LHC Higgs Cross Sections WG
Activity Status Report

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Pavia University and INFN

on behalf of the LHC Higgs Cross Section Working Group

Higgs and BSM Physics at LHC
Trieste, June 24th - 28th, 2013

The Abdus Salam International Centre for Theoretical Physics
www.ictp.it

ggF, VBF, WH/ZH, ttH, BSM Higgs

SM Higgs

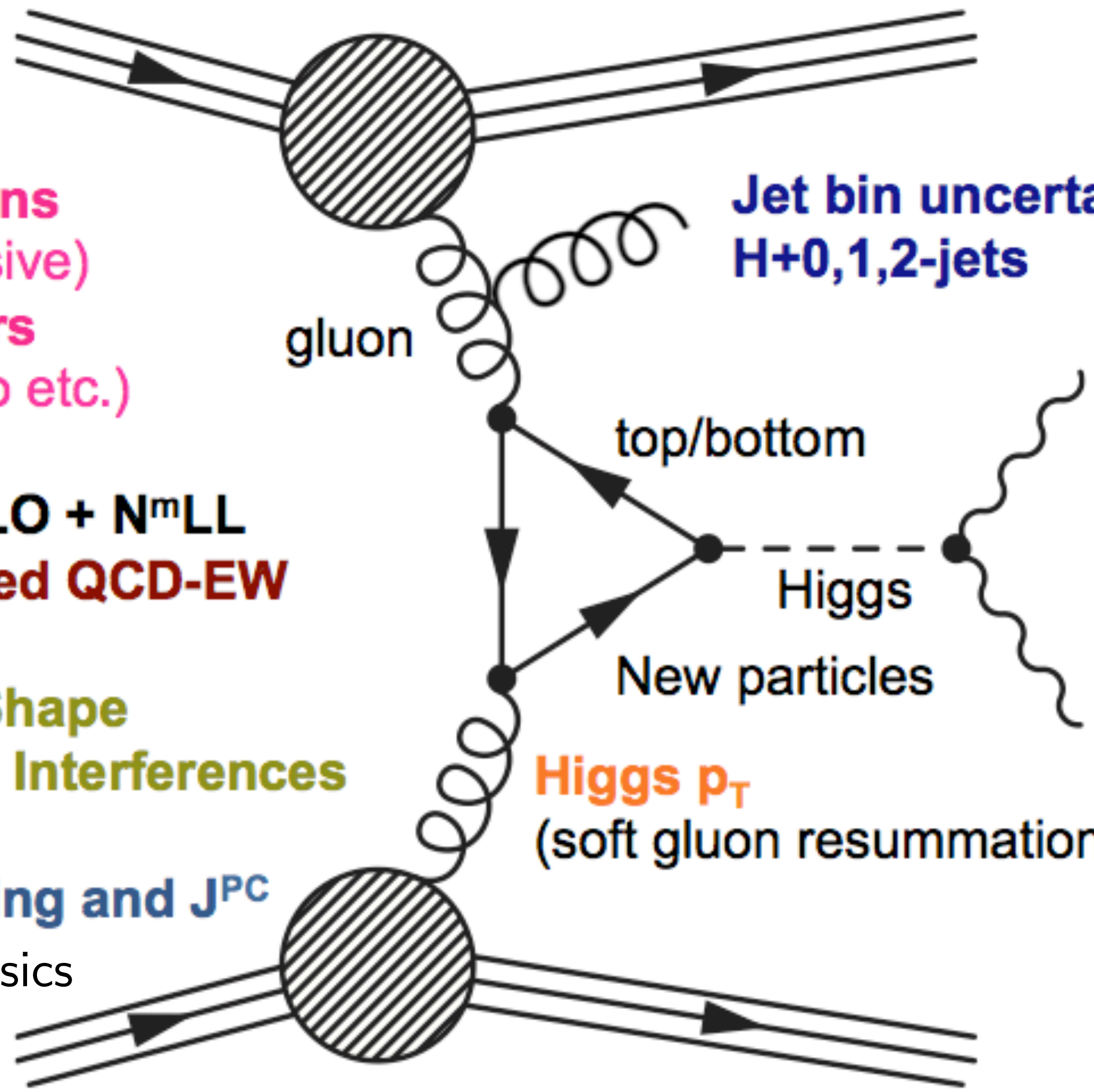
Higgs Cross Sections
(inclusive/exclusive)
Differential K-factors
(effect of jet-veto etc.)

QCD correction N^{k}LO + N^{m}LL
EW correction, Mixed QCD-EW

BMS

Heavy Higgs Line Shape
SM Backgrounds & Interferences

Higgs Mass, Coupling and J^{PC}
→ Precision Higgs physics



Jet bin uncertainty
H+0,1,2-jets

Higgs decay
Branching ratios
(QCD/EW corr.)

Higgs p_T
(soft gluon resummation)

PDF+α_s uncertainties
Renormalization/Factorization scale dependence

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Tools for Higgs (Precision) Physics

ggF, VBF, WH/ZH, ttH, BSM Higgs

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
ggh@NNLO (NNLO QCD)

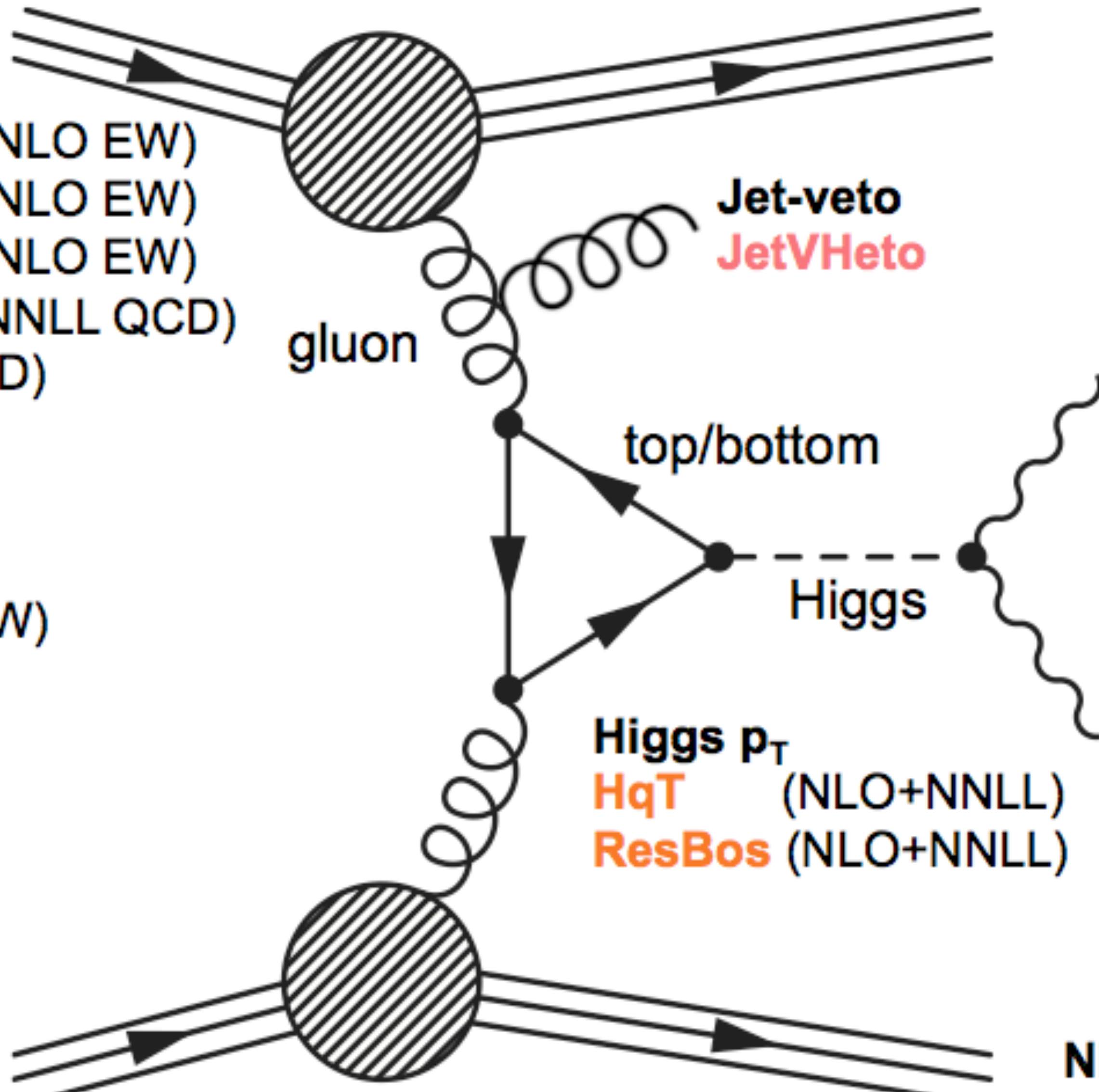
VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO)

WH/ZH
V2HV (NLO QCD)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbH@NNLO (NNLO QCD)

+ private codes.



Jet-veto
JetVHeto

Higgs p_T
HqT (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW2008, CT10, NNPDF2.1, etc.

MSSM
FeynHiggs, SusHi
2HDMC, CPSuperH

Higgs Decay
HDECAY (NLO)
Prophecy4f (NLO)

Higgs Properties
MELA/JHU, MEKD
MadGraph5

NLO MC
aMC@NLO, POWHEG,
SHERPA, HERWIG++
MCFM

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LHC Higgs XS WG Organization

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections]

Overall Contacts

ATLAS	CMS	THEORY	
Reisaburo Tanaka (LAL)	Chiara Mariotti (Torino)	Sven Heinemeyer (IFCA)	Giampiero Passarino (Torino)

Proposal for the evolution of the group after the YR3

Subgroup Contacts and Link for Subgroup Wiki

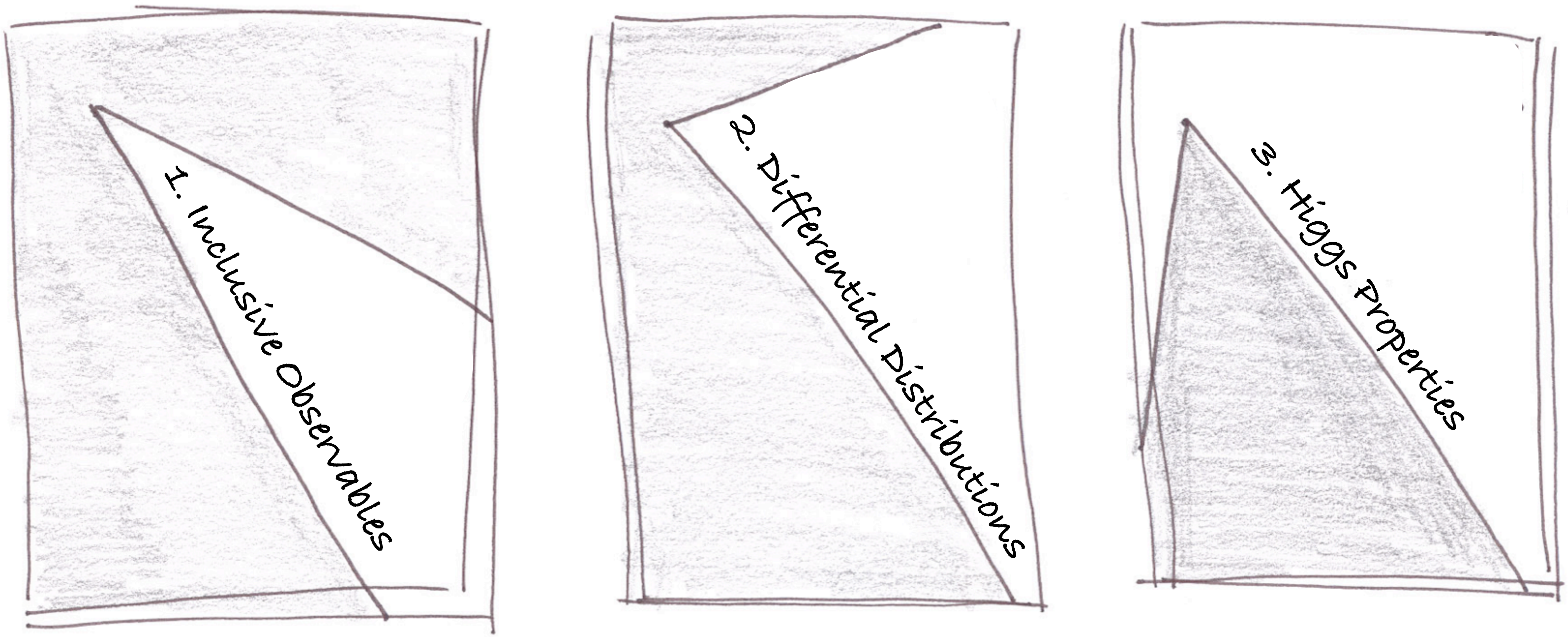
- We are organized in 11 subgroups, with 1-2 experimental contacts from each ATLAS and CMS and 2-4 theoretical contacts for each subgroup.

Group	Higgs decay	ATLAS	CMS	THEORY			
1. ggF	$\gamma\gamma$,WW*,ZZ*	Biagio di Micco (Roma Tre)	Yanyan Gao (FNAL)	Daniel de Florian (Buenos Aires)	Kirill Melnikov (Johns Hopkins)	Frank Petriello (Northwestern)	
2. VBF	$\tau\tau$,$\gamma\gamma$,WW*,ZZ*	Daniela Rebuzzi (Pavia)	Pietro Govoni (CERN)	Ansgar Denner (Würzburg)	Carlo Oleari (Milano-Bicocca)		
3. WH/ZH	bb	Giacinto Piacquadio (CERN)	Andrea.Rizzi (Pisa)	Stefan Dittmaier (Freiburg)	Giancarlo Ferrera (Milano)		
4. ttH	bb	Chris Potter (Oregon)	Chirs Neu (Virginia) Andrea Rizzi (Pisa)	Laura Reina (Florida)	Michael Spira (PSI)		
5. Light Mass Higgs	all	Michael Dührssen (CERN) Kirill Prokofiev (New York)	André Tinoco Mendes (LIP) Marco Zanetti (MIT)	Ansgar Denner (Würzburg)	Massimiliano Grazzini (Zurich)	Christophe Grojean (Barcelona)	Georg Weiglein (DESY)
6.MSSM	Neutral Charged	Trevor Vickey (Witwatersrand) Martin Flechl (Freiburg)	Monica Vazquez Acosta (IC) Sami Lehti (Helsinki)	Robert Harlander (Wuppertal)	Michael Krämer (Aachen)	Pietro Slavich (LPTHE Paris)	Michael Spira (PSI)
7.Heavy Higgs and BSM		Sara Diglio (Melbourne) Krisztian Peters (CERN)	Sara Bolognesi (Johns Hopkins) Mario Kadastik (NICPB Estonia)	Margarete Muehlleitner (Karlsruhe)	Heather Logan (Carleton)		
8. Branching ratios		Daniela Rebuzzi (Pavia)	Ivica Puljak (Split)	Sven Heinemeyer (IFCA)	Alexander Mück (Aachen)		
9. Jets		Bruce Mellado (Wisconsin)	Daniele Del Re (Roma 1)	Gavin Salam (CERN)	Frank Tackmann (DESY)		
10. NLO MC				Stefano Frixione (CERN)	Frank Krauss (Durham)	Fabio Maltoni (Louvain)	Paolo Nason (Milano-Bicocca)
11. PDF		Joey Huston (Michigan State)		Stefano Forte (Milano)	Robert Thorne (UCL)		

Handbooks of LHC Higgs Cross Sections

[https://svnweb.cern.ch/cern/wsvn/lhchiggsxs/cernrep3/trunk/]

....towards the completion of the Trilogy ...



