1%	
$H \to \gamma\gamma$	QCD+EW $\sim$ 1%	$\sim$ 1%

New - YR4

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

VBF

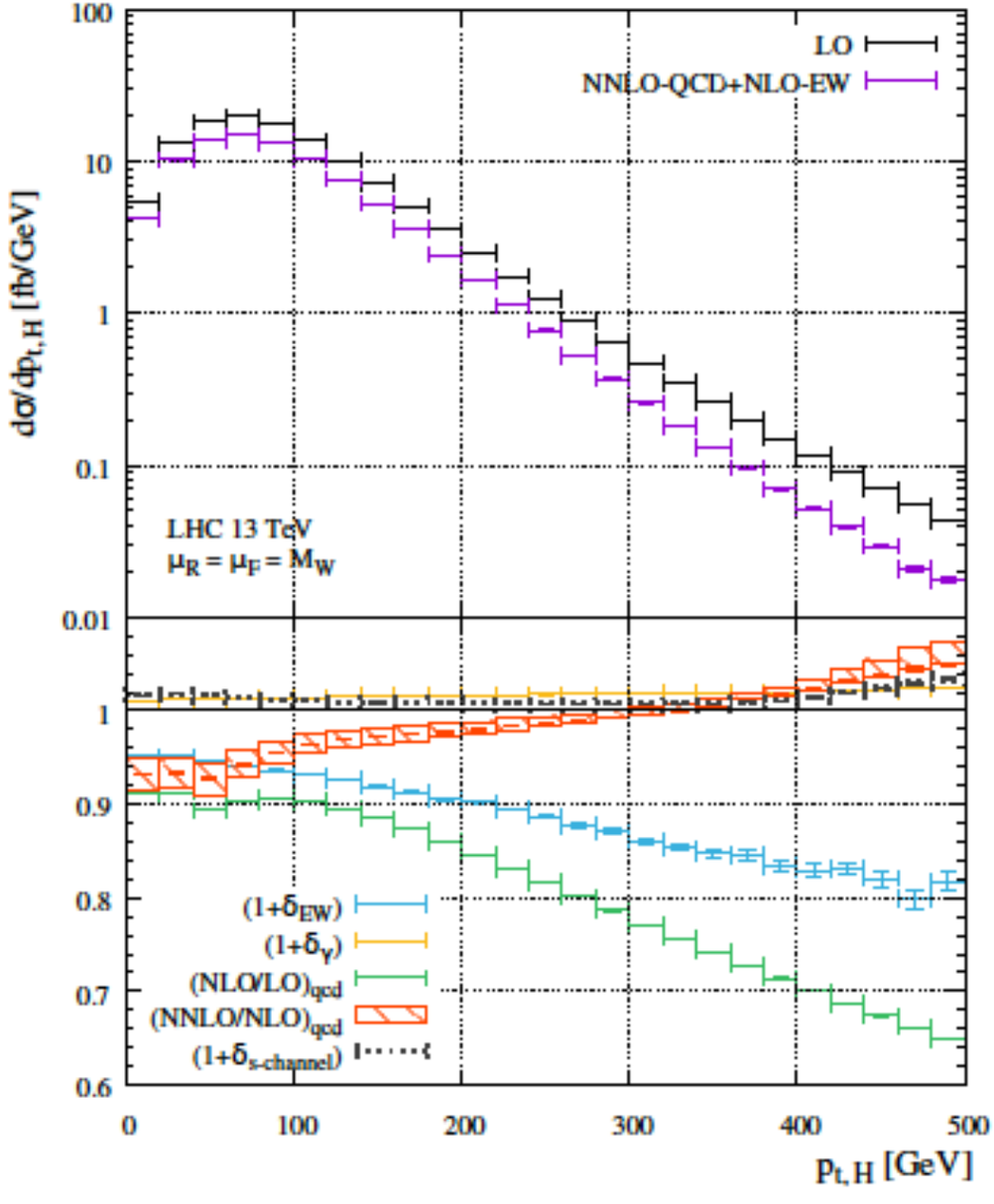
VBF Process

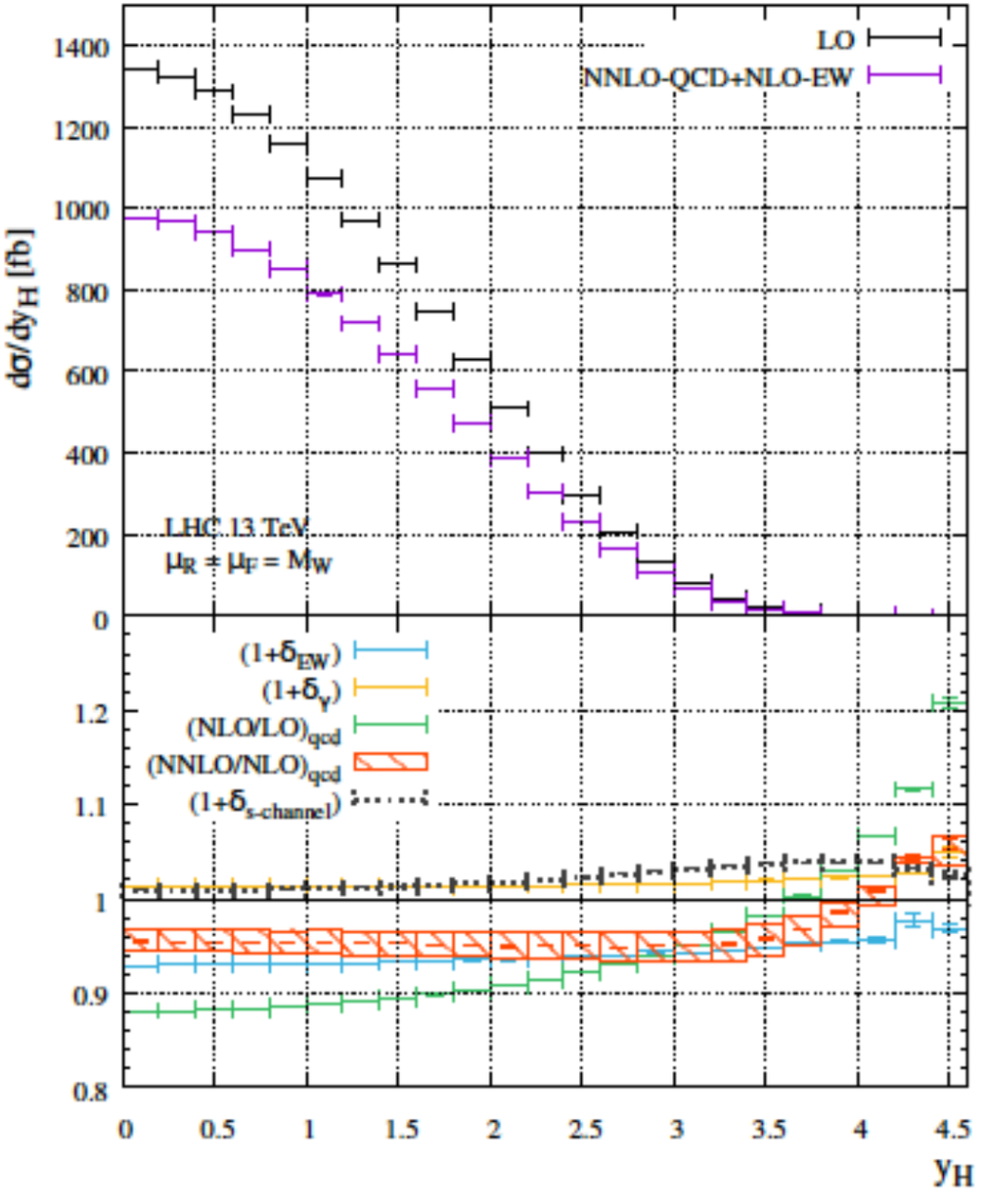
- Cross sections are calculated at (approx.) NNLO QCD and NLO EW accuracies.
- Calculations are the same as CERN Report 3, except it is in NWA (CPS in CERN Report 3).
- Program: NNLO QCD (VBF@NNLO) and NLO EW (HAWK).
- QCD scales: $\mu=\mu_F=\mu_R=M_W$, uncertainty estimated in the range $1/2 < \mu/M_W < 2$ (keeping $\mu_F=\mu_R$).
  - No additional THU nor PU uncertainties assigned.
- PDF set: PDF4LHC15_nnlo_100 (QCD corrections) and NNPDF2.3QED (EW corrections + photon PDF)

$$\sigma^{\mathrm{VBF}} = \sigma^{\mathrm{DIS}}_{\mathrm{NNLOQCD}}(1+\delta_{\mathrm{EW}}) + \sigma_{\gamma}$$

