Leftovers from Run I and ~~experimental~~ challenges for Run II

theoretical

with experimentalist's biased view

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(LAL-Orsay)

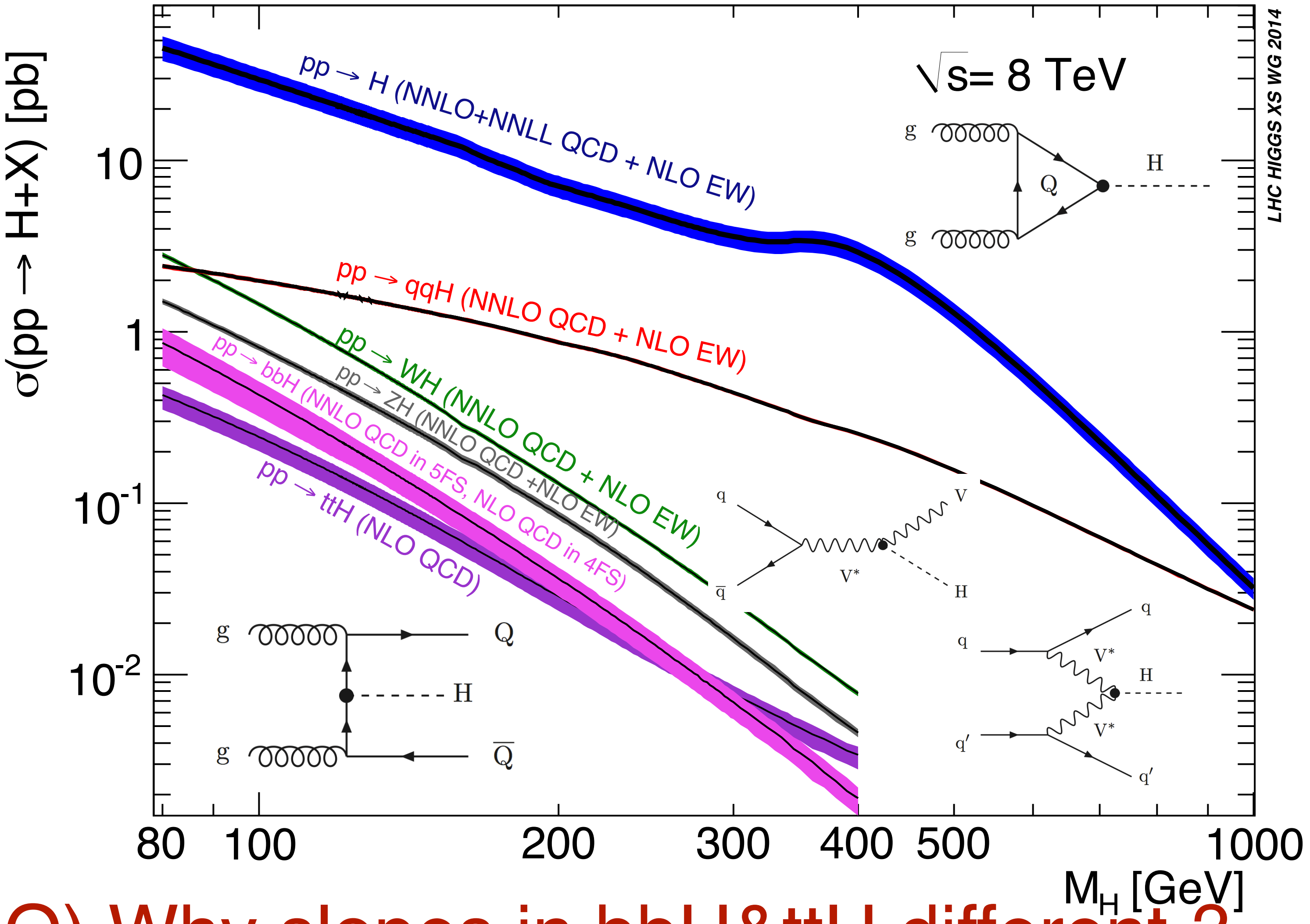
Higgs Days 2015, Santander
September 14, 2015

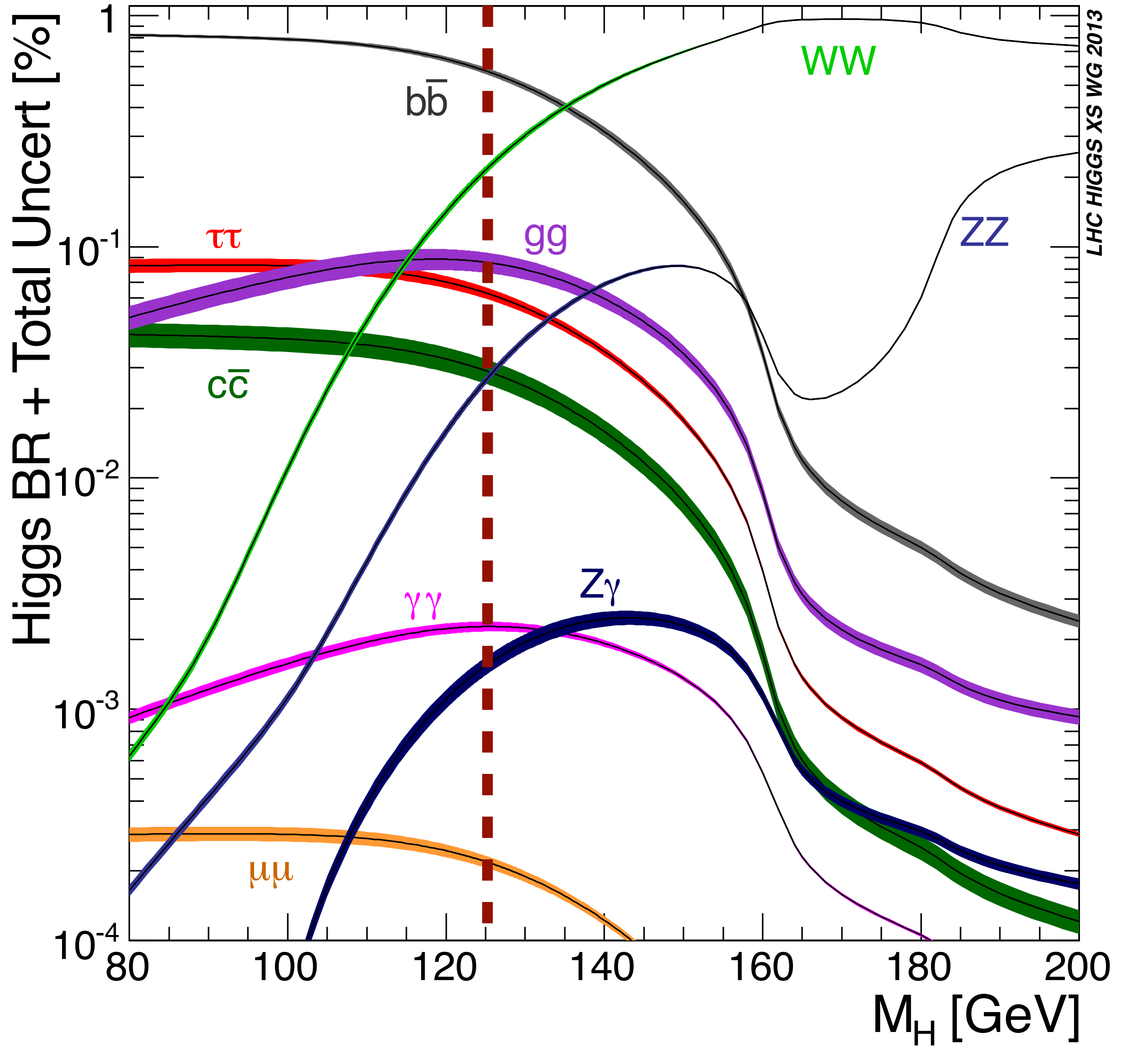
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

cnrs dépasser les frontières
IN2P3
Les deux infinis

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

Higgs Cross Section and Branching Ratio





Q) Why slopes in bbH&ttH different ?

LHC Higgs XS WG CERN Report Trilogy

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)

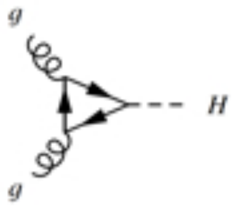
Q) CERN Report 4 > 1000 pages ?

Higgs XS&BR for RUN-2

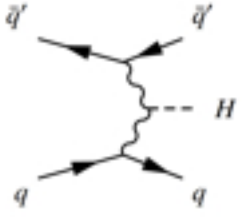
- RUN-2&3
  - L=100 fb^{-1} by the end of RUN-2 in 2018, L=300 fb^{-1} by the end of RUN-3
  - L=3 ab^{-1} at HL-LHC

- Cross section at 13/14TeV wrt 8TeV
  - ttH will get big gain due to phase space opening (→Yukawa Htt/Hbb).

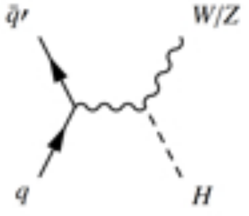
	σ(14TeV)/σ(8TeV)
gg→H	2.6 (M_X=M_H) ●
qq→qqH	2.7 (probes high M_X) ●
qq→WH	2.2 (M_X=M_W+M_H) ●
qq→ZH	2.3 (M_X=M_Z+M_H) ●
gg→ttH	4.7 (phase space+M_{ttH}) ●
gg→bbH	2.9 (M_X=M_{bbH}) ●



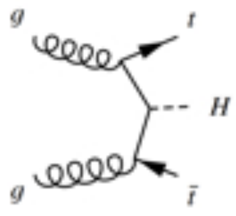
(a) gg → H



(b) VBF

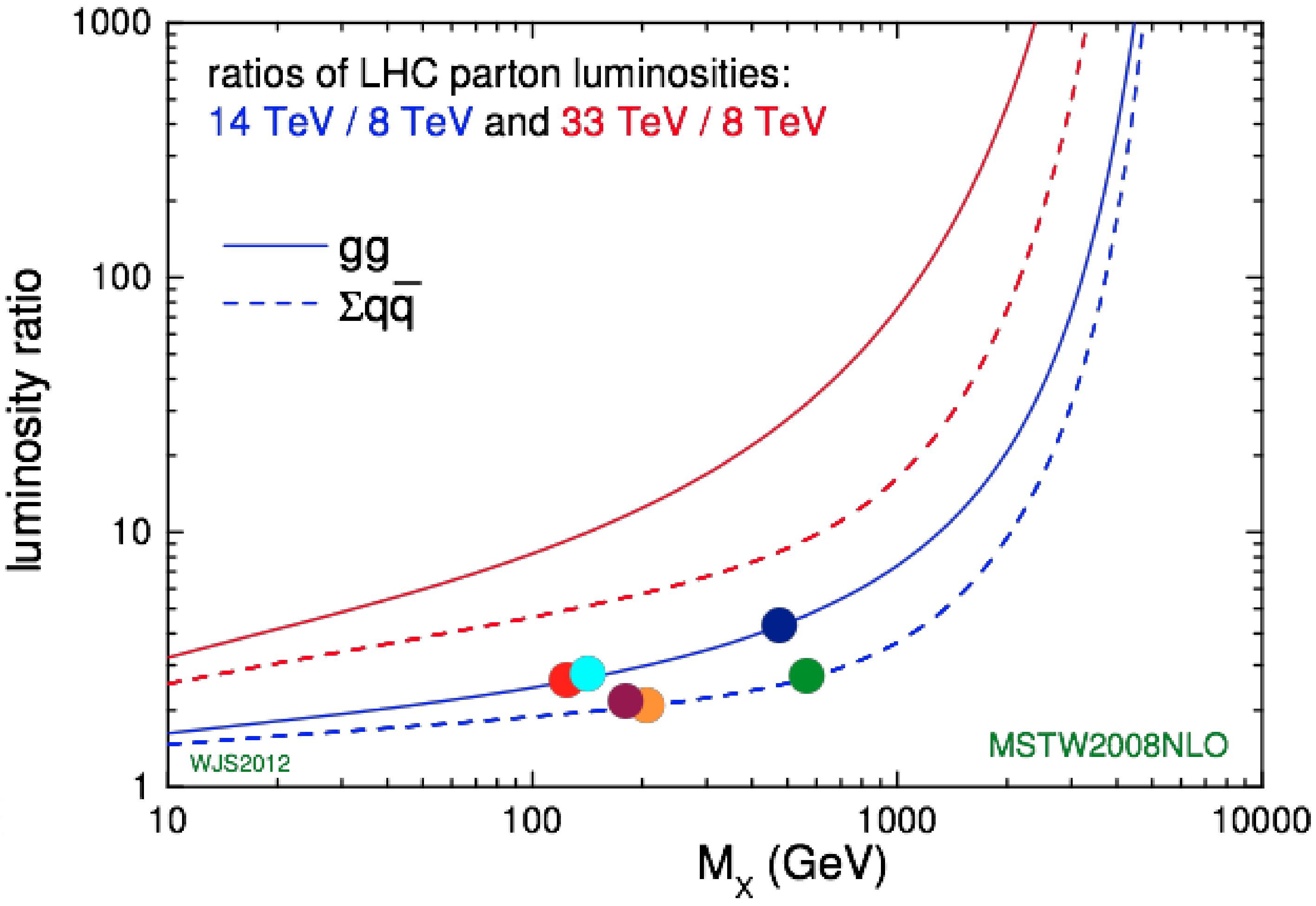


(c) VH



(d) tt̄H

http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

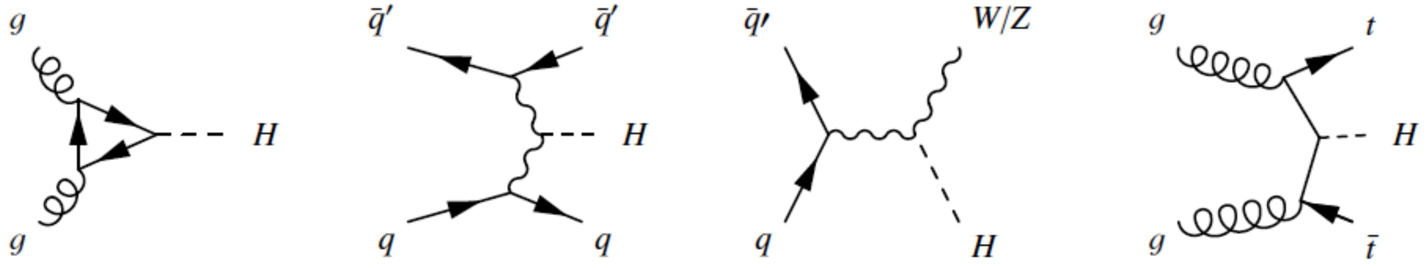


1. QCD Scale Uncertainty

Higgs XS theory uncertainties at 7/8 TeV

M_H=125 GeV

K-factor, QCD scale and PDF uncertainties



(a) $gg \rightarrow H$ (b) VBF (c) VH (d) $t\bar{t}H$

	7 TeV				8 TeV		
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+α_s	Scale +PDF	Scale	PDF+α_s	Scale +PDF
ggF	+25% (+100%)	+7-8%	±8%	**±15%**	+7-8%	±8%	**±15%**
VBF	<1% (+5-10%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
WH/ ZH	+2-6% (+30%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
ttH	- (+5-20%)	+3 -9%	±8%	**+12 -18%**	+4 -9%	±8%	**+12 -17%**

- Renormalization and factorization scale uncertainty study by M. Cacciari et al. work in progress.
- Higher-order calculations, ex. ggF QCD scale: ±8%@NNLO → ±5%@NNNLO in few years ?
- PDF+α_s (PDF4LHC prescription): ±8% → <5% with improvements with LHC data ?
  - jets, top, prompt photons and Z p_T distributions contribute gluon PDF determination.

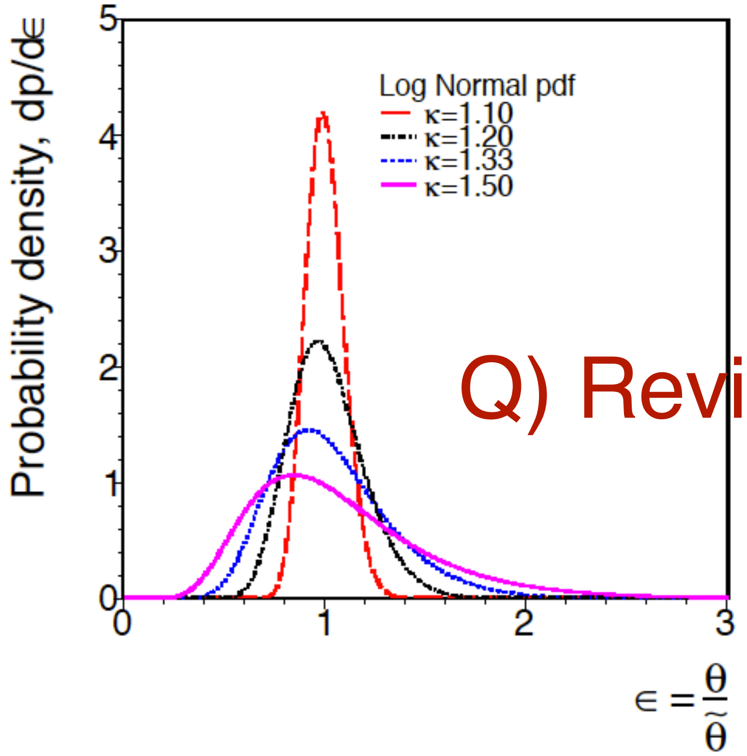
(but paradoxically, ggF is the best measure to determine gg parton luminosity around M_H=125GeV!)

QCD scale uncertainty

- LHC Higgs combination WG's prescription (ATL-PHYS-PUB-2011-011, CMS Note-2011/005)
  - Subdivide nuisance parameters until they become uncorrelated.
  - Take Gaissian/Log-normal for pdf. Practically Gaussian as κ≃1.0 for scale.
- New method by M. Cacciari and N. Houdeau. JHEP 09 (2011) 039
  - Preserves both characteristics of log-normal (tail) and flat-top.
  - Treats renormalization scale only, factorization scale is work in progress.
  - Questions are flat-top width and tail length.

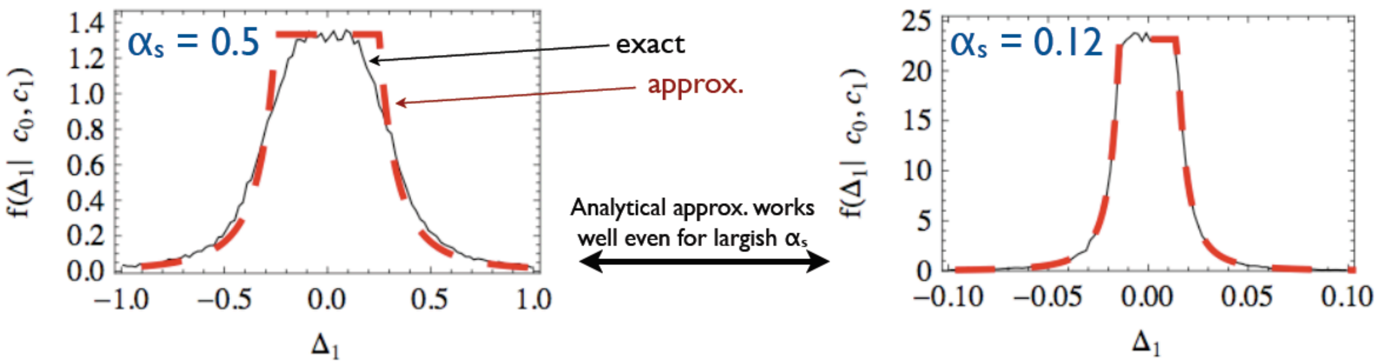
Gaussian/log-normal

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



log-Cacciari-Houdeau

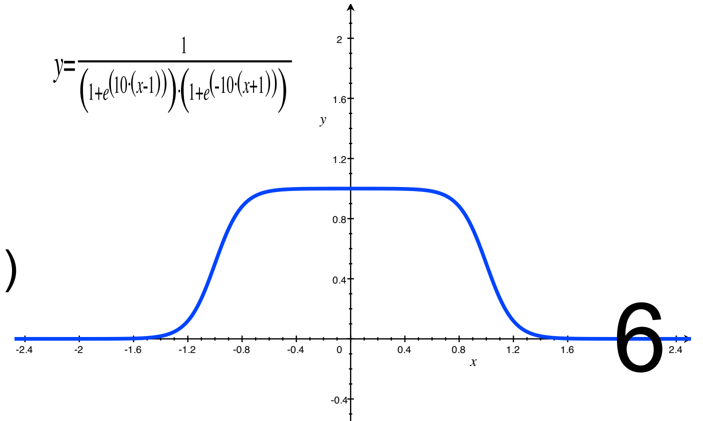
$$f(\Delta_k|c_0,\dots,c_k) \simeq \left(\frac{k+1}{k+2}\right)\frac{1}{2\alpha_s^{k+1}\bar{c}_{(k)}} \begin{cases} 1 & \text{if } |\Delta_k| \le \alpha_s^{k+1}\bar{c}_{(k)} \\ \frac{1}{(|\Delta_k|/(\alpha_s^{k+1}\bar{c}_{(k)}))^{k+2}} & \text{if } |\Delta_k| > \alpha_s^{k+1}\bar{c}_{(k)} \end{cases}$$

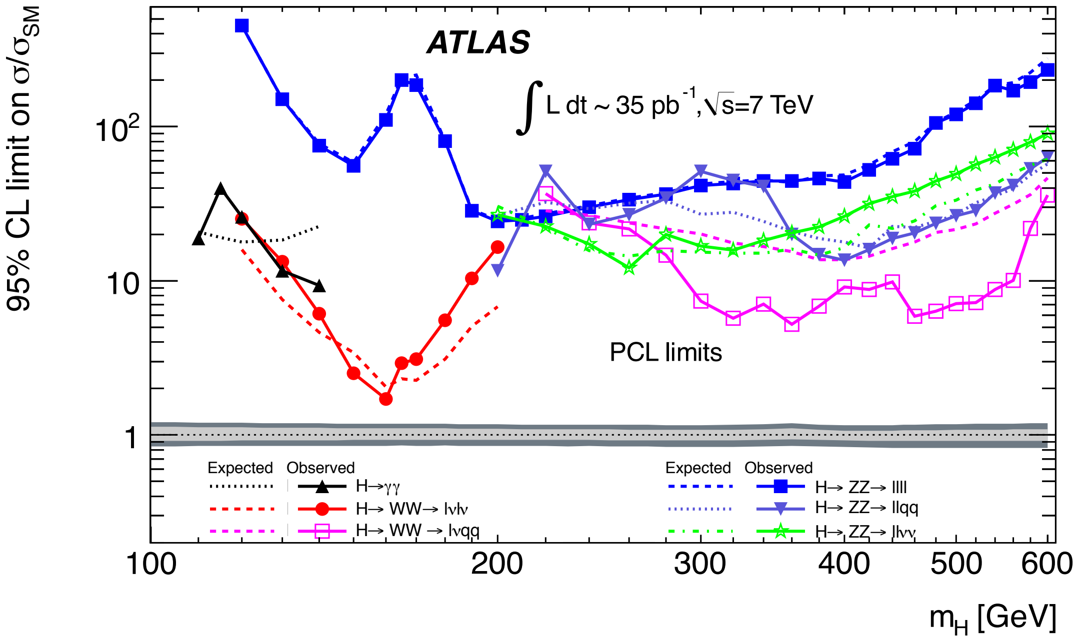


Q) Revisit QCD scale prior issue ?

log-double-Fermi-Dirac to smoothen the edges

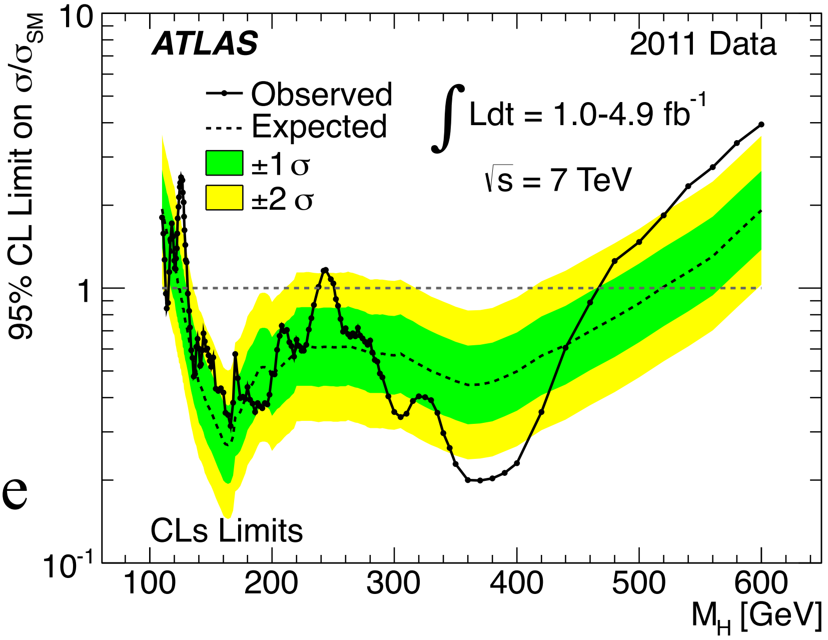
(used in ATLAS-CONF-2013-034)