1. Inclusive Observables	2. Differential Distributions	3. Higgs Properties
64 authors	120 authors	156 authors
151 pages	275 pages	388 pages
370 references	456 references	725 references

Repository closed, make up work still ongoing, to be submitted in arXiv by end of June

Outline

Theory uncertainties are already becoming non-negligible at LHC!

Experimental accuracy $\Delta\mu(\sigma/\sigma_{SM}) = \pm 15\%$ (roughly $\pm 10\%$ for both stat and syst)

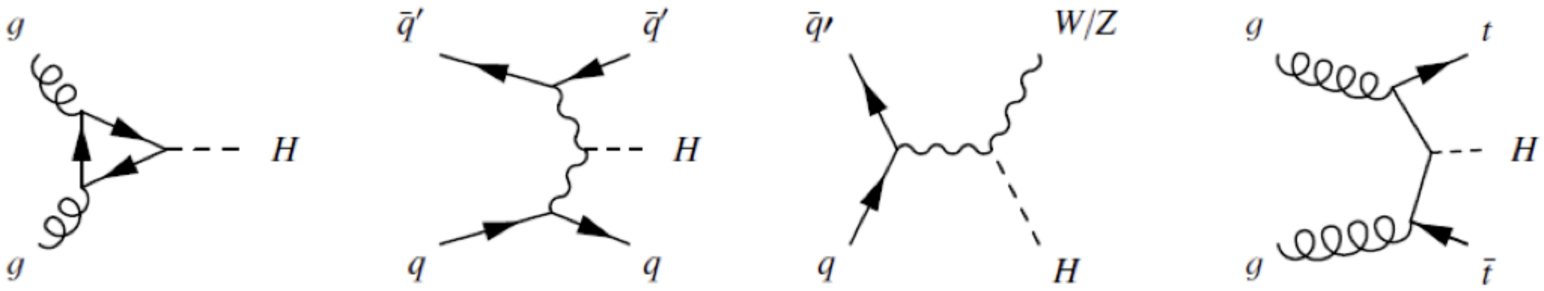
Theory uncertainty is $O(\pm 10\text{-}15\%)$ (dominated by QCD scale and PDF+α_S in gg-fusion)

1. SM Higgs Cross Section and Related Uncertainties
2. New NNLO PDF Studies
3. SM Higgs Decay Branching Ratios with Uncertainties
4. Higgs p_T Uncertainty
5. Jet-bin Uncertainty
6. Proposal for Theoretical Errors Statistics Treatment
7. Interference Effects
8. NLO Monte Carlo Progresses
9. Higgs Properties: Couplings and CP/Spin
10. BSM Higgs Cross Sections and Branching Ratios
11. BMS and High Mass Studies
12. Summary
13. Hot Topics

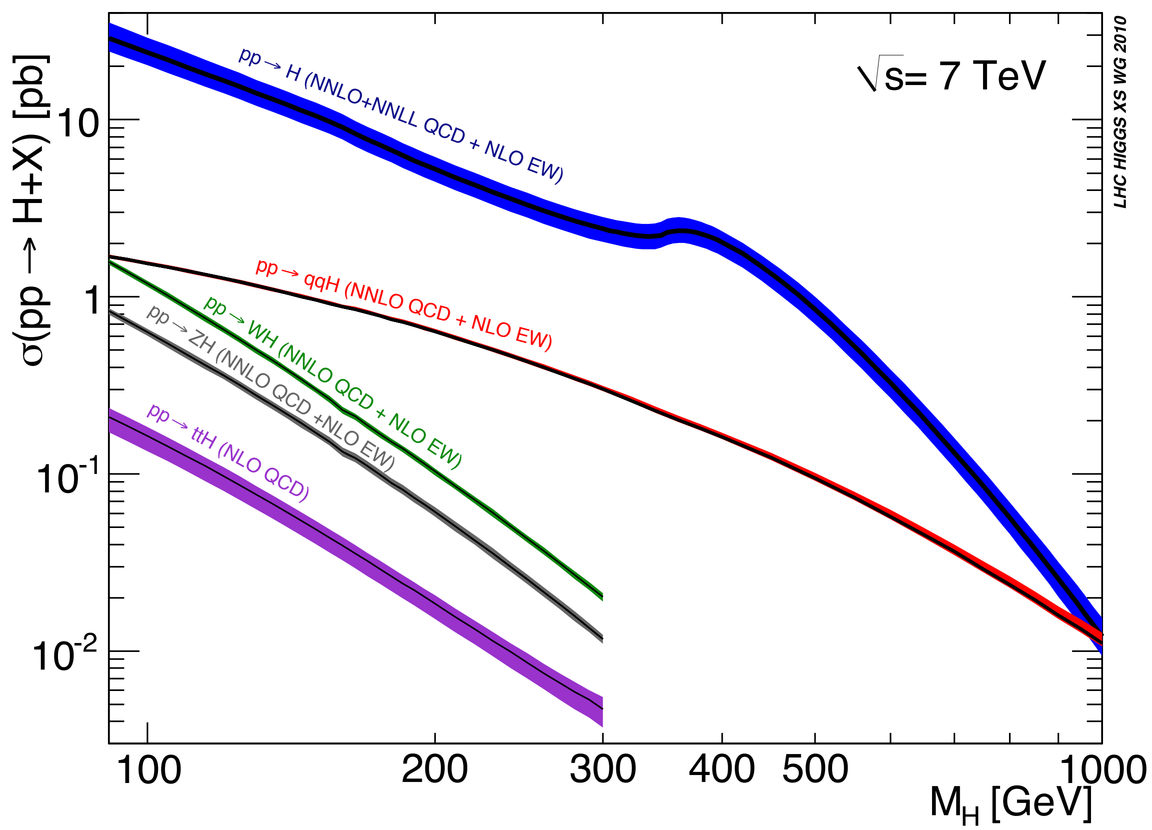
Only a selection of topics!
Emphasis on recent developments in Theory and MC Tools included in the YR3

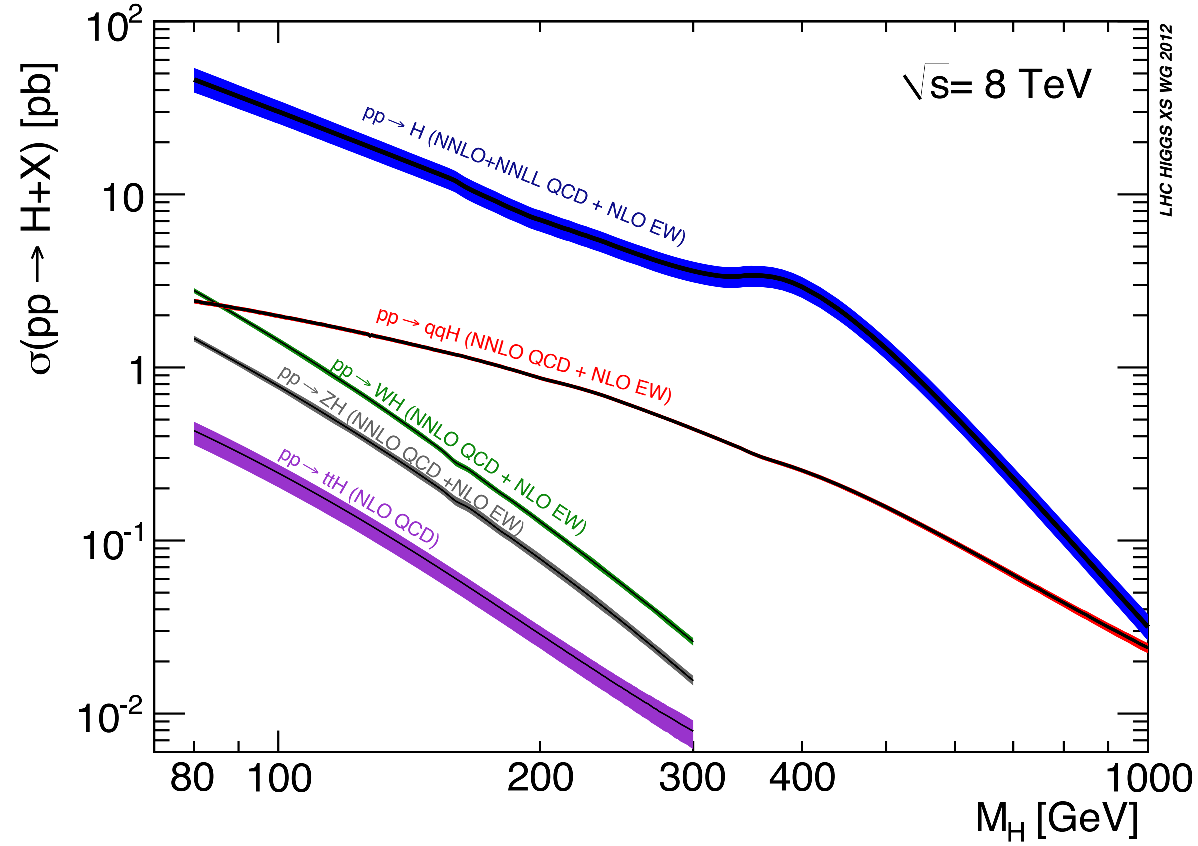
1. SM Higgs Cross Sections

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV]



New (finer) 7 and 8 TeV Higgs mass step in YR3: 321 mass points





- NNLO(+NNLL) QCD calculations for ggF, VBF, WH/ZH and NLO for ttH
- Cross sections with complex-pole-scheme for ggF and VBF for both 7 and 8 TeV
- NLO EW corrections O(5-10%), assuming factorization between QCD and EW dynamics

1. SM Higgs Cross Section Uncertainties

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV]

	7 TeV			**8 TeV**		
	Scale	PDF + α_s	Total	Scale	PDF + α_s	Total
ggF	+12% −8%	±8%	**+20% −15%**	+7% −8%	±8%	**±15%**
VBF	±1%	±4%	**±5%**	±1%	±4%	**±5%**
WH/ZH	±1%	±4%	**±5%**	±1%	±4%	**±5%**
ttH	+3% −9%	±8	**+12% −18%**	+4% −9%	±8%	**+12% −17%**

- **QCD scale uncertainty**: estimated by changing μ_R and μ_F independently by a given factor ξ and $1/\xi$ at (N)NLO QCD ($\xi = 2$ for ggF and VBF)
- **PDF+α_S uncertainty**: calculated according to the PDF4LHC recipe (envelope of MSTW, CTEQ and NNDPF sets at NLO, rescaled to NNLO)

see next slide

- QCD scale and PDF+α_S uncertainties *added linearly* (long debate about that) *but handled separately* by the LHC Higgs Combination WG (different nuisance parameters)

Expected improvements

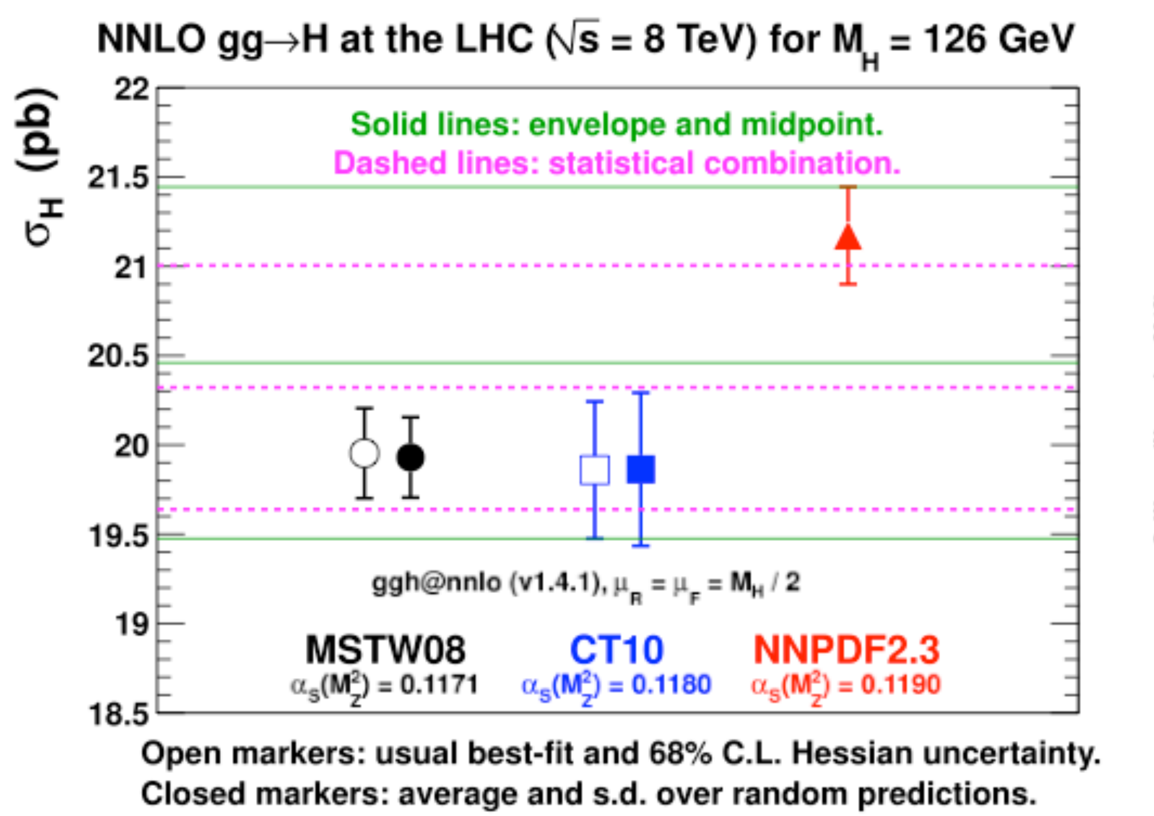
- HO Calculations, ex. ggF QCD Scale ± 8% at NNLO → ± 5% at NNNLO in few years? (*)
- PDF+α_S : ±8% → ± 5% with LHC data? (jets, top, prompt photons and Z p_T distributions contribute gluon PDF determination)

(*) New preprint by S. Forte et al. (arXiv:1303.3590): approximated NNNLO ggF +17% correction to NNLO at 125 GeV! – Calculations by C. Anastasiou et al. at NNNLO to come

2. NNLO PDF+α_S Studies

- **PDF4LHC recipe** for PDF+α_S uncertainty estimation (*) Fully includes available LHC data
  - Current prescription: *Envelope at NLO* (CT10, MSTW08, and NNPDF2.0) using each group prescriptions for combining the two types of errors) → *Envelope at NNLO*: central value from MSTW-NNLO, uncertainties from MSTW-NNLO PDF+α_S band rescaled by NLO envelope
  - New prescription: envelope estimation *directly at NNLO* using CT10, MSTW08, and NNPDF2.3 (*)
  - Comparison between NNLO envelope and 100 random set from CT10, MSTW08, and NNPDF2.3 → Similar results

- New **NNLO benchmark studies**:
  - Comparison of/among five NNLO PDF sets: NNPDF2.3, MSTW2008, CT10, ABM11 ($N_f = 5$), HERAPDF1.5 against ATLAS, CMS and LHCb data (W/Z rapidity, lepton asymmetry, lepton rapidity, inclusive jet cross section)
  - Predictions for SM observables and Higgs production in various channels at 8 TeV



Significant number of important and interesting updates (see References in the YR3 PDF Chapter YR3) but no dramatic changes in the PDFs in the past years

