Sally Dawson, Christoph Englert, Maxime Gouzevitch,
Roberto Salerno, Magdalena Slawinska

on behalf of the HH xGroup

hh: Status of YR4 and plans beyond

LHCHXSWG-INT-2015-003

General Assembly Meeting of LHC Higgs
Cross Section Working Group

15.01.2016

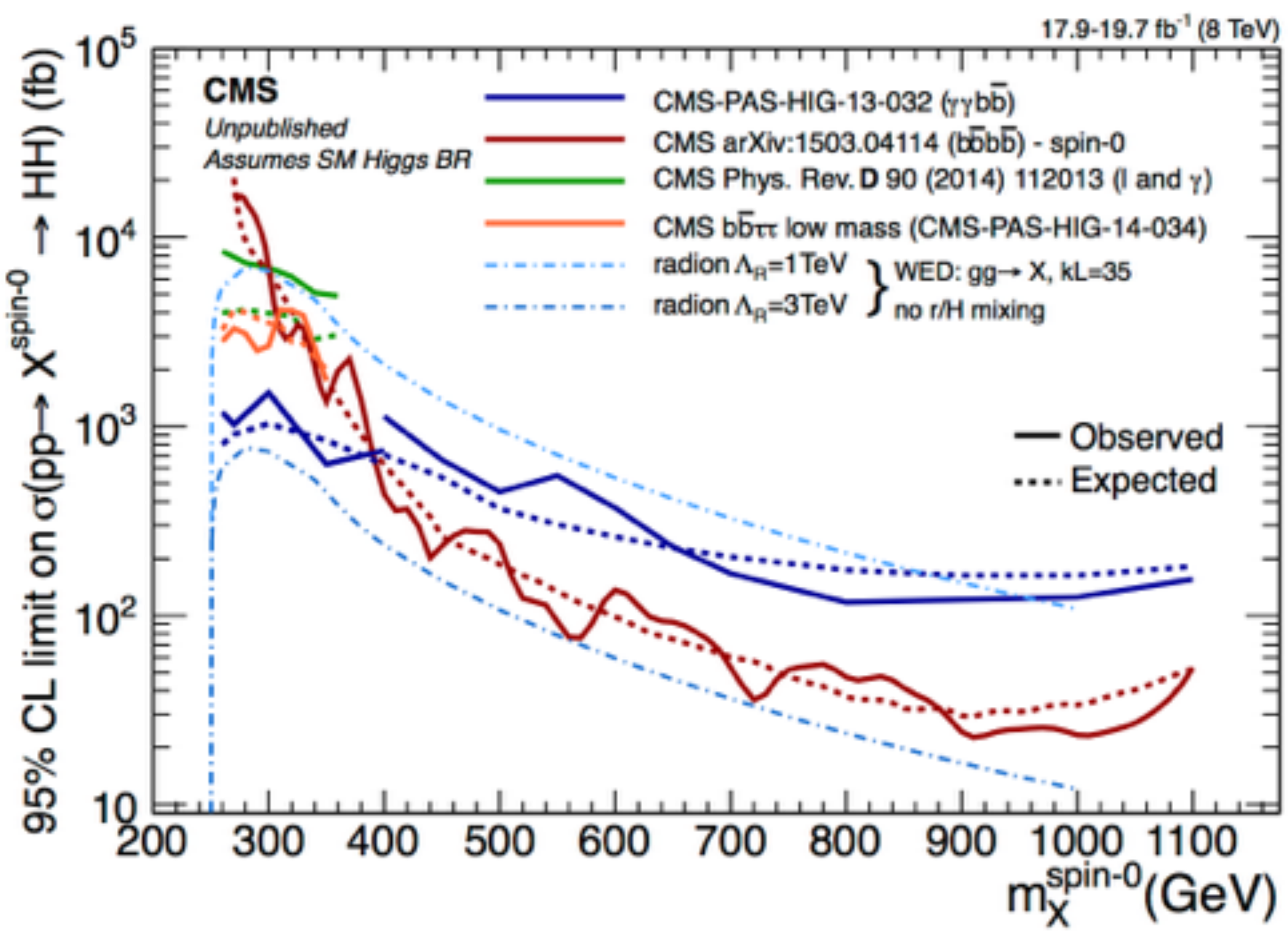
non-resonant hh production (e.g. ATLAS run I)