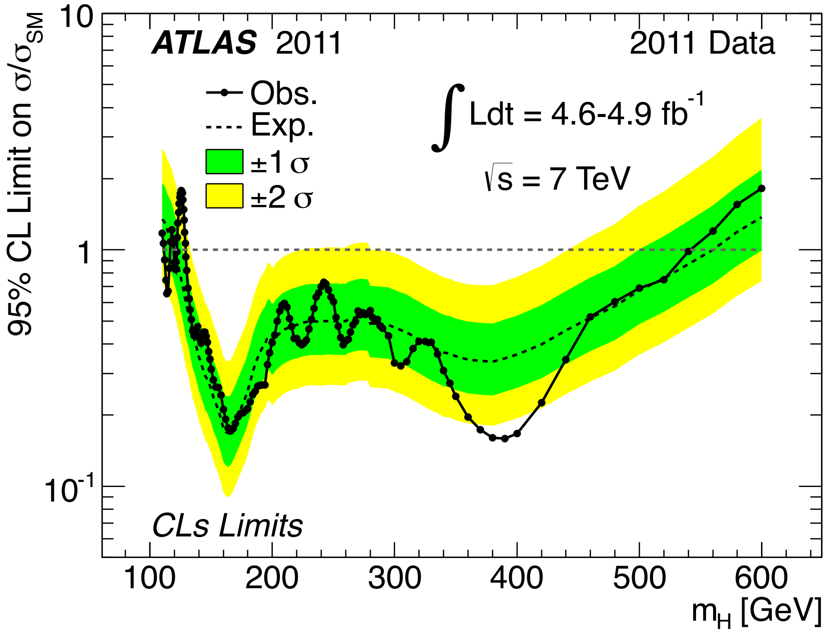


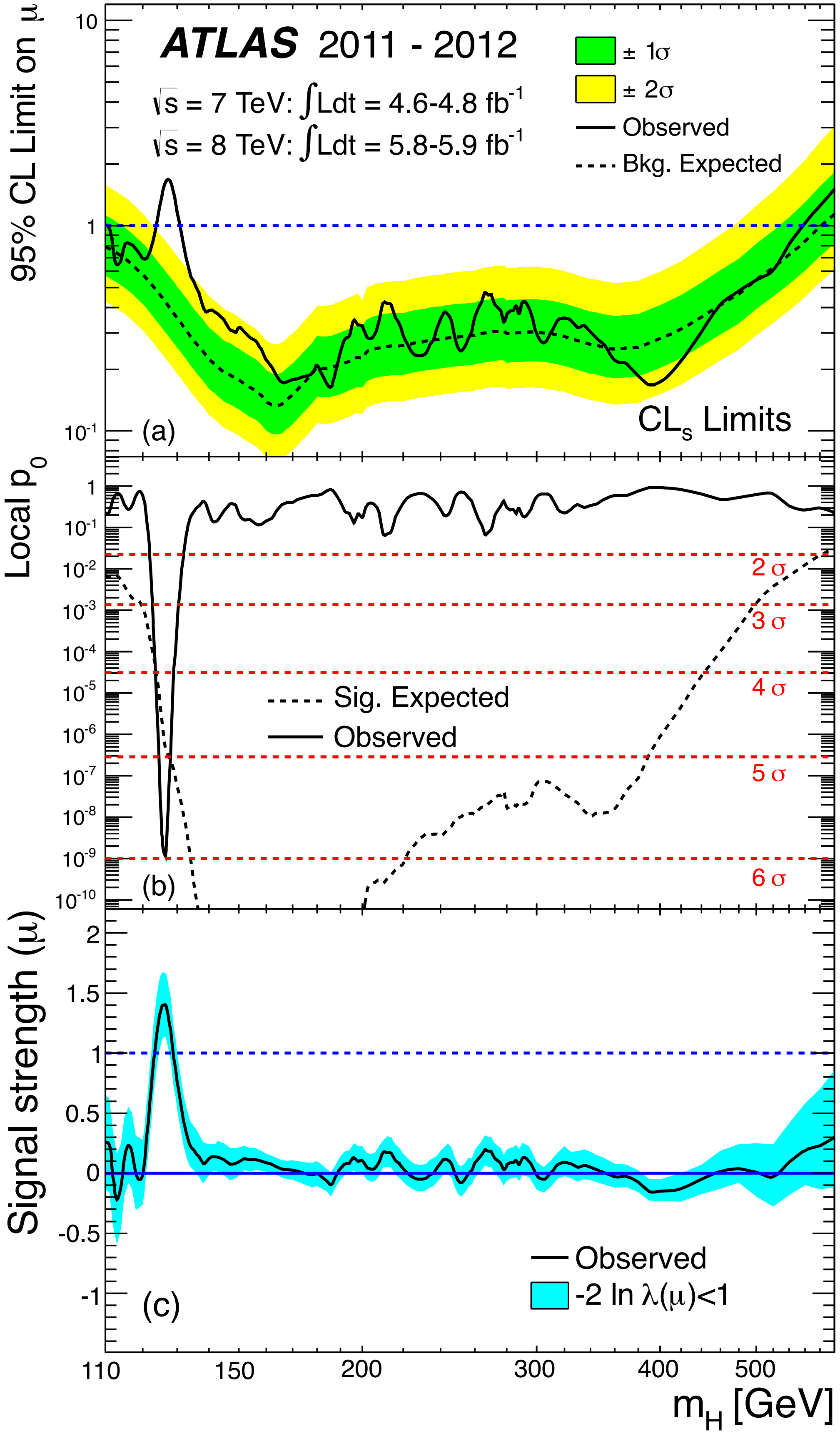


$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

Included theory uncertainty in the fit as nuisance parameter



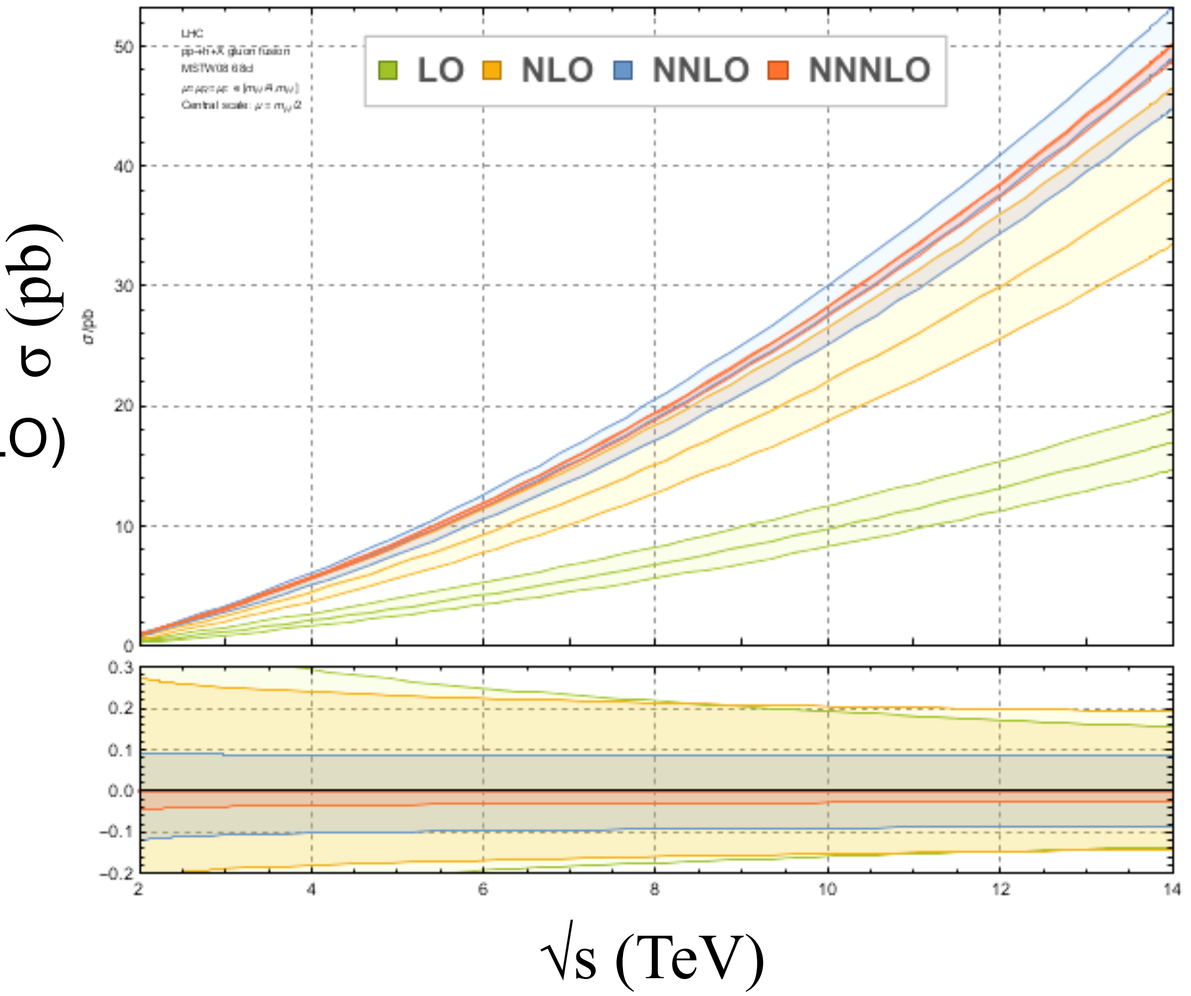




New phenomenal N^{3}LO!

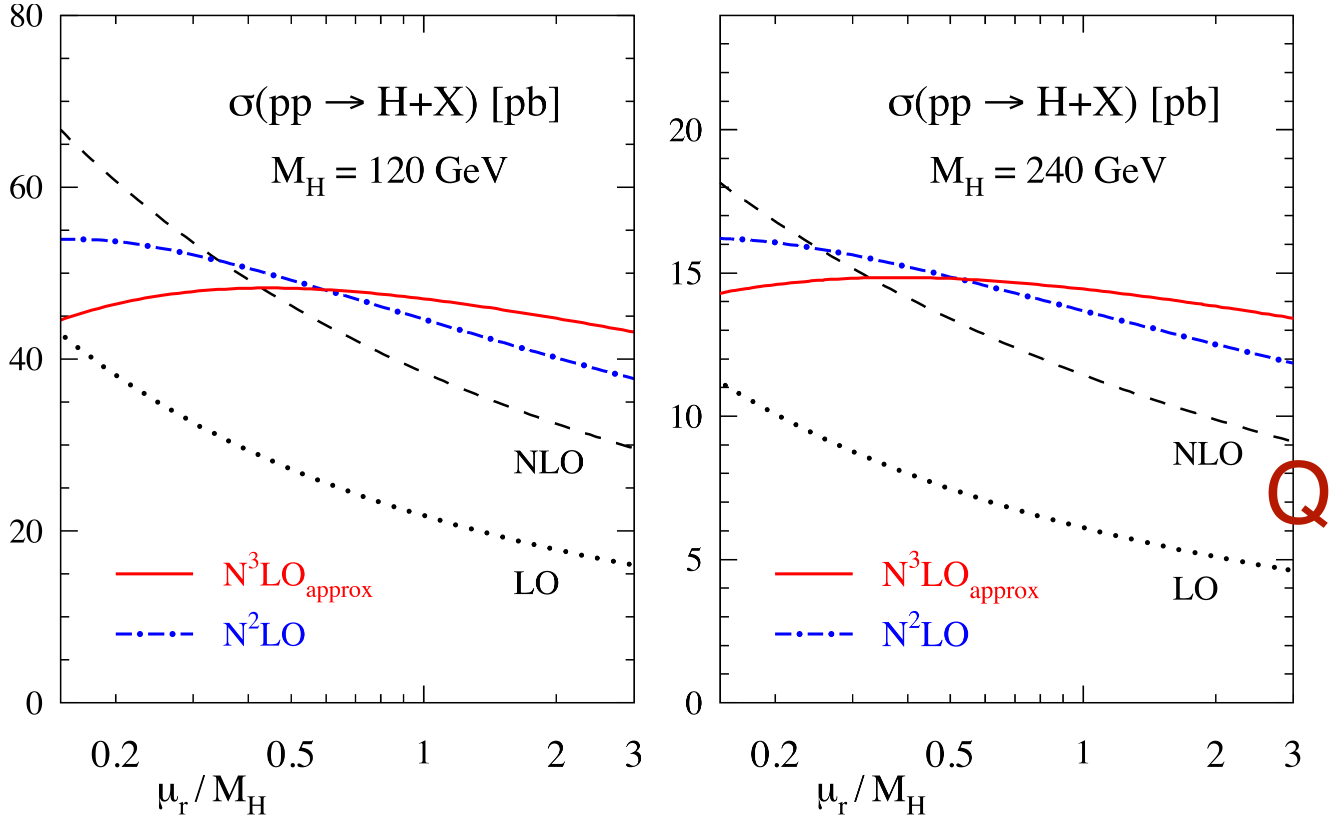
C. Anastasiou et al., PRL **114** (2015) 212001

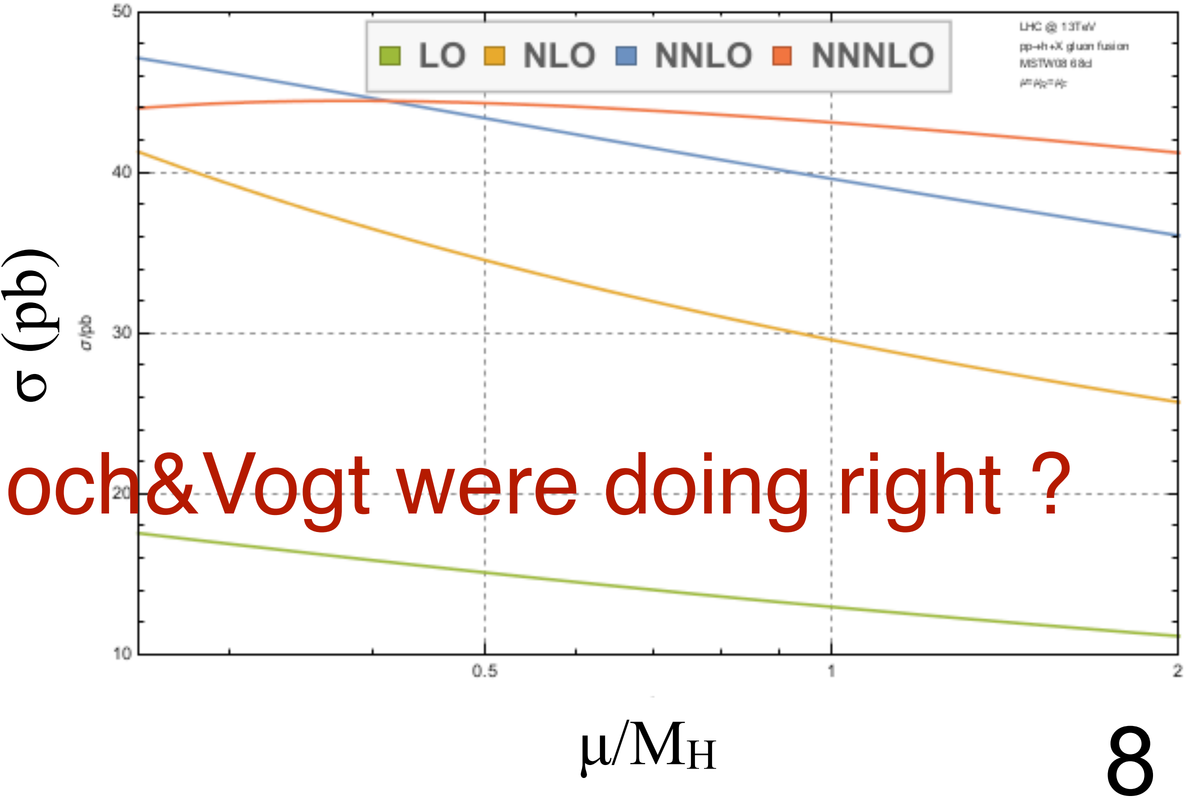
σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$



- Large K-factor for gg→H (+80-100%@NLO, +20%@NNLO)
- Now complete perturbative calculation at NNNLO !
- QCD scale uncertainty reduced from ±8% to few%.
  - As small as qq-initiated VBF or WH/ZH processes !
- Current hot issues:
  - How to reduce PDF and α_s uncertainties.
  - Finite-quark-mass and NLO EW effects.

Moch and Vogt, PLB **631** (2005) 48





Q) Moch&Vogt were doing right ?

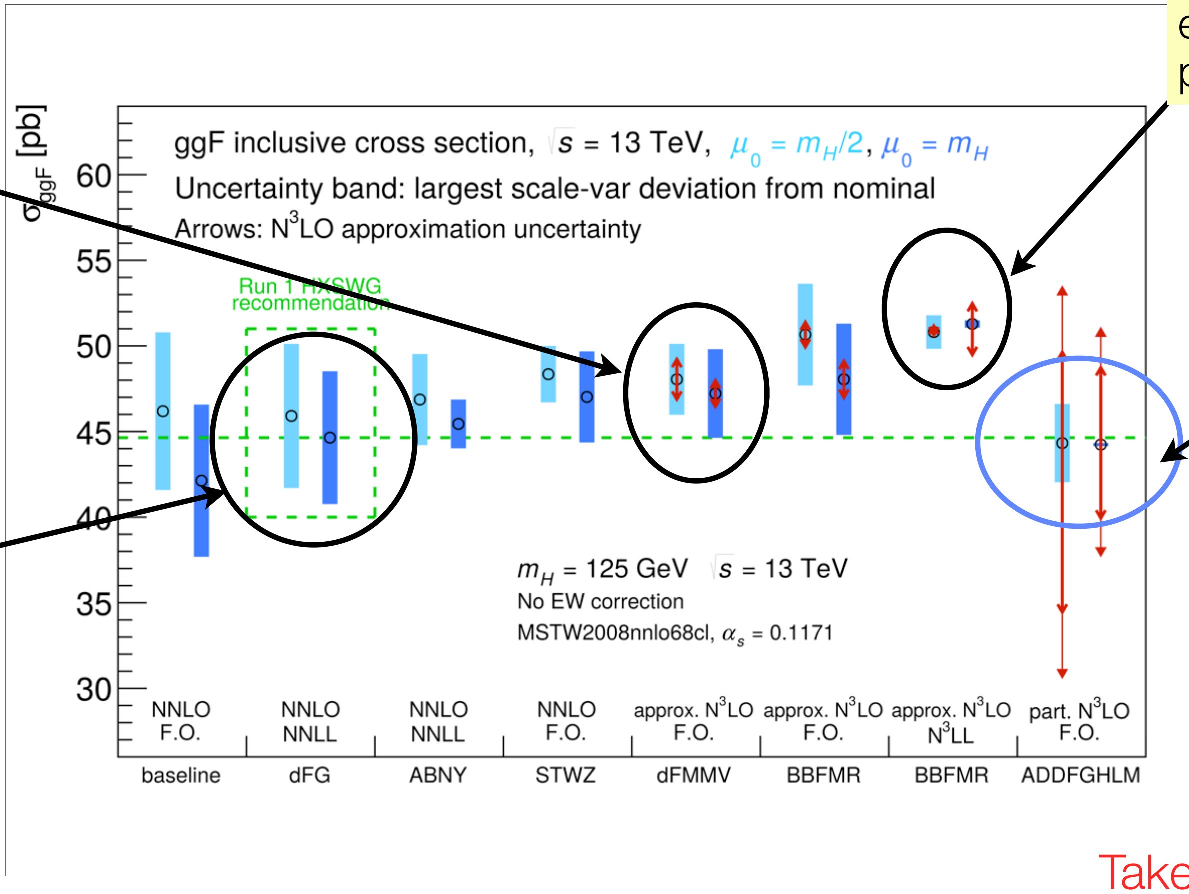
Higgs boson production in gluon fusion

K. Melnikov, LHCP2015

Estimates of N^{3}LO Higgs production cross sections were attempted before an exact calculation using various approximations (essentially, emission or soft gluons or powers of π are assumed to be the dominant source of QCD corrections). The HXWG has assembled various predictions for the Higgs cross section made before the N^{3}LO result became available. The picture below should tell us about the success or failure of these predictions. But it does not...; it leaves more questions than answers. However, the correct answer is important since it will teach us if approximate predictions for Higgs production cross section are reliable and to what extent.

The authors of this result claim the same increase of the cross-section relative to NNLO as the exact N3LO computation shows. Yet, the results on that plot are apparently different.

Good agreement with N3LO; obviously larger errors.



It would be important to understand why this point is so much higher than everybody else and why the claimed precision is so high.

N3LO result

Taken from the HXWG summary

2. BR Uncertainty

Higgs Decay Branching Ratios

Q) THU prior ?

- Use HDECAY and Prophecy4f for best estimate.

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

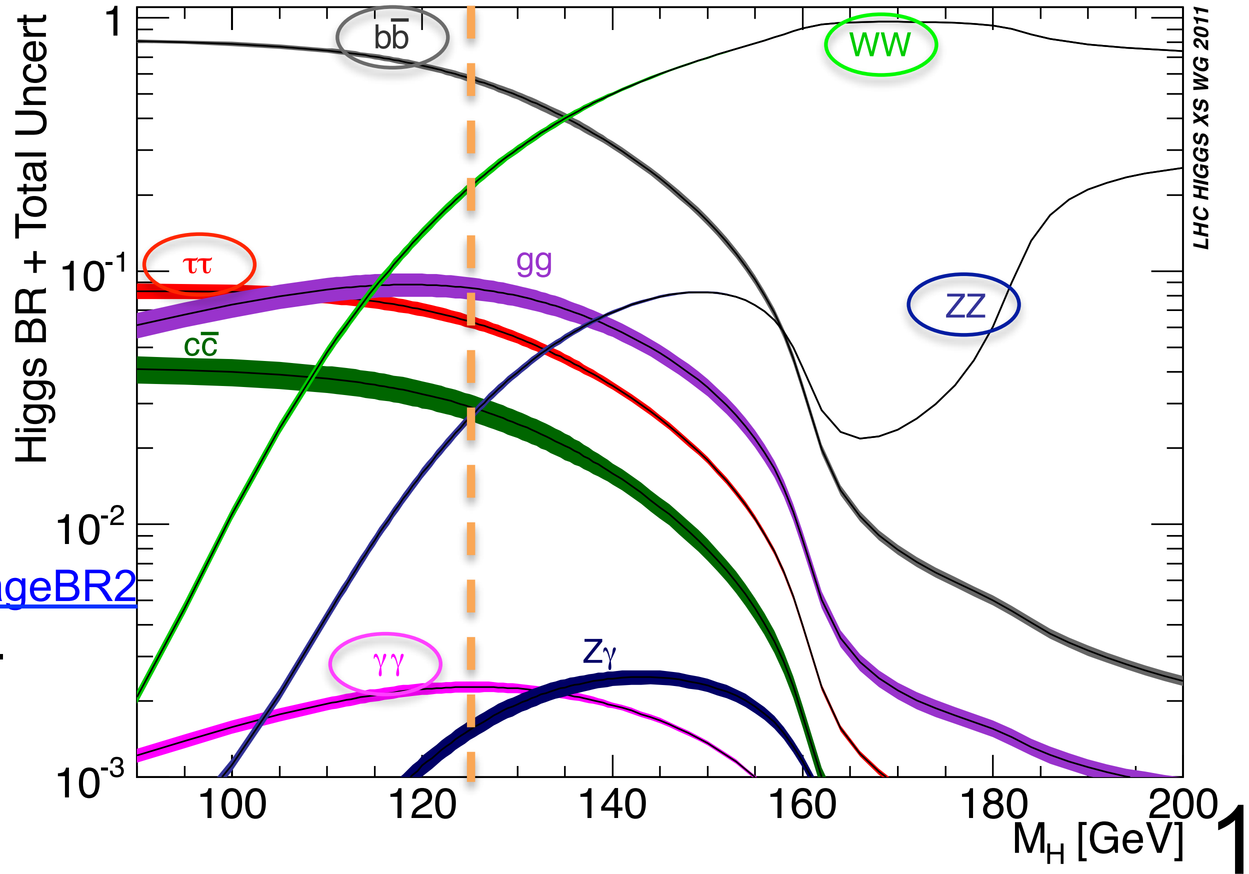
- What are the theory (THU) + parametric (PU) uncertainties ?

- Relatively large uncertainties for H→ττ, μμ, γγ, Zγ/WW/ZZ at low M_H.
- Smaller uncertainties relative to scale and PDF+α_s uncertainties in Higgs production.

A. Denner et al., Eur. Phys. J. C (2011) 71

M_H	Decay	THU	PU	Total
120GeV	H→bb	±1.3%	±1.5%	**±2.8%**
	H→ττ	±3.6%	±2.5%	**±6.1%**
	H→μμ	±3.9%	±2.5%	**±6.4%**
	H→γγ	±2.9%	±2.5%	**±5.4%**
	H→Zγ	±6.9%	±2.5%	**±9.4%**
	H→ZZ	±2.2%	±2.5%	**±4.8%**
	H→WW	±2.2%	±2.5%	**±4.8%**

Separation of BR THU and PU are in progress.
Stick to THU+PU **±5-10%** conservative uncertainty.



Updated numbers in CERN Report 2.
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2
Major change was BR(H→ss) due to quark mass definition.

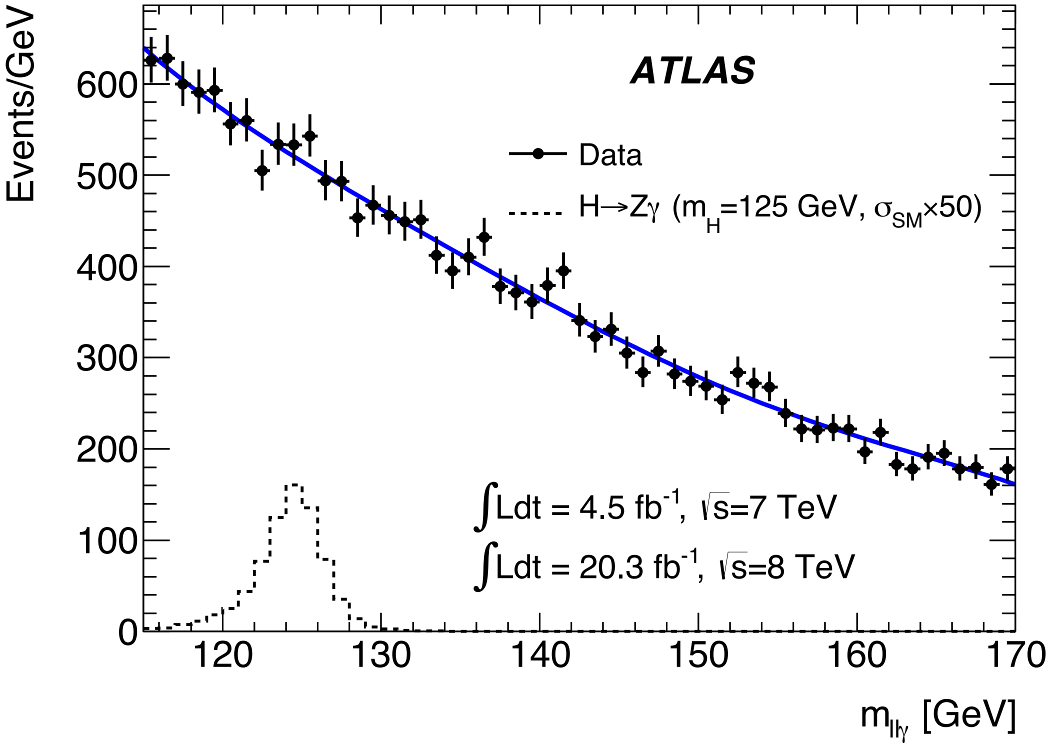
Revisit SM input parameters ☞ $(\alpha_s, m_b, m_c, m_t)$

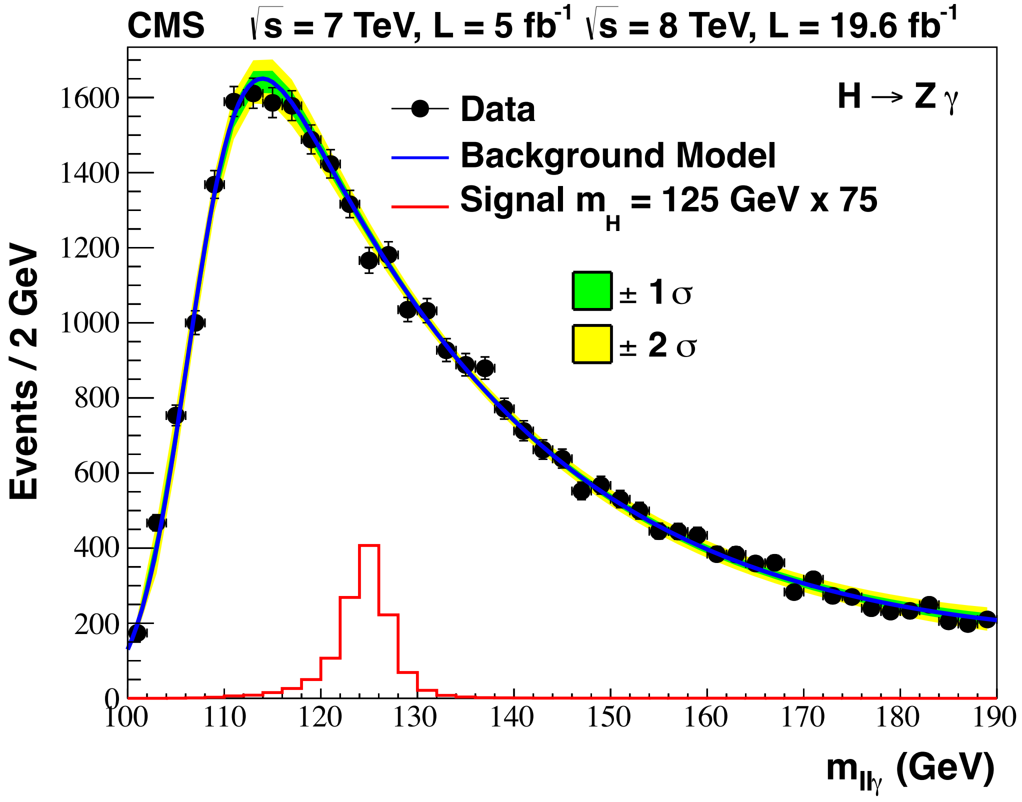
... may affect BR (but not for XS)

H→Zγ, Higgs Dalitz decay

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

Q) A+C should come to common fiducial definition ?