$\sqrt{s}$[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}/\alpha_s/\mathrm{PDF}\oplus\alpha_s}$[%]	$\sigma^{\mathrm{DIS}}_{\mathrm{NNLOQCD}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]	$\sigma_{s\text{-channel}}$[fb]
7	1241.4(1)	$^{+0.19}_{-0.21}$	$\pm 2.1/\pm 0.4/\pm 2.2$	1281.1(1)	−4.4	17.1	584.5(3)
8	1601.2(1)	$^{+0.25}_{-0.24}$	$\pm 2.1/\pm 0.4/\pm 2.2$	1655.8(1)	−4.6	22.1	710.4(3)
13	3781.7(1)	$^{+0.43}_{-0.33}$	$\pm 2.1/\pm 0.5/\pm 2.1$	3939.2(1)	−5.3	51.9	1378.1(6)
14	4277.7(2)	$^{+0.45}_{-0.34}$	$\pm 2.1/\pm 0.5/\pm 2.1$	4460.9(2)	−5.4	58.5	1515.9(6)

VBF


LO
NNLO-QCD+NLO-EW
LHC 13 TeV
$\mu_R = \mu_F = M_W$
$(1+\delta_{EW})$
$(1+\delta_\gamma)$
$(NLO/LO)_{qcd}$
$(NNLO/NLO)_{qcd}$
$(1+\delta_{s\text{-channel}})$
$d\sigma/dp_{t,H}$ [fb/GeV]
$p_{t,H}$ [GeV]