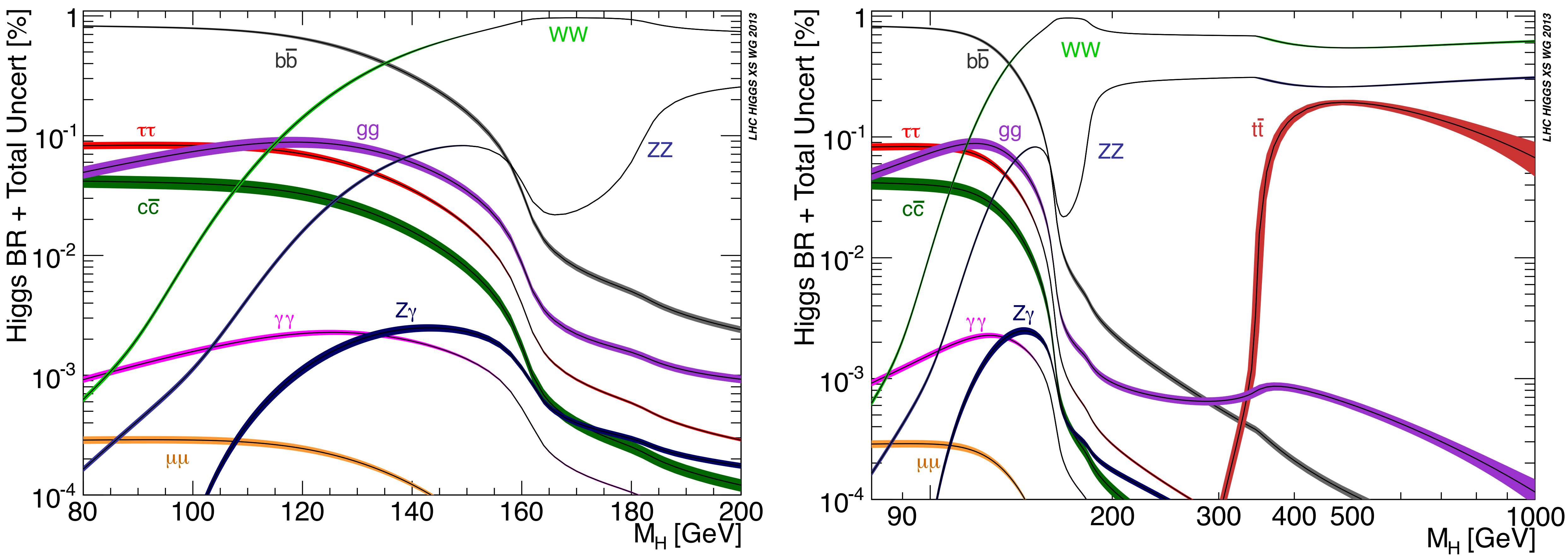
3. SM Higgs Branching Ratios

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs and Eur. Phys. J. C 71, 1753 (2011)]

New (finer) 7 and 8 TeV Higgs mass step in YR3: 321 mass points

- Use of HDECAY and Prophecy4f for the best estimate

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



- Numbers updated in the YR3: small inconsistencies in the uncertainties corrected (at the level of 1% for $M_H > 135$ GeV - for $M_H > 500$ GeV larger changes for $H \to tt$) $\to$ only uncertainties affected, not BR central values
- Detailed description of BR correlations and interference for Higgs masses around 126 GeV

3. BR Uncertainties

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs and Eur. Phys. J. C 71, 1753 (2011)]

- Parametric uncertainties estimated by changing *separately*, while leaving all others at their central values, each of the following relevant parameters: $\boldsymbol{\alpha_S}$, $\boldsymbol{m_b}$, $\boldsymbol{m_c}$, $\boldsymbol{m_t}$

Parameter	Central Value	Uncertainty
α_S	0.119	$\pm$ 0.002 (90% CL)
m_b [GeV]	4.49 (*)	$\pm$ 0.03 (2σ) (**)
m_c [GeV]	1.41 (*)	$\pm$ 0.06 (2σ) (**)
m_t [GeV]	172.5	$\pm$ 2.5

(*) one-loop pole masses
(**) errors from K. G. Chetyrkin, J. H. Kuhn, A. Maier, P. Maierhöfer, P. Marquard, M. Steinhauser, C. Sturm [arXiv:0907.2110]

Upper and lower errors summed in quadrature to obtain a Combined Parametric Error

- Theoretical uncertainties
  - QCD corrections: variation of the Higgs widths from a scale change by factor 2 and 1/2
  - EW corrections: missing HO estimation based on the known structure and size of the NLO corrections

Individual uncertainties combined linearly to obtain a Total Theoretical Uncertainty

- Total Uncertainty: linear sum of the Combined Parametric Error with the Total Theoretical Uncertainty

BR uncertainties in the global fit (ATLAS/CMS or LHC-wide) given in terms of Higgs partial decay width (long debate about that)

4. Higgs p_T Uncertainty

- Higgs p_T important discriminant variable against VBF and SM backgrounds
- Theory uncertainty sources:
  - QCD scales (± 5-10% below 60 GeV), PDF+α_S (~5% below 100 GeV), non-perturbative effects (hadronization, UE)
  - Missing NLO EW corrections not implemented in NLO MC (HAWK and VBFNLO include them but they are not interfaced to PS) → not negligible, reweighting needed!

NLO EW corrections							
ggF	± 5-10%	VBF	-8% (larger for high p_T)	VH	-5% (10-15% for high p_T)	$t\bar{t}$H	-

Reweighting tool available: corrects for CPS and EW corrections + uncertainties

  - Finite quark-mass effect (~8-10%)

Recent discussion on t/b finite mass effect:
E. Bagnaschi et al. JHEP 1202 (2012) 088

Tools:

- HqT2 (and HRes = HNNLO + HqT): HqT has no finite quark-mass effect - O(8-10%)
- POWHEG: finite quark-mass effect for ggF - Higgs p_T tuned to HqT (`hfact` = $M_H/2$)→ no reweighting needed
- MC@NLO: finite quark-mass effect → but recent studies show disagreement with POWHEG

YR3: Comparison among different generators (HRes, POWHEG, Madgraph, aMC@NLO, Sherpa) - good agreement in the central pT region [10, 40] GeV

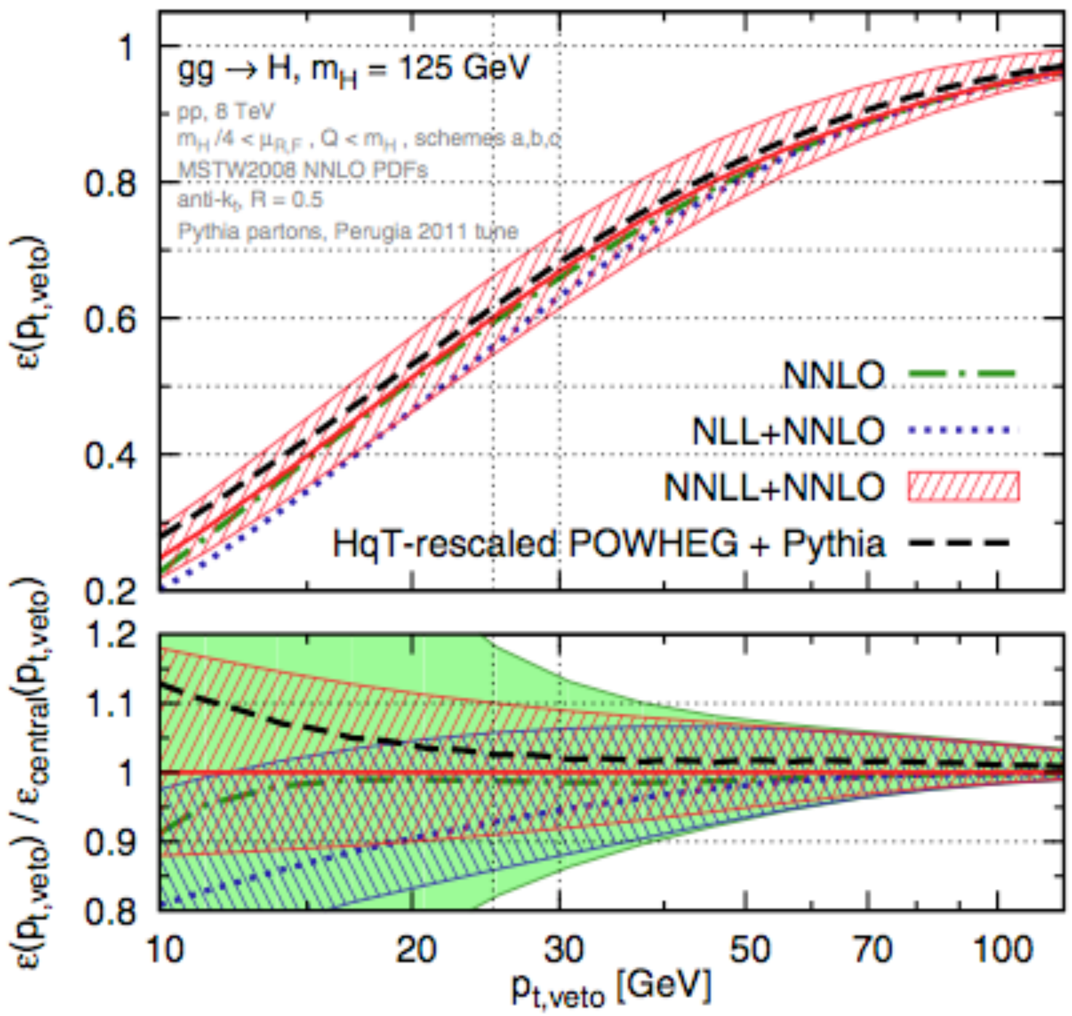
5. ggF Contamination in VBF

- Jet-bin uncertainty important in VBF for ggF + 2j contamination (O(25%) with typical VBF cuts) - largest uncertainties related to jets, especially theoretical uncertainties

Source	ggF+2j	VBF
QCD scale	(*) 25% (30% with CJV)	~1%
Underlying event	30%	6%
Jet Energy Scale	19%	8%
Total	**45%**	**10%**

(*) Uncertainty on $\sigma_{\geq 2}$ for ggF computed with MCFM

[A. Banfi et al. PRL 109 (2012) 202001]



- So far, Stewart&Tackmann prescription
  - Conservative approach assuming that the n-jet inclusive xsec $\sigma_{\geq n\text{-jet}}$ uncertainties are uncorrelated
- Recent proposal by G. Salam *et al.*
  - Use jet-veto efficiency → K-factors cancels in σ_0/σ_{tot}
  - NNLO+NNLL 0-jet bin uncertainty **±9%**
- Work by R. Boughezal *et al.*: H+1jet at NNLO [arXiv:1302.6216]

Focal points:

1. Reduction of uncertainty for 1-jet, ggF+2-jets
2. Development of other categorization methods rather than jet-binning

6. THU Statistical Treatment (Proposal)

Theory uncertainties not negligible anymore → need to update LHC Higgs combination WG prescription (ATL-PHYS-PUB-2011-011, CMS Note-2011/005)

- Long debate on QCD scale and PDF+α_S uncertainty handling
- The LHC Higgs XS WG suggested to separate either THU or PU
- Statistical nature of THU is unknown, while PU is believed to behave as Gaussian (or log-normal) after multiple measurements, due to central limit theorem (i.e. PDF+α_S uncertainty)

Source of theory uncertainties		
QCD scale	±8% for ggF, ±1% for VBF/VH, +4-9% for ttH	flat-prior
PDF+α_s	±8% for gg-initiated and ±4% for qq-initiated	Gaussian
BR uncertainty	±2-4% for THU ±2-3% for PU	flat-prior for THU Gaussian for PU
Higgs p_T	mixture of missing higher-order correction (ex. NLO EW), QCD scale, PDF+α_s, UE, etc.	flat-prior to be conservative
jet-bin uncertainty	inclusive 0,1,2-jet bin uncertainty is $\sigma_{\geq 0}$ (±10%), $\sigma_{\geq 1}$ (±20%), $\sigma_{\geq 2}$ (±20-30%, NLO)	flat-prior
underlying event	±10% for ggF+2j and ±3% for VBF	flat-prior
shape uncertainty in bkg. estimation	ex. Z+jets bkg., WW/ZZ bkg. etc.	flat-prior

[R. Tanaka for the LHC Higgs XS WG]

- ZWA in general not adequate also for a light SM Higgs boson $\rightarrow$ off-shell contributions essential for an accurate signal normalization and for the extraction of the Higgs couplings
  - For $H \rightarrow ZZ/WW$, ZWA deviations in the total cross section are **O(5-10%)** w/o optimized selection cuts
- In addition, for $M_H > 2M_V$, O(10%) S/B interference effects, which may have impact also for $M_H << 2M_V$ (for a light Higgs, suppression via $M_T<M_H$ cut)
  - $gg \rightarrow H \rightarrow \gamma\gamma$: few % effect for light Higgs after experimental cuts [L. Dixon]
  - $gg \rightarrow H \rightarrow WW$: -10% negative interference for light Higgs and large positive for heavy Higgs [MCFM by K. Ellis *et al.*, gg2WW by N. Kauer]
  - $gg \rightarrow H \rightarrow ZZ$: as $H \rightarrow WW$ but smaller interference [G. Passarino arXiv:1206.3824]

➡ Prescription exists for heavy Higgs analysis more in BSM slides later

- Interference effect in **Higgs decay** (Prophecy4f)
  - $H \rightarrow ZZ \rightarrow 4e$ or 4μ (-11%@$M_H = 120$ GeV) .... corrected in the analysis
  - $H \rightarrow WW/ZZ \rightarrow e\nu e\nu$, $\mu\nu\mu\nu$ (-5.4%@$M_H = 120$ GeV) ..... not corrected as no $H \rightarrow 4f$ MC!
  - Interference with SM background $qq/gg \rightarrow ZZ \rightarrow 4e/4\mu$ also exists

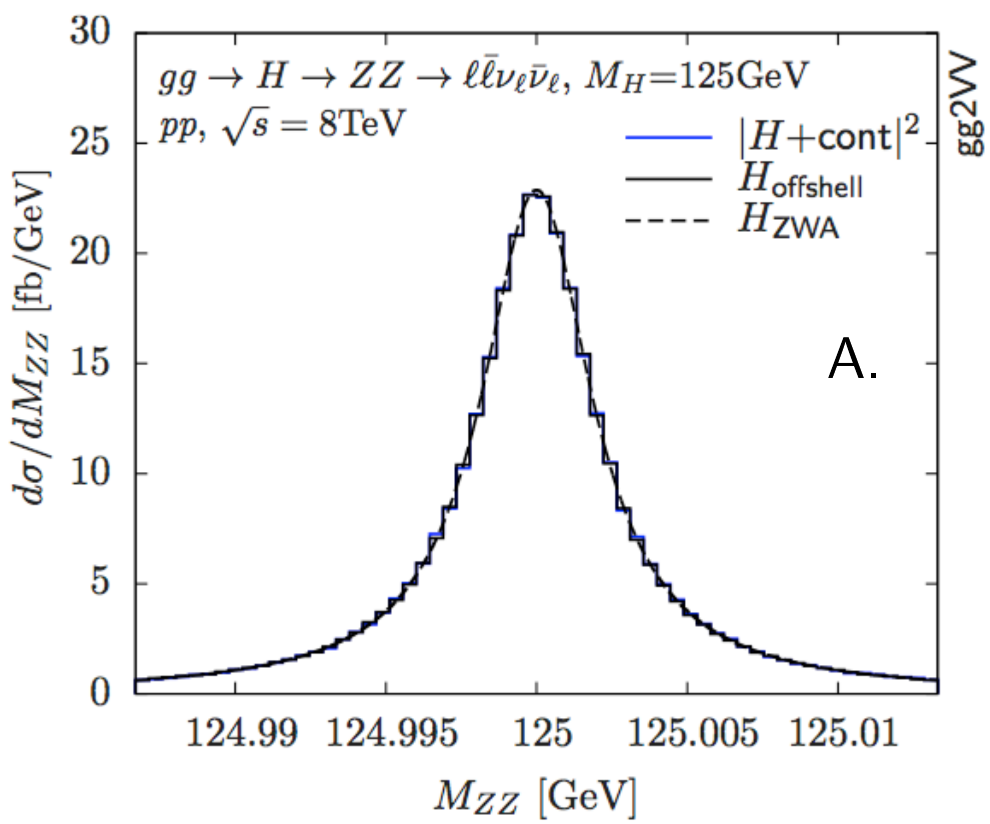
- Prediction of a O(-150 MeV) Higgs invariant mass peak shift in gg→H→γγ for M_H = 125 GeV [S. Martin, Phys. Rev. D86 (2012) 073016, arXiv 1208.1533]
- Is there any sizable effect also for H→ZZ$^{(*)}$?