3. PDF Uncertainty

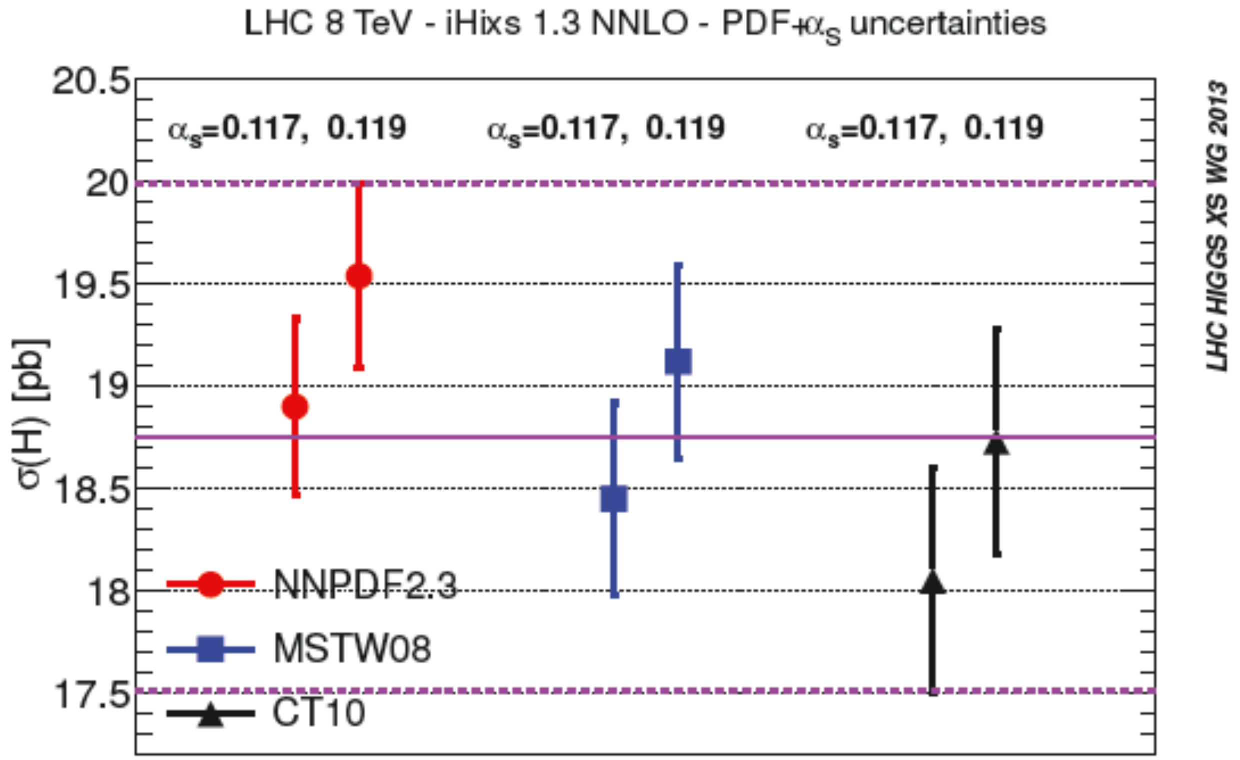
PDF+α_s Uncertainty

Q) α_s=0.118±0.015 for both NNLO and NLO?
Q) How to improve α_s?
Q) N3LO PDF needed?

Update of PDF4LHC Prescription (2011)

- "The PDF4LHC Working Group Interim Recommendations", arXiv:1101.0538 ... envelope of MSTW2008, CTEQ and NNPDF.
- Can we get the new PDF4LHC recommendation at NNLO?
- We should separate QCD α_s ($d\sigma/\sigma \simeq 3 d\alpha_s/\alpha_s$ though α_s^2 at LO)
  - ±1% uncertainty in α_s would corresponds to ±3% in XS which is comparable with scale uncertainty in N3LO ggF !
- Now many PDF sets are at NNLO (CT10, MSTW, NNPDF, ABM11, HEARPDF, ...) and LHC data start to play the role.

CERN Report 3, Fig. 59



Recent progress in PDF

Q) PDF4LHC15 (LHAPDF6) for XS but also for MC?

- Now many NNLO PDF sets exist.
- Major updates to CT14, MMHT2014, NNPDF3.0
  - CT10, MSTW2008 and NNPDF2.3 in RUN-1
- Almost perfect agreement between global PDF fits now !
  - All sets have changed a lot. Now all include lots of LHC RUN-I data. MMHT and CT have enlarged their parametrization and use orthogonal polynomials. NNPDF uses a closure test to tune the methodology. So there is no single simple explanation. (S. Forte)

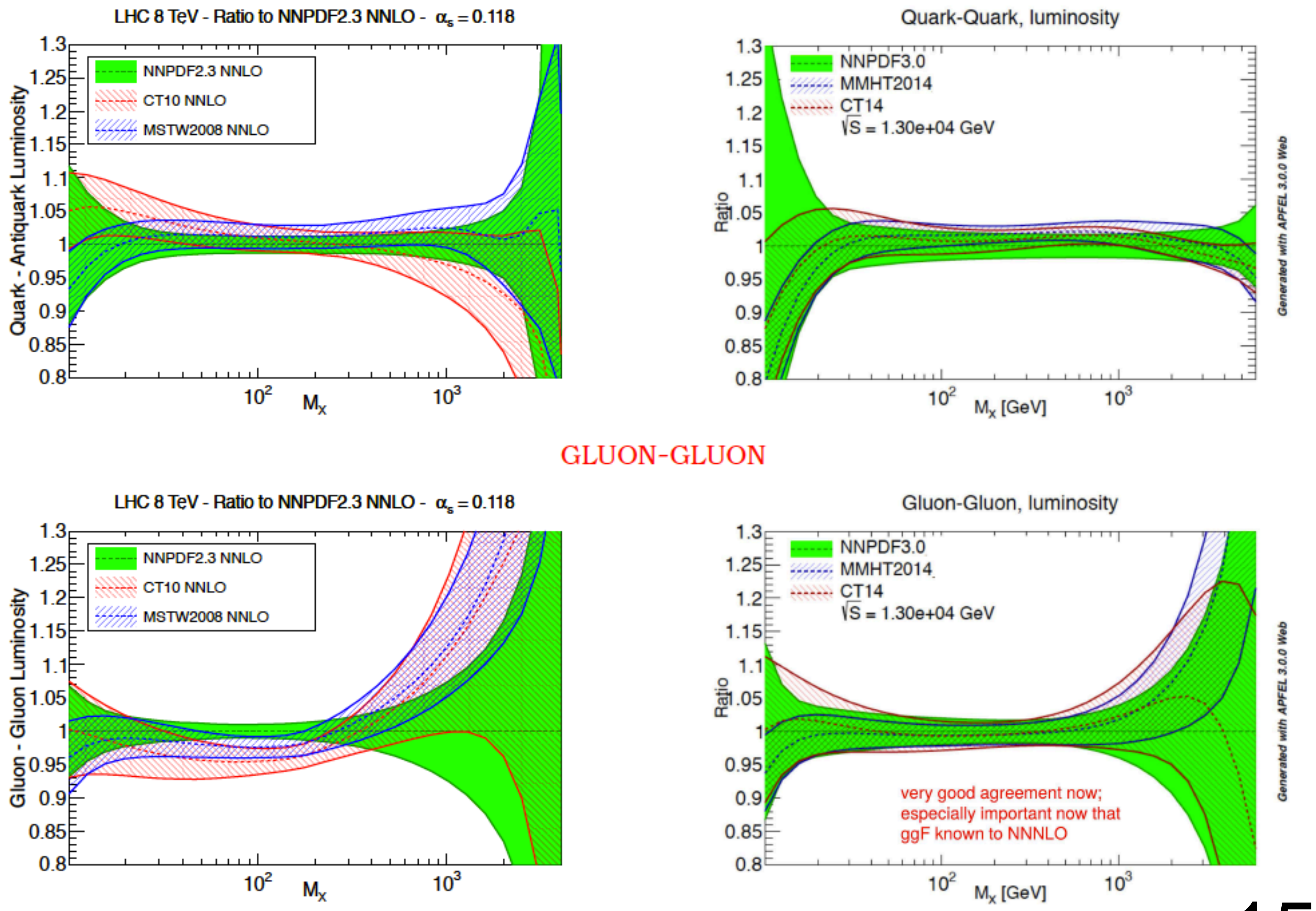
ggF cross section at NNLO

	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

J. Huston, PDF4LHC meeting, Apr. 13, 2015

2012

2015



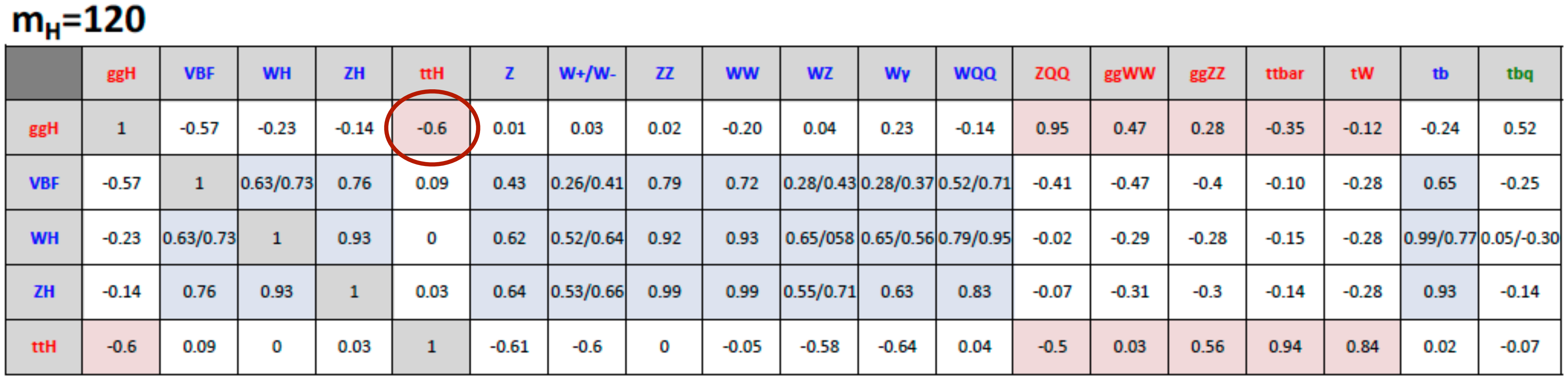
GLUON-GLUON

very good agreement now; especially important now that ggF known to NNNLO

PDF+α_S uncertainty correlations between Higgs signal and SM backgrounds

- Previous prescription based upon LHC Higgs Combination prescription in 2011.

100% correlated PDF+α_S uncertainties for gg-initiated (ggF, ttH, gg->VV) and qq-initiated (VBF, VH, VV) processes.



m_H=120

	ggH	VBF	WH	ZH	ttH	Z	W+/W-	ZZ	WW	WZ	Wγ	WQQ	ZQQ	ggWW	ggZZ	ttbar	tW	tb	tbq
ggH	1	-0.57	-0.23	-0.14	-0.6	0.01	0.03	0.02	-0.20	0.04	0.23	-0.14	0.95	0.47	0.28	-0.35	-0.12	-0.24	0.52
VBF	-0.57	1	0.63/0.73	0.76	0.09	0.43	0.26/0.41	0.79	0.72	0.28/0.43	0.28/0.37	0.52/0.71	-0.41	-0.47	-0.4	-0.10	-0.28	0.65	-0.25
WH	-0.23	0.63/0.73	1	0.93	0	0.62	0.52/0.64	0.92	0.93	0.65/058	0.65/0.56	0.79/0.95	-0.02	-0.29	-0.28	-0.15	-0.28	0.99/0.77	0.05/-0.30
ZH	-0.14	0.76	0.93	1	0.03	0.64	0.53/0.66	0.99	0.99	0.55/0.71	0.63	0.83	-0.07	-0.31	-0.3	-0.14	-0.28	0.93	-0.14
ttH	-0.6	0.09	0	0.03	1	-0.61	-0.6	0	-0.05	-0.58	-0.64	0.04	-0.5	0.03	0.56	0.94	0.84	0.02	-0.07

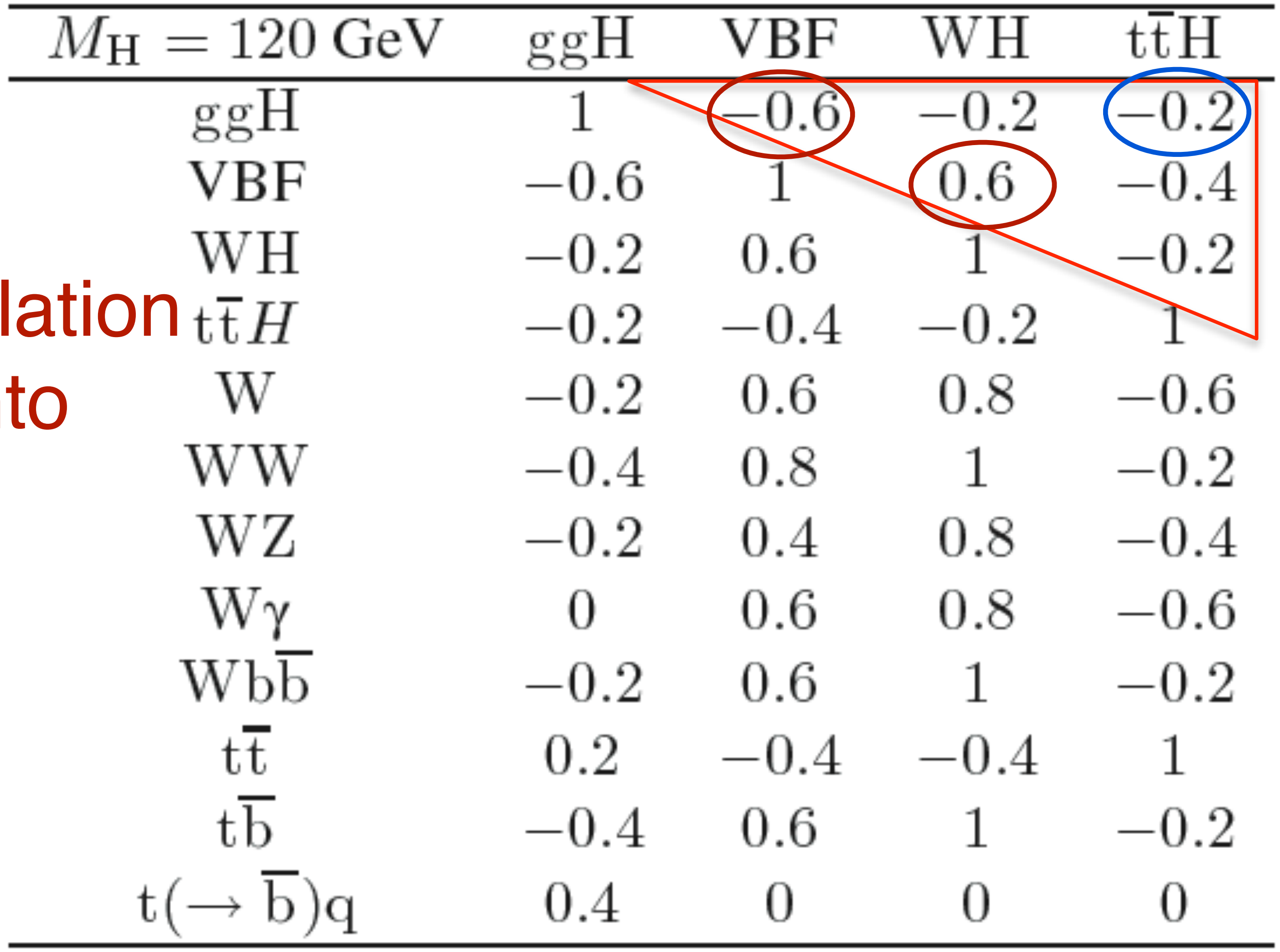
- The correlation between ggF and ttH was negative ρ=-0.6 (with CTEQ?).

PDF+α_s uncertainty

- Currently assume separate gg-initiated ±8% and qq-initiated ±4%.
  - Assumes NO PDF+α_s correlation between (ggF, ttH, tt, …) and (VBF, VH, VV, …).
- Full correlation study in CERN Report 2 (https://cds.cern.ch/record/1416519)
  - ggF – VBF ρ=-0.6 … due to sum rule of Σ(gg+qq+qqbar)=1.
  - ggF – WH ρ=-0.2 … due to small correlation between gg vs qqbar.
  - ggF – ttH ρ=-0.2 … it's the different Bijorken-x.

CERN Report 2

Table 10



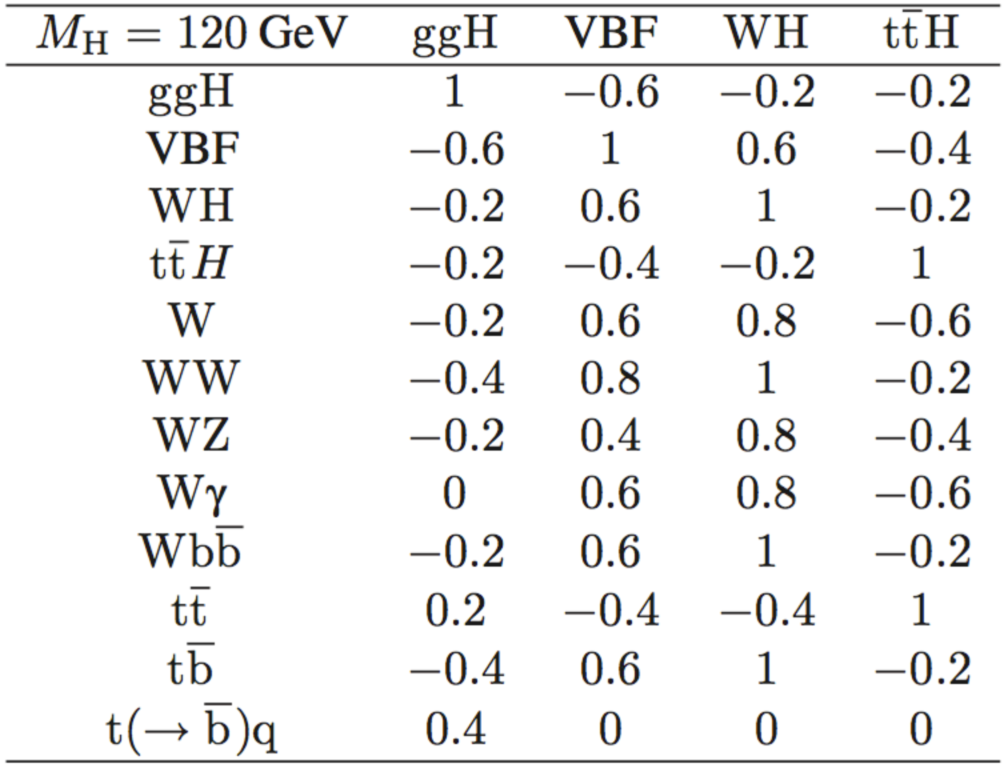
$M_{\rm H}$ = 120 GeV	ggH	VBF	WH	$t\bar{t}$H
ggH	1	−0.6	−0.2	−0.2
VBF	−0.6	1	0.6	−0.4
WH	−0.2	0.6	1	−0.2
$t\bar{t}H$	−0.2	−0.4	−0.2	1
W	−0.2	0.6	0.8	−0.6
WW	−0.4	0.8	1	−0.2
WZ	−0.2	0.4	0.8	−0.4
Wγ	0	0.6	0.8	−0.6
$Wb\bar{b}$	−0.2	0.6	1	−0.2
$t\bar{t}$	0.2	−0.4	−0.4	1
$t\bar{b}$	−0.4	0.6	1	−0.2
$t(\rightarrow \bar{b})q$	0.4	0	0	0

Q) Which PDF correlation should we take into account ?

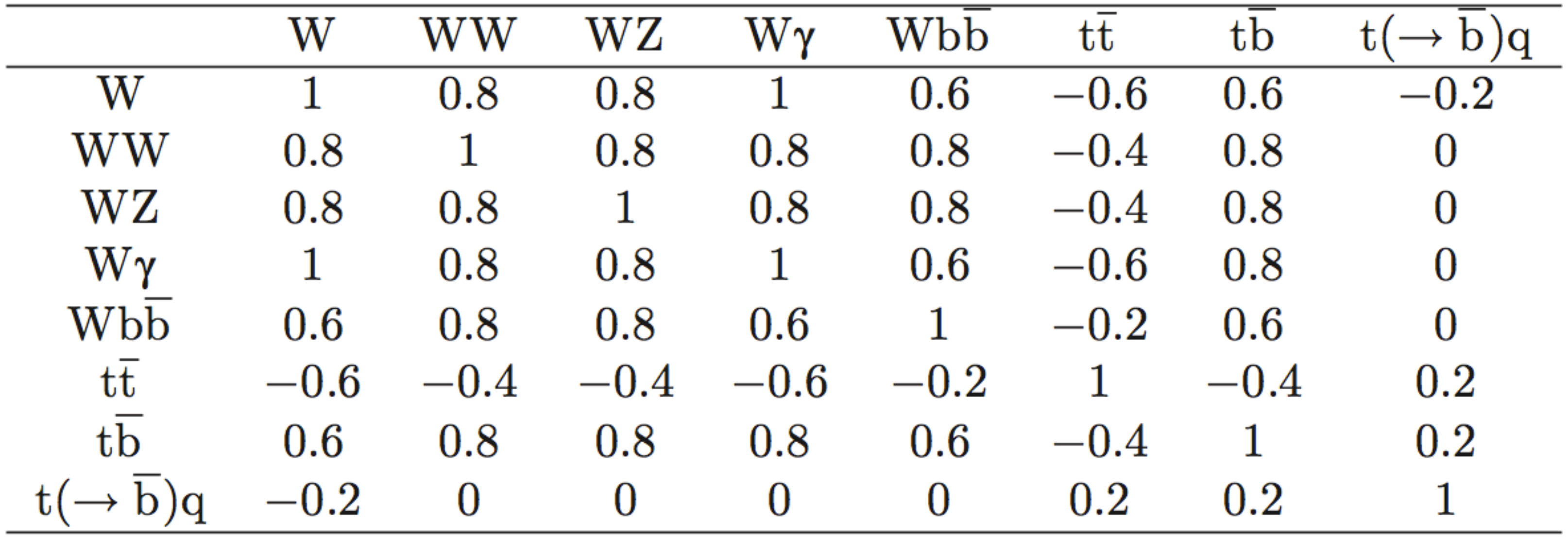
- All these issues should be discussed in LHC Higgs Combination WG.

PDF+α_S uncertainty correlations between Higgs signal and SM backgrounds

- PDF4LHC average for the PDF correlations (CERN Report 2, PDF section, Table 10 and 11)
- The correlation between ggF and VBF is ρ=-0.6 due to sum rule of parton luminosity Σ(gg+qq+qqbar)=1.
- The correlation between ggF and WH is ρ=-0.2 due to small correlation in parton luminosity between gg vs qqbar.
- The correlation between ggF and ttH is negative ρ=-0.2 contrary to naive intuition. It is due to the fact that these processes are hitting different Bjorken-x regime (ttH system requires much heavier final state than ggF), hence anti-correlated in gg-parton luminosity. For heavier Higgs, the correlation becomes positive (ex. ρ=+0.8 for M_H=800GeV) as shown in Table 10 in CERN Report 2.



$M_H = 120$ GeV	ggH	VBF	WH	$t\bar{t}$H
ggH	1	−0.6	−0.2	−0.2
VBF	−0.6	1	0.6	−0.4
WH	−0.2	0.6	1	−0.2
$t\bar{t}H$	−0.2	−0.4	−0.2	1
W	−0.2	0.6	0.8	−0.6
WW	−0.4	0.8	1	−0.2
WZ	−0.2	0.4	0.8	−0.4
Wγ	0	0.6	0.8	−0.6
$Wb\bar{b}$	−0.2	0.6	1	−0.2
$t\bar{t}$	0.2	−0.4	−0.4	1
$t\bar{b}$	−0.4	0.6	1	−0.2
$t(\rightarrow \bar{b})q$	0.4	0	0	0



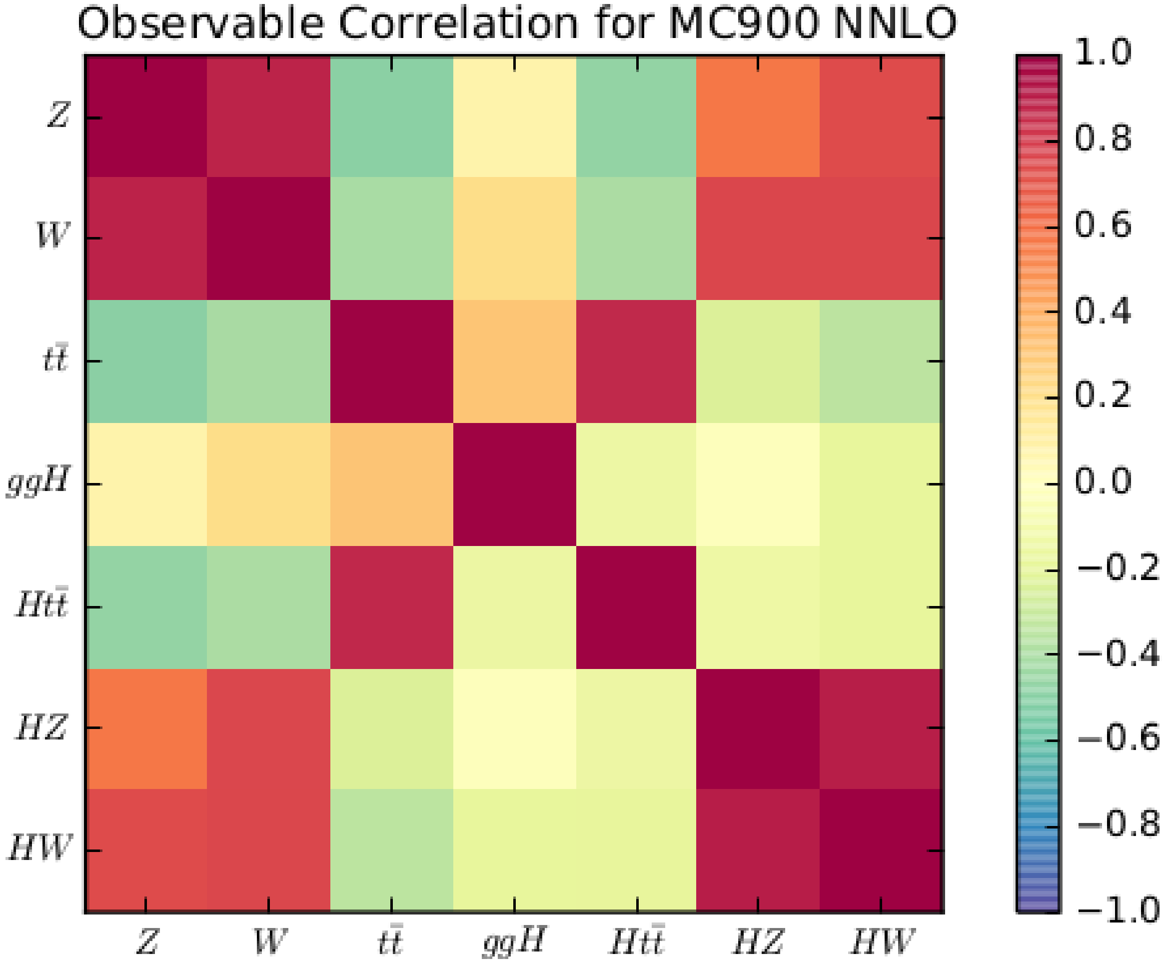
	W	WW	WZ	Wγ	$Wb\bar{b}$	$t\bar{t}$	$t\bar{b}$	$t(\rightarrow \bar{b})q$
W	1	0.8	0.8	1	0.6	−0.6	0.6	−0.2
WW	0.8	1	0.8	0.8	0.8	−0.4	0.8	0
WZ	0.8	0.8	1	0.8	0.8	−0.4	0.8	0
Wγ	1	0.8	0.8	1	0.6	−0.6	0.8	0
$Wb\bar{b}$	0.6	0.8	0.8	0.6	1	−0.2	0.6	0
$t\bar{t}$	−0.6	−0.4	−0.4	−0.6	−0.2	1	−0.4	0.2
$t\bar{b}$	0.6	0.8	0.8	0.8	0.6	−0.4	1	0.2
$t(\rightarrow \bar{b})q$	−0.2	0	0	0	0	0.2	0.2	1

C) Asking PDF4LHC WG for full correlation table for Higgs and SM bkg.

Recent updates (S. Forte)

- √s=13TeV, α_s=0.118 (do not expect large change for 7&8TeV)
- Combination PDF4LHC set, obtained by combining 300 replicas each for CT14, MMHT, NNPDF3.0.