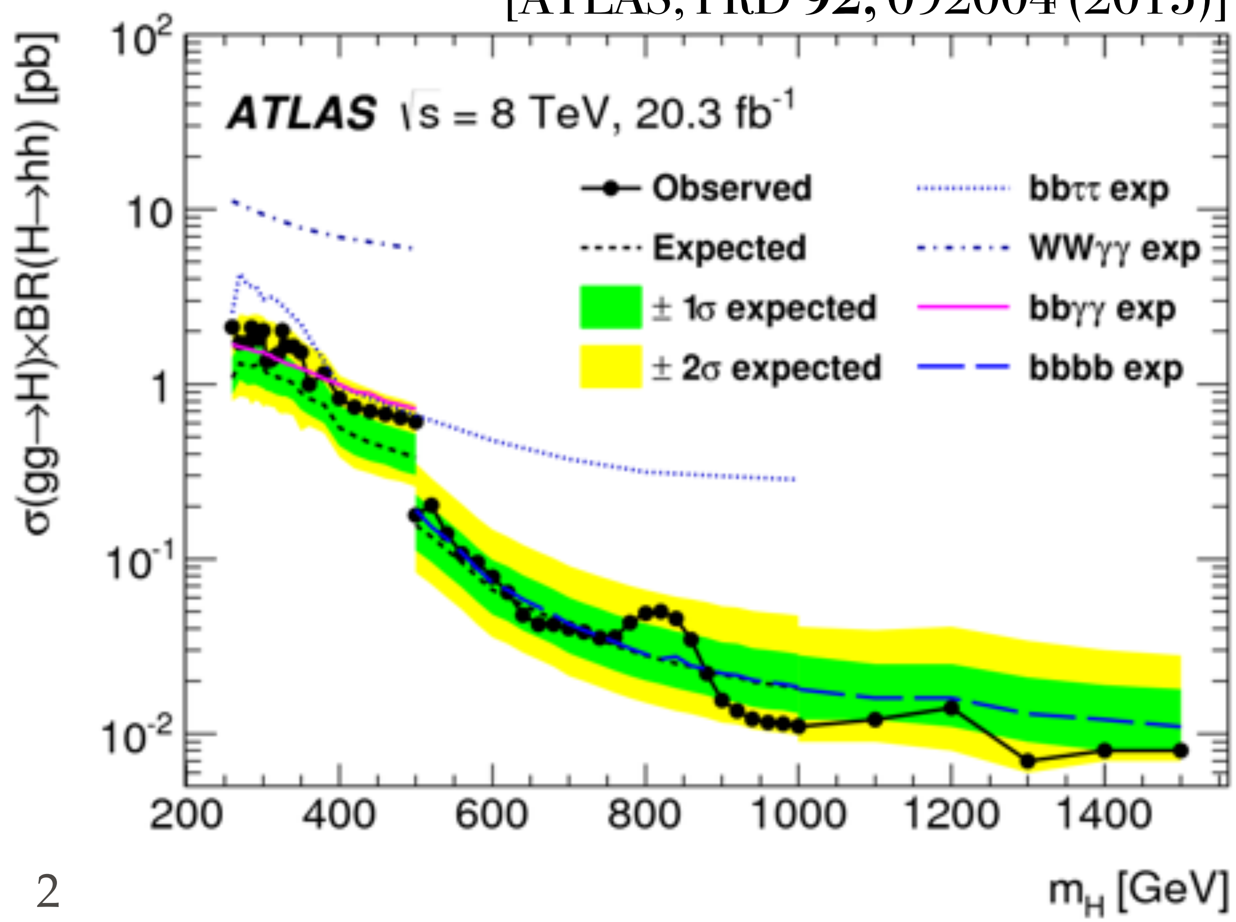
[ATLAS, PRD **92**, 092004 (2015)]