LO
NNLO-QCD+NLO-EW
LHC 13 TeV
$\mu_R = \mu_F = M_W$
$(1+\delta_{EW})$
$(1+\delta_\gamma)$
$(NLO/LO)_{qcd}$
$(NNLO/NLO)_{qcd}$
$(1+\delta_{s\text{-channel}})$
$d\sigma/dy_H$ [fb]
y_H

VH

- EW correction O(-7)% for WH and O(-5)% for ZH
- Photon-induced process O(3-4)%
- Larger gg→ZH contribution (14%@13TeV) at higher Ecm
  - Larger QCD scale uncertainty compared to lower Ecm and WH

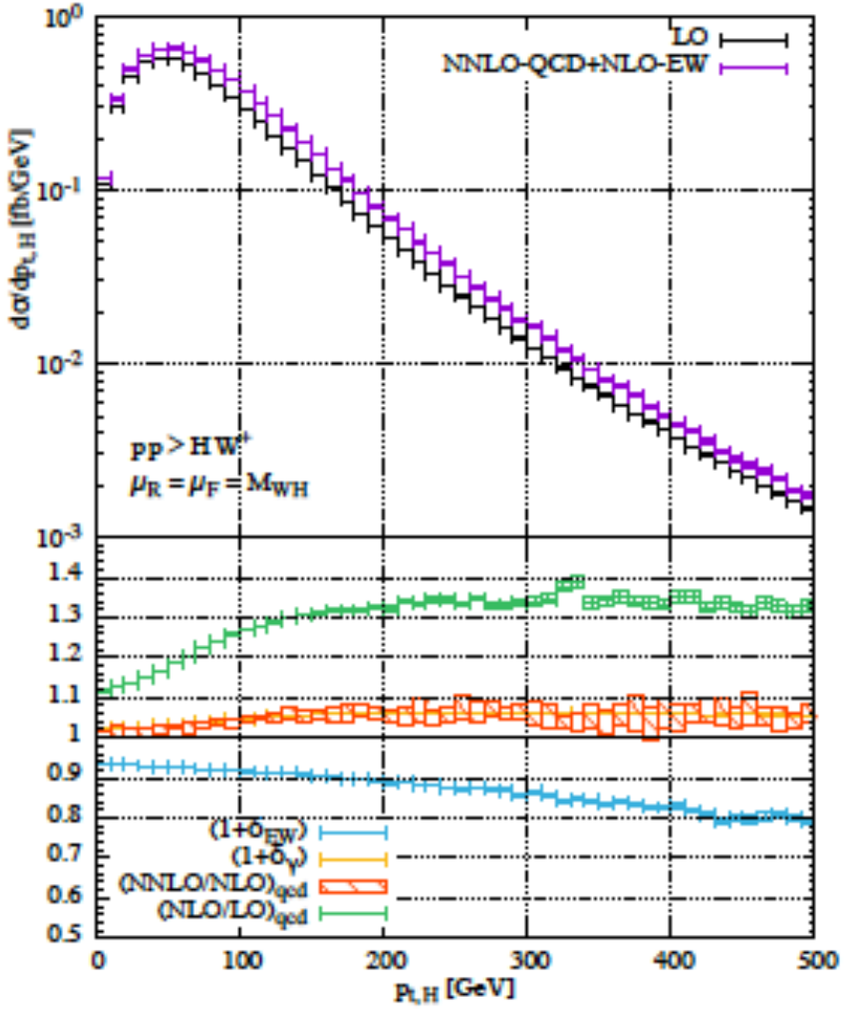
$$\sigma^{\mathrm{WH}} = \sigma^{\mathrm{WH,DY}}_{\mathrm{NNLOQCD}}(1+\delta_{\mathrm{EW}}) + \sigma_{\text{t-loop}} + \sigma_{\gamma},$$
$$\sigma^{\mathrm{ZH}} = \sigma^{\mathrm{ZH,DY}}_{\mathrm{NNLOQCD}}(1+\delta_{\mathrm{EW}}) + \sigma_{\text{t-loop}} + \sigma_{\gamma} + \sigma^{\mathrm{ggZH}}$$