S. Forte


Observable Correlation for MC900 NNLO

Z	+1	+0.89	-0.49	+0.08	-0.46	+0.56	+0.74
W	+0.89	+1	-0.40	+0.20	-0.40	+0.76	+0.77
tt	-0.49	-0.40	+1	+0.30	+0.87	-0.23	-0.34
ggH	+0.08	+0.20	+0.30	+1	-0.13	-0.01	-0.17
ttH	-0.46	-0.40	+0.87	-0.13	+1	-0.13	-0.17
WH	+0.56	+0.76	-0.23	-0.01	-0.13	+1	+0.90
ZH	+0.74	+0.77	-0.34	-0.17	-0.17	+0.90	+1
	Z	W	tt	ggH	ttH	WH	ZH

4. ggF and Jet-bin Uncertainty

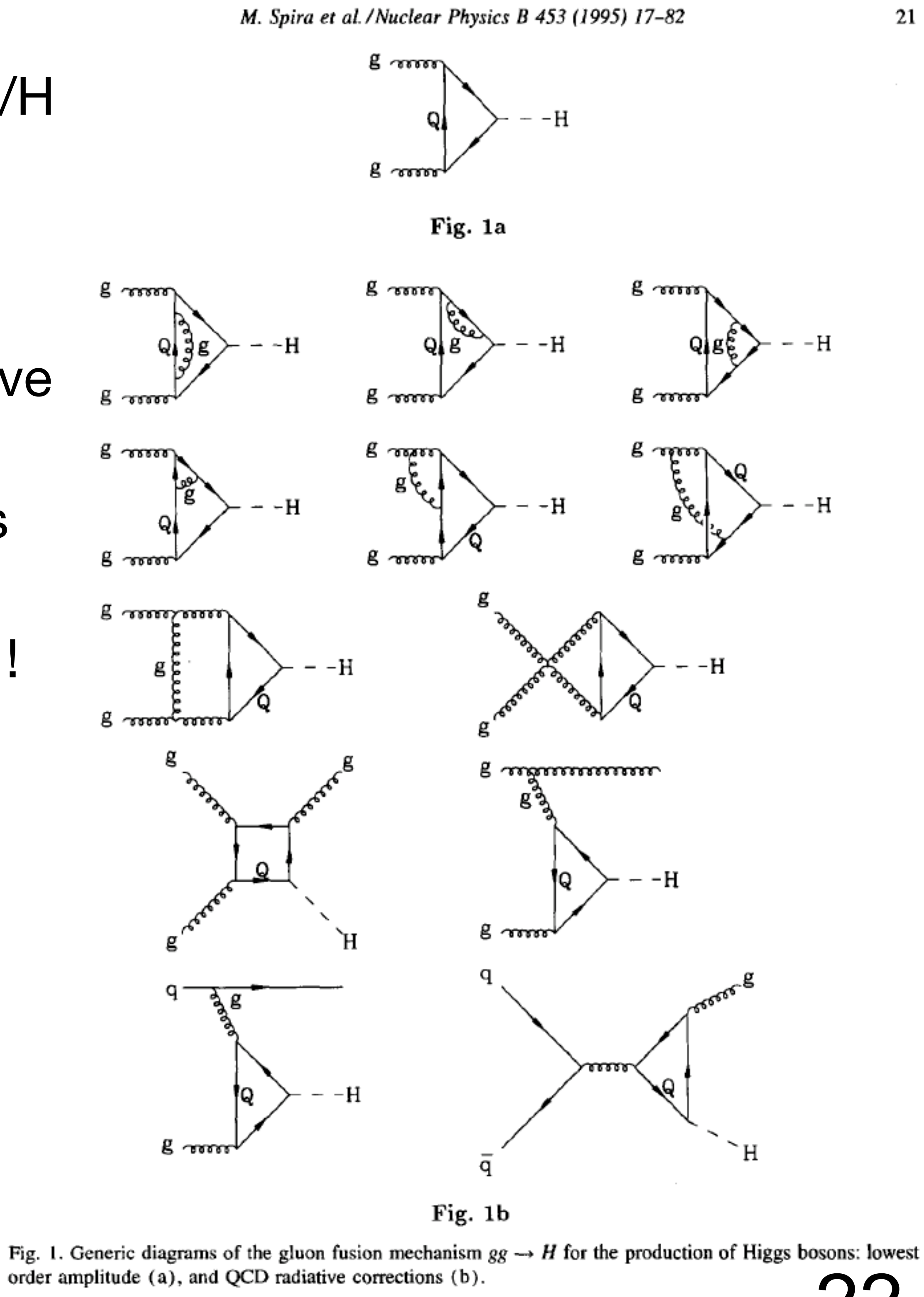
ggF

- NLO MC for H+2-jets
  - we still observe discrepancies among different generators.
  - use Sherpa H+2-jet@NLO to evaluate the CJV uncertainty if we use the JVE method?
- Uncertainties in jet-bin
  - need to continue discussions with S&T, JVE-resummed, improved S&T and other SCET approaches.
  - study jet-bin fractions/jet-veto efficiencies and p_T^H. Compare them with different NLO ME+PS MCs.
- NNLO exclusive cross sections
  - need to follow up the recent progresses in H+0/1/2-jet(s) NNLO exclusive cross sections [Glover et al.], [Melnikov, et al.].
- Integration of Prophecy4f H→4f decay into (N)NLO MC (general issue).
- Trying to coordinate discussions on i) NLO ME+PS MCs, ii) H+0/1/2-jet exclusive/inclusive calculations, iii) Jet-bin via S&T, JVE-resummed, iv) Higgs p_T, etc.

(N)NLO QCD + NLO EW MC

- NNLO QCD + NLO EW MC does not exist yet !
  - New developments in NNLO QCD MC in W/Z/H for 2→1 (colorless) process at LHC.

- NLO ME+PS Monte Carlo
  - Normalize with NNLO QCD + NLO EW inclusive cross section.
  - NLO EW effect O(5-10%) correction via Higgs p_T reweighing (poor-man's solution).
  - Attention to non-accounted diagrams in NLO ! gq/qq negligible (< few %) in NNLO inclusive, but gq is 30% in H+1-jet exclusive !
  - Many matching schemes: POWHEG MiNLO, Fx-Fx aMC@NLO, SHERPA MEPS@NLO, PYTHIA9/UNLOPS, HW++/Matchbox.



M. Spira et al. / Nuclear Physics B 453 (1995) 17–82 21

Fig. 1a

Fig. 1b

Fig. 1. Generic diagrams of the gluon fusion mechanism $gg \to H$ for the production of Higgs bosons: lowest order amplitude (a), and QCD radiative corrections (b).

Jet-bin Uncertainty in ggF

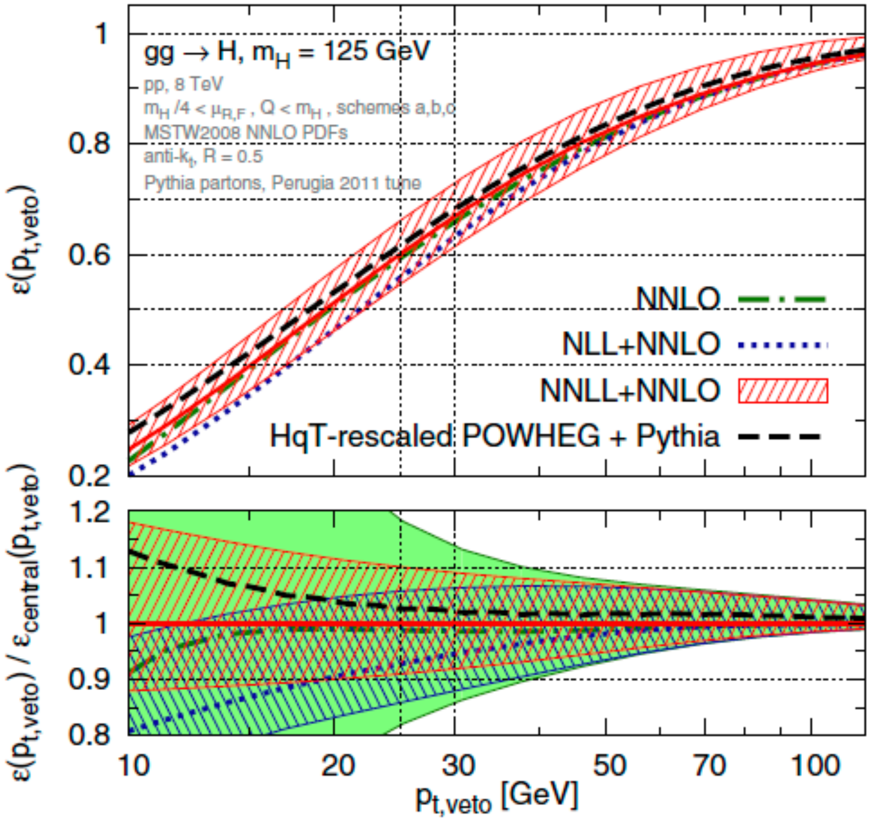
1) Stewart&Tackmann prescription ... fixed order calculation. (PRD **85** (2012) 034011)
2) Jet Veto Efficiency (JVE-resummed) by Banfi, Salam, et al.
   - improvements in 0- and 1-jet bin uncertainty. (PRL**109** (2012) 202001)
3) Updated S&T with 0,1-jet rsummation by Tackmann, Petriello et al. (PRD **89** (2014) 074044)
4) Other groups with SCET(soft-collinear effective theory) (Neubert et al.)

NNLO+NNLL for 0-jet bin uncertainty is ±15%→±9% ! (code JetVHeto)

- JVE-resummed method will affect Δμ and Δσ substantially in exclusive analysis (ex. H→WW) !
- Higgs p_T (p_{Tt}) and jet-bin should be strongly correlated.

∵ Higgs p_T is generated by gluon, while Y by PDF.

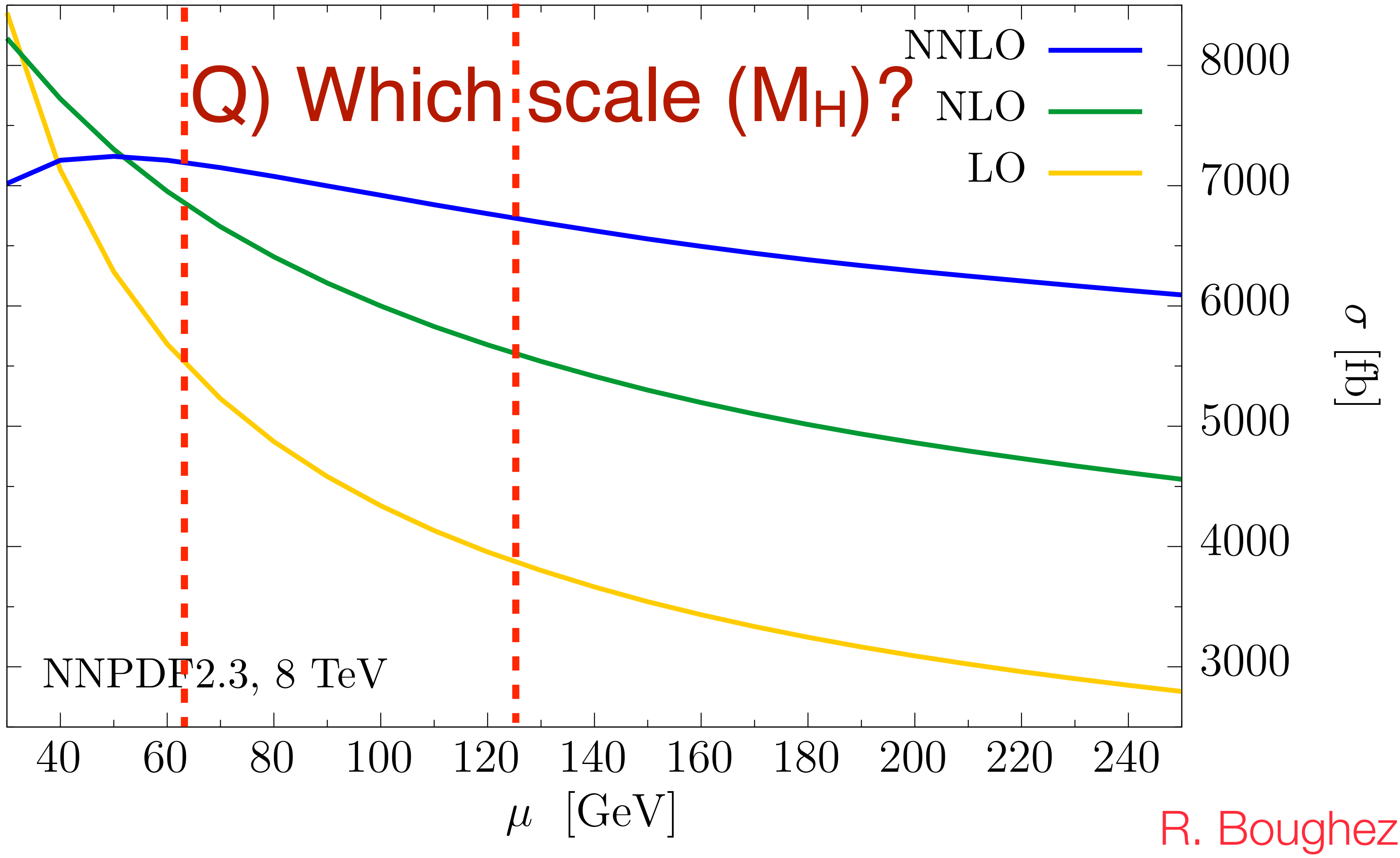
- Jets in PS MC needs special attention.
- Recent preprint by Boughezal et al. (PRL 115 (2015) 082003) on exclusive H+1-jet NNLO QCD calculation.
- Still a lot of discussions on H+0/1-jet NNLO+NNLL exclusive cross sections on scale choice etc.
- Improvements expected in jet-bin uncertainty due to N3LO, etc.



K. Melnikov, LHCP2015

H+jet @ NNLO

The NNLO QCD corrections to H+jet production at the LHC were computed recently. They increase the H+jet production cross section by O(20%) and significantly reduce the scale dependence uncertainty . This is similar to corrections to the inclusive Higgs production cross section although corrections to H+j are slightly smaller.



Q) Which scale (M_H)?

$$\sigma_{\mathrm{LO}} = 3.9^{+1.7}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NLO}} = 5.6^{+1.3}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 6.7^{+0.5}_{-0.6}\ \mathrm{pb}$$

The cross sections for the anti-k_t algorithm with the jet transverse momentum cut of 30 GeV at the 8 TeV LHC.

R. Boughezal, F. Caola, K.M., F. Petriello, M. Schulze

Combine with N3LO+NNLL for exclusive jet bins !

Using these results and the N^{3}LO computation of the Higgs total cross section, one can find the fraction of Higgs boson events without detectable jet radiation.

LHC13 efficiencies: 0- and 1-jet bin

[Many thanks to P. F. Monni and F. Dulat]

F. Caola, LHCHXSWG WG1 meeting, May 2015

0-jet bin

ord	$\sigma^{\text{f.o.}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
N^3LO	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (scales)	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{\geq 1-\text{jet}}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

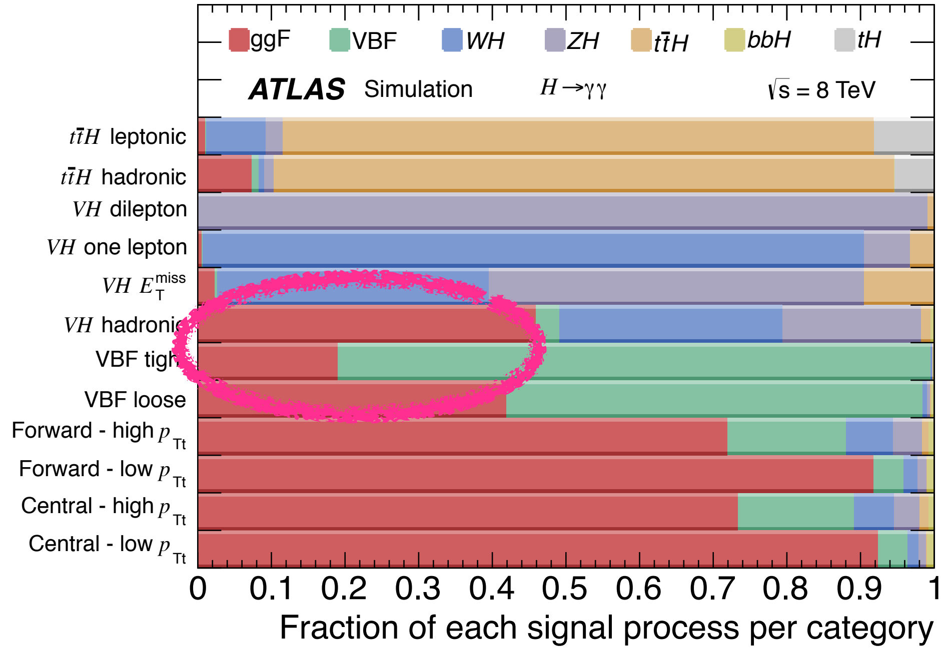
- Logs completely under control
  (logR: see [Dasgupta, Dreyer, Salam, Soyez (2015)])
- No breakdown of f.o. perturbation theory for p_T ~ 30 GeV
- Reliable error estimate from lower orders
- Logs help in reducing uncertainties
- Significant decrease of pert. uncertainty

Q) What EXPs should do for H+1/2-jet bin in RUN-2 (H+0-jet in NNLO)?

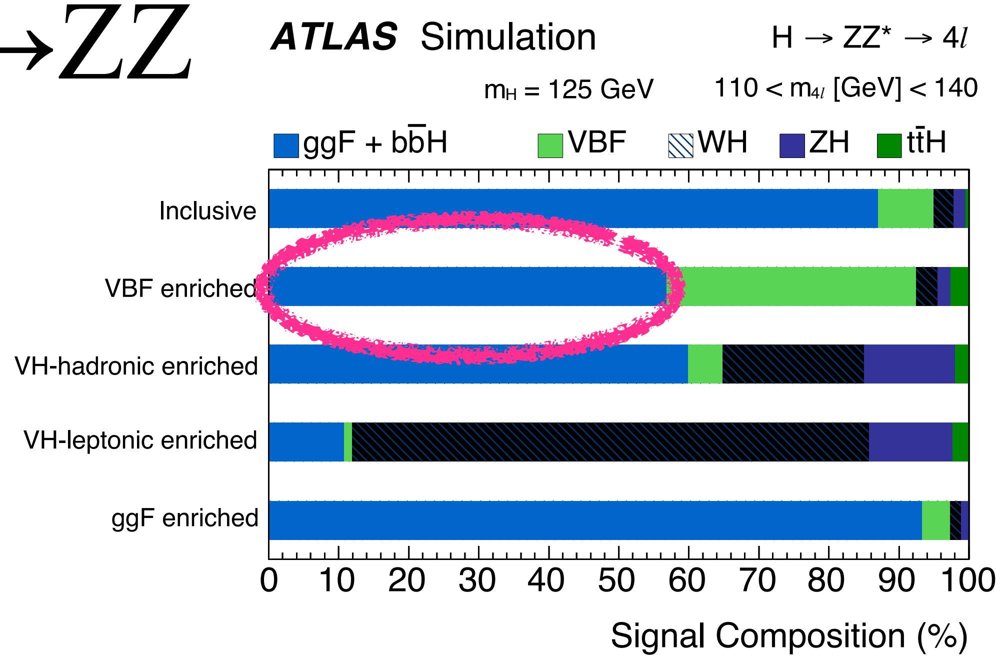
ggF contamination in VBF category

- Needs significant improvements in reduction of ggF contamination and reduction of theory uncertainty with Gosam HJJJ etc.

$H \rightarrow \gamma\gamma$



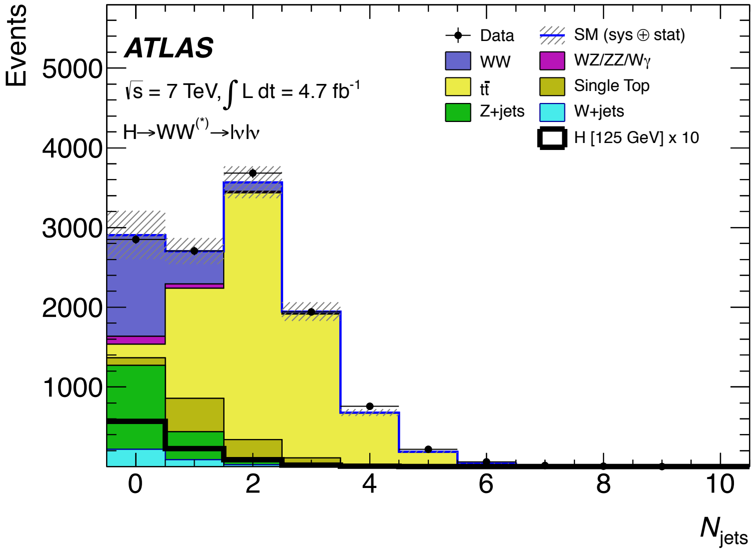
$H \rightarrow ZZ$

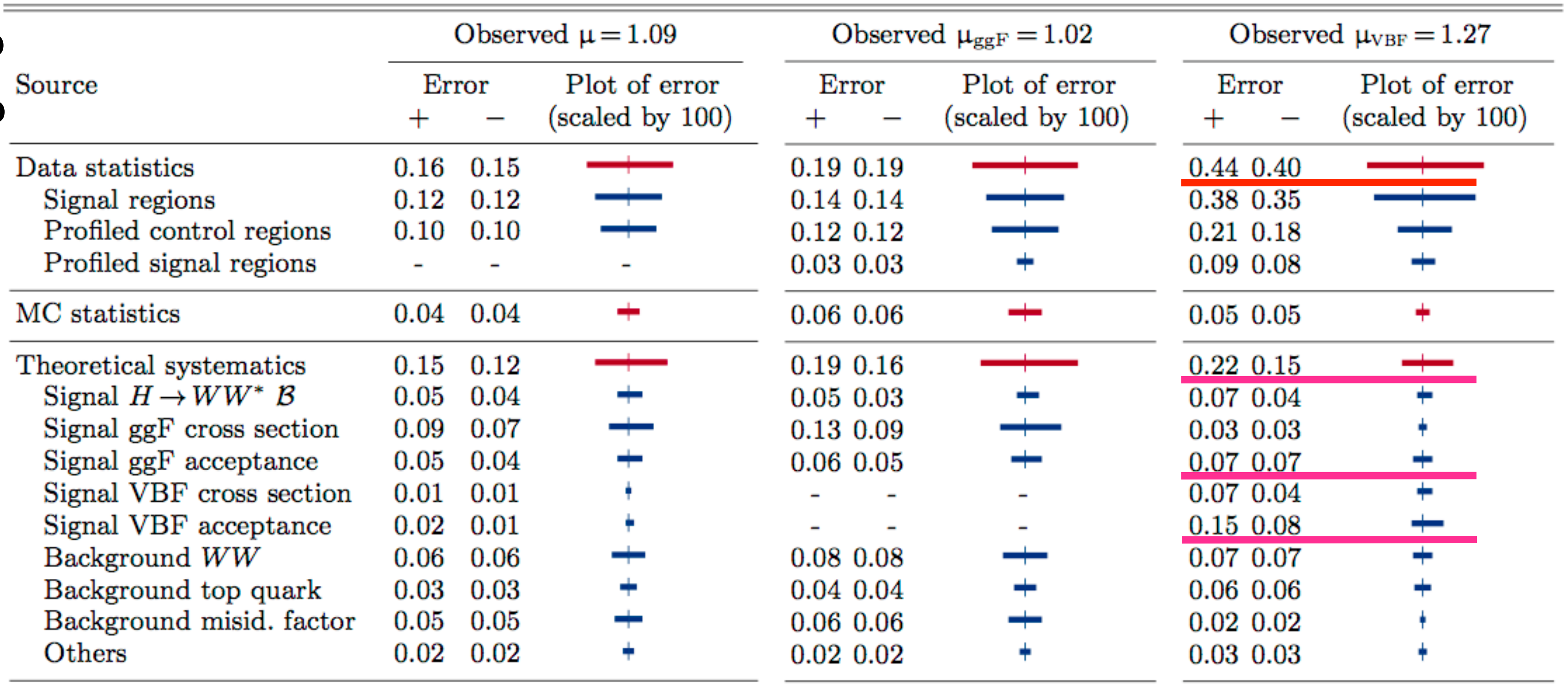


$H \rightarrow WW$

JVE method

$\Delta\varepsilon_0 = \pm 11\%$
$\Delta\varepsilon_1 = \pm 15\%$





Source	Observed $\mu = 1.09$ Error +	−	Plot of error (scaled by 100)	Observed $\mu_{ggF} = 1.02$ Error +	−	Plot of error (scaled by 100)	Observed $\mu_{VBF} = 1.27$ Error +	−	Plot of error (scaled by 100)
Data statistics	0.16	0.15		0.19	0.19		0.44	0.40	
Signal regions	0.12	0.12		0.14	0.14		0.38	0.35	
Profiled control regions	0.10	0.10		0.12	0.12		0.21	0.18	
Profiled signal regions	-	-	-	0.03	0.03		0.09	0.08	
MC statistics	0.04	0.04		0.06	0.06		0.05	0.05	
Theoretical systematics	0.15	0.12		0.19	0.16		0.22	0.15	
Signal $H \rightarrow WW^{*}$ $\mathcal{B}$	0.05	0.04		0.05	0.03		0.07	0.04	
Signal ggF cross section	0.09	0.07		0.13	0.09		0.03	0.03	
Signal ggF acceptance	0.05	0.04		0.06	0.05		0.07	0.07	
Signal VBF cross section	0.01	0.01		-	-	-	0.07	0.04	
Signal VBF acceptance	0.02	0.01		-	-	-	0.15	0.08	
Background *WW*	0.06	0.06		0.08	0.08		0.07	0.07	
Background top quark	0.03	0.03		0.04	0.04		0.06	0.06	
Background misid. factor	0.05	0.05		0.06	0.06		0.02	0.02	
Others	0.02	0.02		0.02	0.02		0.03	0.03	

5. Higgs p_T

Higgs p_T in ggF

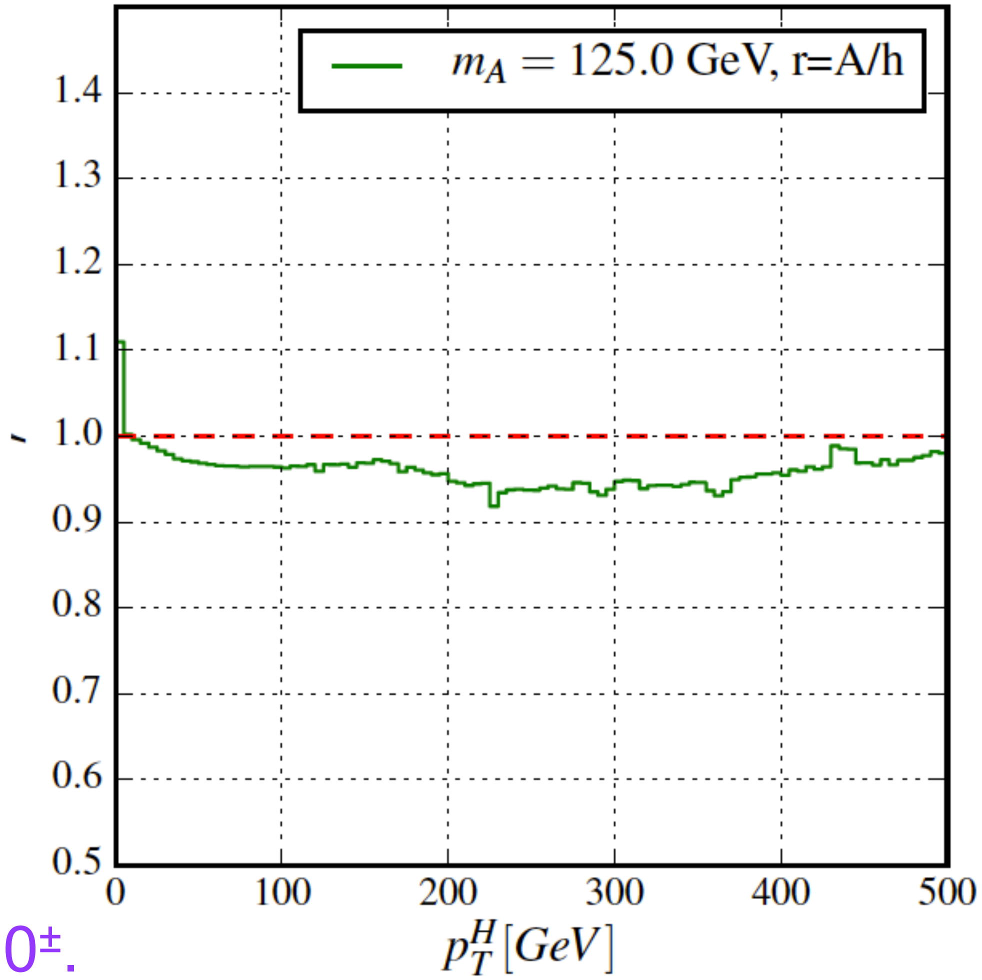
- **Higgs p_T uncertainty in ggF**, Higgs p_T uncertainty assignment ($d\sigma/dp_T$)
- MC reweighting study with HRes(v2) in NNLL+NNLO.
  - Decided to survive with reweighting for legacy paper.

Q) How to avoid MC reweighing for Higgs pT and NLO EW?

  - Still to check dynamical scale, which is relevant in boosted regime ($p_T > M_H$).
- To do *hfact* tune in POWHEG.

Q) Higgs p_T in BSM?

- Some interest for BSM Higgs p_T and physics in via $d\sigma/dp_T$.
  - MSSM/2HDM Higgs p_T in POWHEG by A. Vicini et al.
  - bottom quark softens the p_T spectrum compared to top (MSSM already exists).