  A. Parton level study [arXiv:1206.4803]→ no difference perceptible between S and S+B+I

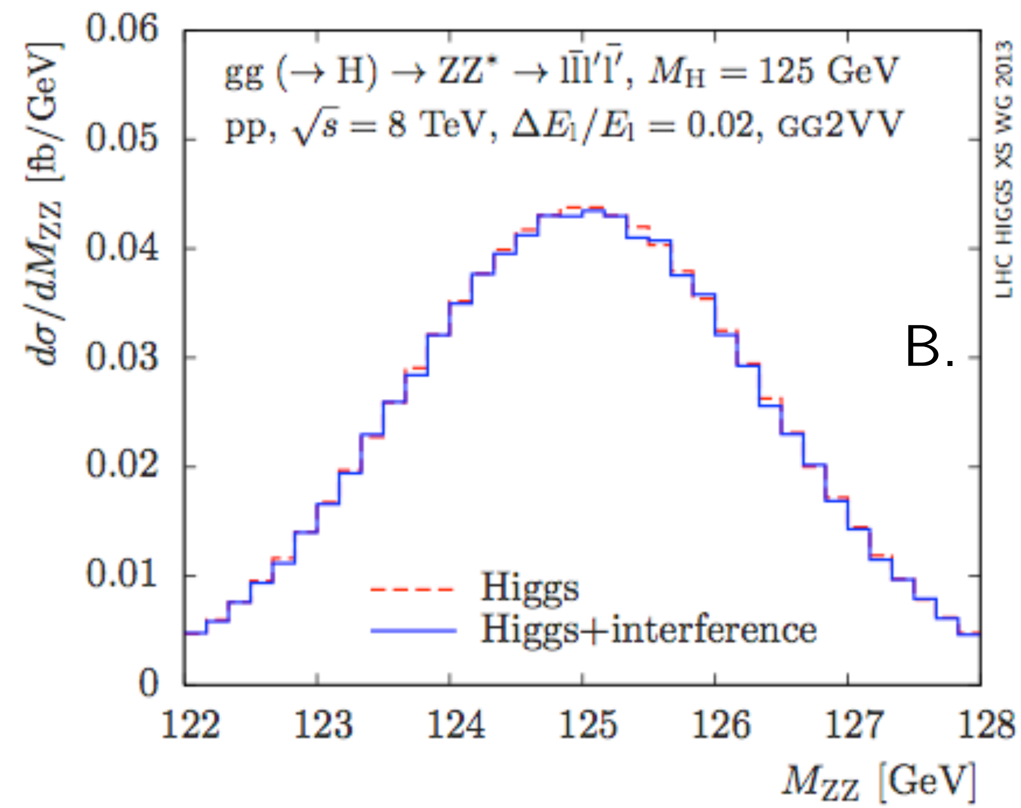
  B. At 125 GeV the SM Higgs width is way smaller than the M_{ZZ} resolution, detector effects needed (ΔE/E = 0.02 smearing to charged lepton momenta) → Any shift between S and S+I distribution is tiny compared to the bin width (167 MeV)

Effect much smaller than for H→γγ due to tree-level enhanced Higgs decay and suppressed B process for ZZ$^{(*)}$ vs γγ

G. Passarino, N. Kauer arXiv:1206.4803]



[YR3 - ggF Chapter]



Many progresses in (N)NLO Monte Carlos during the last months

Higgs signal

- POWHEG widely used for both ggF and VBF, but new **POWHEG MINLO MC** [K. Hamilton *et al.*, JHEP 10 (2012) 155 arXiv:1206.3572 arXiv:1212.4504]

  Proposal:
  - Replace current POWHEG+PY with MINLO HJ to achieve NLO in both inclusive and H+jet distributions - NNLO accuracy via weigthing
  - Use new MINLO HJJ when 2-jets are required (i.e. VBF analysis)
  - *Caveat:* no finite quark-mass effect nor HqT tune in MINLO HJ currently

- **Higgs decay with Prophecy4f can be interfaced to NLO MC** $\rightarrow$ important step towards precision Higgs physics with NLO QCD+EW corrections, interference effect, etc.

SM backgrounds

$\gamma\gamma$:	2γNNLO
V+jets:	ALPGEN, BlackHat for V+ 4-jets (V+5-jets in progress)
	SHERPA, POWHEG-MINLO for V+0,1,2-jets, MEPS@NLO
VV+jets:	POWHEG-BOX $WWjj$ (EW) - $ZZjj$?
$Vb\bar{b}$:	POWHEG-BOX $Wb\bar{b}$ - $Zb\bar{b}$

Comparisons in the YR3 NLO MC Chapter

[LHC Light Higgs Mass Subgroup interim recommendations - arXiv:1209.0040v1 [hep-ph]]

- **Purpose:** define a framework in which *either confirm* that the discovered resonance matches the properties of the SM Higgs *or establish a deviation from the SM behavior*

- **Overall assumptions:**
  - Only one underlying state, SM-like, at ~126 GeV
  - Narrow Width Approximation (NWA) $\rightarrow$ $(\sigma \cdot \mathrm{BR})(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$
  - Only modifications of coupling strengths, tensor structure of the couplings assumed to be the same as in the SM (i.e. a CP-even scalar)

No Couplings and Spin/CP common framework at present

- **Framework** to parameterize coupling dependency of measured yields $\rightarrow$ *LO coupling scale factors for partial widths (at NLO, they are modified by corrections)*

SM equivalent to all κ_i=1

$$\kappa_g^2 = \frac{\sigma_{ggH}}{\sigma_{ggH}^{\mathrm{SM}}},\ \kappa_{\mathrm{VBF}}^2,\ \kappa_W^2,\ \kappa_Z^2,\ \kappa_t^2 \quad \kappa_W^2 = \frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{\mathrm{SM}}},\ \kappa_Z^2,\ \kappa_b^2,\ \kappa_\tau^2,\ \kappa_\gamma^2,\ \kappa_{Z\gamma}^2 \quad \text{undetectable decay modes}$$

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

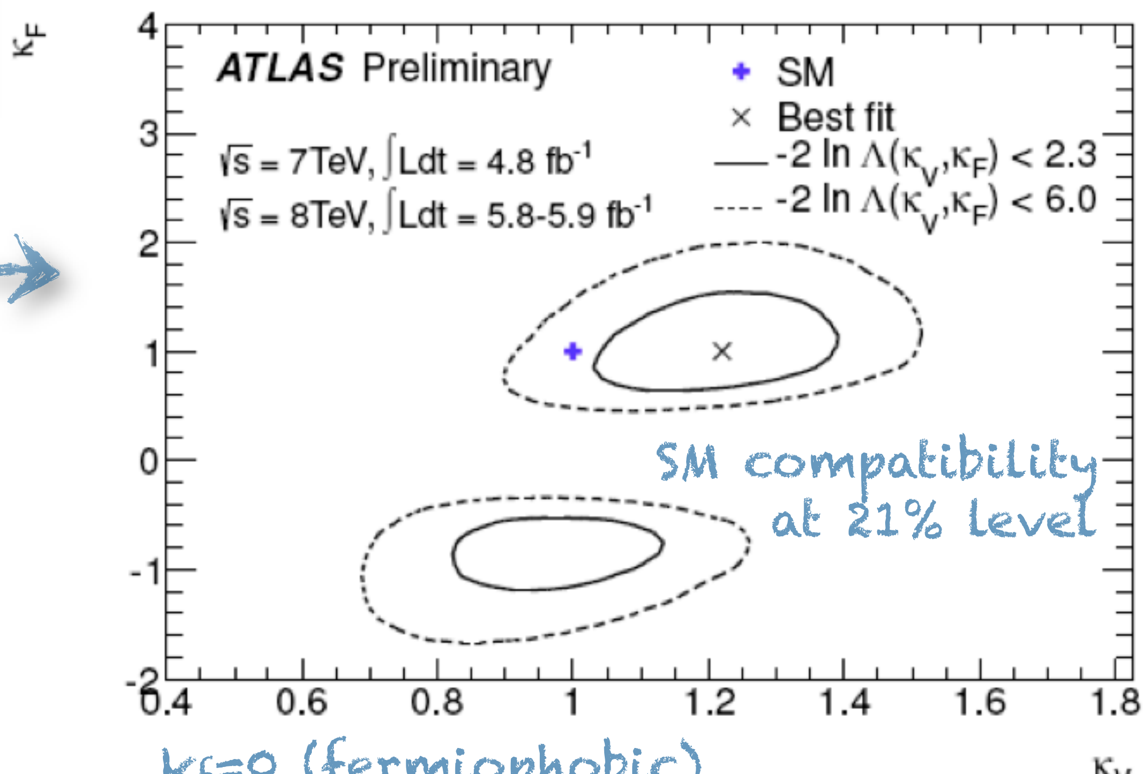
- *Total width not accessible*: observables at LHC are the ratios of scale factors $\rightarrow$ to move from measurements of the ratios to absolute coupling scale factors κ *further assumptions are needed*

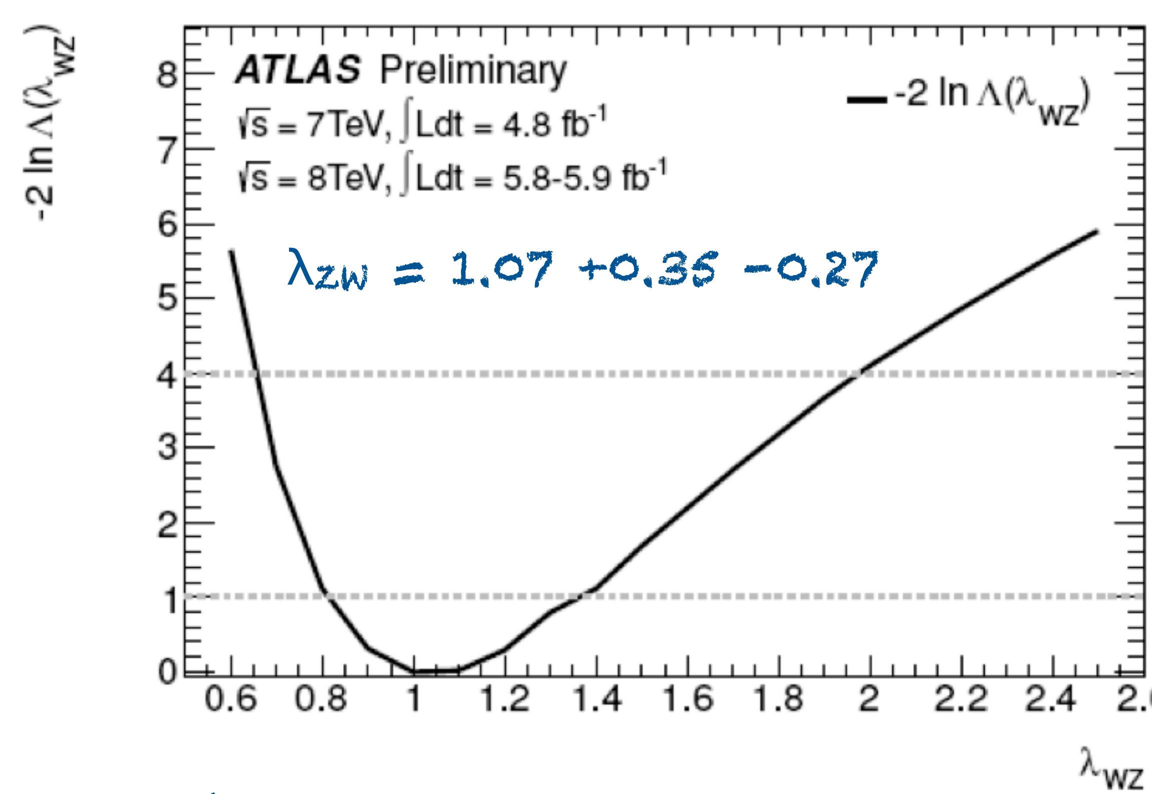
[LHC Light Higgs Mass Subgroup interim recommendations - arXiv:1209.0040v1 [hep-ph]]

Several **benchmark parameterizations** (i.e. nuisance parameters in the fit), for instance:

used by CMS and Atlas since 7/2012

1. Check the *fundamental compatibility with the SM hypothesis* $\rightarrow$ one scale factor
$$\mu = \frac{\kappa^2 \cdot \kappa^2}{\kappa^2} = \kappa^2 \Rightarrow \kappa = 1.19 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}) \pm 0.06(\text{theory})$$
2. *Assuming custodial symmetry* $\rightarrow \kappa_V, \kappa_f$ (assumption on total width and loop content)
3. *Probing custodial symmetry* $\rightarrow \lambda_{WZ} = \kappa_W/\kappa_Z$ with κ_Z and κ_f nuisance parameters
4. *Probing the fermion sector* $\rightarrow$ distinct couplings for up-type and down-type fermions or consider quark and leptons separately, etc.





k_f=0 (fermiophobic) excluded at >2σ

Within the achieved precision, all is consistent with the SM!

9. Higgs properties - Spin/Parity

The observation of the resonance in many decay modes allows for *multiple, independent tests of its tensor structure*

- Landau-Yang theorem: observation in the $H \to \gamma\gamma$ mode (+angular distributions) rules out the spin 1 hypothesis and fixes C = +1 (if no C-violating effects in the Higgs sector)
- Current data also disfavor $J^{CP} = 0^-$ and $2^{\pm}$

- Next step would be CP-mixture and CP-violation in $0^{\pm}$
  - Investigate $H \to bb$ and $H \to \tau\tau$? For fermions, CP-even and CP-odd components have the same magnitude (also Htt production, would offer a nice opportunity)
  - CP mixture with interference: which benchmark model, with which couplings?
  - Which MC tools are available? Which are the main observables? $\Delta\phi_{ZZ}$?
- Measuring J does not identify uniquely a tensor structure
  - How can we test single contributions?