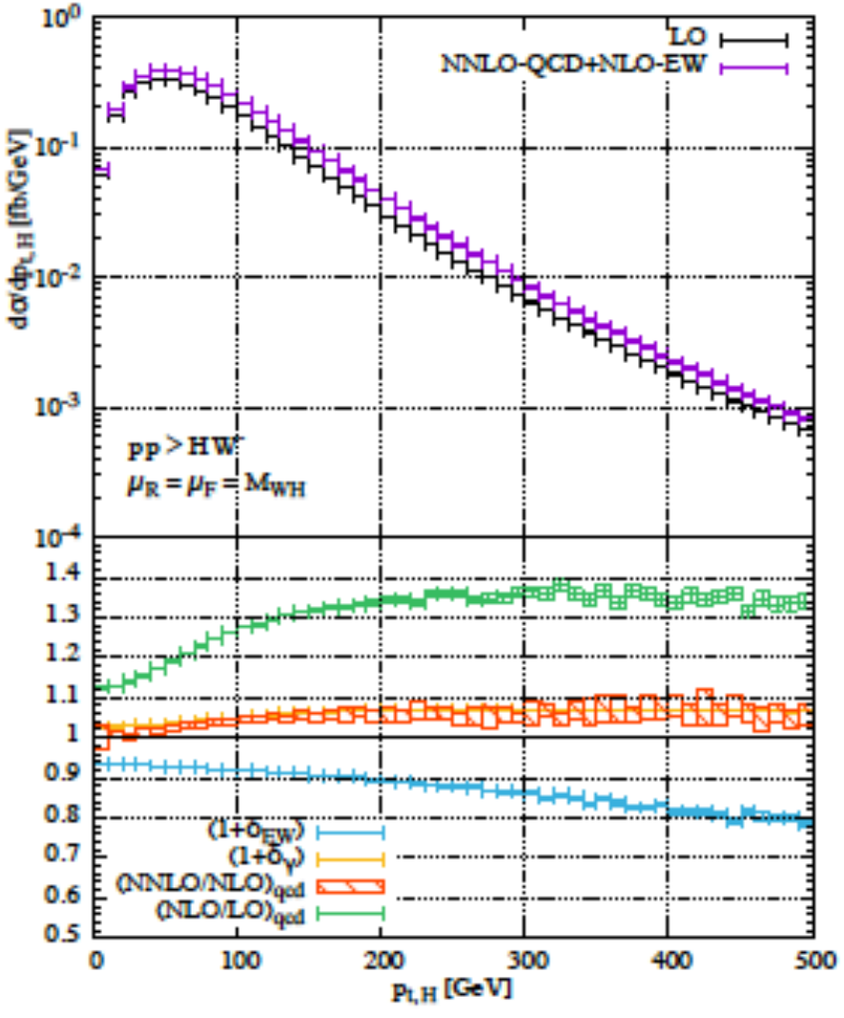
$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}/\alpha_s/\mathrm{PDF}\oplus\alpha_s}$[%]	$\sigma^{\mathrm{DY}}_{\mathrm{NNLOQCD}}$[fb]	$\sigma_{\text{t-loop}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]
7	40.99	$^{+0.7}_{-0.9}$	$\pm1.9/\pm0.7/\pm2.0$	42.78	0.42	−7.2	$0.88^{+1.10}_{-0.10}$
8	49.52	$^{+0.6}_{-0.9}$	$\pm1.8/\pm0.8/\pm2.0$	51.56	0.53	−7.3	$1.18^{+1.38}_{-0.14}$
13	94.26	$^{+0.5}_{-0.7}$	$\pm1.6/\pm0.9/\pm1.8$	97.18	1.20	−7.4	$3.09^{+3.33}_{-0.37}$
14	103.63	$^{+0.3}_{-0.8}$	$\pm1.5/\pm0.9/\pm1.8$	106.65	1.36	−7.4	$3.55^{+3.72}_{-0.43}$

$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}/\alpha_s/\mathrm{PDF}\oplus\alpha_s}$[%]	$\sigma^{\mathrm{DY}}_{\mathrm{NNLOQCD}}$[fb]	$\sigma^{\mathrm{ggZH}}_{\mathrm{NLO+NLL}}$[fb]	$\sigma_{\text{t-loop}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]
7	11.43	$^{+2.6}_{-2.4}$	$\pm1.6/\pm0.7/\pm1.7$	10.91	0.94	0.11	−5.2	$0.03^{+0.04}_{-0.00}$
8	14.18	$^{+2.9}_{-2.4}$	$\pm1.5/\pm0.8/\pm1.7$	13.36	1.33	0.14	−5.2	$0.04^{+0.05}_{-0.00}$
13	29.82	$^{+3.8}_{-3.1}$	$\pm1.3/\pm0.9/\pm1.6$	26.66	4.14	0.31	−5.3	$0.11^{+0.12}_{-0.01}$
14	33.27	$^{+3.8}_{-3.3}$	$\pm1.3/\pm1.0/\pm1.6$	29.47	4.87	0.36	−5.3	$0.12^{+0.13}_{-0.01}$

VH

- Differential distributions: (New for YR4)