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
			Upper limit on the cross section [pb]		
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
			Upper limit on the cross section relative to the SM prediction		
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

resonant hh production

[ATLAS, PRD **92**, 092004 (2015)]





hh x-Subgroup Taks

- recommendations for precise SM gluon fusion hh production cross sections and differential distributions
- recommendations for SM cross sections for additional subdominant production modes
- recommendations for new physics searches in the hh final state

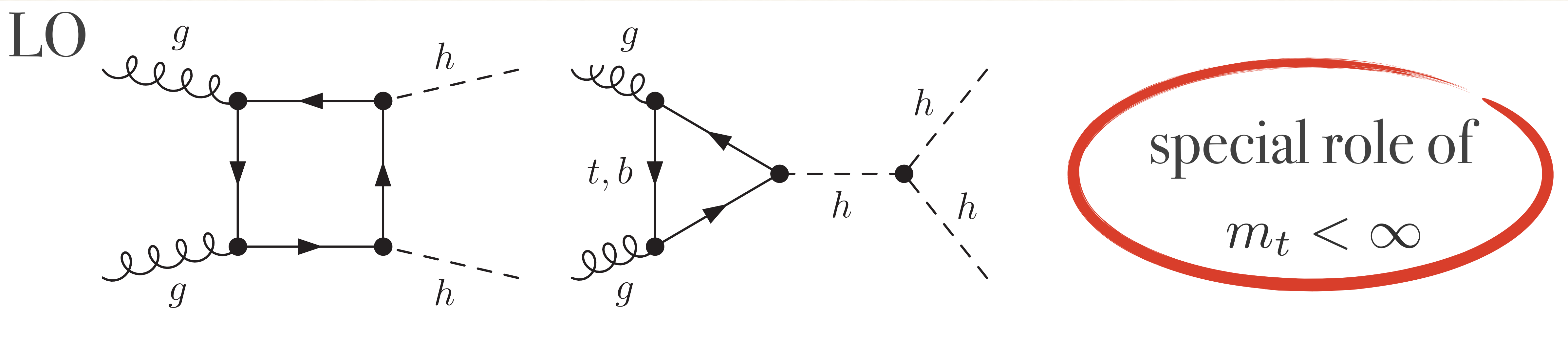
non-resonant: EFT

resonant: simple and transparent

Total SM Cross Sections: Gluon Fusion

- finite top mass effects crucial already at LO

[Glover, van der Bij `88] [Plehn, Spira, Zerwas `96] [Djouadi et al `99] …



Total SM Cross Sections: Gluon Fusion

- finite top mass effects crucial already at LO

  [Glover, van der Bij `88] [Plehn, Spira, Zerwas `96] [Djouadi et al `99] …

- QCD corrections dominated by soft radiation: use $m_t \to \infty$

  [Dawson, Dittmaier, Spira `98] [de Florian, Mazzitelli `13]

- recent developments

$O(5\%)$

  - NNLO+NNLL in $m_t \to \infty$ limit (normalised to exact LO)

    [de Florian, Mazzitelli `13, `15]

  - m_t expansion of NNLO cross section

    [Grigo, Hoff, Melnikov, Steinhauser `13]

$O(10\%)$

  - exact m_t for real emission & LO reweighted virtuals

    [Frederix et al `14] [Maltoni, Vryonidou, Zaro `14]

  - progress towards full m_t dependence at NLO

    $\to$ *Stephen Jones' talk*

Total SM Cross Sections: Gluon Fusion

- currently we can only estimate NLO m_t uncertainties by comparing different approximations

Example

NLO QCD reweighted by exact LO

[Dawson, Dittmaier, Spira `98]
[de Florian, Mazzitelli `13]

m_h (GeV)	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=13$ TeV	$\sqrt{s}=14$ TeV
125	$6.415^{+20\%}_{-16.8\%}$	$9.318^{+19.5\%}_{-16.4\%}$	$31.81^{+18.2\%}_{-15.0\%}$	$37.79^{+18\%}_{-14.8\%}$

exact m_t for real emission & virtual reweighting at NLO by LO

[Frederix et al `14]
[Maltoni, Vryonidou, Zaro `14]

m_h (GeV)	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=13$ TeV	$\sqrt{s}=14$ TeV
125	$6.12^{+17.7\%}_{-15.8\%}\pm 4.0\%$	$8.87^{+17.3\%}_{-15.4\%}\pm 3.6\%$	$29.76^{+15.5\%}_{-13.4\%}\pm 2.7\%$	$35.31^{+15.1\%}_{-13.4\%}\pm 2.6\%$