H→ZZ→4l channel offers the maximum amount of information → ZZ decays and their supplements will result in a unique determination of Higgs spin/parity for pure states

- Instead on relying on specific kinematic variables, exploit the full information on the event → matrix element method, carried out with *effective Lagrangian* (MadGraph) or *anomalous couplings* (JHU, MELA/MEKD)

Review of these methods in the YR3

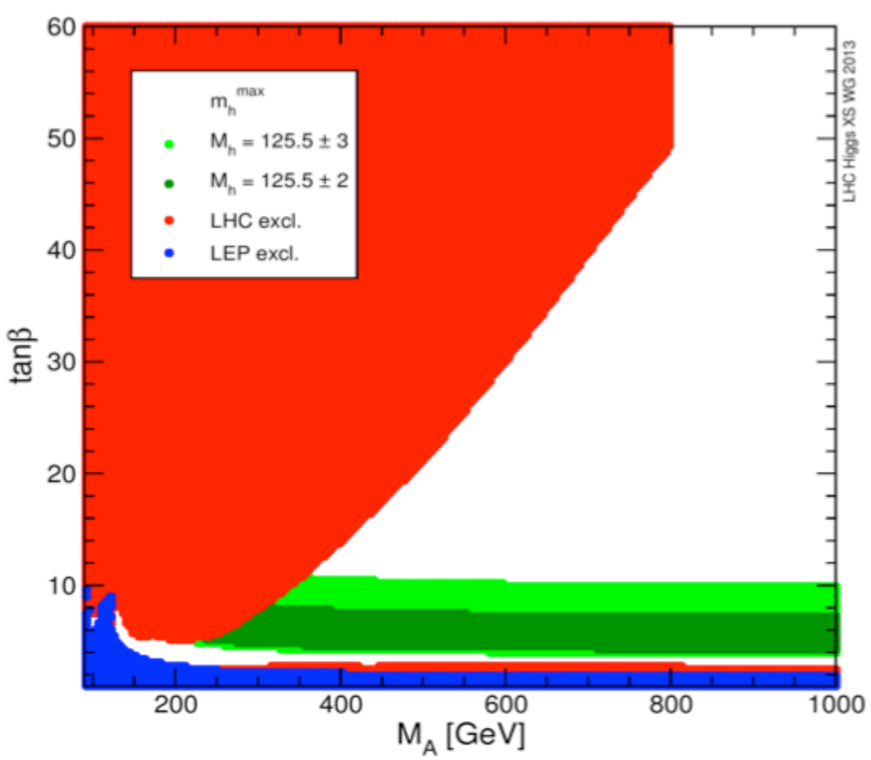
10. BSM Higgs Cross Sections

[Higgs BR, MSSM Neutral and MSSM Charged YR3 Chapters]

New benchmark scenarios for BSM Higgs searches (on the top of SM-like Higgs signal at M_H = 125 GeV) needed → currently discussed are MSSM, 2HDM, EW singlet models

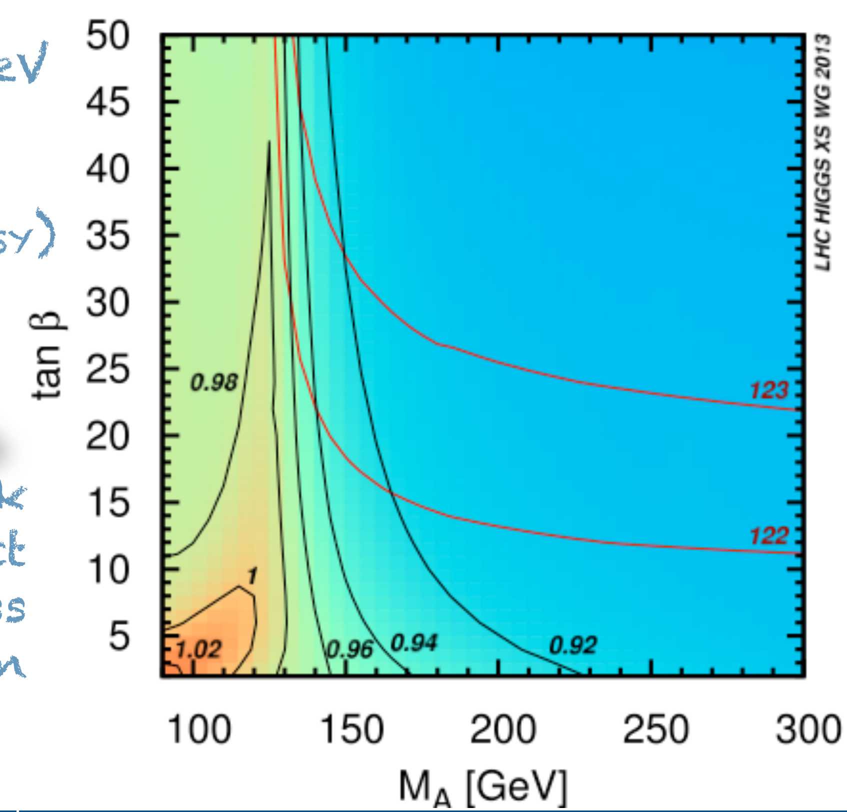
Several new benchmark **MSSM scenarios** proposed: m_h^{mod+}, m_h^{mod-}, light stop, light stau, τ-phobic Higgs, low-M_H scenarios

- Neutral Higgs cross sections (NLO QCD calculation of quark/squark contributions plus dominant NNLO QCD and NLO EW effects adapted from SM calculation)
- Charged Higgs cross sections in 4FS and 5FS, combined with Santander matching
- Theoretical uncertainties: scale variation, PDF, m_b and α_S uncertainty, evaluated according to the PDF4LHC and Higgs XS WG recommendations



MSSM if M_h = 125.5 GeV → tanβ > 4 in all benchmark scenarios (for not too high M_{SUSY})

EW and squark contribution effect (SusHi) on h cross section



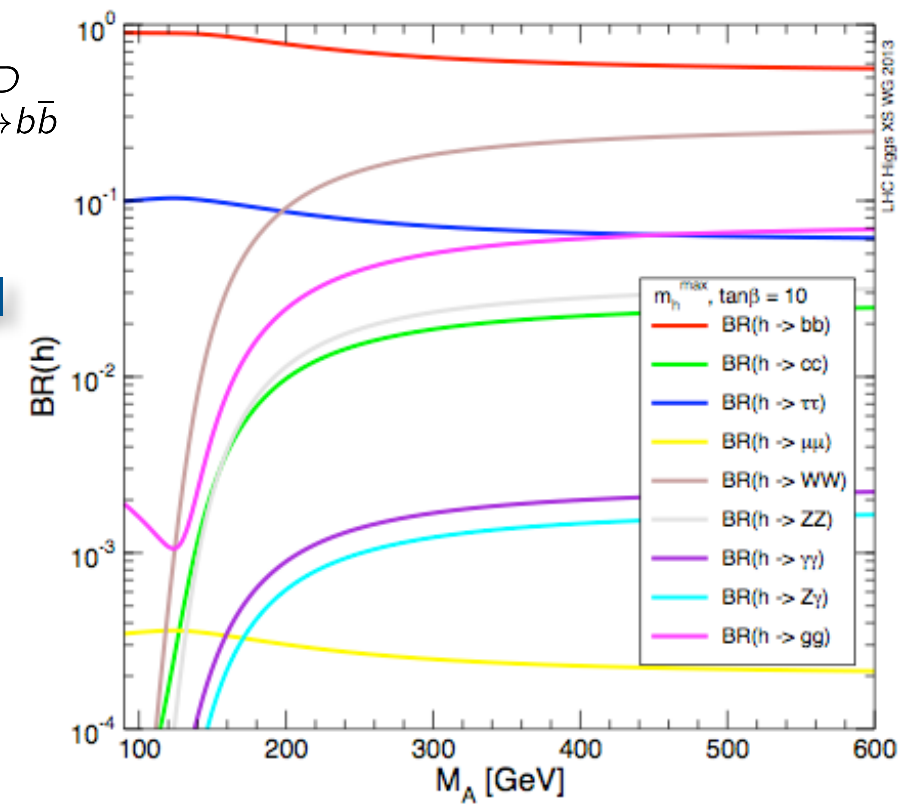
10. BSM Higgs Branching Ratios

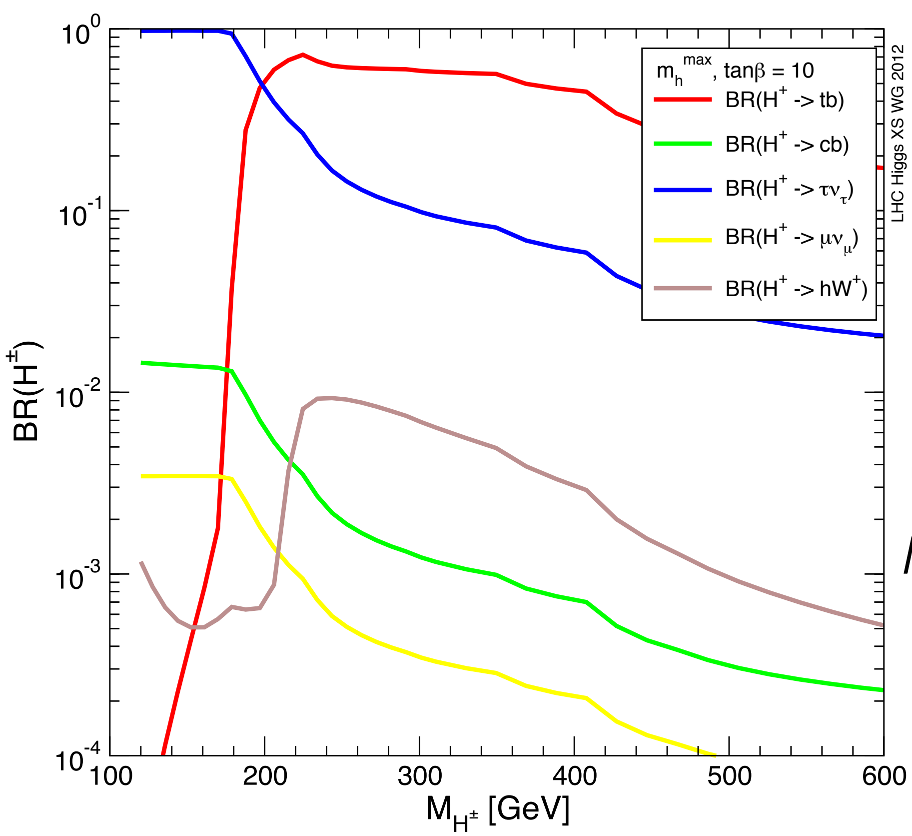
[Higgs BR, MSSM Neutral and MSSM Charged YR3 Chapters]

- As for the SM, combine calculations (HDECAY, FeynHiggs and Prophecy4f) for the best estimate

$$\Gamma_\phi = \Gamma^{FH}_{\phi\to\tau\tau} + \Gamma^{FH}_{\phi\to\mu\mu} + \Gamma^{FH/P4f}_{\phi\to W^{(*)}W^{(*)}} + \Gamma^{FH/P4f}_{\phi\to Z^{(*)}Z^{(*)}} + \Gamma^{HD}_{\phi\to b\bar{b}}$$
$$+ \Gamma^{HD}_{\phi\to t\bar{t}} + \Gamma^{HD}_{\phi\to c\bar{c}} + \Gamma^{HD}_{\phi\to gg} + \Gamma^{HD}_{\phi\to\gamma\gamma} + \Gamma^{HD}_{\phi\to Z\gamma}$$

Neutral





Charged

$$\Gamma_\phi = \Gamma^{FH}_{\phi\to\tau\nu} + \Gamma^{FH}_{\phi\to\mu\nu} + \Gamma^{FH}_{\phi\to e\nu} + \Gamma^{FH}_{\phi\to hW} + \Gamma^{FH}_{\phi\to HW} + \Gamma^{FH}_{\phi\to AW}$$
$$+ \Gamma^{HD}_{\phi\to t\bar{b}} + \Gamma^{HD}_{\phi\to t\bar{s}} + \Gamma^{HD}_{\phi\to t\bar{d}} + \Gamma^{HD}_{\phi\to c\bar{b}} + \Gamma^{HD}_{\phi\to c\bar{s}} + \Gamma^{HD}_{\phi\to c\bar{d}} + \Gamma^{HD}_{\phi\to u\bar{b}}$$
$$+ \Gamma^{HD}_{\phi\to u\bar{s}} + \Gamma^{HD}_{\phi\to u\bar{d}} + \Gamma^{FH}_{\phi\to SUSY}$$

- Results calculated in m_h^{max}, m_h^{mod+}, m_h^{mod-}, light stop, light stau and τ-phobic Higgs scenarios
- No Tables as in the SM but a code (shell script) to calculate BRs in several parameter space points for a given input choice

11. Heavy Higgs in BSM

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSMMinutes]

Determine if the 125 GeV Higgs-like particle is fully responsible for the generation of the masses - if not then additional new physics must be there to play this role

Several BSM models, compatible with the observed ~126 GeV resonance (h_1) and EW fit, predict a second 'SM-like' heavy Higgs state, h_2 (longitudinal scattering amplitude unitarization)

- Even with few reasonable assumptions (spin-0, CP-even, custodial symmetry, no FCNC), parameter space is large
- Two **benchmark models** proposed:
  - 1-parameter model (125 GeV Higgs + EW singlet) [Giardino, Kannike, Raidal, Strumia, J. Wells, ...]
  - 2-parameter model (2HDM Type I and Type II)
- **Overall assumption:** Higgs couplings modified w.r.t. SM but with the same structure, i.e. same kinematics for EW-singlet and backgrounds - for 2HDM also kinematics changes (e.g. p_T, due to the relative top/bottom loop changes)

11. Heavy Higgs in (B)SM

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSMMinutes]

First goal: exploit the possibility of a SM Higgs over the full mass range (up to 1 TeV)!

- Heavy Higgs in the SM:

1. Higgs lineshape: Breit-Wigner approximation fails - proper lineshape implemented in the Complex-Pole-Scheme [Nucl.Phys. B864 (2012) 530-579]

   $\rightarrow$ effects on both cross section and shapes [Goria, Passarino, Rosco arXiv:1112.5517 - Kauer, Passarino arXiv:1206.4803]

   Status: most of the MC implements CPS - EW corrections to be recalculated

   Alternative lineshape proposal based on effective lagrangian arXiv:1211.4835

2. Large S/B interference in gg$\rightarrow$VV for high masses [G. Passarino, arXiv:1206.3824] - full S+B+I computation available at LO only, large K-factor LO$\rightarrow$NNLO for S and I as well

   Typically σ_S and σ_B are know at different perturbative orders

   $\rightarrow$ affects cross section and lineshape for H$\rightarrow$ZZ, and also other diff distrib for H$\rightarrow$WW

   Strategy: extract I from LO MC, rescaling it to NNLO using K-factors - associate an uncertainty to the rescaling [reduction of K-factor uncertainty: M. Bonvini, F. Caola, K. Melnikov, S. Forte, G. Ridolfi, arXiv:1304.305]

   SM: it is the only complete calculation we have today

11. Heavy Higgs in BSM - SM Higgs + EW Singlet

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSMMinutes]

- Two resonances with couplings rescaled w.r.t. SM:
  - coupling of h125 (h) = $C \times$ SM
  - coupling of heavy Higgs (H) ~ $C' \times$ SM

Unitarization : $C'^2 + C^2 = 1$
[C. Grojean, K. Kumar, H.E. Logan]

One new possible BR (BR_{new}): H→hh (+new unknown decays)

- Two parameter space for each M_H hypothesis

$$\mu' = C'^2 \cdot (1 - BR_{new}) \qquad \Gamma'_{tot} = \frac{C'^2}{1 - BR_{new}} \Gamma_{SM}$$

widths different w.r.t. SM

1. Very narrow width possible for small BR_{new} and C': $C' \leq (1 - BR_{new})$ regime $\longrightarrow \leq$ SM
2. Very broad width possible for large BR_{new}: $C' > (1 - BR_{new})$ regime $\longrightarrow >$ SM

- H constrained by h observation:

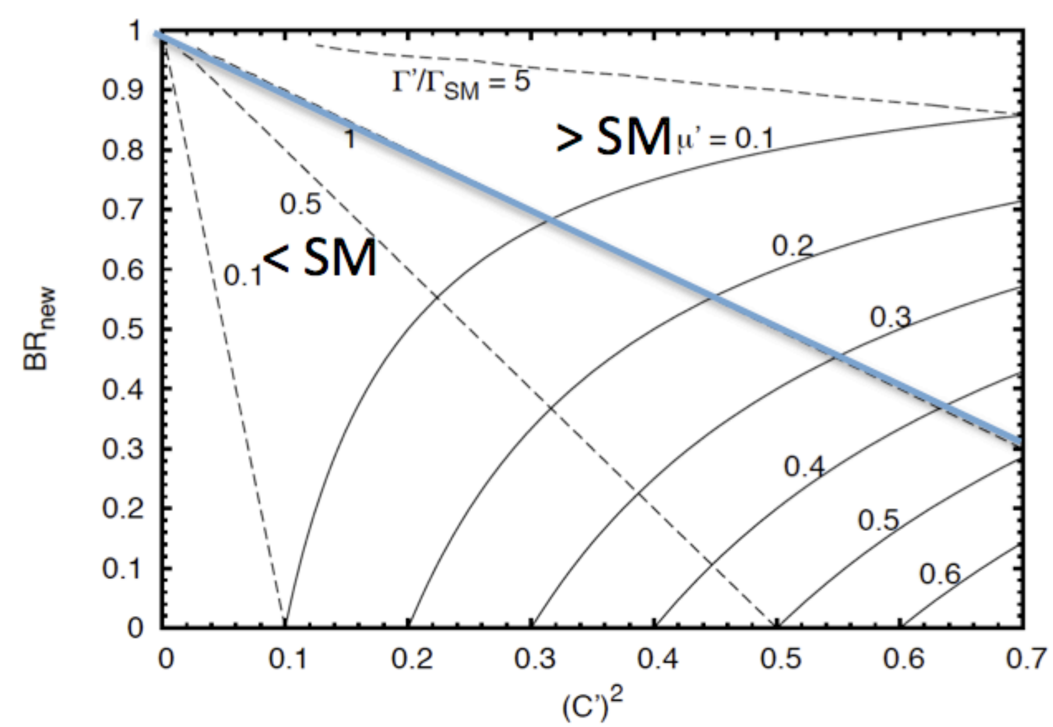
$\mu_{ATLAS} = 1.3 \pm 0.2$ $\quad \mu_{CMS} = 0.88 \pm 0.21$ (Moriond 2013)

→ taking (Gaussian) 2σ lower bound on μ:

$\mu_{ATLAS} > 0.9 \rightarrow \mu' < 0.1$ $\quad \mu_{CMS} > 0.41 \rightarrow \mu' < 0.46$

Region μ' > 0.1 excluded by ATLAS results!

Status: ATLAS starting now, CMS already published results for WW→lvqq and ZZ→2l2v



11. Heavy Higgs in BSM - 2DHM

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSMMinutes]

A simple extension of the SM is the addition of a second Higgs doublet → 5 Higgs bosons (h, H, A, $H^{\pm}$) - *is the 125 GeV resonance the lightest one?*

2HDM models classified according to the fermion coupling:

- Type I: all quarks couple to just one of the Higgs doublets → fermiophobic limit
- Type II: up and down quarks couple to different Higgs doublets (e.g. MSSM at tree level)

- Benchmark and strategies to be defined for heavy Higgs searches
- Different xsec/width rescaling for fermions/bosons
  - different kinematics w.r.t. SM (e.g. Higgs p_T) - to be checked
  - QCD corrections and uncertainties available, to be rescaled according to the modified couplings of the heavy Higgs
  - EW corrections and uncertainties need to be computed
- Once proper rescaling of couplings identified (benchmark points) → previous recipe for lineshape and interference can be adapted (hopefully just new K-factors)

Strategy: scan over M_H and $\sin(\alpha-\beta)$ plane for different $\tan\beta$ - CMS starting now, ATLAS already published results for WW→eνμν (prior to LHCHXSWG activity on this topic)

Joint effort between ATLAS/CMS and theorists from BSM LHCHXSWG
(O. Stål, H. Logan, M. Mühlleitner, H. Haber, R. Harlander, ..)

12. Summary

LHCHXSWG succeeded in having the "state of the art" TH prediction for SM and MSSM Higgs used coherently by Atlas and CMS $\rightarrow$ from "Day 0" results comparable and easy to combine

Two prominent pillars for Higgs physics at LHC for post-discovery era:

- Precision measurements on Higgs properties of couplings and spin/parity
- Direct searches for the signature of BSM Higgs on top of 125 GeV signal

Theory uncertainties are already becoming non-negligible!

- Lots of activities ongoing within the LHC Higgs XS WG and converging into the YR3 - just a selection presented here!

  https://svnweb.cern.ch/cern/wsvn/lhchiggsxs/cernrep3/trunk/YRHXS3.pdf

1. VV scattering workshop to be organized by the Heavy Higgs and BSM subgroup
Tuesday, June -July to be organized

2. Informal discussions on Higgs p_T theoretical issues to discuss common theoretical issues in HSGi
Last June 20th - https://indico.cern.ch/conferenceDisplay.py?confId=258327

3. Higgs couplings vs. mass [document by M. Spira https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SMInputParameter#MSbar_running_masses_for_the_qua]
Last June 12th - https://indico.cern.ch/conferenceDisplay.py?confId=256831

4. Dalitz decay: BR($H \to \mu\mu/ee/Z\gamma$) $\to$ signal contamination from $H \to Z\gamma \to ee+\gamma$ (from the tail of the BW) - calculation of BR($H \to ff\gamma$) with NLO EW corrections ready [G. Passarino]
Last June 12th https://indico.cern.ch/conferenceDisplay.py?confId=256830
Last May 7th https://indico.cern.ch/conferenceDisplay.py?confId=250520

5. Discussion with theorists in LHC Higgs XS WG on **ggF and VBF separation**, but also **Higgs property measurements**
June/July, to be organized with help from VBF, Jets, Light Mass and NLO MC subgroups

Backup slides

QCD Scale Uncertainty (A Different Approach)

[M. Cacciari and N. Houdeau, arXiv:1105.5152 - M. Cacciari, E. Bagnaschi, A. Guffanti, L. Jenniches, work in progress]

THU Task Force kick-off meeting April 13th https://indico.cern.ch/conferenceDisplay.py?confId=245988

Standard recipe for QCD scale uncertainty estimation:

1. Choose a central scale μ_0 and a range ξ for scale variations
2. Vary scales (possibly independently/with constraints) in this range $[\mu_0/\xi, \mu_0\xi]$
3. Determine an uncertainty band using the values of the cross sections for $\mu \in [\mu_0/\xi, \mu_0\xi]$

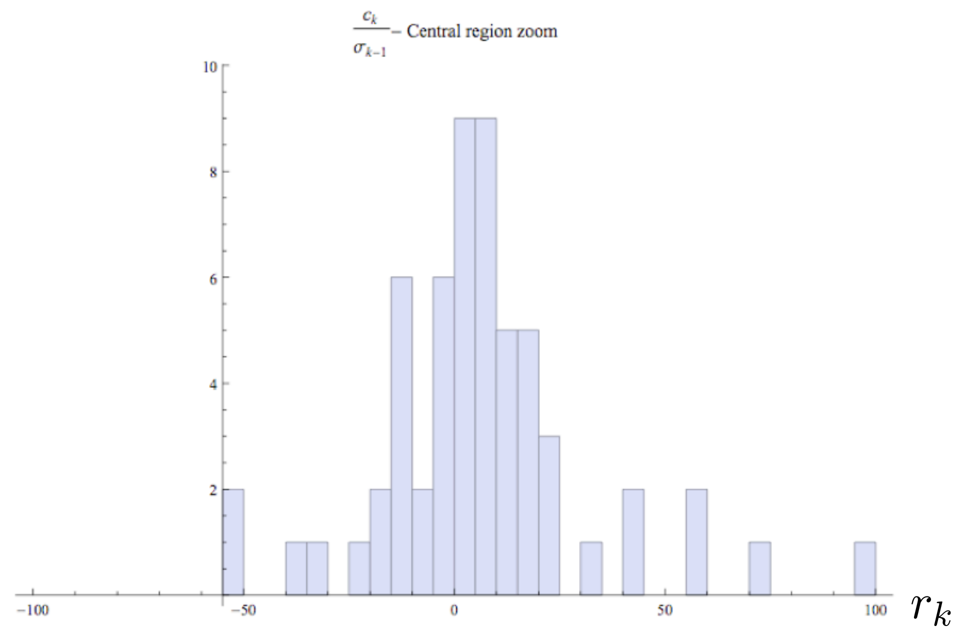
Simple, reasonable, and has served us well for 30+ years, but...

Crucial issues: What is the appropriate value for μ_0? Which ξ do we choose? What does the band mean in terms of confidence (or credibility)?

How are higher orders actually distributed?

- Select many (20+) non-hadronic observables known at least to NNLO$\rightarrow$ At NLO, 68% starts being approached for $\xi > 2.5$
- How are higher coefficient distributed?

$$r_k \equiv \frac{1}{\alpha_s^k} \frac{\sigma_k - \sigma_{k-1}}{\sigma_{k-1}} = \frac{c_k}{\sigma_{k-1}}$$

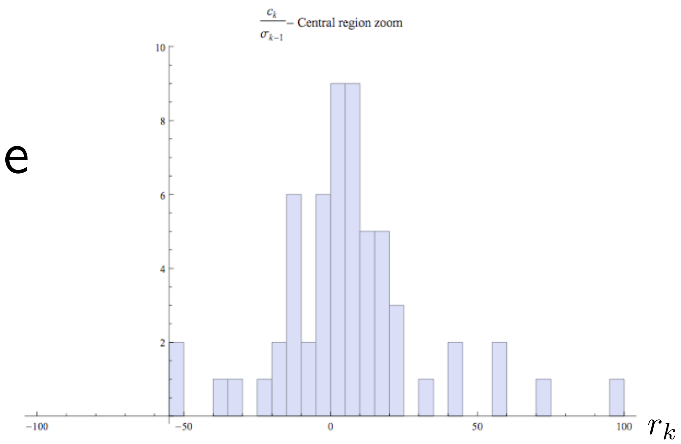


Certainly not a box (e.g. with size given by the scale variation band), likely not a Gaussian (with sigma related to the scale variation band)

QCD Scale Uncertainty (A Different Approach)

[M. Cacciari and N. Houdeau, arXiv:1105.5152 - M. Cacciari, E. Bagnaschi, A. Guffanti, L. Jenniches, work in progress]

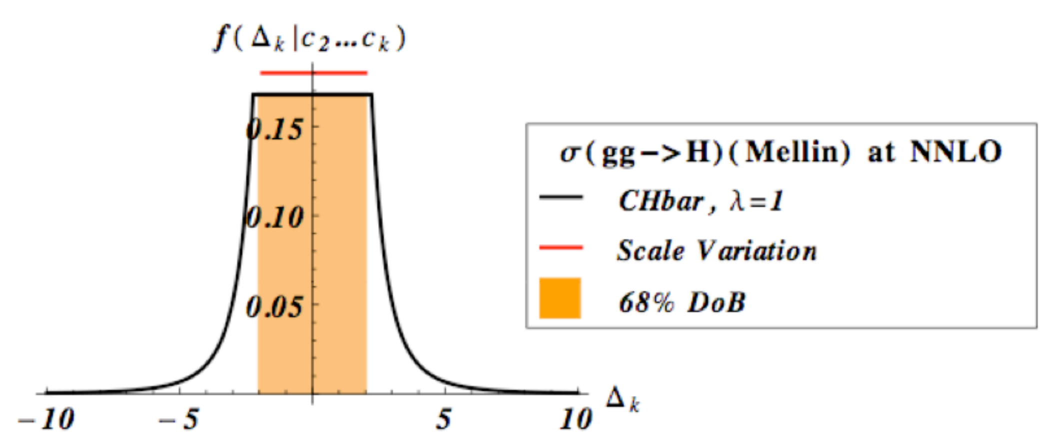
- It could look like a *roughly flat top with falling tails*
  - *Flat top* is justified by higher order corrections that are often sizable but with no typical preferred value
  - *Falling tails* account for the fact that huge higher order corrections tend to be rare



Method to systematize the derivation of a reasonable uncertainty profile for perturbative calculations by estimating the degree of belief of given intervals of the reminder of a perturbative series → *Bayesian model* containing the hypothesis that scale variations effectively takes the last calculated perturbative order and adds an α_s (and some coefficients), but where *all priors are made explicit*

- Assume that all coefficients c_k in a perturbative expansion of the form $\sigma = \Sigma\, \alpha_s^k\, c_k$ have similar size → this leads to the credibility profile for the uncertainty Δ_k, $f(\Delta_k \mid c_l, \ldots c_k)$ and to *p%-credible intervals*

Credibility distribution shares characteristics with both the log-normal distribution (tails) and the flat one (in the central region)



A Different ('Meaningful') Approach

[M. Cacciari and N. Houdeau, arXiv:1105.5152]

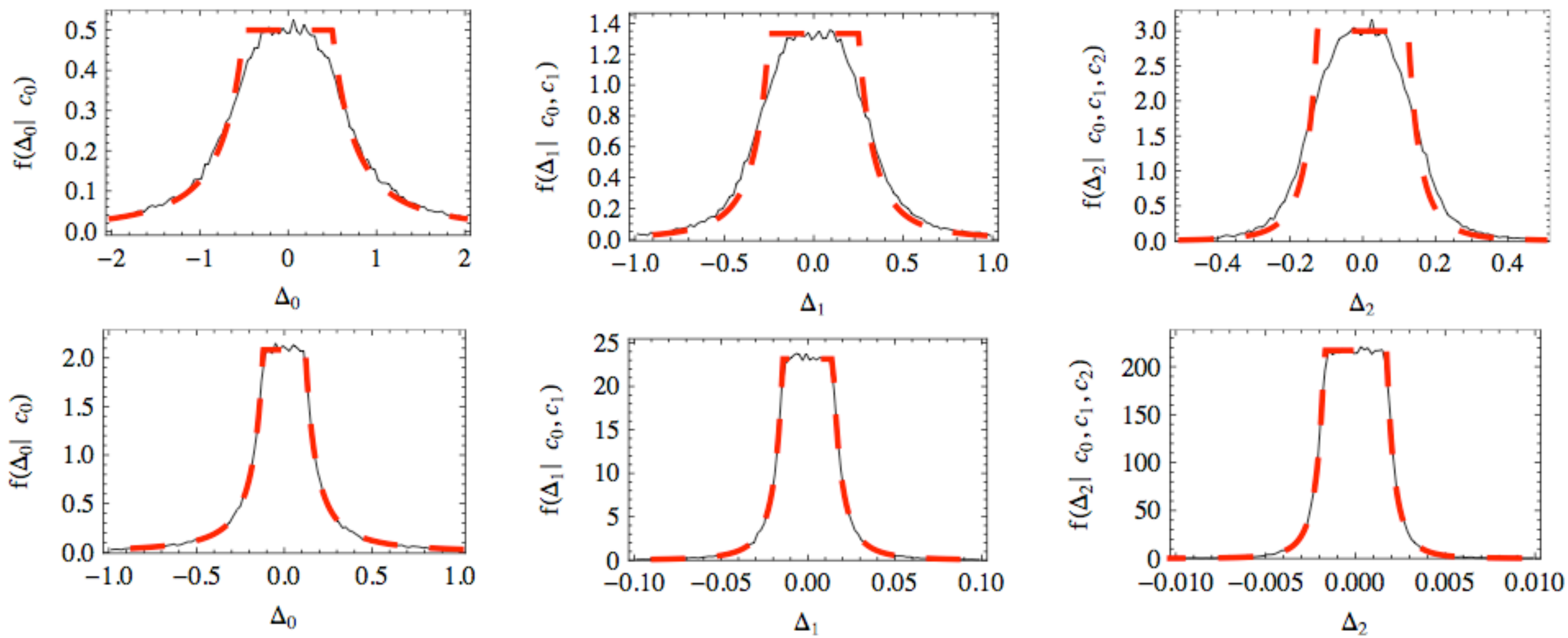


Figure 2: Numerical estimates of the exact densities $f(\Delta_k|c_0,\ldots,c_k)$ (continuous curves) and their analytical approximations in eq. (34) (dashed curves) in the case $\bar{c}_{(k)} = 1$ for $k = 0$ (left), $k = 1$ (middle), and $k = 2$ (right), for $\alpha_s = 0.5$ (top row) and $\alpha_s = 0.12$ (bottom row). These numerical estimates are computed by integrating over the distributions for 10 unknown coefficients, the results being stable when using more. Using values of α_s of the order of 0.2 or 0.3 does not degrade significantly the quality of the approximation seen here in the $\alpha_s = 0.12$ case.