ttH

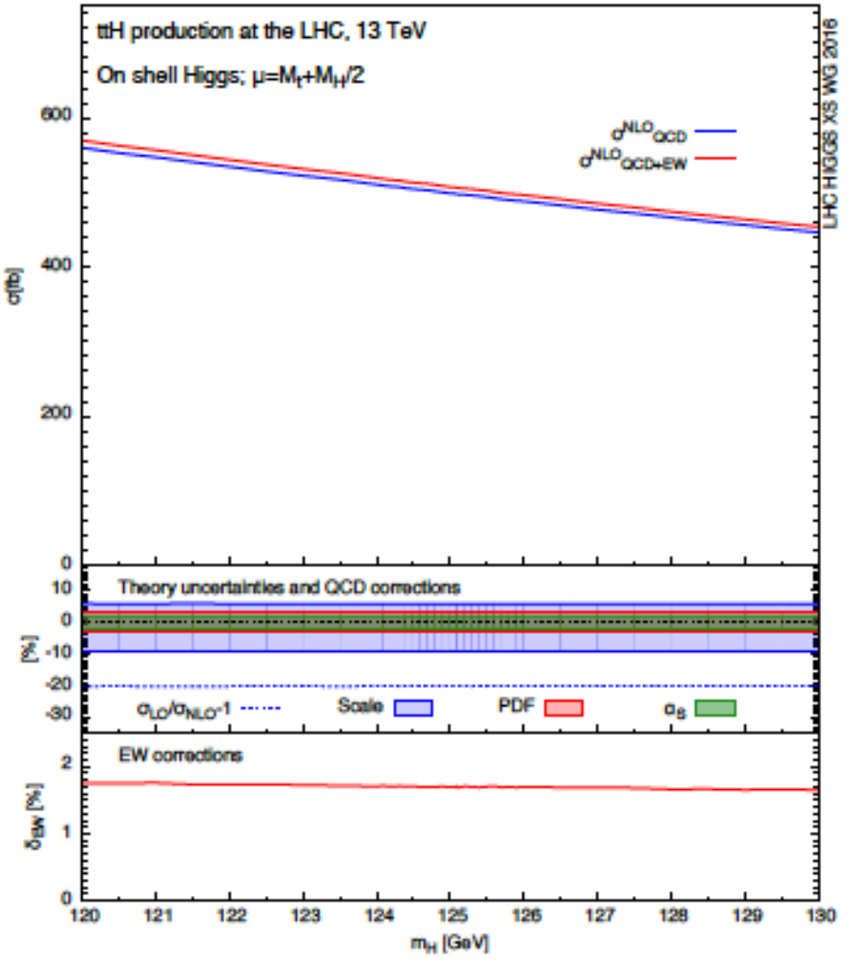
Cross sections are calculated at NLO QCD and NLO EW

- •NLO EW O(1-2)%, photon-induced negligible

Studies documented in YR4:

- •Offshell effects in ttH production
- •ttH beyond NLO
  - •NLO + NLL soft-gluon resummation in partonic centre of mass limit
  - •aNNLO via soft-gluon resummation in the pair-invariant mass (PIM) threshold limit

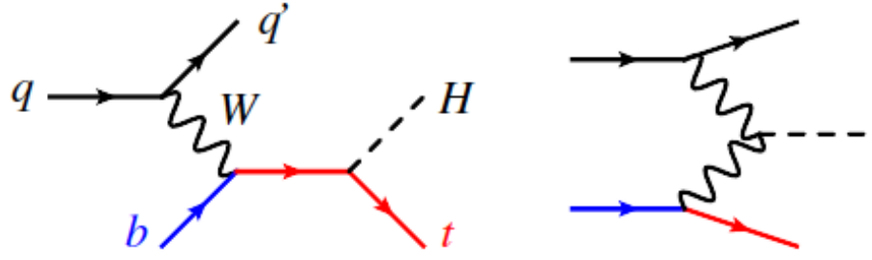
SM backgrounds: ttbb(NLO QCD), ttV(NLO QCD+EW), ttVV(NLO QCD)