Bagnaschi, ATLAS (N)NLO MC &Tools WS, Dec. 17, 2014

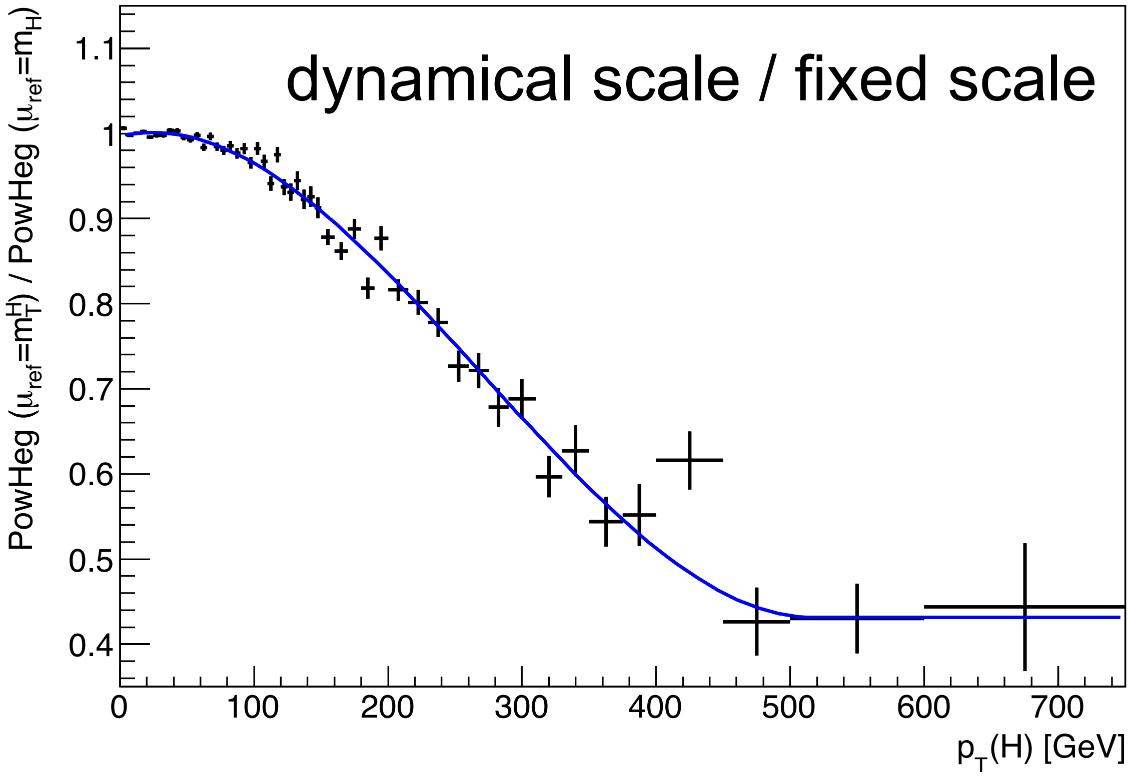
→ POWHEG should be useful for CP-mixing study in $J^P=0^\pm$.

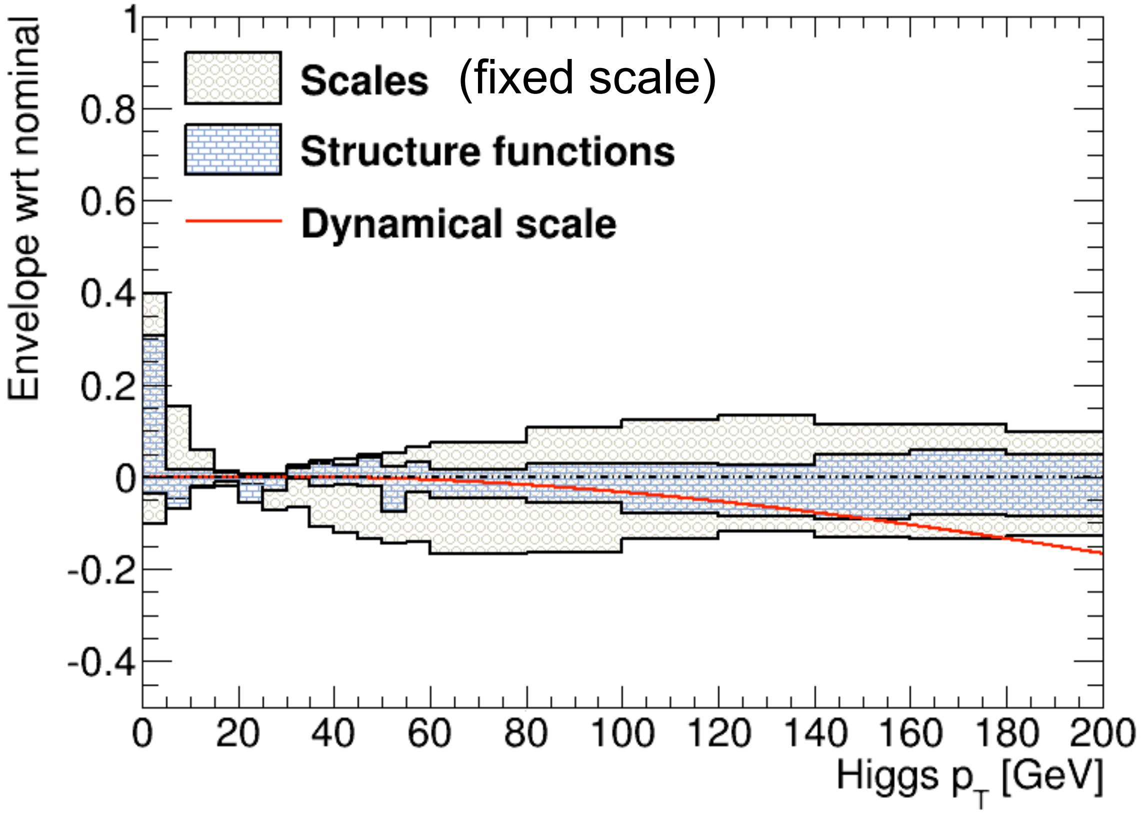
Dynamical scale

- Dynamical scale is relevant in boosted regime (typically p_T>100GeV or M_H).
  - ex. gg→H with $\mu=\sqrt{p_T^2+M_H^2}$ instead of fixed $\mu=M_H$.
  - Reduces cross section but also changes the shape! Same issue for SM bkg.!
  - Dynamical scale recently implemented in HRes2.1.
  - Dynamical scale effect for VH is relatively small (5%) due to the fact that Higgs is recoiling against V not against jets. How about VBF, SM VV?

Recommends to use dynamical scale for Higgs signal and bkg. when relevant.

Q) Suggests dynamical scale of boosted and other analysis?





6. Higgs Interferometry

Higgs Interferometry

- Interference exists when

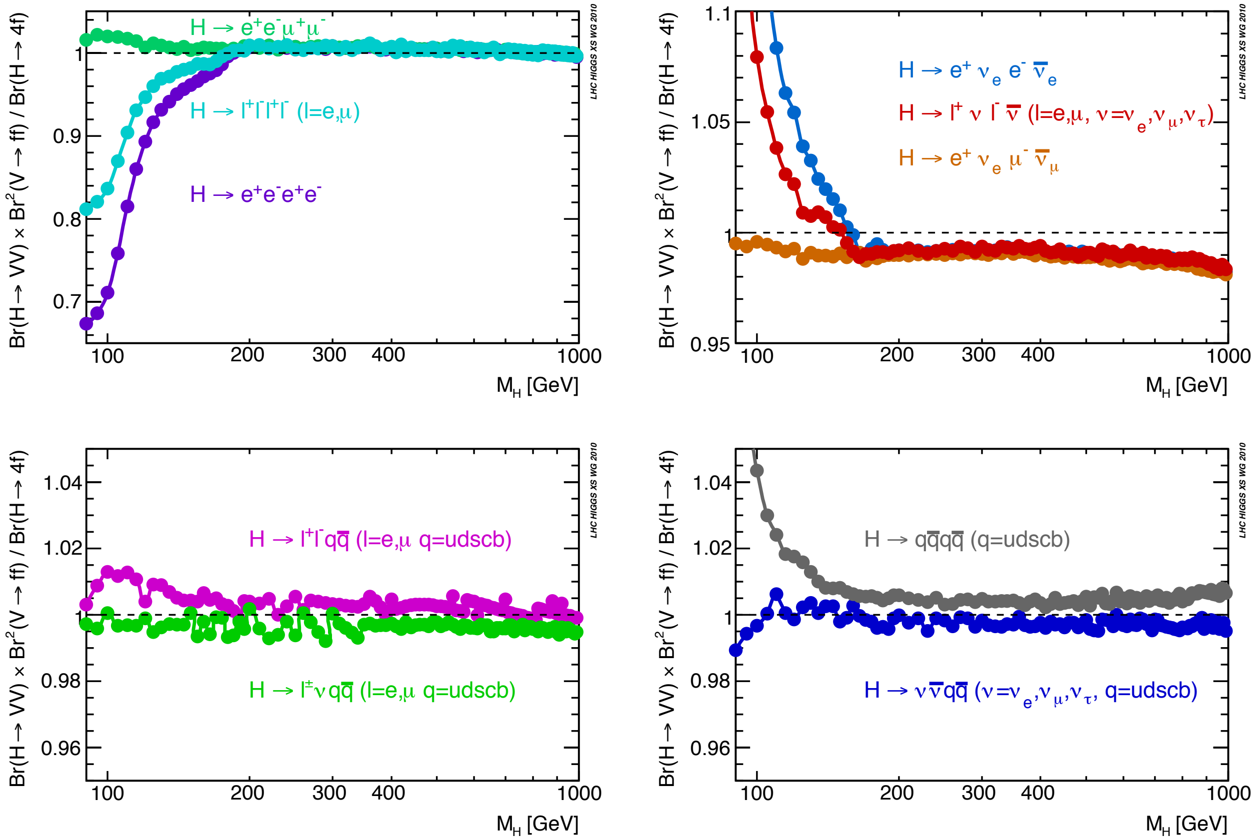
(i) identical initial and final state

(ii) at the same order in perturbative theory, $\alpha_{EW}^{m} \times \alpha_{QCD}^{n}$ (not always true?)

1. Interference with continuum background in gg→γγ and VV, VBF
2. Loops in Higgs boson production and decay, gg→H→γγ,Zγ (via t,b,W), gg→ZH (via t,Z), tH (via t,W)
3. Identical particles in the decay, H→WW/ZZ→4f for M_H=120GeV,
   - +11% in H→ZZ*→eeee,μμμμ
   - -5.4% in H→WW*/ZZ*→eνeν,μνμν

CERN Report 2

$$R = \frac{BR(H \to VV) \times BR(V \to f\bar{f}) \times BR(V \to f\bar{f})}{BR_{Prophecy4f}(H \to 4f)}$$



Q) Why the interference is almost always destructive?

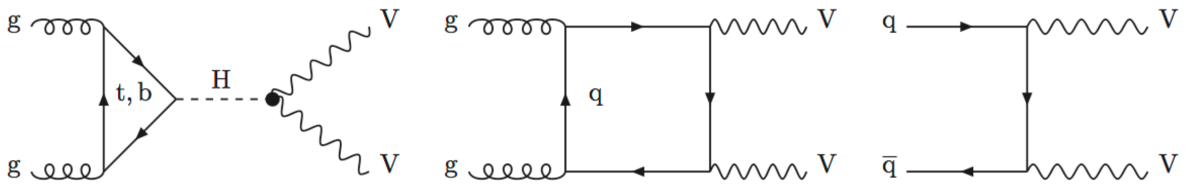
A) Accidental except the case related to unitarity constraint.

Higgs Interferometry in H→4 leptons

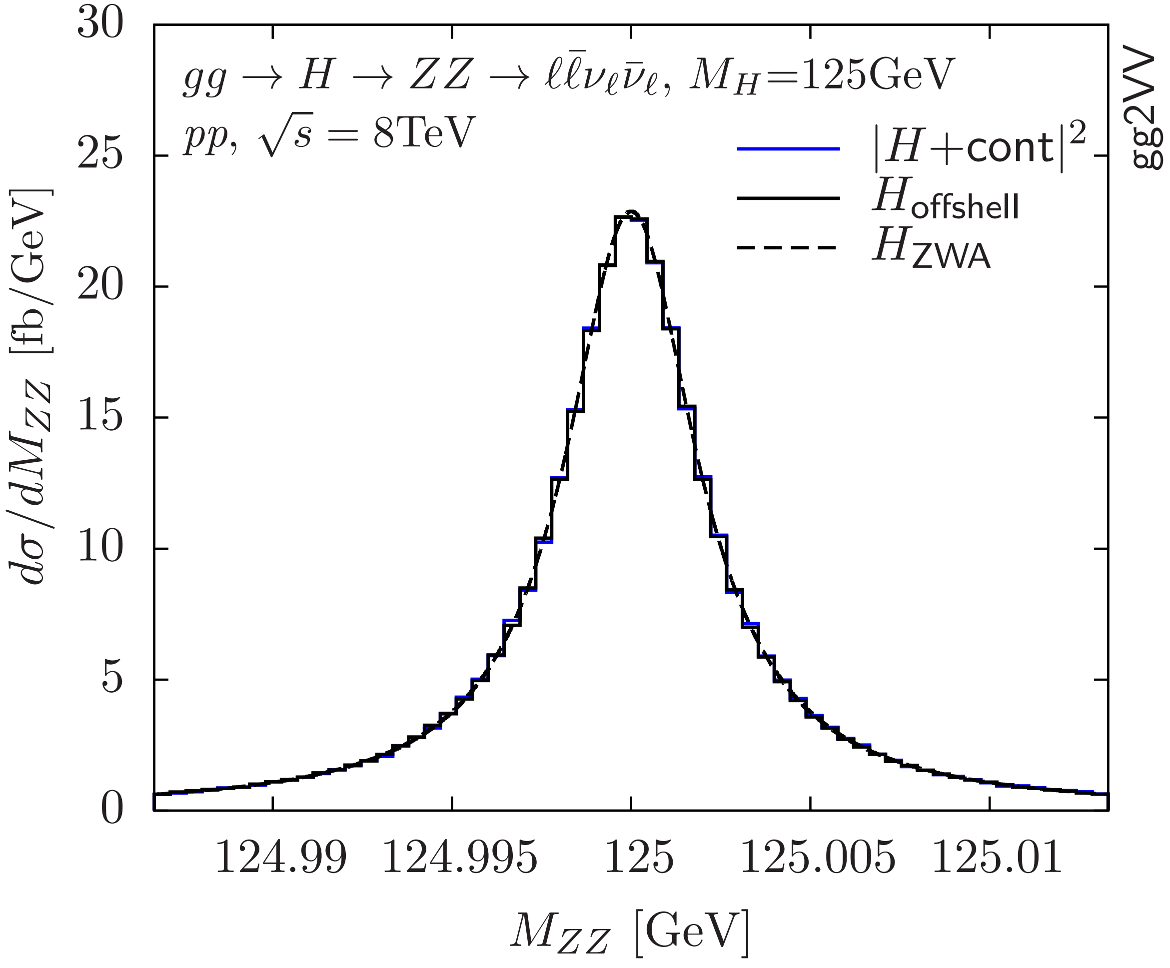
- Kauer-Passarino-Caola-Melnikov Effect
  - Off-shell signal cross section is independent of Γ_H !
  - On-shell signal cross section is proportional to $1/\Gamma_H$
  - Take the ratio in σ !
- More pronounced at 13/14TeV as gg parton-luminosity increases.

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

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

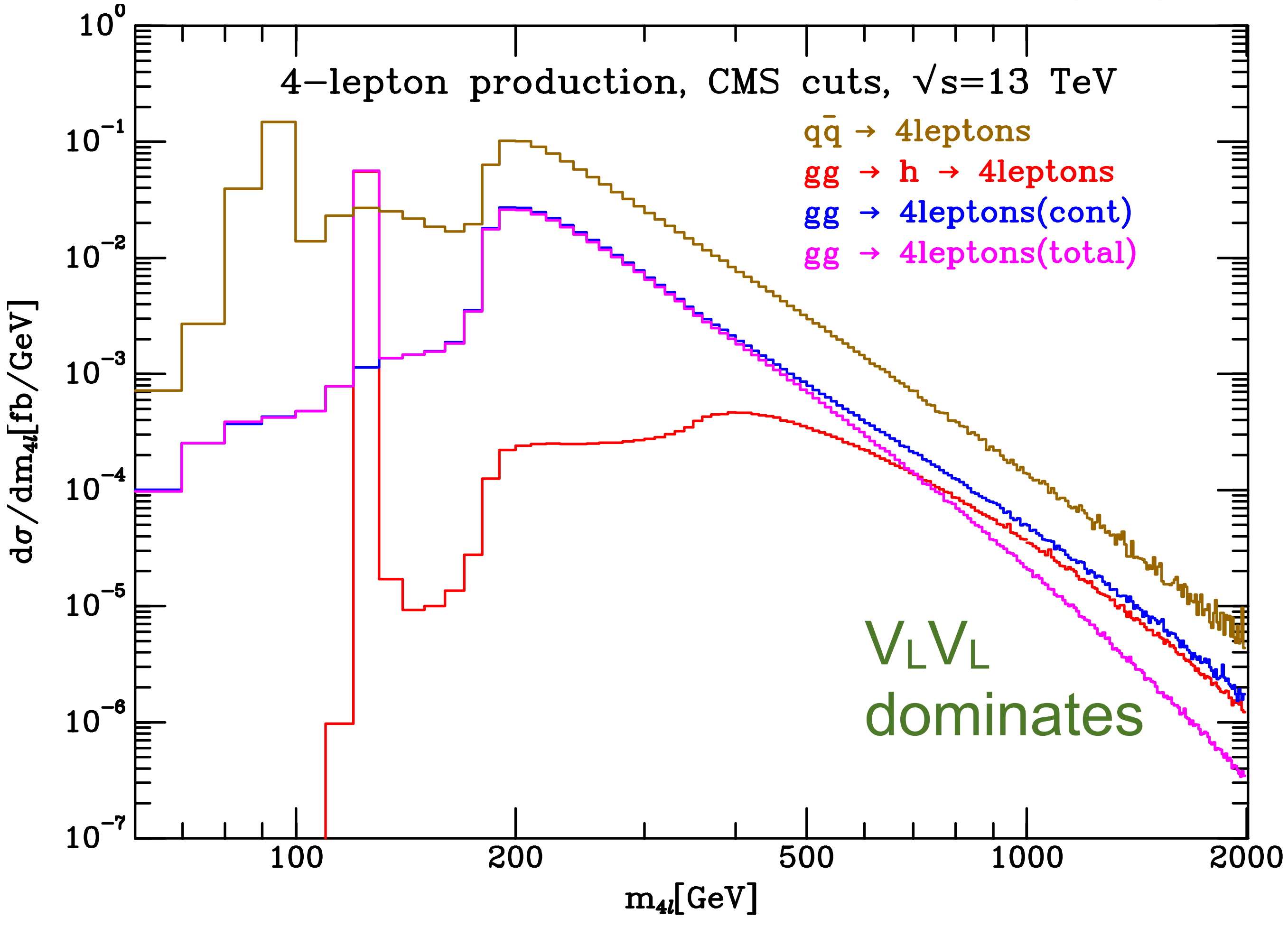


Kauer and Passarino, JHEP **08** (2012) 116



No interference effect for on-shell

Campbell et al. JHEP **04** (2014) 060



Q) K-factor for gg→VV (int √K)?

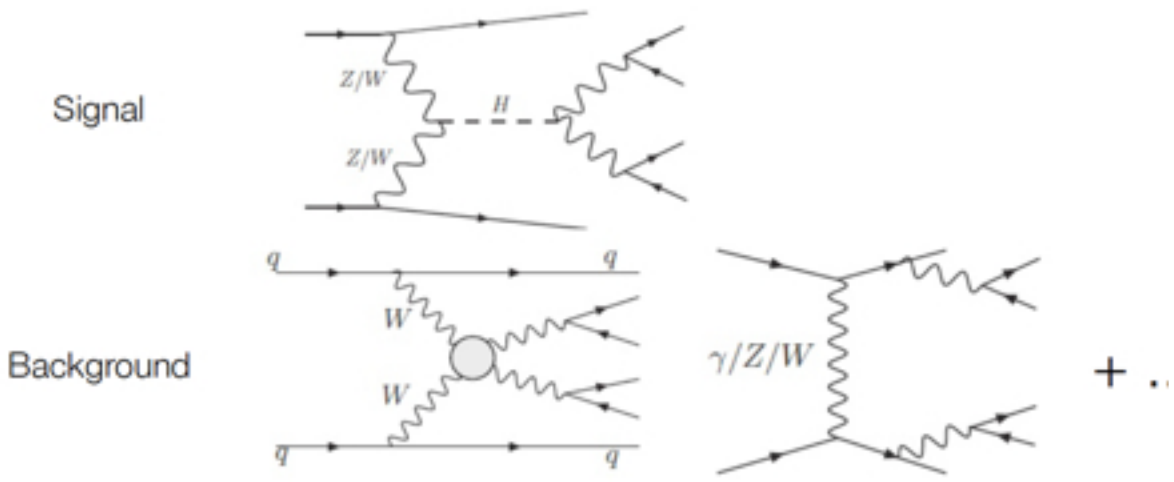
VBF Interference meeting in LHCHXSWG, Dec. 19, 2013

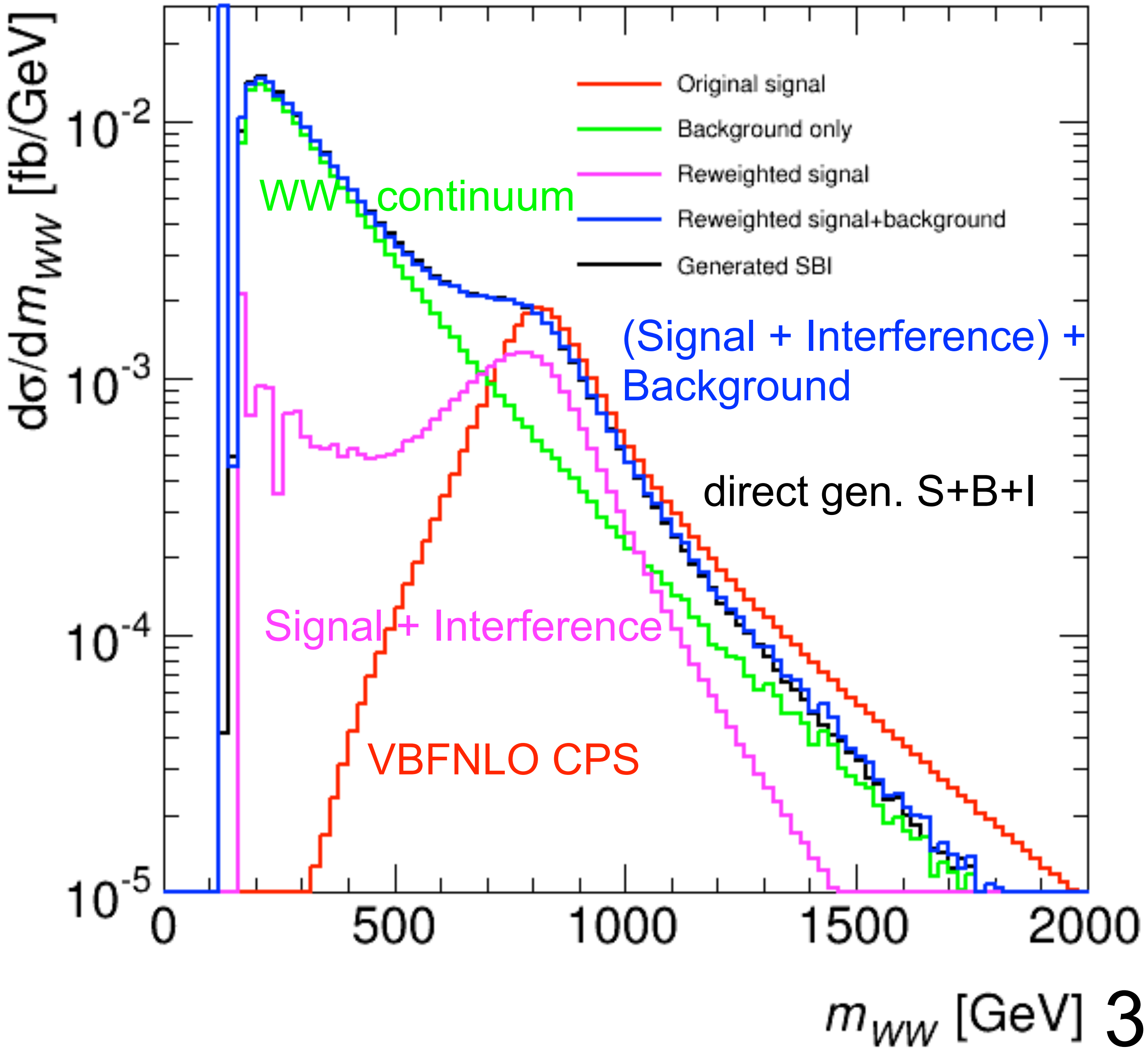
Heavy Higgs width and interference discussion in LHCHXSWG, May 4, 2015

Higgs Interference in VBF

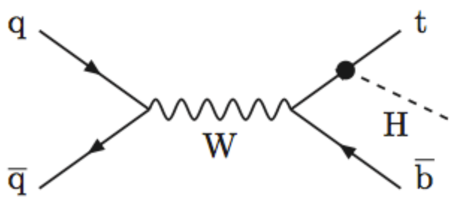
Interference in VBF H→WW/ZZ

- becomes significant for $M_H > 400$GeV.
- MadGrapn5, SHERPA, Phantom, VBFNLO, etc.
- Study reweight (S+I)/S.