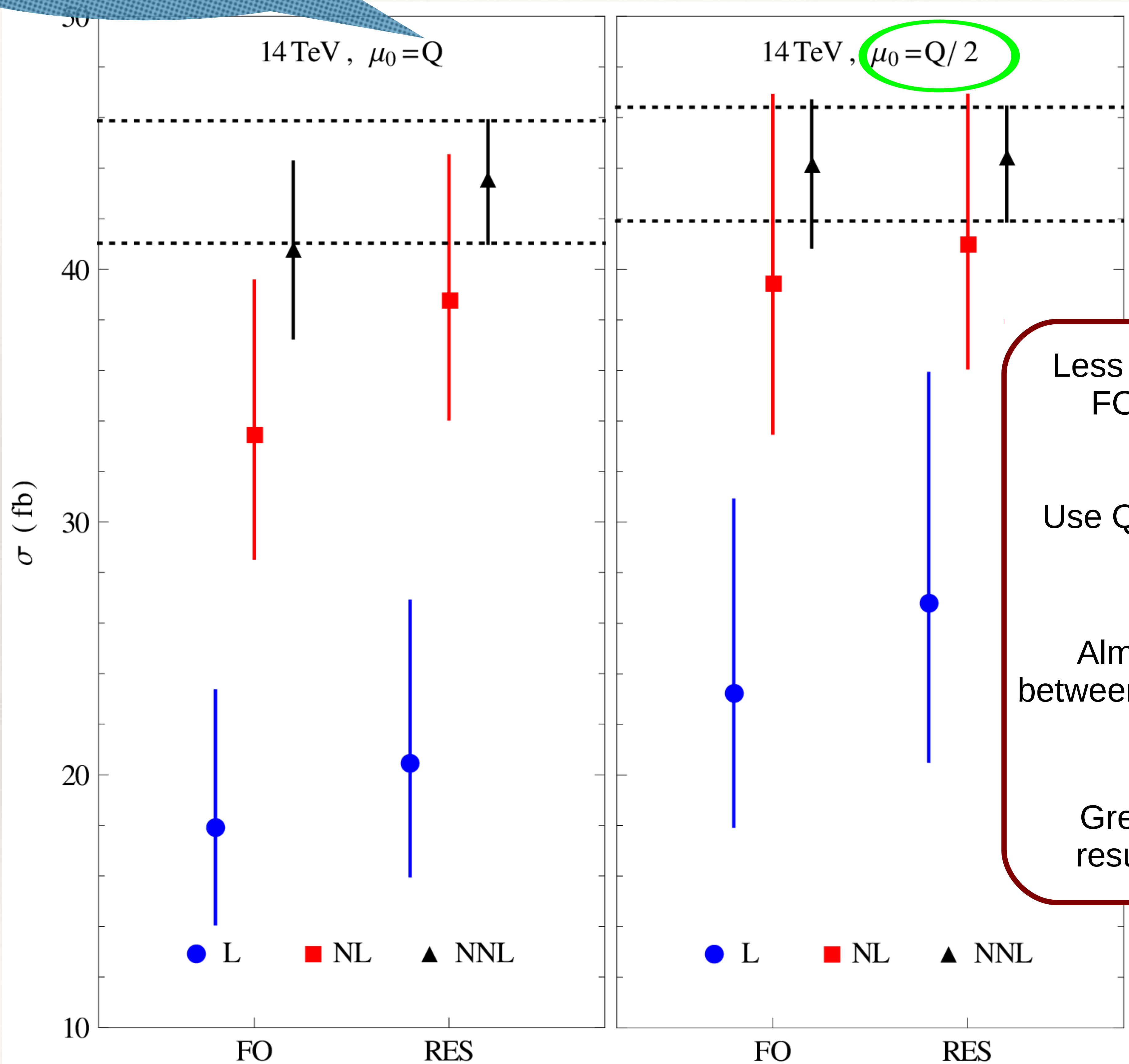
Recommendation:

assign 10% uncertainty to unknown m_t effects: **largest uncertainty**

Gluon Fusion: QCD and Scales

invariant Higgs pair mass

de Florian, Mazzitelli



Less differences between FO and RES for Q/2

↓

Use Q/2 for FO predictions

Almost no difference between Q and Q/2 at NNLL

↓

Great stability of the resummed NNLL XS

[de Florian, Mazzitelli `13, `15]

Gluon Fusion: SM Cross Section

Recommended values

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

$m_h = 124.5\ GeV$	$\sigma_{NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	PDF+α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.77	$+4.0 - 5.7$	±3.4	±4.4
$\sqrt{s} = 8$ TeV	11.3	$+4.1 - 5.7$	±3.0	±4.0
$\sqrt{s} = 13$ TeV	38.2	$+4.3 - 6.0$	±2.1	±3.1
$\sqrt{s} = 14$ TeV	45.3	$+4.4 - 6.0$	±2.1	±3.0
$\sqrt{s} = 100$ TeV	1760	$+5.0 - 6.7$	±1.7	±2.7

$m_h = 125\ GeV$	$\sigma_{NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	PDF+α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.72	$+4.0 - 5.7$	±3.4	±4.4
$\sqrt{s} = 8$ TeV	11.2	$+4.1 - 5.7$	±3.1	±4.0
$\sqrt{s} = 13$ TeV	38.0	$+4.3 - 6.0$	±2.1	±3.1
$\sqrt{s} = 14$ TeV	45.1	$+4.4 - 6.0$	±2.1	±3.0
$\sqrt{s} = 100$ TeV	1749	$+5.1 - 6.6$	±1.7	±2.7

$m_h = 125.09\ GeV$	$\sigma_{NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	PDF+α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.71	$+4.0 - 5.7$	±3.4	±4.4
$\sqrt{s} = 8$ TeV	11.2	$+4.1 - 5.7$	±3.1	±4.0
$\sqrt{s} = 13$ TeV	37.9	$+4.3 - 6.0$	±2.1	±3.1
$\sqrt{s} = 14$ TeV	45.0	$+4.4 - 6.0$	±2.1	±3.0
$\sqrt{s} = 100$ TeV	1748	$+5.0 - 6.5$	±1.7	±2.6

$m_h = 125.5\ GeV$	$\sigma_{NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	PDF+α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.66	$+4.0 - 5.7$	±3.4	±4.4

$\mu_0 = M_{hh}/2$ (+ conservative ±10% top mass uncertainty)

[de Florian, Mazzitelli ` 13, ` 15]

Gluon Fusion: K Factors

$$\left.\begin{aligned} K &\equiv \frac{\sigma_{NNLL}}{\sigma_{NLO}} \\ K' &\equiv \frac{\sigma_{NNLL}}{\sigma_{LO}} \end{aligned}\right\} \quad m_t \to \infty$$