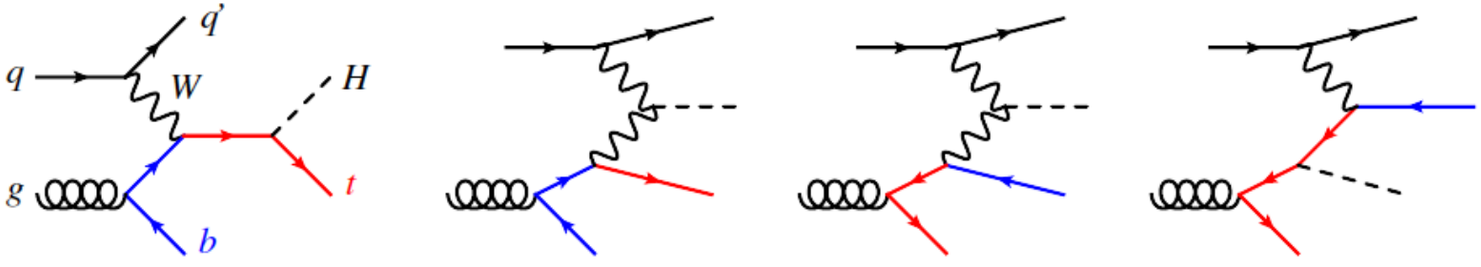


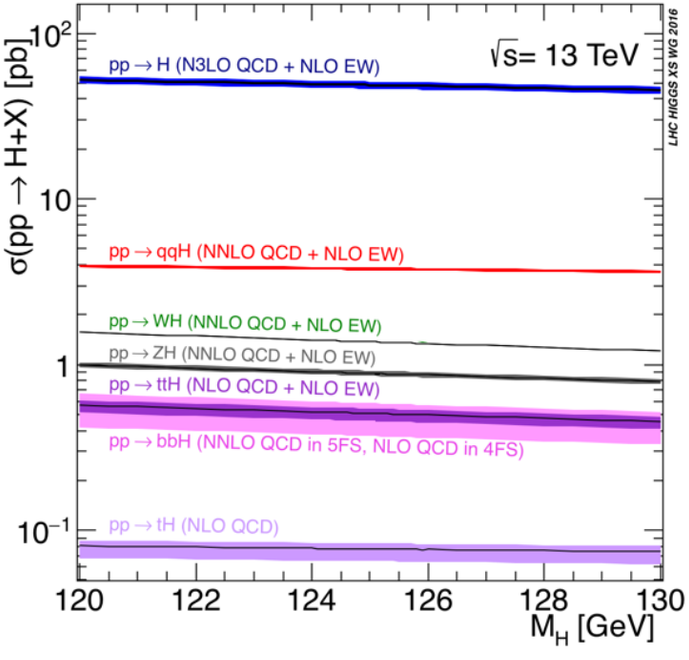
TH

NLO QCD calculation

- s-channel
- t-channel
  - 4 flavour-scheme
  - 5 flavour-scheme





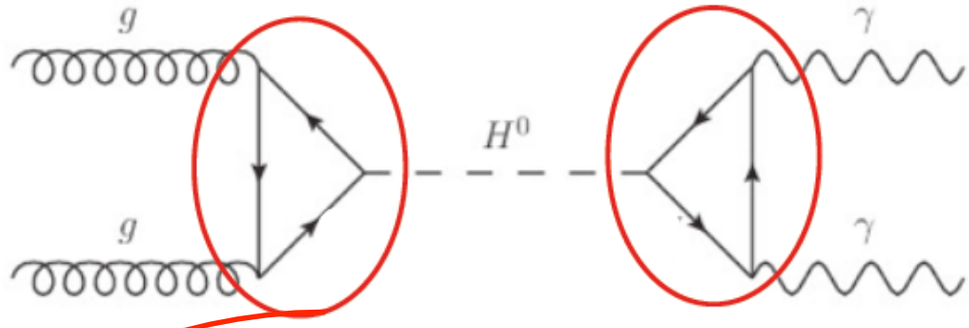


$$\sigma(tH)^{t\text{-ch}}_{TOT} = 74.25\ ^{+6.5\%}_{-14.9\%}\ (\text{scale,FS})\ \pm 3.7\%(\text{pdf},\alpha_s)\ \text{fb}$$

$$\sigma(tH)^{s\text{-ch}}_{TOT} = 2.879\ ^{+2.4\%}_{-1.8\%}\ (\text{scale})\ \pm 2.2\%(\text{pdf},\alpha_s)\ \text{fb}$$

Kappa Framework

Updates to kappa framework:



- ggF
  - Change in central QCD scale from Mh (YR3) to Mh/2 (YR4).
  - inclusion of charm quark
  - change in quark-mass definition from on-shell mass in YR3

- YR3: $\kappa_g^2 = 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$
- YR4: $\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$

- VBF
  - Cross sections are calculated in NNLO QCD with VBF@NNLO
  - QCD scales: μ=μF=μR=MW
  - PDF set: PDF4LHC15_nnlo_30_pdfs

- gg->ZH
  - Cross sections are calculated in LO QCD with VH@NNLO
  - QCD scales: $\mu=\mu F=\mu R=M_{ZH}$
  - PDF set: PDF4LHC15_nnlo_mc

Beyond the κ Framework

The inputs to the kappa framework are σ*BR measurements

With the increased statistics of Run 2, we can move beyond this framework to more sophisticated measurements and interpretations

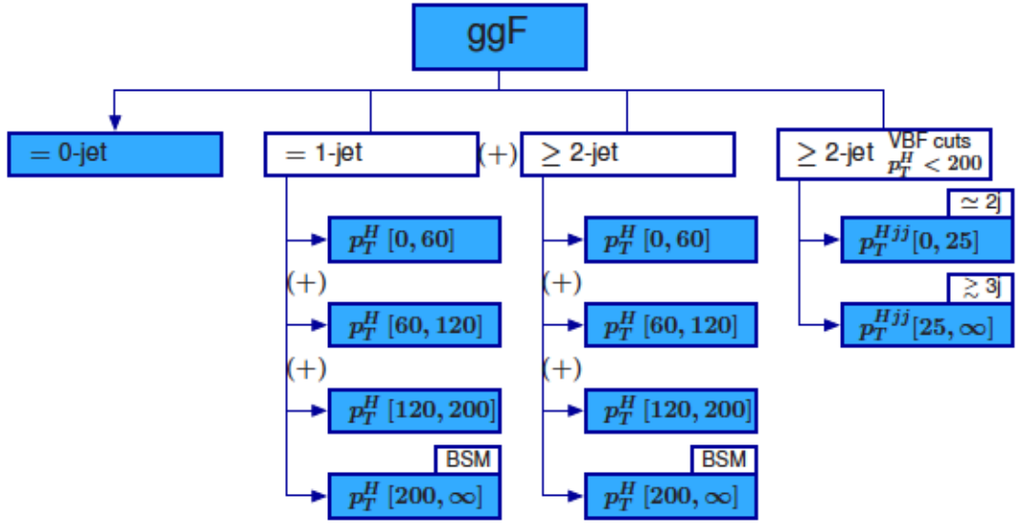
WG2 has investigated expanding the measurement inputs and their interpretation:

- Template (simplified) cross sections
- Fiducial cross sections
- Pseudo-Observables
- Effective Field Theory (will be discussed later this week)
  - YR4 provides definitions of the theory frameworks that can be used to extend the SM
  - Discussion of the limitations that such effective descriptions have in describing different BSM physics scenarios (UV completions)
  - Tool development, including morphing techniques