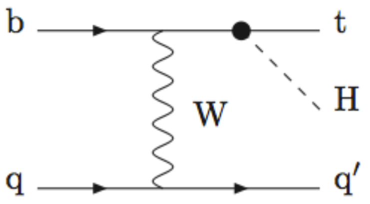




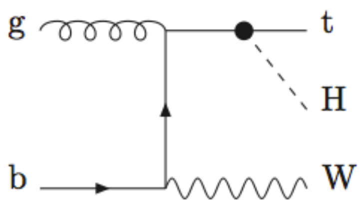
Resolving the degeneracy in κF with interference in tH



(a) s-channel

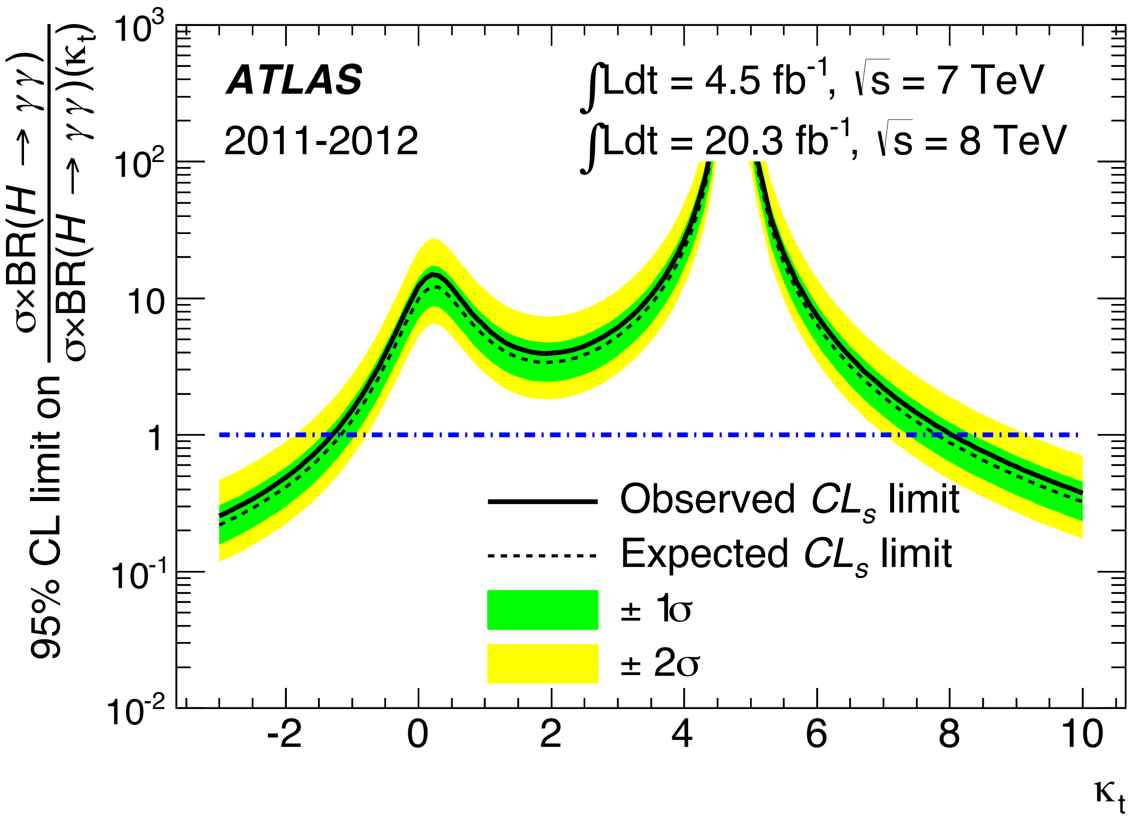


(b) t-channel

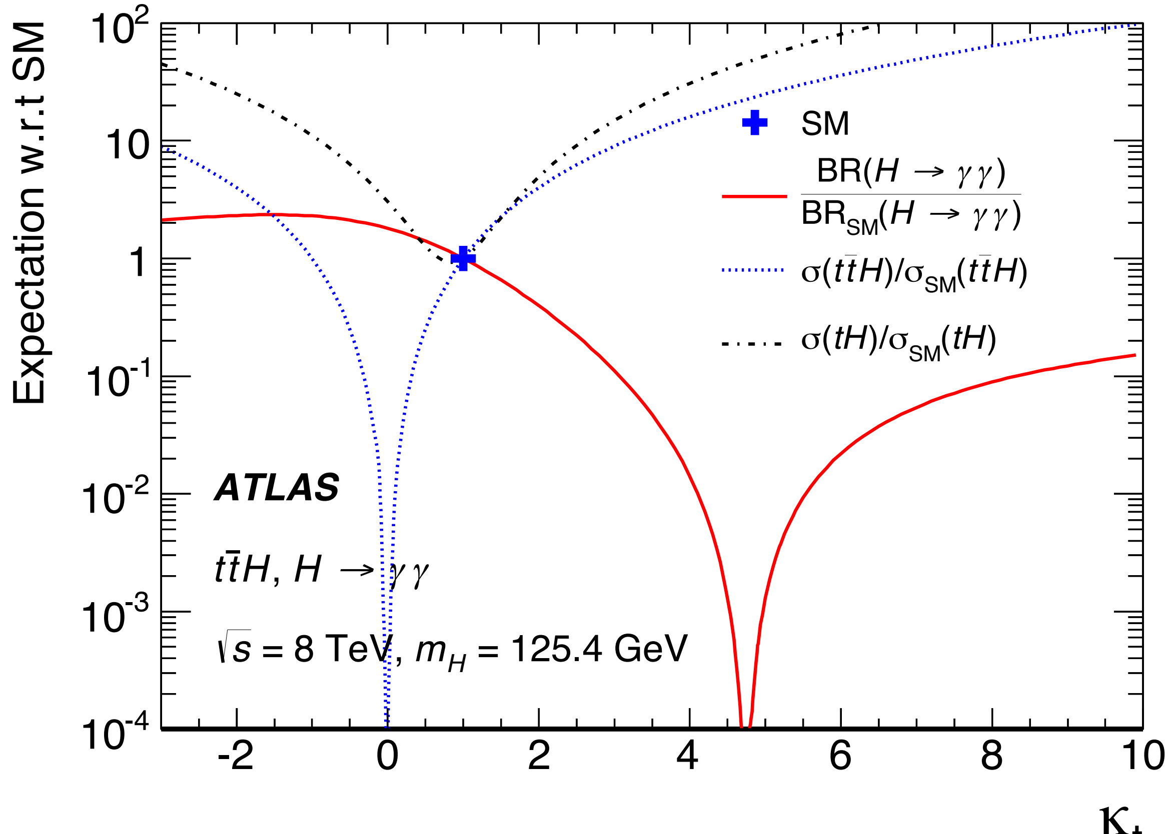


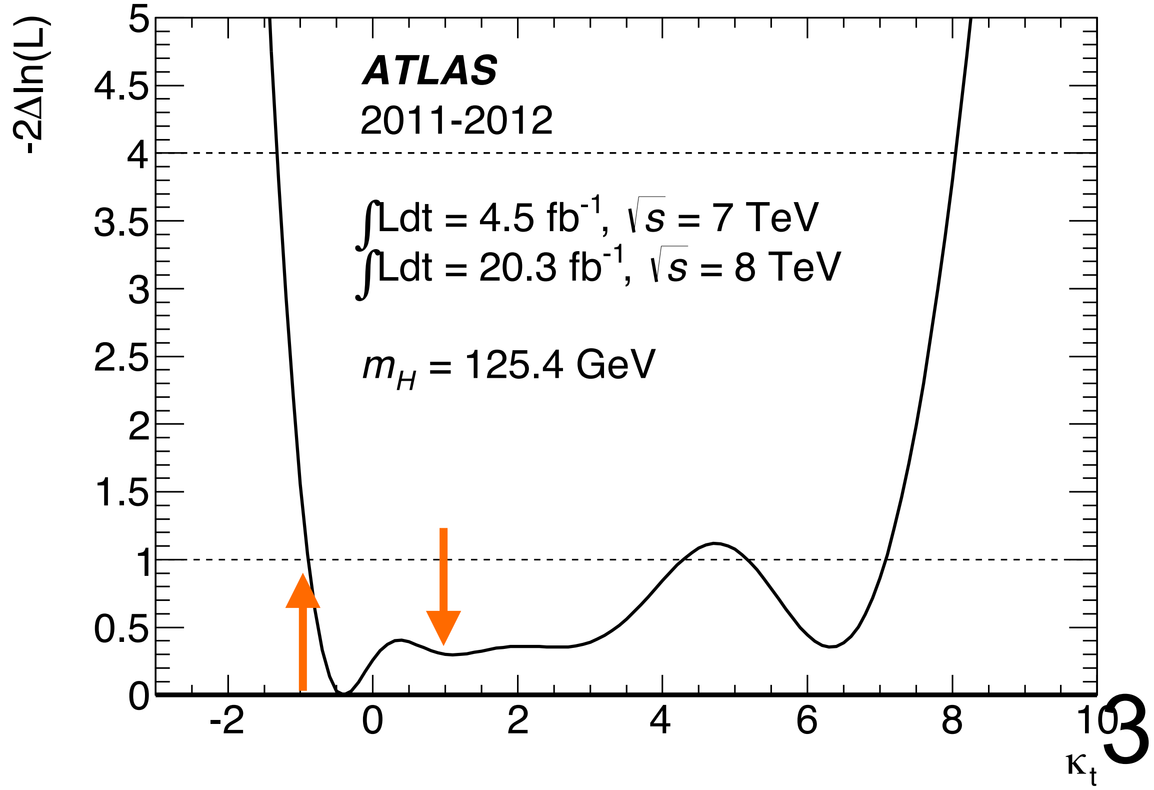
(c) W-associated

ATLAS PLB **740** (2015) 222



Q) Any other cool channel
for interference effect ?





7. NNLO Differential VV

Q) NNLO QCD + NLO EW pp→VV MC? NLO QCD MC for gg→VV?

pp→WW/WZ/ZZ/Wγ/Zγ@NNLO

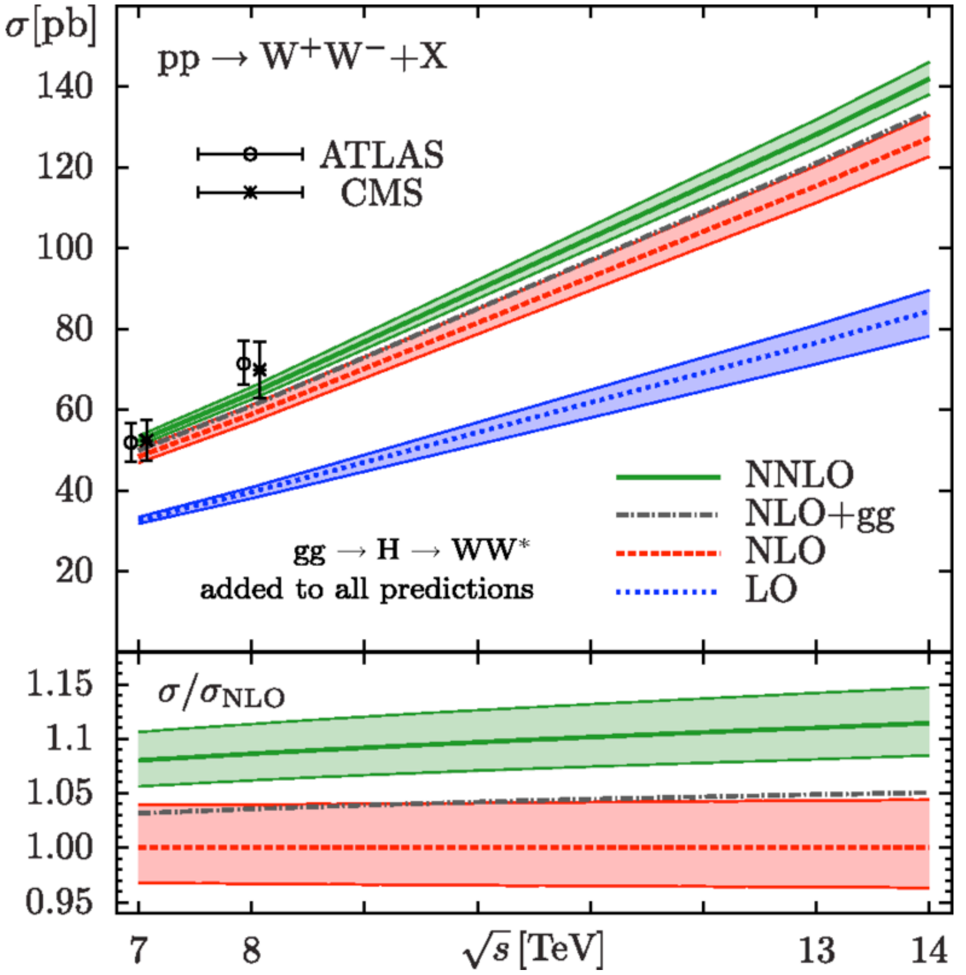
- NNLO QCD pp→WW/WZ/ZZ/Wγ/Zγ calculations by M. Grazzini et al.
  - Onshell gauge-boson (except WZ). Offshell case completed recently (Z*Z* ready in arXiv:1507.06257).
  - NNLO correction at 9-12% for pp→WW (gg→WW contributes 35% at NNLO).
  - We survived with K(m_{4l}) for RUN-1 with scale at $\mu=m_{4l}/2$.
  - Needs to re-calculate QCD scale and PDF+αs uncertainties for 13TeV (apart from YR2) !
  - The final goal is to have a public program MATRIX that can deal with all these processes, including leptonic decay and off shell effects, at the fully differential level (M. Grazzini).

- VBFNLO for pp→ZZ (includes offshell) with approx. NNLO
  - M .Raychem et al. (arXiv:1504.05588).
  - Can interface to Les Houches format.

- NLO EW correction
  - NLO EW should be important as NNLO QCD.
  - Small for integrated observable but large in HE tail.
  - RECOLA, OpenLoops, SHERPA and MUNICH, MadGraph5_aMC@NLO
    → Complete NLO EW for all VV(+jets) processes.

- gg→VV'
  - NNLO O(α_s^2) correction of O(5%) to pp→VV'.
  - Largest source of uncertainty at NNLO.
    More important at higher energies.
  - Dominant part of 2-loop amplitudes recently calculated, Caola et al. (arXiv:1503.08759), von Manteuffel et al. (arXiv:1503.08835).
  - Expect full NLO corr. soon. NLO MC development ?

German et al., PRL **113** (2014) 212001

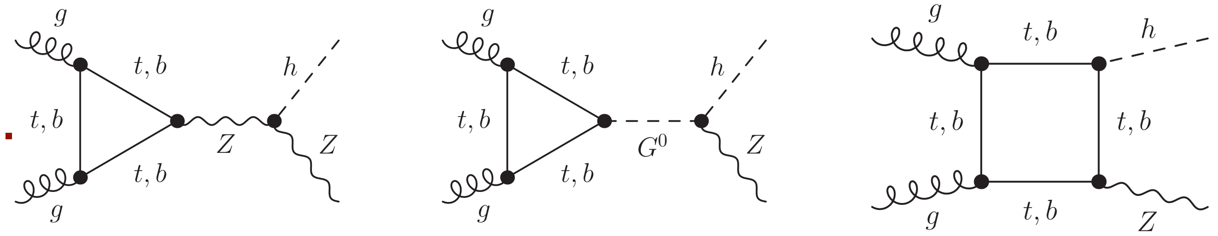


8. gg→VV, gg→HZ via box-diagram

Higgs p_T in VBF and WH/ZH

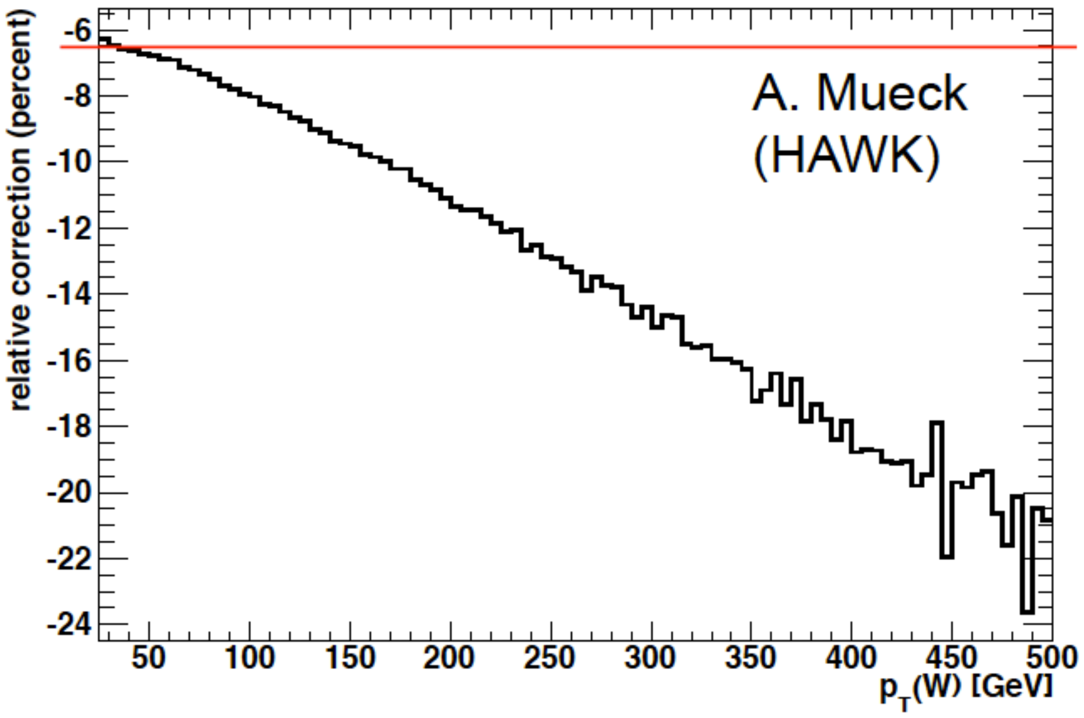
- **NLO EW effect on Higgs p_T in VBF, WH/ZH** and **dynamical scale issue**.
- Prescription and reweighting tool at ATLAS Higgs XS TWiki page.
  - Needs to take into account Higgs p_T dependence of NLO EW radiative correction via MC reweighting (cf. irrelevant in case of ggF). → Reweight !
  - Largely different Higgs p_T in gg→ZH.
  - gg→HZ (LO) is now available in POWHEG version 2.0.

Q) Dedicated gg→ZH analysis?
C) EXPs want to have NLO QCD gg→ZH MC.

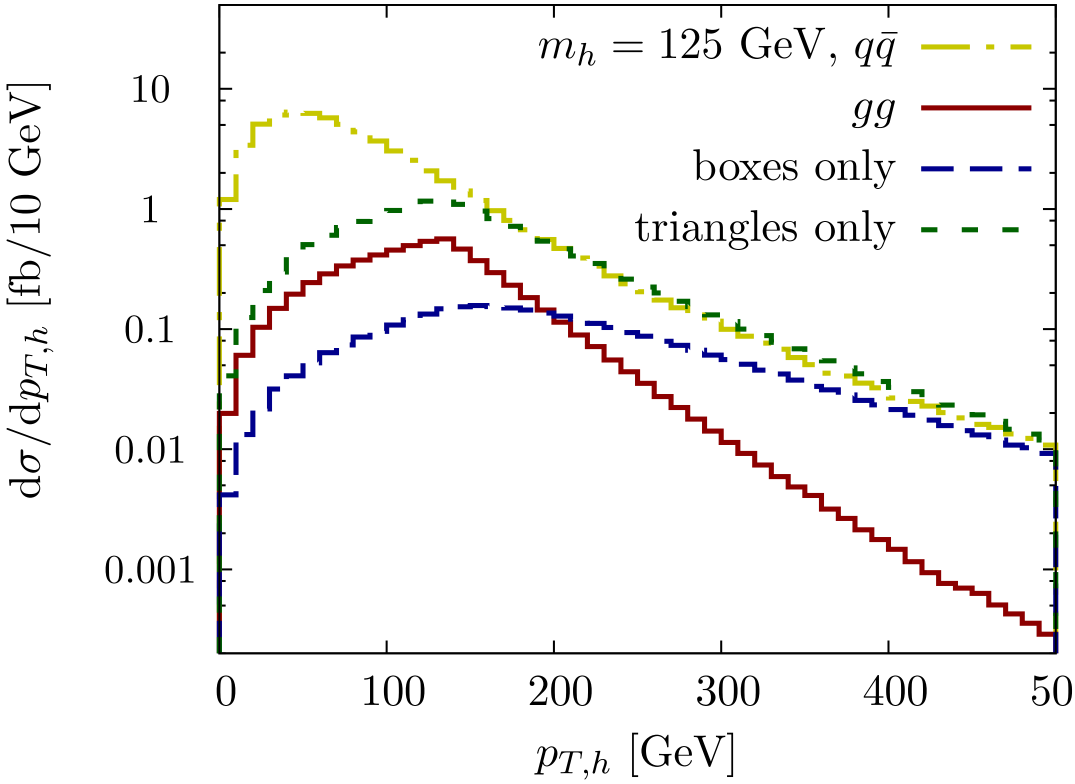


NLO EW corrections

inclusive corr.



C. Englert et al. PRD **89** (2014) 013013

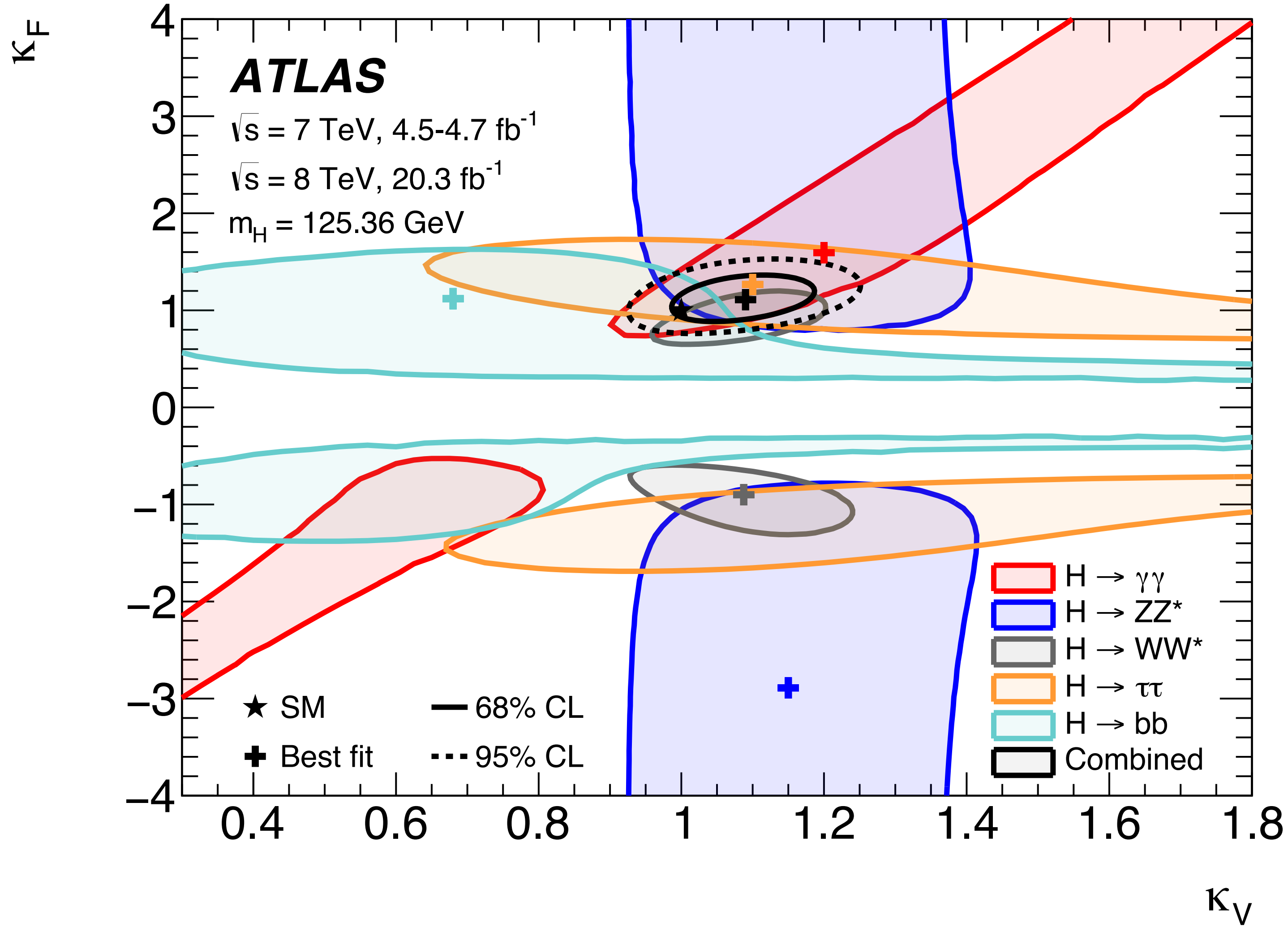


9. Higgs Boson Coupling

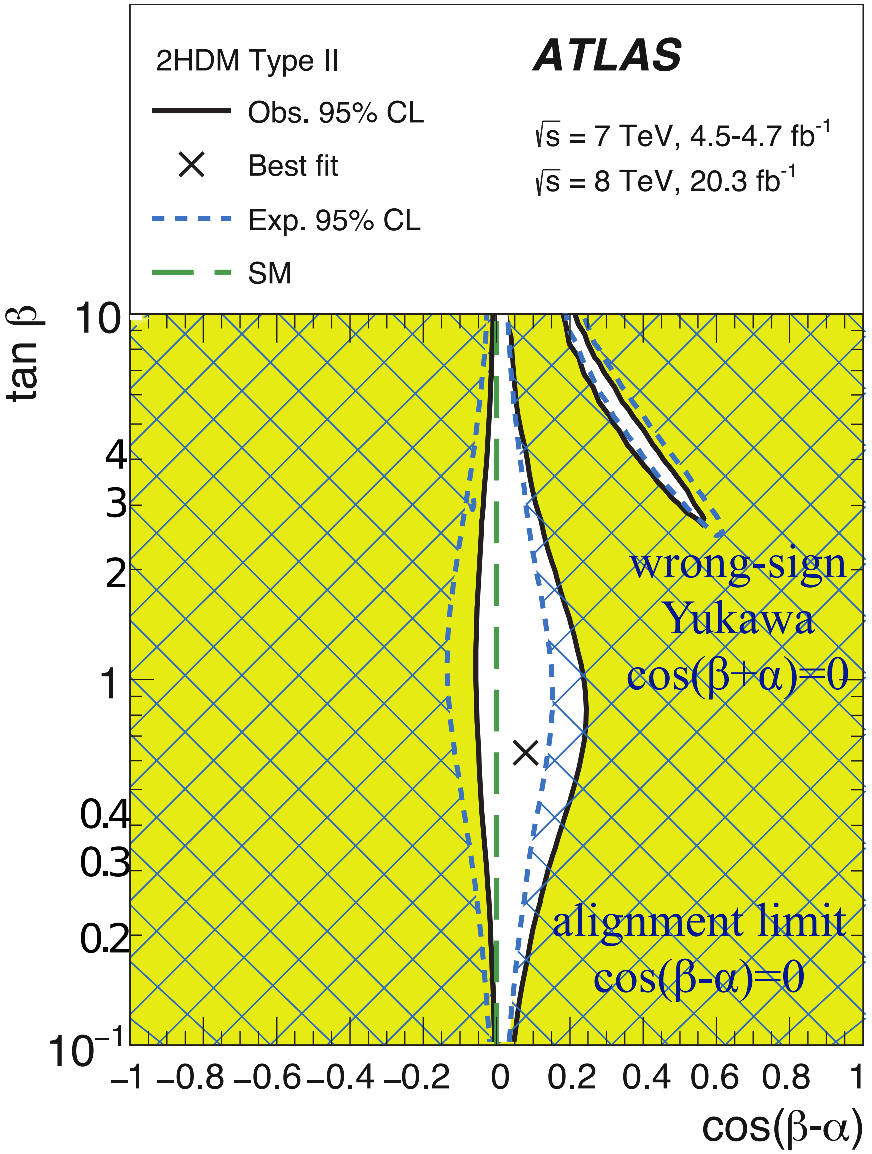
On the sign of k_F (convention $k_V>0$)

- 2HDM/MSSM predicts $k_F<1$, but $k_F>1$ is possible in Little Higgs, Higgs triplet model.
- Different sign in up/down-type fermion is possible in limited parameter space in 2HDM/MSSM, ex. Type-II $k\_d = \sin(\beta-\alpha) - \cos(\beta-\alpha)\times\tan\beta$.
- "Wrong-sign Yukawa coupling", $\cos(\beta+\alpha)=0$.
- Composite top-quark that could give $\lambda_$top-bottom < 0 but for the light quarks it would be much more complicated.
- $k_F<0$ in EFT would require very large higher-dimensional operators.