PDF4LHC recipe in short

[http://www.hep.ucl.ac.uk/pdf4lhc/]

- **CTEQ6L1 (7 TeV) or CT10 (8 TeV)**

$$\sigma^{CTEQ}(\alpha_S + PDF, \pm) = \sqrt{(\sigma^{CTEQ}(PDF, \pm))^2 + (\sigma^{CTEQ}(\alpha_S, \pm))^2}$$

where $\sigma^{CTEQ}(\alpha_S, \pm) = (\mathcal{O}_{\alpha_S}^{(\pm)} - \mathcal{O}_0) \cdot \frac{6}{5}$

All the uncertainties are rescaled to 68% C.L.

- **MSTW2008**

$$\sigma^{MSTW}(\alpha_S + PDF, \pm) = \sqrt{(\sigma^{MSTW}(PDF, \pm))^2 + (\sigma^{MSTW}(\alpha_S, \pm))^2}$$

where $\sigma^{MSTW}(\alpha_S, +) = (\mathcal{O}_{\alpha_S}^{(+)} - \mathcal{O}_0), \sigma^{MSTW}(\alpha_S, -) = (\mathcal{O}_{\alpha_S}^{(-)} - \mathcal{O}_0) \cdot \frac{4}{5}$

- **NNPDF2.0 (7 TeV) or NNPDF2.1 (8 TeV)**

Central value: $\mathcal{O}_0 = \frac{1}{N_{rep}} \Sigma_{j=1}^{N_\alpha} \Sigma_{k_j=1}^{N_{rep}^{\alpha^{(j)}}} \mathcal{O}(PDF^{(k_j,j)}, \alpha_S^{(j)})$

Standard Dev: $\sigma^{NNPDF}(\alpha_S + PDF) = \left[\frac{1}{N_{rep} - 1} \Sigma_{j=1}^{N_\alpha} \Sigma_{k_j=1}^{N_{rep}^{\alpha^{(j)}}} (\mathcal{O}(PDF^{(k_j,j)}, \alpha_S^{(j)}) - \mathcal{O}_0)^2 \right]^{1/2}$

- **Envelope at NLO** (i = CTEQ, MSTW2008, NNPDF)

$$U = \max_i \{\mathcal{O}_0^i + \sigma^{(i)}(\alpha_S + PDF, +)\}, L = \min_i \{\mathcal{O}_0^i - \sigma^{(i)}(\alpha_S + PDF, -)\}, M = (U + L)/2$$

- **Envelope at NNLO** calculated by the MSTW-NNLO α_S+PDF band, multiplied by a rescaling factor obtained from NLO envelope

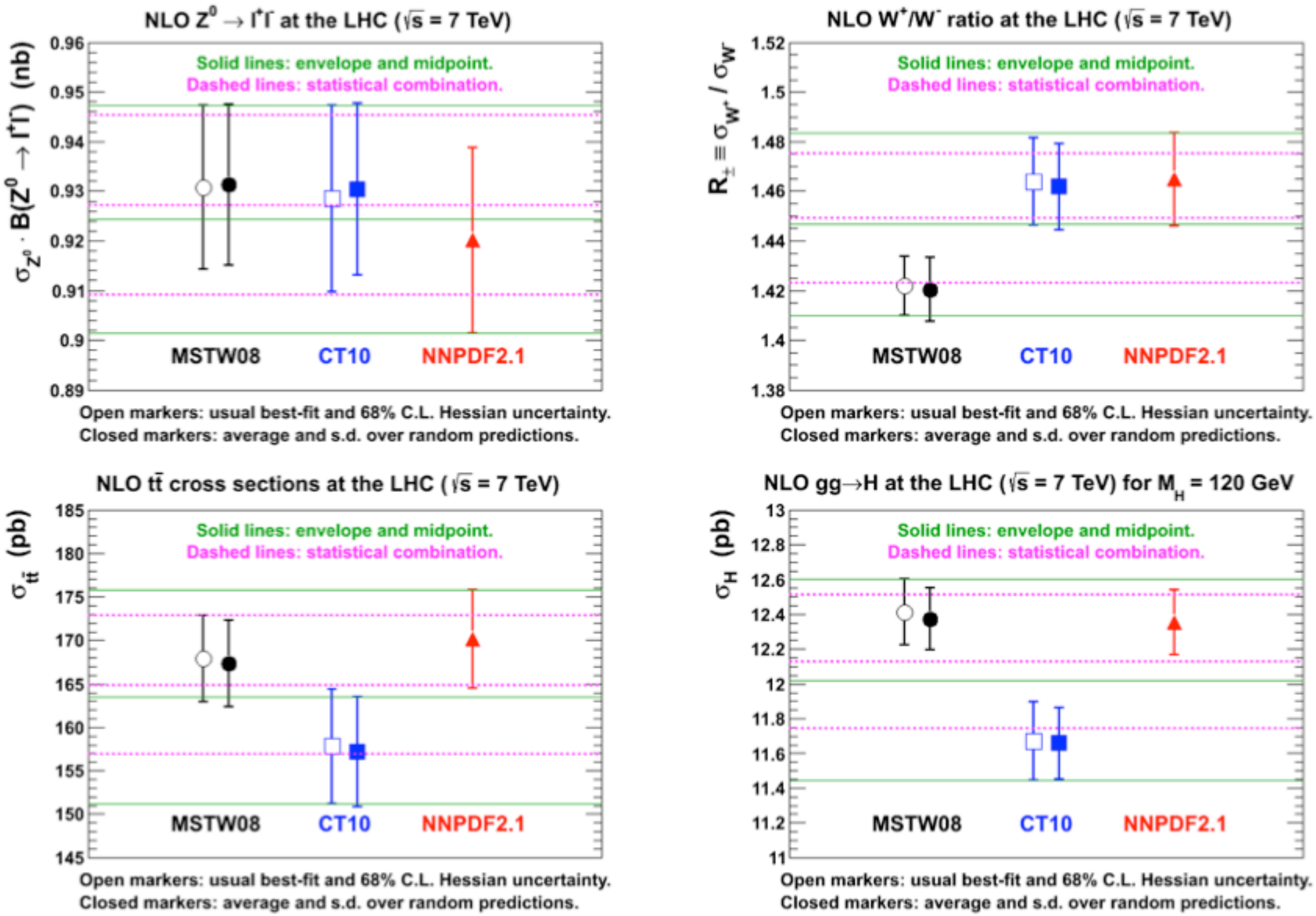
PDF Benchmarking

[J. Rojo and A. Guffanti - PDF4LHC Meeting Oct 8, 2012]

	DATASET	PERT. ORDER	HQ TREATMENT	α_s	PARAM.	UNCERT.
ABM11	DIS Drell-Yan	NLO NNLO	FFN (BMSN)	Fit (multiple values available)	6 indep. PDFs Polynomial (25 param.)	Hessian ($\Delta\chi^2$=1)
CT10	Global	LO NLO NNLO	GM-VFNS (S-ACOT)	External (multiple values available)	6 indep. PDFs Polynomial (26 param.)	Hessian ($\Delta\chi^2$=100)
JR09	DIS Drell-Yan Jets	NLO NNLO	FFN VFN	Fit	5 indep. PDFs Polynomial (15 param.)	Hessian ($\Delta\chi^2$=1)
HERAPDF1.5	DIS (HERA)	NLO NNLO	GM-VFNS (TR)	External (multiple values available)	5 indep. PDFs Polynomial (14 param.)	Hessian ($\Delta\chi^2$=1)
MSTW08	Global	LO NLO NNLO	GM-VFNS (TR)	Fit (multiple values available)	7 indep. PDFs Polynomial (20 param.)	Hessian ($\Delta\chi^2$~25)
NNPDF2.1/2.3	Global	LO NLO NNLO	GM-VFNS (FONLL)	External (multiple values available)	7 indep. PDFs Neural Nets (259 param.)	Monte Carlo

[R. Thorne - PDF4LHC Meeting Oct 8, 2012]

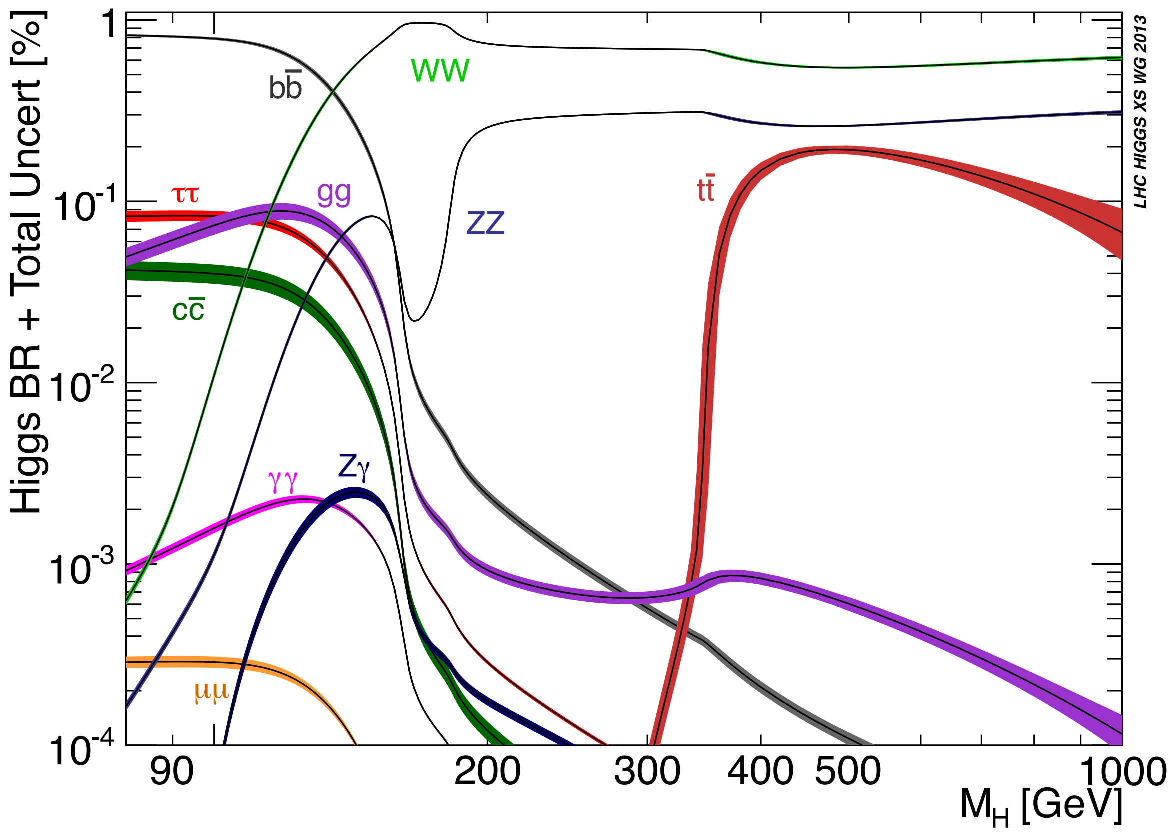
Can combine different PDF sets, e.g. comparison to PDF4LHC prescription.



Smaller uncertainty and shifted central value if disagreement between individual predictions. (Plots by G. Watt at http://mstwpdf.hepforge.org/random/).

Total BR Uncertainties

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs and Eur. Phys. J. C 71, 1753 (2011)]



$M_H = 126$ GeV			
Decay	THU [%]	PU [%]	Total [%]
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	$\pm$ 1.9	± 3.3
$H \to \tau\tau$	± 3.5	± 2.1	± 5.6
$H \to WW$	± 2.0	± 2.2	± 4.1
$H \to ZZ$	± 2.0	± 2.2	± 4.2

Similar Tables provided also to the Higgs Tevatron WG

Total Uncertainties on BRs for $M_H < 200$ GeV			
$H \to b\bar{b}$	O(3-4%)	$H \to \tau\tau$	O(3-6%)
$H \to c\bar{c}$	O(10-13%) (*)	$H \to gg$	O(15-17%) (**)
$H \to WW$	below 1% for $M_H > 150$ GeV	$H \to ZZ$	below 1% for $M_H > 150$ GeV

Total Uncertainties on BRs for $M_H > 200$ GeV			
$H \to WW$	O(2%) for $M_H > 360$ GeV	$H \to ZZ$	O(2%) for $M_H > 350$ GeV
$H \to t\bar{t}$	O(40-50%) for $260 < M_H < 380$ GeV, O(200%) for $M_H \approx 2m_t$ (*)		
	below 10% for $M_H < 800$ GeV (**)		

(*) parametric errors dominant (**) theoretical errors dominant

TU Estimation Baselines

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs and Eur. Phys. J. C 71, 1753 (2011)]

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%

(*) HDECAY + Prophecy4f uncertainties on the Higgs partial widths

- **Comments**:
  - QCD corrections: variation of the Higgs widths from a scale change by factor 2 and 1/2
  - EW corrections: missing HO estimation based on the known structure and size of the NLO corrections
  - For $M_H > 500$ GeV: higher-order heavy-Higgs corrections dominate error
  - Different uncertainties on a given channel added linearly

BR Uncertainties: YR2 vs YR3

Small inconsistencies **only affecting the BR uncertainties** (NOT the BR central values) have been spotted out and removed in the YR3:

- THU for bb and cc channels has been set to zero for $M_H > 135$ GeV $\rightarrow$ in the YR3 they are set to 2% over all the mass range (this uncertainty might be even bigger, but we assume that bb will not be relevant above 135 GeV)
- THU for WW and ZZ channels got calculated with an additional contribution entering the tt channel as if high mass EW corrections were not only included in WW/ZZ (but actually they are included in HDECAY)
- THU for tt channel for $M_H < 500$ GeV set to 5+2 = 7%, while the table stated 5% for the total uncertainty $\rightarrow$ in YR3 5% is assumed as total uncertainty (QCD uncertainties are significantly *smaller* than 5% above the threshold - the 5% only originate from the uncertainties in the vicinity of the threshold and are a conservative upper bound $\rightarrow$ this is the reason, why we took a 5% error overall)

How to take into account BR Uncert

1. Work with BR uncertainties
   - One has to take care of anti-correlation arising from ΣBR=1 $\rightarrow$ current LHC Higgs combination framework does not allow partial anti-correlation but 100% +correlation or no-correlation only

2. Work with Higgs decay partial width
   - Work with the partial decay width uncertainty
   - Correlations are automatically taken into account

PU: 1 nuisance parameter
TU: 5 (6) nuisance parameters
H→ff, tt, gg, γγ, (Zγ) and WW/ZZ
[proposal by A. Denner, A. Korytov]

3. Work with Higgs coupling uncertainty
   - While partial widths are well-defined, this does not apply to couplings beyond LO
   - One has to agree on a definition of the couplings - then there are uncertainties that cannot be attributed to the couplings. etc.