FIDUCIAL AND TEMPLATE

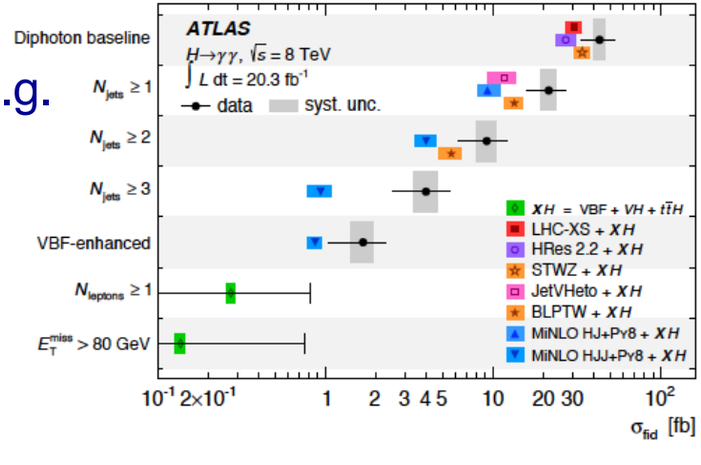
Template (simplified) cross sections new in YR4. Progress on experimental side:

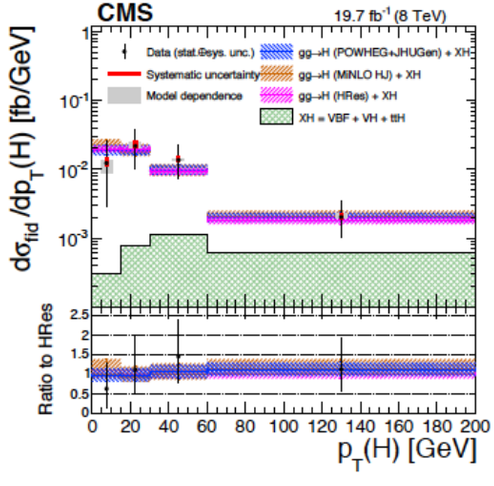
- we have a first "generator independent" implementation of the stage-0 and stage-1 HTXS categorization.
- Code in the HXSWG SVN



- Fiducial and differential cross sections

- Developed set of recommendations e.g.
  - Fiducial definitions
  - Unfolding of detector effects
  - Preservation of data
  - Etc
- Work to be done to perform combinations





Beyond the SM: WG3

No sign of physics beyond the SM yet where we have searched

- Run 2 extends the search range with the higher LHC energy and increased integrated luminosity
- Important to make sure that the phase space if fully explored
  - Develop benchmarks
  - Plug holes in the search parameter space

A lot of work went into YR4 updating calculations, providing new benchmarks, tools, and investigating new BSM scenarios

- MSSM
- NMSSM
- Neutral Extended Scalars
- Charged Higgs
- Exotic Decays

WG3: MSSM and NMSSM

MSSM:

- Provide files for various MSSM scenarios (now extended to 2 TeV in YR4)
- Mh max, mh mod+/-, tauphobic, light stop, light stau
- Scenarios for low tanβ: hMSSM, low-tanβ-high.

scenario	m_A [GeV]	$\tan\beta$	$\sqrt{s}$ [TeV]	authors
"low-tb-high"	$150 - 500$	$0.5 - 10$	$8, 13$	[Heinemeyer '15]
hMSSM	$130 - 1000$	$1 - 60$	$8, 13$	[Maiani et al. '13; Djouadi et al. '13 '15]
m_h^{max}	$90 - 2000$	$0.5 - 60$	$13, 14$	[Carena et al. '13]
$m_h^{\text{mod}+}, \mu \in \mu^{\text{val}}$	$90 - 2000$	$0.5 - 60$	$8, 13, 14$	[Carena et al. '13]
$m_h^{\text{mod}-}$	$90 - 2000$	$0.5 - 60$	$13, 14$	[Carena et al. '13]
light stau	$90 - 2000$	$0.5 - 60$	$13, 14$	[Carena et al. '13]
light stop	$90 - 650$	$0.5 - 60$	$13, 14$	[Carena et al. '13]
τ-phobic	$90 - 2000$	$0.5 - 50$	$13, 14$	[Carena et al. '13]