ATLAS HIGG-2014-06



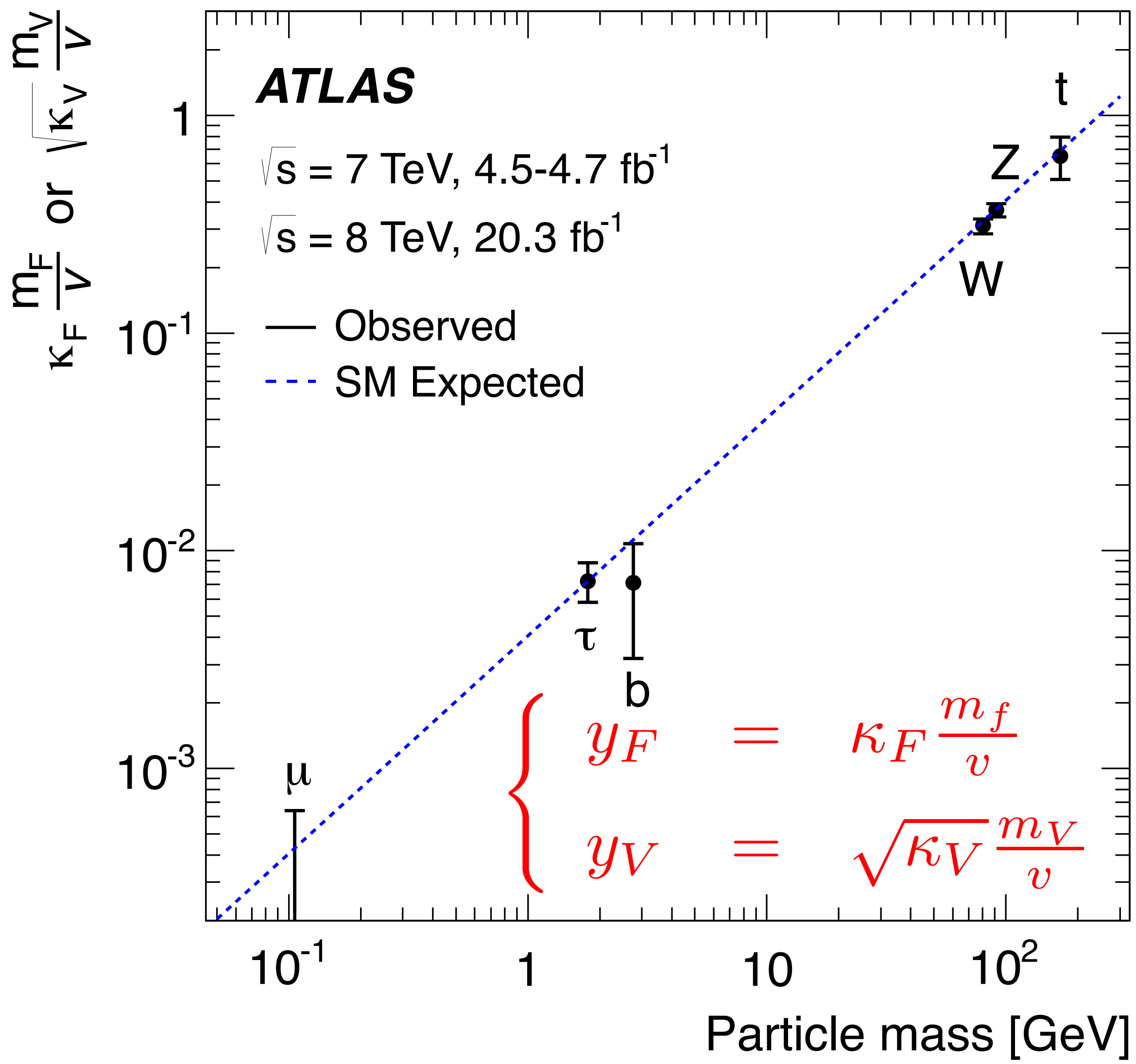
ATLAS HIGG-2015-03



Couplings versus Mass - Higgs-gauge boson and Yukawa -

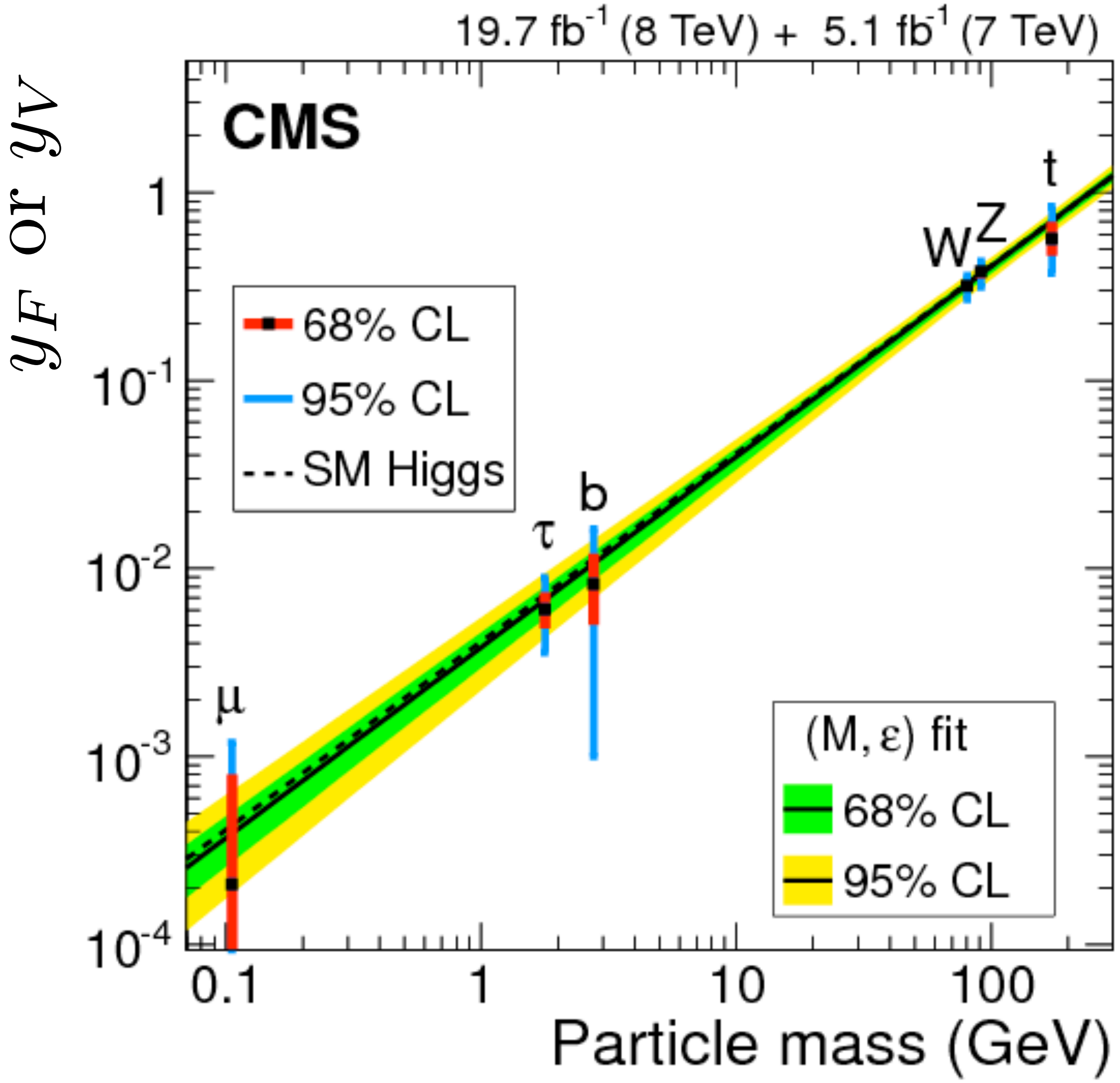
- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W/Z gage bosons and fermions and unitarity conservation below 1 TeV.
- Non-linear relation would indicate the Higgs sector is not single doublet.

ATLAS HIGG-2014-06



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

CMS-HIG-14-009



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

Note on Coupling versus Mass relation

- Discussions on quark mass (M. Spira)

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

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

- Prescription for mass vs coupling plot

https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWGSMInputParameter/Higgs_coupling.pdf

1. One can define quark mass for Yukawa coupling,

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

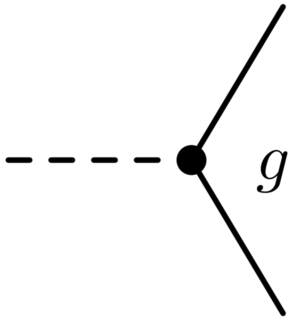
2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,

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

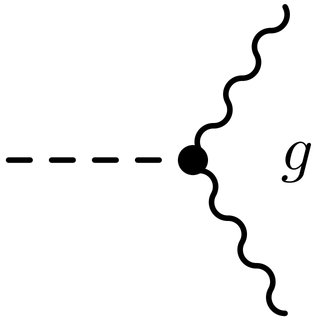
$$m_b(m_b) = 4.16\,\mathrm{GeV}, m_b(M_H) = 2.76\,\mathrm{GeV}$$

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

4. Use PDG values for leptons and W/Z boson masses.

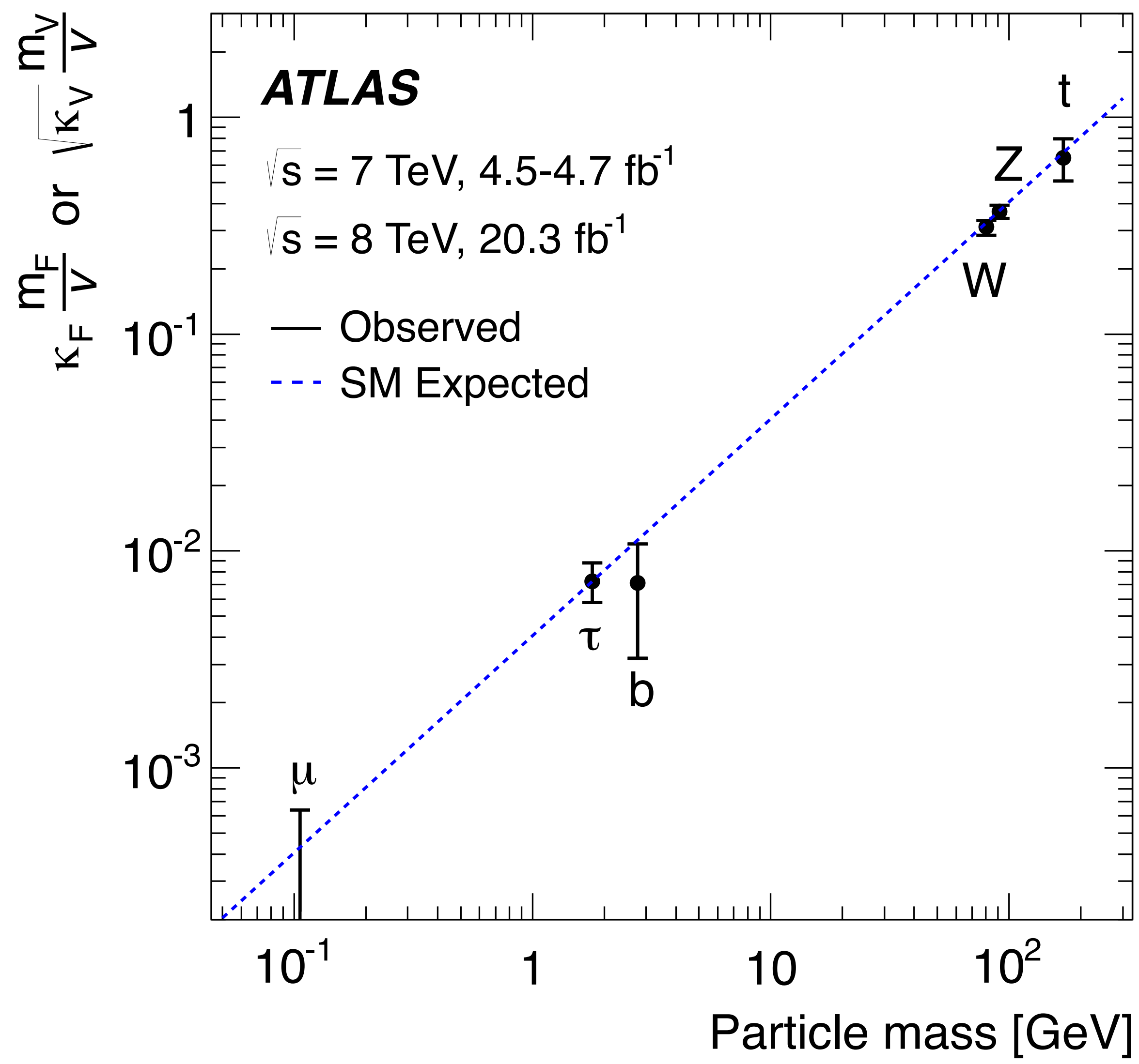


$$g_F = \sqrt{2}\frac{m_f}{v}$$



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

ATLAS HIGG-2014-06

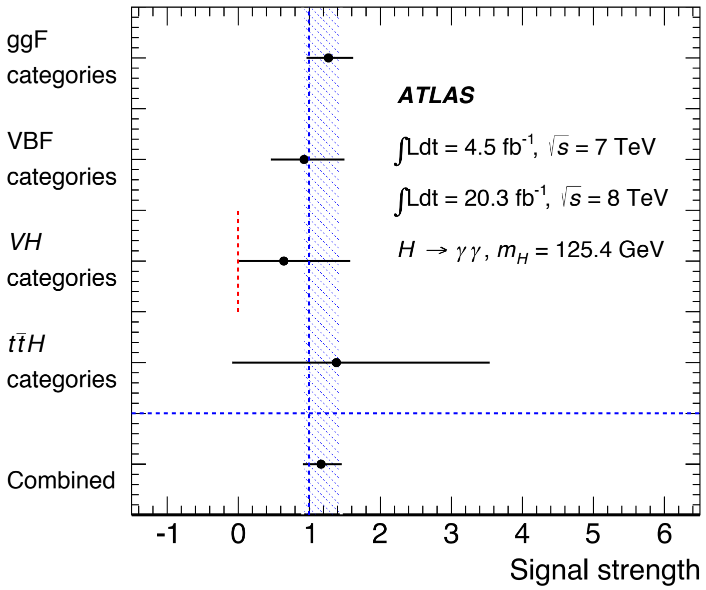


$$m_b(m_b) = 4.16\,\mathrm{GeV}, m_b(M_H) = 2.76\,\mathrm{GeV}$$

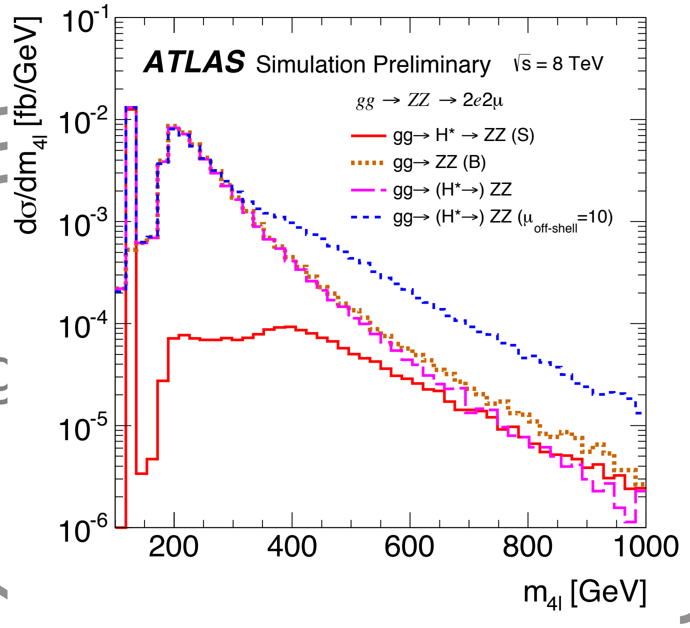
Q) top-mass (172.5GeV) in MC?

Higgs Analysis in Unified HEFT ?

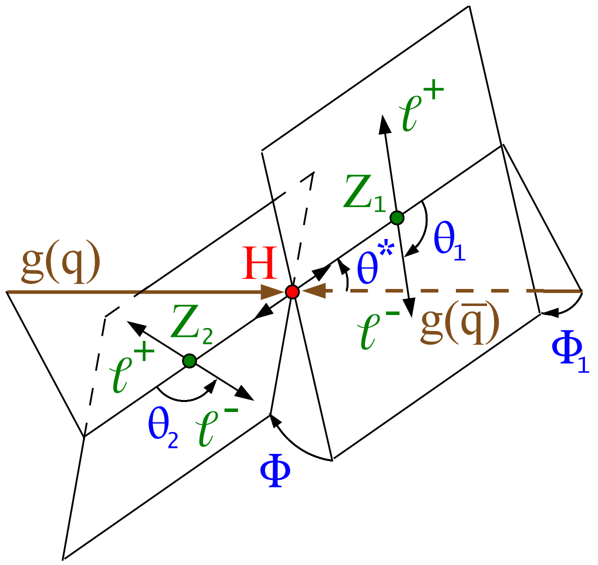
Higgs coupling in h(125)

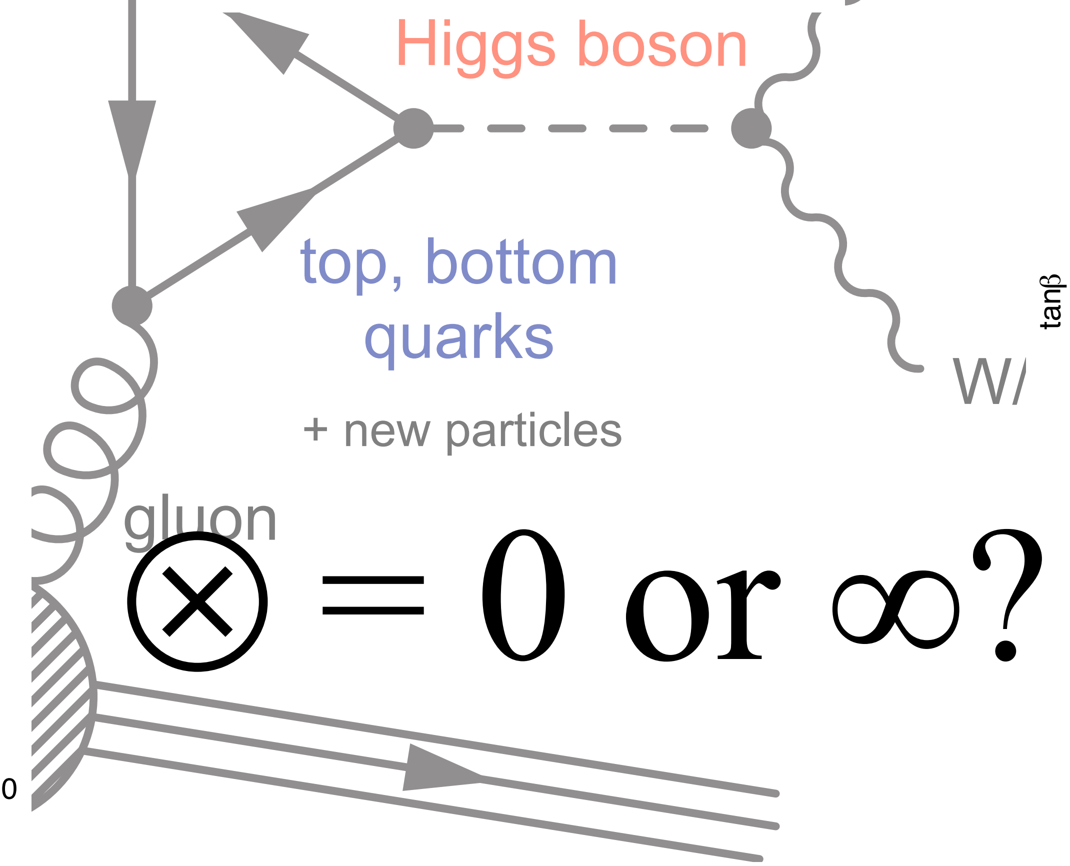


Higgs off-shell coupling



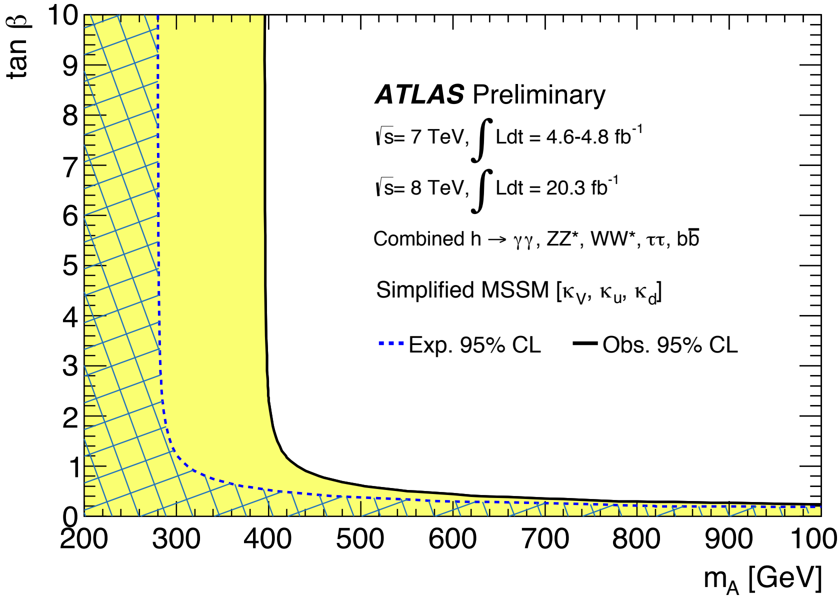
Spin/CP mix/viol. Tensor structure



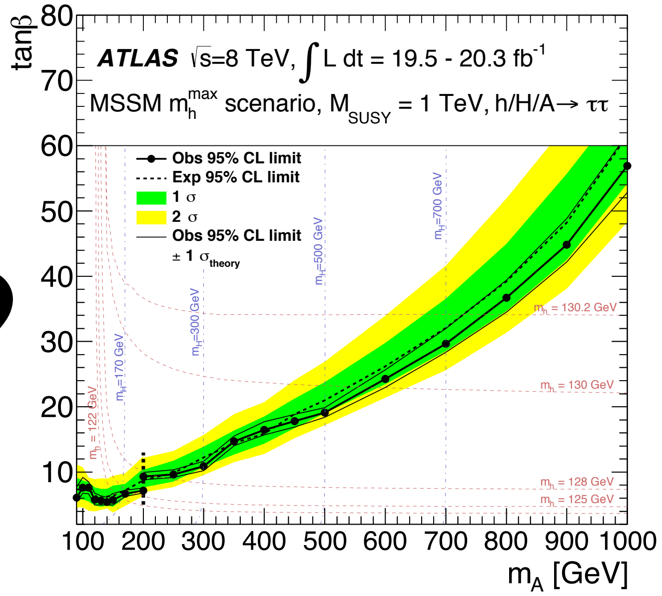


$$\otimes = 0 \text{ or } \infty ?$$

Higgs coupling interpretation



BSM Higgs Searches



10. Higgs XS&BR for RUN-2

Processes

Q) Higgs mass range M_H=[60,1000]GeV?
M_H=125±5GeV with 0.1GeV step?

Q) Reference Higgs mass 125 or 125.09GeV?

- Needs to survey detectable processes for Higgs production and decay for RUN-2 and beyond !
- Tool development is also very important aspect.

I. Main production processes	[H, qqH, VH]
II. Associated Higgs production with heavy quarks	[ttH/bbH/ccH]
III. Associated Higgs production with single top quark	[tHq, WtH, btH, tH, bH]
IV. Higgs boson pair/triple production	[HH, qqHH, VHH, ttHH, tjHH, HHH]
V. Higgs production in association with gauge bosons	[VVH]
VI. Higgs production in association with a gauge boson and two jets	[qqHV]
VII. Gauge boson scattering	[WW→WW, WW→HH, etc.]
VIII. Rare process and decay	[qq→Hγ, t→cH, etc.] [quarkonia J/Ψ(Υ)+γ, γ/W/Z+P, etc.]

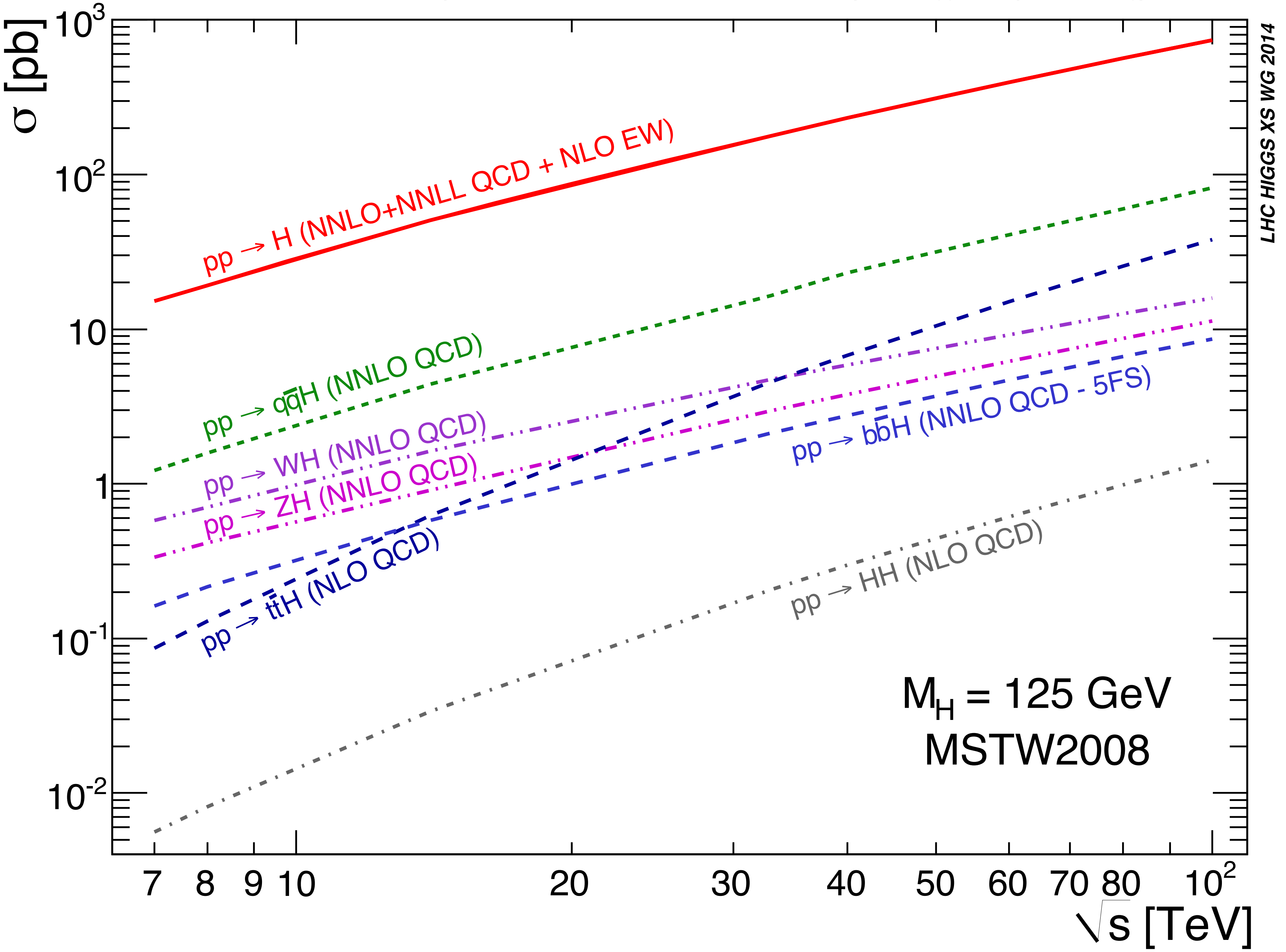
+ any other process ?

Q) Recalculation of SM BR with new SM inputs ?
(α_s=0.119→0.118, updated quark mass)

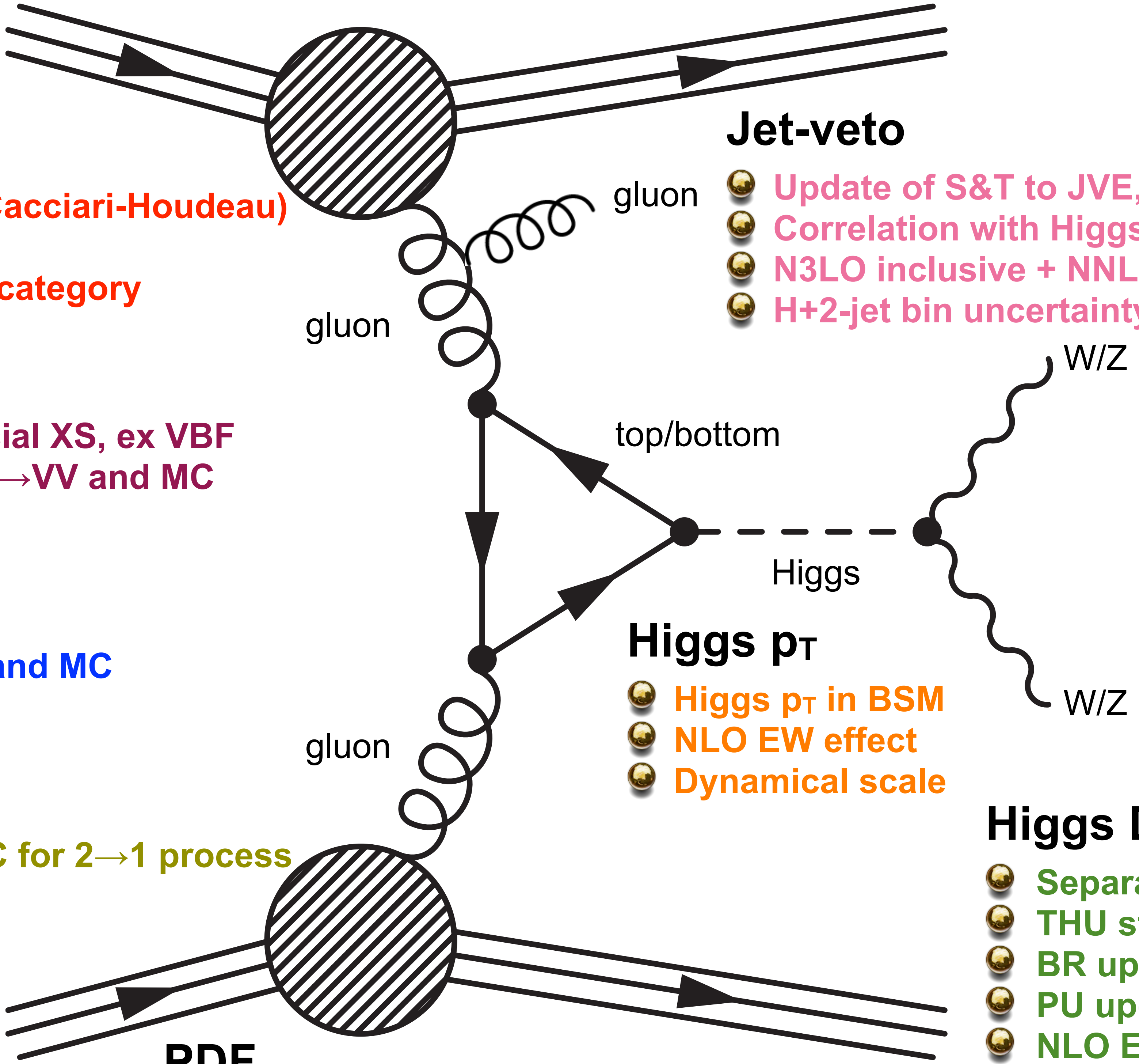
FCC-hh

Q) Different theory consideration needed for 100TeV?