Live discussions in Low Mass Higgs subgroup in LHC Higgs XS WG

☞ **Suggestion is to adopt approach 2.** (work in progress)

Higgs width Tables provided by the LHC Higgs BR subgroup

CMS already adopted this prescription for their SM4 results - ATLAS used ±5% BR uncertainty for Higgs discovery paper

BR Uncertainty Prescription

[A. Denner, A. Korytov]

1. Nuisance parameters

a) Parametric Uncertainty: *only 1 nuisance parameter*

- $H \to bb$ is the dominant source of the uncertainty
- m_c, m_b, m_t and α_s uncertainties could be added in quadrature

b) Theory Uncertainty: *5 (6) nuisance parameters*

- $H \to ff$, tt, gg, $\gamma\gamma$, ($Z\gamma$) and WW/ZZ

- Construct nuisance parameters in analogy to QCD scale and PDF uncertainties

2. Tables [Reference: BR paper Eur. Phys. J. C 71, 1753 (2011), Table 14]

- Prepare full list of Γ_i and $d\Gamma_i$ as a function of M_H
- Convert it into dBR_i/BR_i with $BR=\Gamma_i/\Sigma\Gamma_j$
- Symmetrize the uncertainty by either max|+err,-err| or $\sqrt{(1+err)/(1-err)} - 1$

Higgs width Tables provided by the LHC Higgs BR subgroup to the LHC Higgs Combination WG

☞ *Suggestion was to take into account BR uncertainties with this prescription after ICHEP: it is work in progress (ATLAS used ±5% BR uncertainty for Higgs discovery paper)*

BR Nuisance Parameters

[Table 14 from BR paper Eur. Phys. J. C 71, 1753 (2011), proposal by A. Korytov]

Table 14 SM Higgs branching ratios and their relative parametric (PU), theoretical (TU) and total uncertainties for a selection of Higgs masses. For PU, all the single contributions are shown. For these four columns, the upper percentage value (with its sign) refers to the positive variation of the parameter, while the lower one refers to the negative variation of the parameter. Results for the full mass range, including the total uncertainties, are listed in tables at the end of the document

Channel	M_H [GeV]	BR	Δm_c	Δm_b	Δm_t	$\Delta\alpha_s$		PU	TU		Total
$H \to b\bar{b}$	120	6.48E−01	−0.2% +0.2%	+1.1% −1.2%	+0.0% −0.0%	−1.0% +0.9%		+1.5% −1.5%	+1.3% −1.3%		+2.8% −2.8%
	150	1.57E−01	−0.1% +0.1%	+2.7% −2.7%	+0.1% −0.1%	−2.2% +2.1%		+3.4% −3.5%	+0.6% −0.6%		+4.0% −4.0%
	200	2.40E−03	−0.0% +0.0%	+3.2% −3.2%	+0.0% −0.1%	−2.5% +2.5%		+4.1% −4.1%	+0.5% −0.5%		+4.6% −4.6%
	500	1.09E−04	−0.0% +0.0%	+3.2% −3.2%	+0.1% −0.1%	−2.8% +2.8%		+4.3% −4.3%	+3.0% −1.1%		+7.2% −5.4%
$H \to \tau^+\tau^-$	120	7.04E−02	−0.2% +0.2%	−2.0% +2.1%	+0.1% −0.1%	+1.4% −1.3%		+2.5% −2.4%	+3.6% −3.6%		+6.1% −6.0%
	150	1.79E−02	−0.1% +0.1%	−0.5% +0.5%	+0.1% −0.1%	+0.3% −0.3%		+0.6% −0.6%	+2.5% −2.5%		+3.0% −3.1%
	200	2.87E−04	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.1%	+0.0% −0.0%	1	+0.0% −0.1%	+2.5% −2.5%	1	+2.5% −2.6%
	500	1.53E−05	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.1%	−0.1% +0.0%		+0.1% −0.1%	+5.0% −3.1%		+5.0% −3.2%
$H \to \mu^+\mu^-$	120	2.44E−04	−0.2% +0.2%	−2.0% +2.1%	+0.1% −0.1%	+1.4% −1.3%		+2.5% −2.5%	+3.9% −3.9%		+6.4% −6.3%
	150	6.19E−05	−0.0% +0.0%	−0.5% +0.5%	+0.1% −0.1%	+0.3% −0.3%		+0.6% −0.6%	+2.5% −2.5%		+3.1% −3.2%
	200	9.96E−07	−0.0% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+0.0% −0.0%		+0.1% −0.1%	+2.5% −2.5%		+2.6% −2.6%
	500	5.31E−08	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.1%	−0.0% +0.0%		+0.1% −0.1%	+5.0% −3.1%		+5.1% −3.1%
$H \to c\bar{c}$	120	3.27E−02	+6.0% −5.8%	−2.1% +2.2%	+0.1% −0.1%	−5.8% +5.6%		+8.5% −8.5%	+3.8% −3.7%		+12.2% −12.2%
	150	7.93E−03	+6.2% −6.0%	−0.6% +0.6%	+0.1% −0.1%	−6.9% +6.8%		+9.2% −9.2%	+0.6% −0.6%		+9.7% −9.7%
	200	1.21E−04	+6.2% −6.1%	−0.2% +0.1%	+0.1% −0.2%	−7.2% +7.2%		+9.5% −9.5%	+0.5% −0.5%		+10.0% −10.0%
	500	5.47E−06	+6.2% −6.0%	−0.1% +0.1%	+0.1% −0.1%	−7.6% +7.6%		+9.8% −9.7%	+3.0% −1.1%		+12.8% −10.7%
$H \to t\bar{t}$	350	1.56E−02	+0.0% +0.0%	−0.0% +0.0%	−78.6% +120.9%	+0.9% −0.9%		+120.9% −78.6%	+6.9% −12.7%		+127.8% −91.3%
	360	5.14E−02	−0.0% −0.0%	−0.0% +0.0%	−36.2% +35.6%	+0.7% −0.7%		+35.6% −36.2%	+6.6% −12.2%		+42.2% −48.4%
	400	1.48E−01	+0.0% +0.0%	−0.0% +0.0%	−6.8% +6.2%	+0.4% −0.3%		+6.2% −6.8%	+5.9% −11.1%	2	+12.2% −17.8%
	500	1.92E−01	−0.0% +0.0%	−0.0% +0.0%	−0.3% +0.1%	+0.1% −0.2%		+0.1% −0.3%	+4.5% −9.5%		+4.6% −9.8%

Numbers refer to nuisance parameter #

BR Nuisance Parameters

[Table 14 from BR paper Eur. Phys. J. C 71, 1753 (2011), proposal by A. Korytov]

H → gg	120	8.82E−02	−0.2% +0.2%	−2.2% +2.2%	−0.2% +0.2%	+5.7% −5.4%	+6.1% −5.8%	+4.5% −4.5%	+10.6% −10.3%
	150	3.46E−02	−0.1% +0.1%	−0.7% +0.6%	−0.3% +0.3%	+4.4% −4.2%	+4.4% −4.3%	+3.5% −3.5%	+7.9% −7.8%
	200	9.26E−04	−0.0% −0.0%	−0.1% +0.1%	−0.6% +0.6%	+3.9% −3.8%	+3.9% −3.9%	+3.7% −3.7%	+7.6% −7.6%
	500	6.04E−04	−0.0% +0.0%	−0.0% +0.0%	+1.6% −1.6%	+3.4% −3.3%	+3.7% −3.7%	+6.2% −4.3%	+9.9% −7.9%
H → γγ	120	2.23E−03	−0.2% +0.2%	−2.0% +2.1%	+0.0% +0.0%	+1.4% −1.3%	+2.5% −2.4%	+2.9% −2.9%	+5.4% −5.3%
	150	1.37E−03	+0.0% +0.1%	−0.5% +0.5%	+0.1% −0.0%	+0.3% −0.3%	+0.6% −0.6%	+1.6% −1.5%	+2.1% −2.1%
	200	5.51E−05	−0.0% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+0.0% −0.0%	+0.1% −0.1%	+1.5% −1.5%	+1.6% −1.6%
	500	3.12E−07	−0.0% +0.0%	−0.0% +0.0%	+8.0% −6.5%	−0.7% +0.7%	+8.0% −6.6%	+4.0% −2.1%	+11.9% −8.7%
H → Zγ	120	1.11E−03	−0.3% +0.2%	−2.1% +2.1%	+0.0% −0.1%	+1.4% −1.4%	+2.5% −2.5%	+6.9% −6.8%	+9.4% −9.3%
	150	2.31E−03	−0.1% +0.0%	−0.6% +0.5%	+0.0% −0.1%	+0.2% −0.3%	+0.5% −0.6%	+5.5% −5.5%	+6.0% −6.2%
	200	1.75E−04	−0.0% −0.0%	−0.0% +0.0%	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.1%	+5.5% −5.5%	+5.5% −5.6%
	500	7.58E−06	−0.0% +0.0%	−0.0% +0.0%	+0.8% −0.6%	−0.0% +0.0%	+0.8% −0.6%	+8.0% −6.1%	+8.7% −6.7%
H → WW	120	1.41E−01	−0.2% +0.2%	−2.0% +2.1%	−0.0% +0.0%	+1.4% −1.4%	+2.5% −2.5%	+2.2% −2.2%	+4.8% −4.7%
	150	6.96E−01	−0.1% +0.1%	−0.5% +0.5%	−0.0% +0.0%	+0.3% −0.3%	+0.6% −0.6%	+0.3% −0.3%	+0.9% −0.8%
	200	7.41E−01	−0.0% −0.0%	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%
	500	5.46E−01	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+2.3% −1.1%	+2.4% −1.1%
H → ZZ	120	1.59E−02	−0.2% +0.2%	−2.0% +2.1%	−0.0% +0.0%	+1.4% −1.4%	+2.5% −2.5%	+2.2% −2.2%	+4.8% −4.7%
	150	8.25E−02	−0.1% +0.1%	−0.5% +0.5%	+0.0% +0.0%	+0.3% −0.3%	+0.6% −0.6%	+0.3% −0.3%	+0.9% −0.8%
	200	2.55E−01	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%
	500	2.61E−01	+0.0% −0.0%	−0.0% +0.0%	+0.0% +0.0%	−0.0% +0.0%	+0.1% −0.0%	+2.3% −1.1%	+2.3% −1.1%

Numbers refer to nuisance parameter #

Theoretical Errors on Couplings

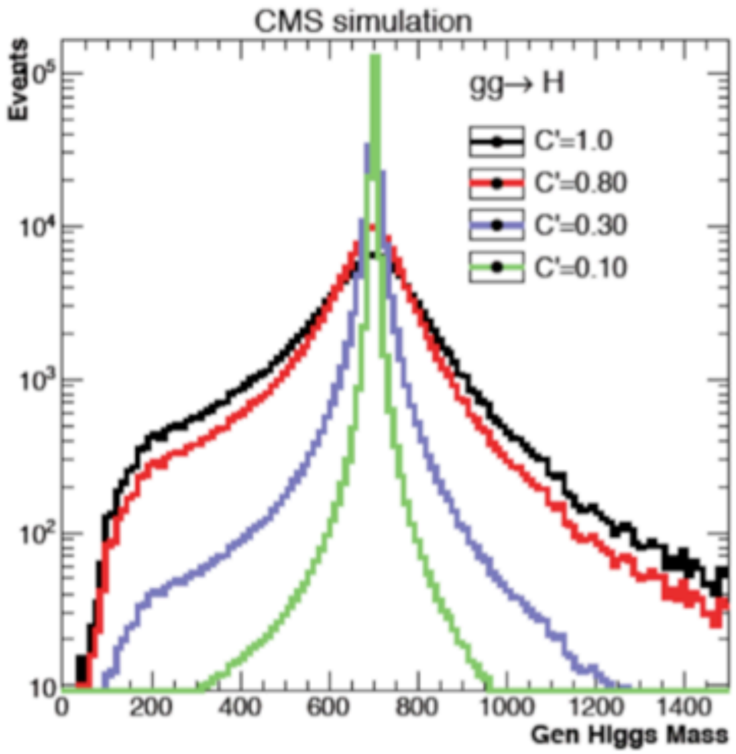
[arXiv:1209.0040v1 [hep-ph] and Light Mass Higgs Subgroup recent Meetings]

- *Same theoretical uncertainty treatment as for the Higgs discovery*:
  - Cross section uncertainties from LHC Higgs XS WG TWiki
  - BR uncertainties from LHC Higgs XS WG TWiki - for now still the 'old' BR uncertainties used by both ATLAS and CMS, but for HCP this should/will be updated to Denner&Korytov's proposal
  - Theory jet bin uncertainties (for the signal) according to the *Stewart&Tackmann method* (consider inclusive H+jet(s) cross sections σ_{total} , $\sigma{\geq}1$, $\sigma{\geq}2$ ... and treat them as uncorrelated)
- TU currently implemented as log-normal PDFs
- Uncertainty on Higgs p_T shape under discussion with theorists

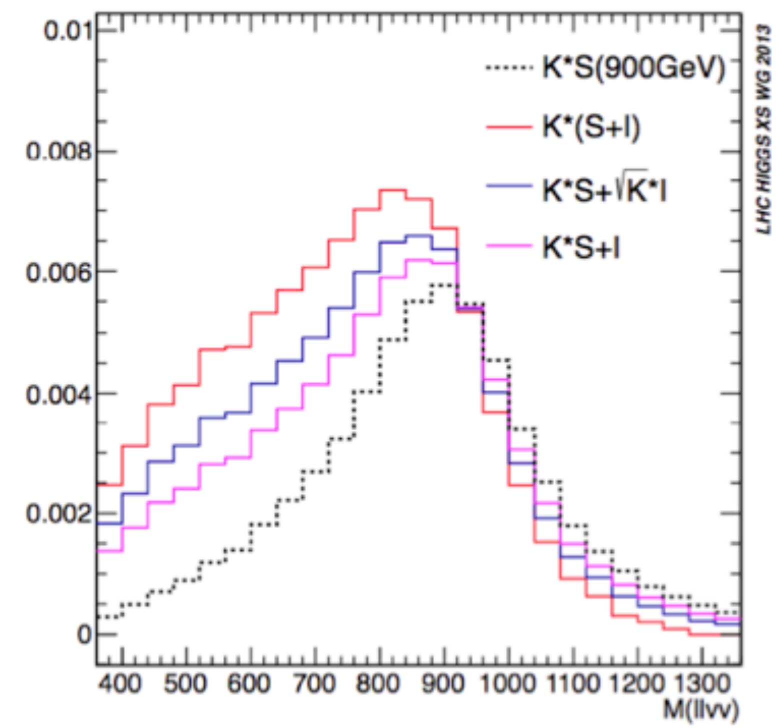
Discussion ongoing [Informal discussions on Higgs property measurements, Oct 3 2012 https://indico.cern.ch/conferenceDisplay.py?confId=211324]

- How to reduce the theory uncertainties? Currently O(10%) for both QCD scale and PDF in ggF (VBF, VH are much smaller)
- QCD scale uncertainty reduction by NNNLO calculation in ggF near future?
- PDF prediction improvements with precision LHC data? (PDF4LHC)?

Complex Pole Scheme and Interference



From the SM MC simulation,
The events are rescaled for a smaller
Width   C\`=Γ\`/Γ.



If the couplings of the new state to vector bosons are of similar nature as h(126):

– Interference is expected with the VV continuum
– Expect destructive (constructive) interference above (below)mass pole
– Simple re-scaling of the interference effects:

$$(\mu+I)_{BSM}=\mu_{SM}\,C'^2+I_{SM}C'$$

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