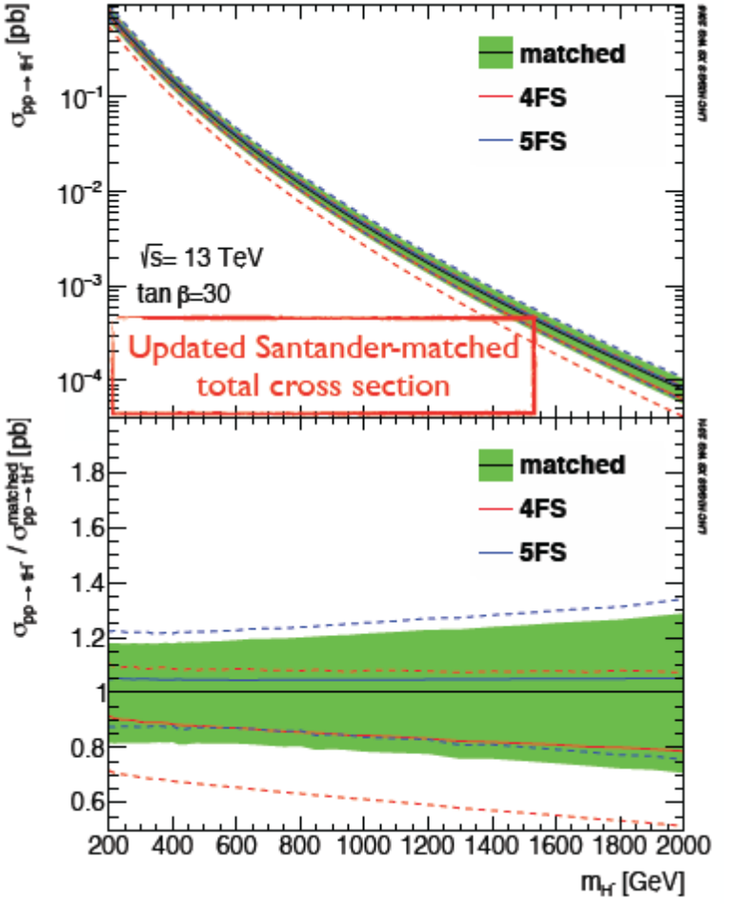
NMSSM

- Provided details of calculations, discussed uncertainties, and tools
- Categorized NMSSM-specific signatures:
  - Direct H125 production and decays
  - Direct light H_S/A_S production and decays
  - Direct H/A production and decays
  - Higgs bosons in squark/gluino/chargino/neutralino decays, singlino-like LSP
  - Displaced vertices
- 9 benchmarks provided

WG3: H^+, Extended Scalars

Charged Higgs:

- Charged Higgs chapter in YR4 focuses on predictions for heavy charged Higgs
  - Updated Santander-matched predictions
  - Fully differential simulation in the 4FS and comparison with 5FS
- First NLO computation of charged Higgs cross section in the intermediate-mass range
- Reduction of scale uncertainties down to 10-20% (were 40% at LO)



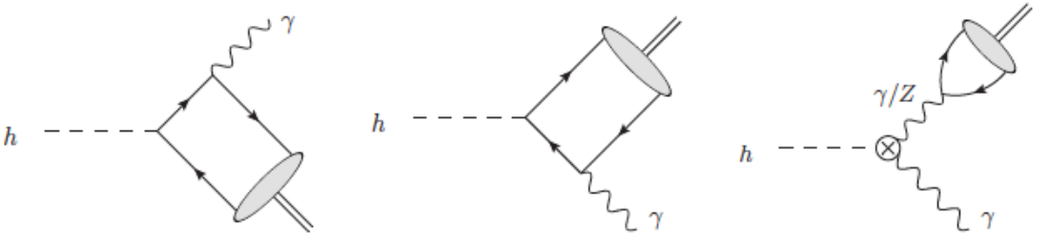
Extended Neutral Scalars:

- 2HDM, singlet, GM triplet: concrete recommendations
- Numbers and benchmarks for all these. Many benchmarks…
  - Useful to make sure we cover search phase space
  - Unclear what will be used by the experiments

WG3: Rare and Exotic Decays

Exotic decays

- New group has established good theory/experiment interactions, productive interactions with experiments regarding triggers



- For YR4
  - Recommended BRs for SM exclusive mesonic modes (M)
    - h->γM , h->MZ, MW
    - Experimental status and prospects
    - Theoretical survey of models yielding enhanced rates
    - exclusive mesonic branching fractions
  - General recommendations for exotic searches
    - presentation of search results
    - signal event generation
    - Study of parton-level kinematics for h->aa (ss)->4f
    - Feasibility study for semi-invisible h 2γ + MET
    - Benchmarks and recommendations for displaced decays

Upcoming Meeting

The next general meeting will be October 12 to 14, 2016 at CERN

The indico page can be found at:

http://indico.cern.ch/event/555360/

Please register and arrange your trip as soon as possible

A preliminary agenda is under construction

- Discuss shorter term goals for the analysis of the 2016 dataset
- Discuss medium term goals for the analysis of the full Run 2 dataset
- Discuss long term goals (Run3 and HL-LHC)

Your feedback and suggestions during this workshop will be very much appreciated

LHC HXSWG Organization

After discussions with community and management of ATLAS and CMS:

- Preserve existing structure but improve communication by assigning steering committee members to follow the activities of a WG closely and communicate on regular basis with the conveners
- Opportunity to revise structure in the coming year if further changes are needed

- Current structure
  - Steering committee
  - 3 Working Groups
    - SM Higgs
    - Higgs Properties
    - BSM
  - Subgroups
    - Keep current set but can add new groups, de-activate/re-activate subgroups based on needs at a given time

Conclusions

- Yellow Report 4 is under final review and will be out very soon
  - Reference for the first Run 2 publications
- A lot of data will be collected in the next 2 years
  - Strong theory/experiment collaboration necessary to fully exploit the physics potential
  - Many open issues following YR4
    - identify and work on high priority items
    - Continue working on longer term projects
- Your feedback, suggestions, ideas are most welcome

Backup Slides