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy#6_Plots



Leftover from RUN-1 and challenge for RUN-2



ggF

- N3NLO QCD correction
- Scale uncertainty prior (Cacciari-Houdeau)
- α_s uncertainty reduction
- Reduction of ggF in VBF category

Differential NNLO

- NNLO QCD effect in fiducial XS, ex VBF
- NNLO QCD + NLO EW $pp\to VV$ and MC (include offshell, ex Z^*Z^*)

Higgs Interferometry

- NLO QCD in $gg\to VV$, ZH and MC
- Interferometry in VBF

(N)NLO MC

- NNLO QCD + NLO EW MC for 2→1 process
- H+0/1/2-jets (N)NLO MC
- H+3-jets NLO MC for CJV
- $\Delta\Phi_{jj}$ in H+2-jets MC

Jet-veto

- Update of S&T to JVE, new SCET approach
- Correlation with Higgs p_T
- N3LO inclusive + NNLO H+0/1-jet comb.
- H+2-jet bin uncertainty beyond NLO

Higgs p_T

- Higgs p_T in BSM
- NLO EW effect
- Dynamical scale

Higgs Decay

- Separation of THU and PU
- THU statistical prior
- BR update (ex $H\to bb$)
- PU update (α_s, m_b, m_c, m_t)
- NLO EW differential (Prophecy4f/Hto4l)
- Dalitz decay common def.

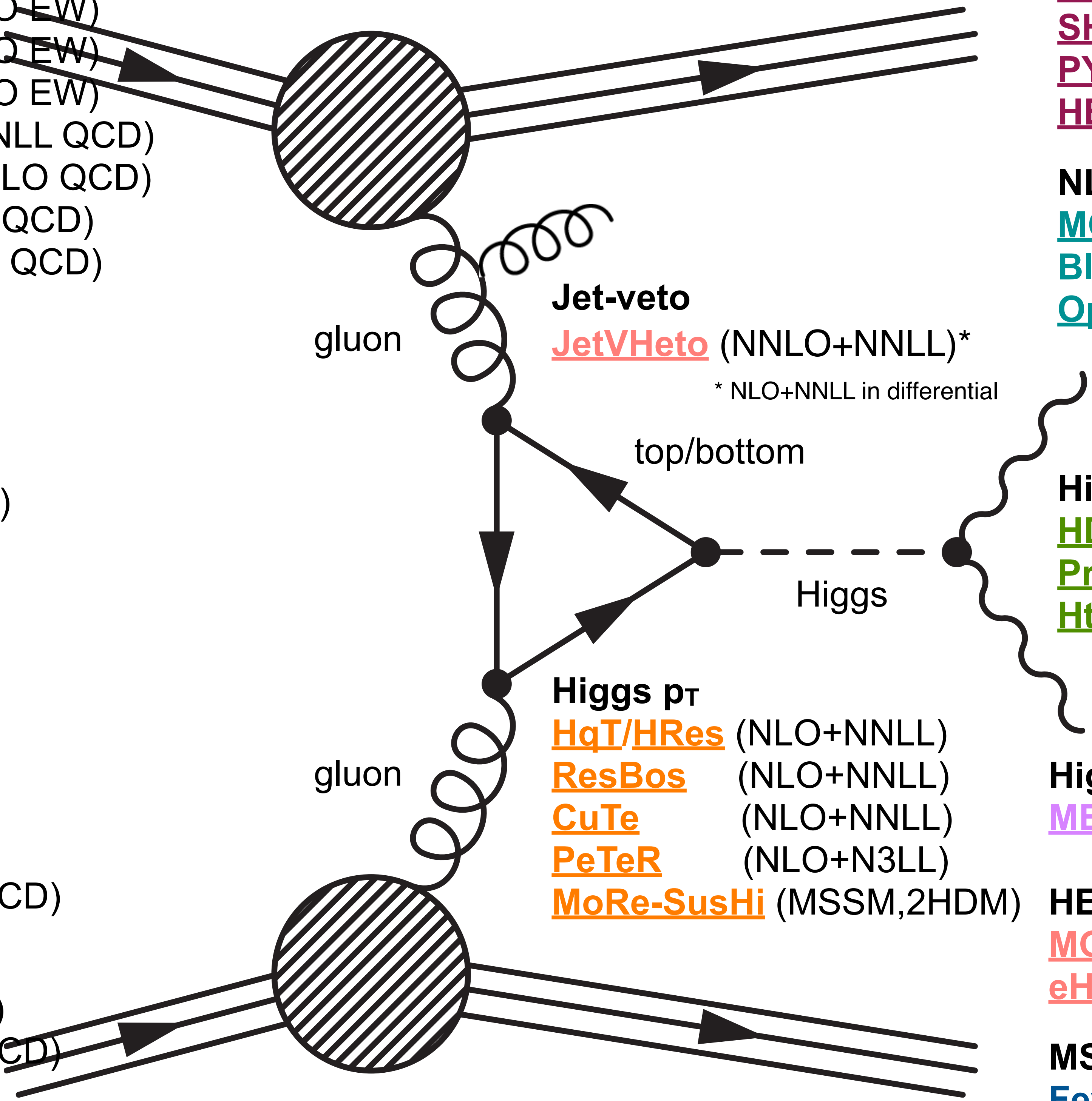
PDF

- N3LO PDF
- PDF4LHC15 (LHAPDF) for XS and MC
- PDF correlation between Higgs and SM bkg.

Compiled by R. Tanaka, Sep. 2015

Clickable Link

Tools for Higgs Analysis



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

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

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

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

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

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

+ private codes.

Jet-veto
JetVHeto (NNLO+NNLL)*
* NLO+NNLL in differential

Higgs p_T
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)
CuTe (NLO+NNLL)
PeTeR (NLO+N3LL)
MoRe-SusHi (MSSM,2HDM)

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

SM: MCFM, MG5_aMC@NLO, VVamp, gg2VV,
DiffTop

NLO MC
POWHEG-BOX MiNLO
MadGraph5_aMC@NLO
SHERPA MEPS@NLO
PYTHIA8 UNLOPS
HERWIG++ Matchbox

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

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

Higgs Properties
MELA/JHU, MEKD, Lilith

HEFT
MG5_aMC@NLO (SILH,HC)
eHDECAY

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

Compiled by R. Tanaka, June 2015

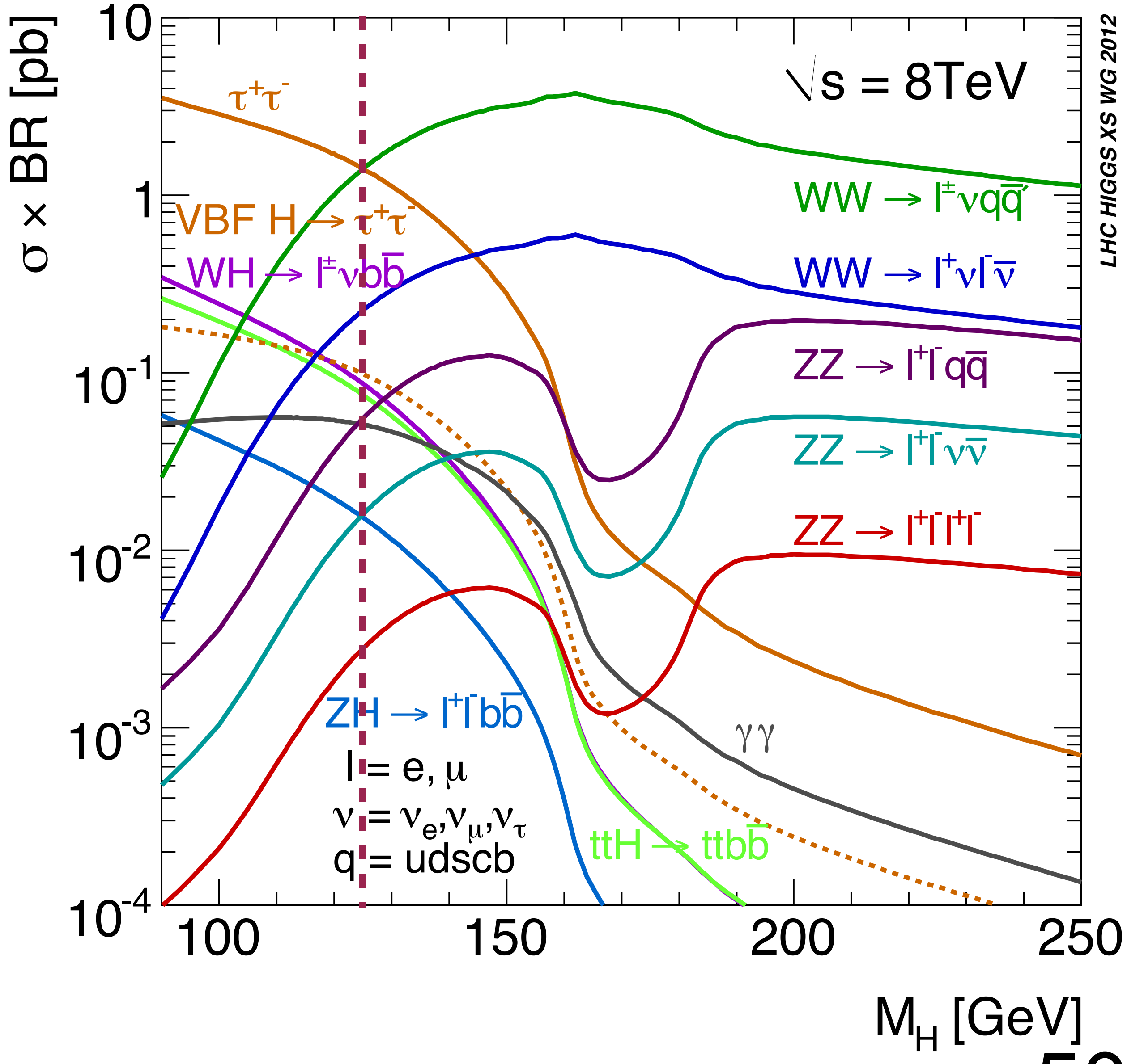
backup

Frequently asked question: which M_H for μ ?

- Pay attention to M_H when discussing the μ-value !
- Total cross section and BR are changing slowly for M_H=125GeV.
  - BR(H→γγ) is at plateau.
  - But BR(H→WW,ZZ) are changing rapidly due to phase space.

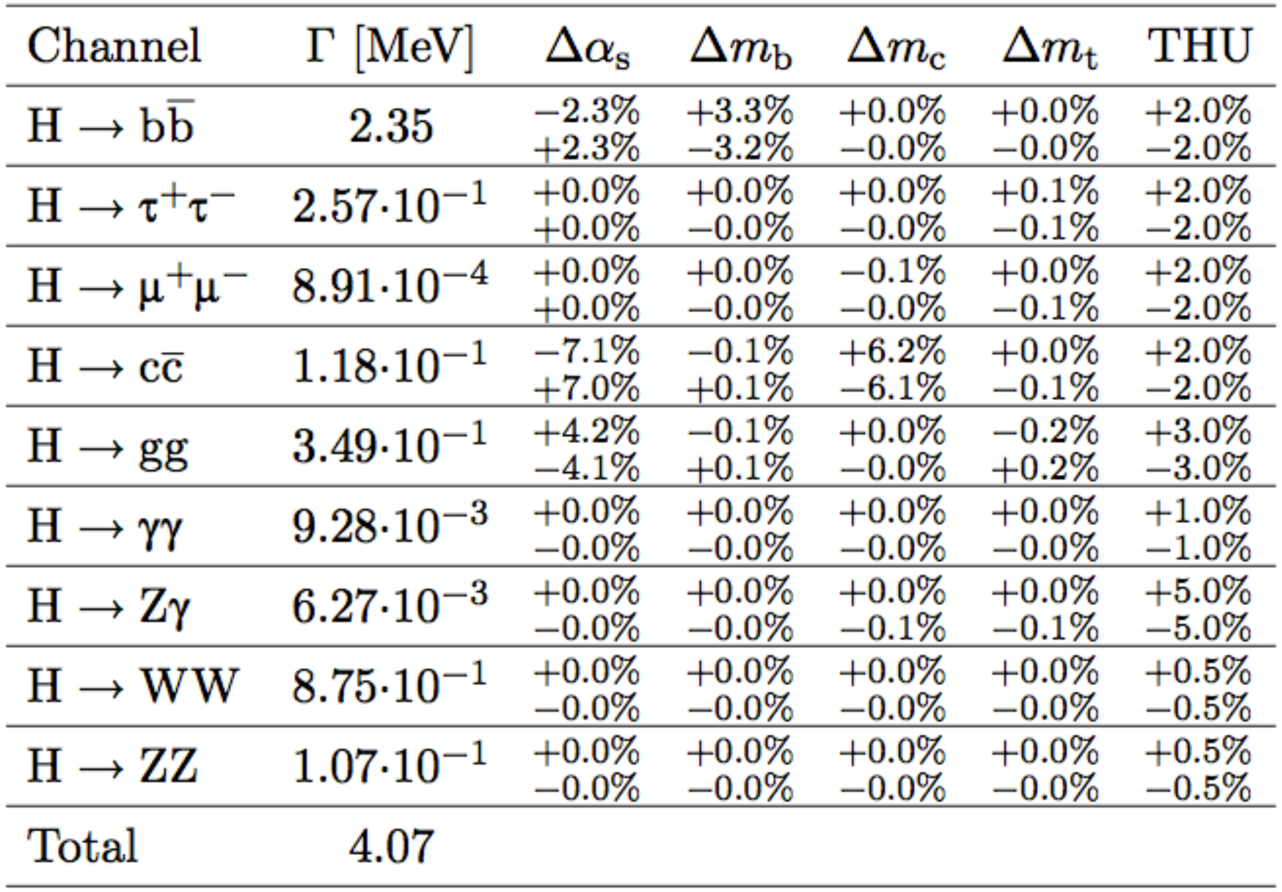
Process	dσ/dM, dBR/dM
σ(ggF+VBF+VH+ttH+bbH)	-2%/GeV
BR(H→bb,ττ,cc,μμ)	-3%/GeV
BR(H→gg)	-1%/GeV
BR(H→γγ)	±0%/GeV
BR(H→Zγ)	+5%/GeV
BR(H→WW)	+8%/GeV
BR(H→ZZ)	+9%/GeV

@M_H=125GeV



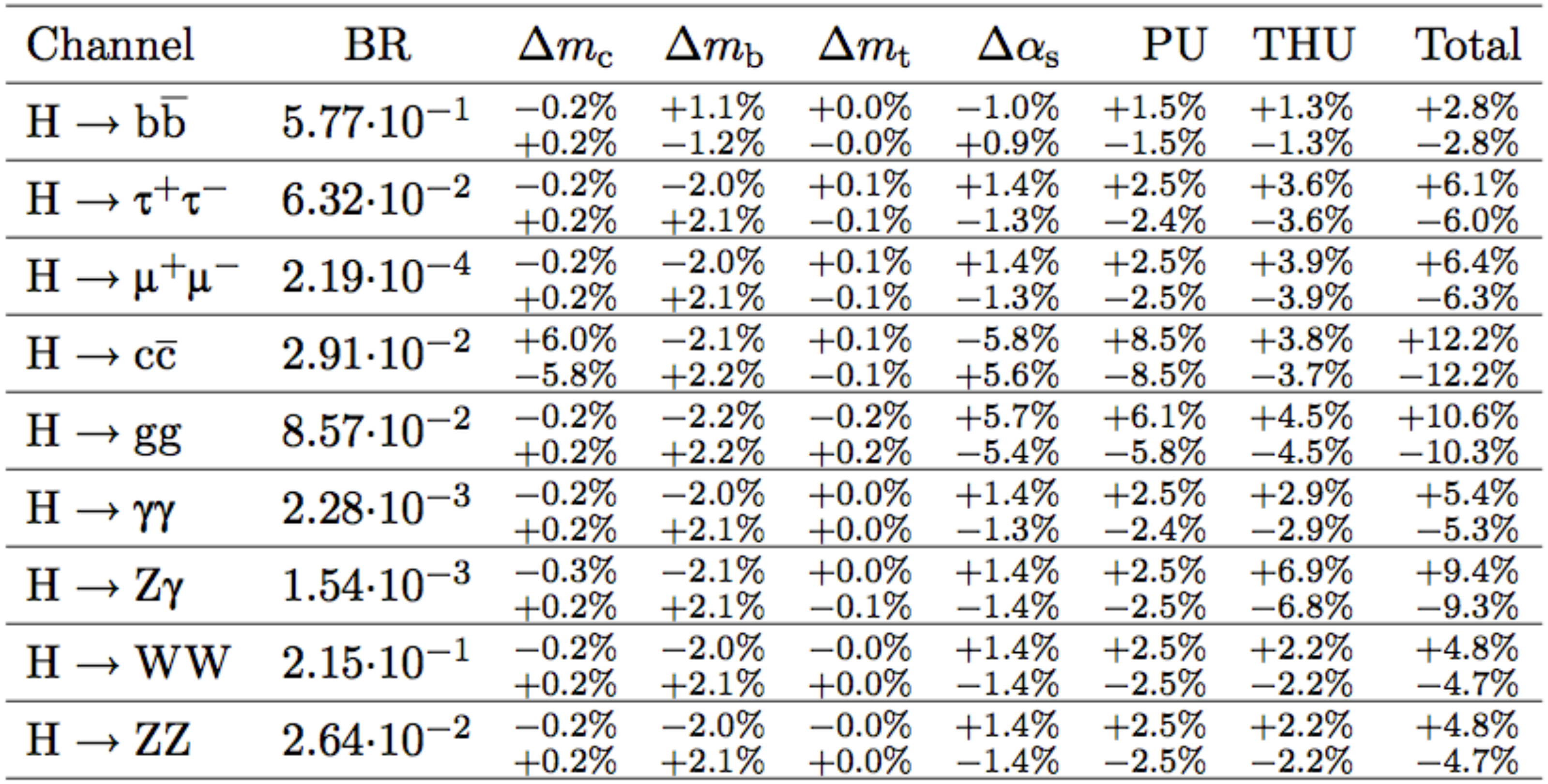
Higgs boson decay uncertainty

Uncertainty in width



Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.35	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \to \tau^+\tau^-$	$2.57 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
$H \to \mu^+\mu^-$	$8.91 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
$H \to c\bar{c}$	$1.18 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
$H \to gg$	$3.49 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% +0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
$H \to \gamma\gamma$	$9.28 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
$H \to Z\gamma$	$6.27 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
$H \to WW$	$8.75 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to ZZ$	$1.07 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
Total	4.07					

Uncertainty in BR



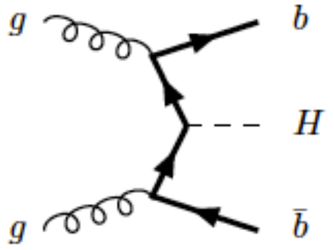
Channel	BR	Δm_c	Δm_b	Δm_t	$\Delta\alpha_s$	PU	THU	Total
$H \to b\bar{b}$	$5.77 \cdot 10^{-1}$	−0.2% +0.2%	+1.1% −1.2%	+0.0% −0.0%	−1.0% +0.9%	+1.5% −1.5%	+1.3% −1.3%	+2.8% −2.8%
$H \to \tau^+\tau^-$	$6.32 \cdot 10^{-2}$	−0.2% +0.2%	−2.0% +2.1%	+0.1% −0.1%	+1.4% −1.3%	+2.5% −2.4%	+3.6% −3.6%	+6.1% −6.0%
$H \to \mu^+\mu^-$	$2.19 \cdot 10^{-4}$	−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%
$H \to c\bar{c}$	$2.91 \cdot 10^{-2}$	+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%
$H \to gg$	$8.57 \cdot 10^{-2}$	−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%
$H \to \gamma\gamma$	$2.28 \cdot 10^{-3}$	−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%
$H \to Z\gamma$	$1.54 \cdot 10^{-3}$	−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%
$H \to WW$	$2.15 \cdot 10^{-1}$	−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%
$H \to ZZ$	$2.64 \cdot 10^{-2}$	−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%

bbH - SM bbH cross section is not negligible! (forgotten...)

- SM bbH XS at 7TeV and 8TeV released for M_H = 125.0, 125.5 and 126.0 GeV.
  - 1.1% of ggF at 7-8TeV (ttH 0.6-0.7% of ggF) but ggF scale uncertainty is O(10%).
- Needs bbH (4FS) MC ⇨ Sherpa-MC@NLO, MG5_aMC@NLO ⇨ check acceptance.

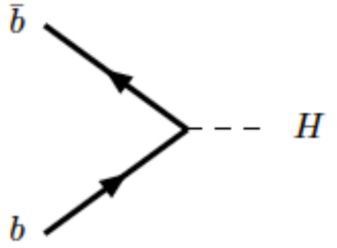
(ii) $b\bar{b}$+Higgs production

4FS



NLO

5FS



NNLO

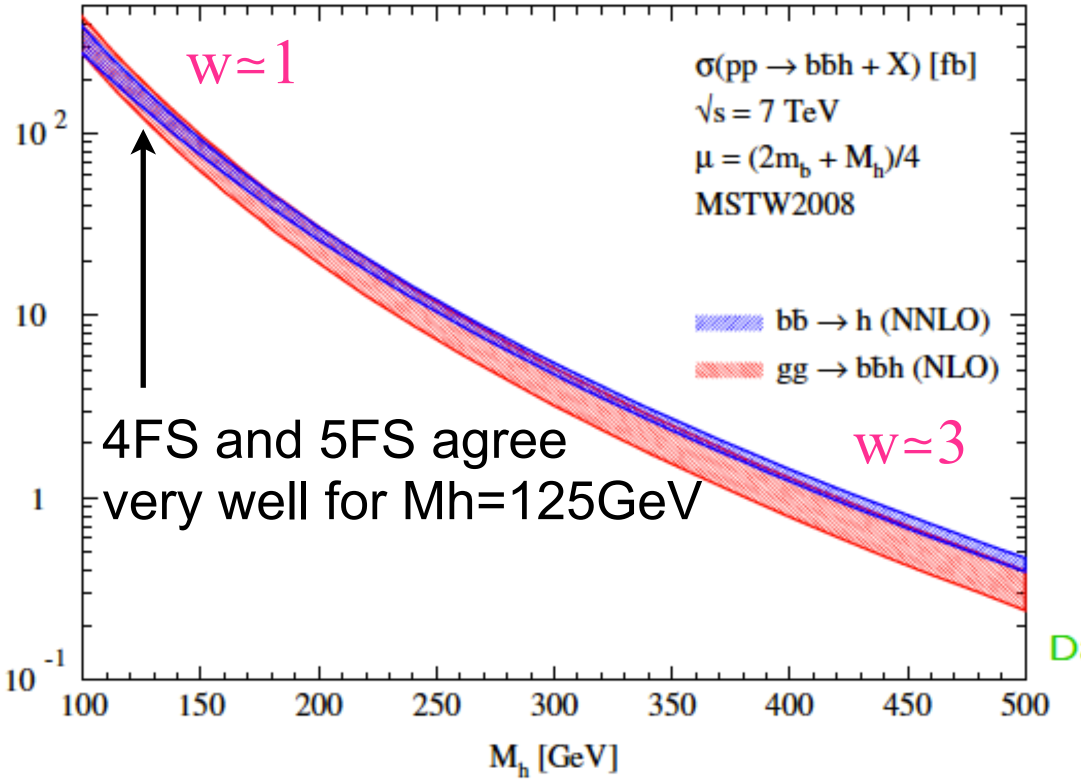
M. Spira

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of $\log M_H^2/m_b^2$ terms

massless/on-shell b's, no p_{Tb}

resummation of $\log M_H^2/m_b^2$ terms



4FS and 5FS agree very well for Mh=125GeV

Santander matching:

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

$$w = \log\frac{M_H}{m_b} - 1$$

Harlander, Krämer, Schumacher

Dittmaier, Krämer, S. Dawson, Jackson, Reina, Wackeroth

Harlander, Kilgore

- bbH NLO MC in 4FS under validation by MadGraph5_aMC@NLO.

How about ccH ?

ccH/bbH cross section ratio estimation

1) parton distribution

From figure in PDG review, f(x) ratio between bottom/charm is about 1/1.5 for x = 1.0~1.5x10^-2 for mu=100GeV.

Sea quark PDF is the same for quark and anti-quark.

2) Yukawa coupling

The running mass ratio at Q2=MH^2 is Y_bottom/Y_charm = 4.5.

Thus cross section ratio bbH/ccH = (1/1.5)^2 * (4.5)^2 = 9.

bbH cross section in variable or five flavor PDF is 1.1-1.2% of ggF,

thus ccH contribution is O(0.1%) of ggF, being completely negligible.

12 *18. Structure functions*

PDG Review

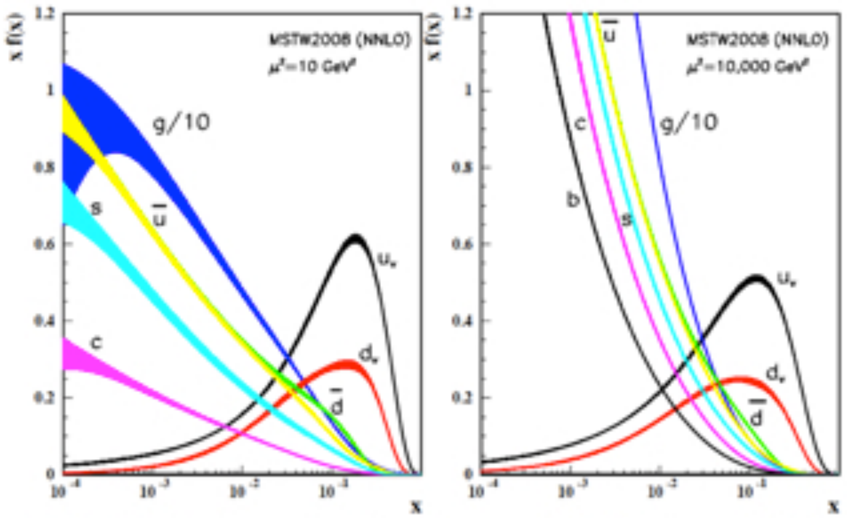


Figure 18.4: Distributions of x times the unpolarized parton distributions $f(x)$ (where $f = u_v, d_v, \bar{u}, \bar{d}, s, c, b, g$) and their associated uncertainties using the NNLO MSTW2008 parameterization [13] at a scale $\mu^2 = 10$ GeV^2 and $\mu^2 = 10,000$ GeV^2.

ccH measurement

1. charm tag (difficult at hadron collider)

2. Higgs boson decays to quarkonia

BR(H→J/Ψ+γ) = 2.5×10^{-6}

BR(H→ Υ+γ) = 1.4×10^{-8}

➪ ~50 $\mu^+\mu^-\gamma$ events @ 14TeV, $3ab^{-1}$

G. Bodwin et al. Phys. Rev. D88 (2013) 053003

BR and Rare Process&Decay

- Branching ratios
  - theory and parametric (α_s, $m_{b,c,t}$, m_H, etc.) uncertainty reduction?
- Rare process and decay (common uncertainty assignment)
  - $qq \rightarrow H\gamma$
  - $t \rightarrow cH$
  - quarkonia $J/\psi(\Upsilon)+\gamma$
  - $\gamma/W/Z+P$
  - ... etc.

ccH measurement

1. charm tag (difficult at hadron collider)
2. Higgs boson decays to quarkonia

$BR(H \rightarrow J/\Psi+\gamma) = 2.5\mathrm{x}10^{-6}$

⇨ 4.7 $J/\psi+\gamma$ events at 3 ab^{-1}

$BR(H \rightarrow \Upsilon+\gamma) = 1.4\mathrm{x}10^{-8}$

⇨ ~50 $\mu^+\mu^-\gamma$ events @ 14TeV, 3ab^{-1}

G. Bodwin et al. Phys. Rev. D88 (2013) 053003

VP mode	$\mathcal{B}^{\mathrm{SM}}$	VP^* mode	$\mathcal{B}^{\mathrm{SM}}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	2.2×10^{-6}

G. Isidori et al., PLB 728 (2014) 131