$\mu_0 = M_{hh}/2$

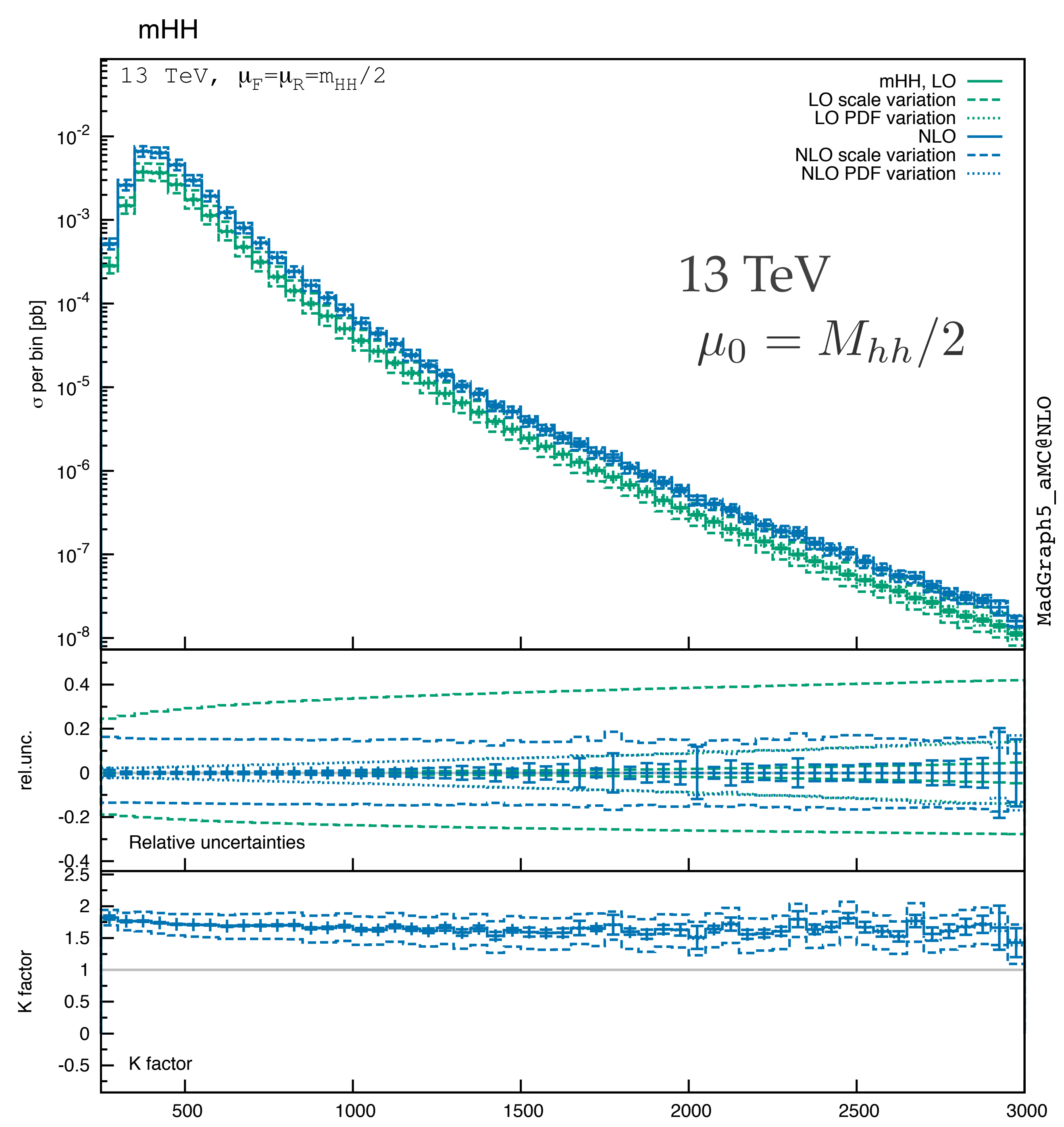
	$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 8\ TeV$	$\sqrt{s} = 13\ TeV$	$\sqrt{s} = 14\ TeV$	$\sqrt{s} = 100\ TeV$
K	1.203	1.200	1.193	1.192	1.195
K'	2.299	2.296	2.301	2.304	2.472

$\mu_0 = M_{hh}$

	$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 8\ TeV$	$\sqrt{s} = 13\ TeV$	$\sqrt{s} = 14\ TeV$	$\sqrt{s} = 100\ TeV$
K	1.426	1.413	1.378	1.373	1.305
K'	2.987	2.949	2.847	2.835	2.699

Gluon Fusion: Differential Distributions

- based on Born-improved HEFT NLO approximation using merged MG5 + Pythia 8
  - full $m_t < \infty$ for reals
  - $m_t < \infty$ reweighting based on LO of $m_t \to \infty$ virtuals
- differential uncertainties from scale and pdfs is $O(30\%)$



[Frederix et al `14]
[Maltoni, Vryonidou, Zaro `14]
Hespel, Vryonidou, Zaro

Gluon Fusion: Differential Distributions

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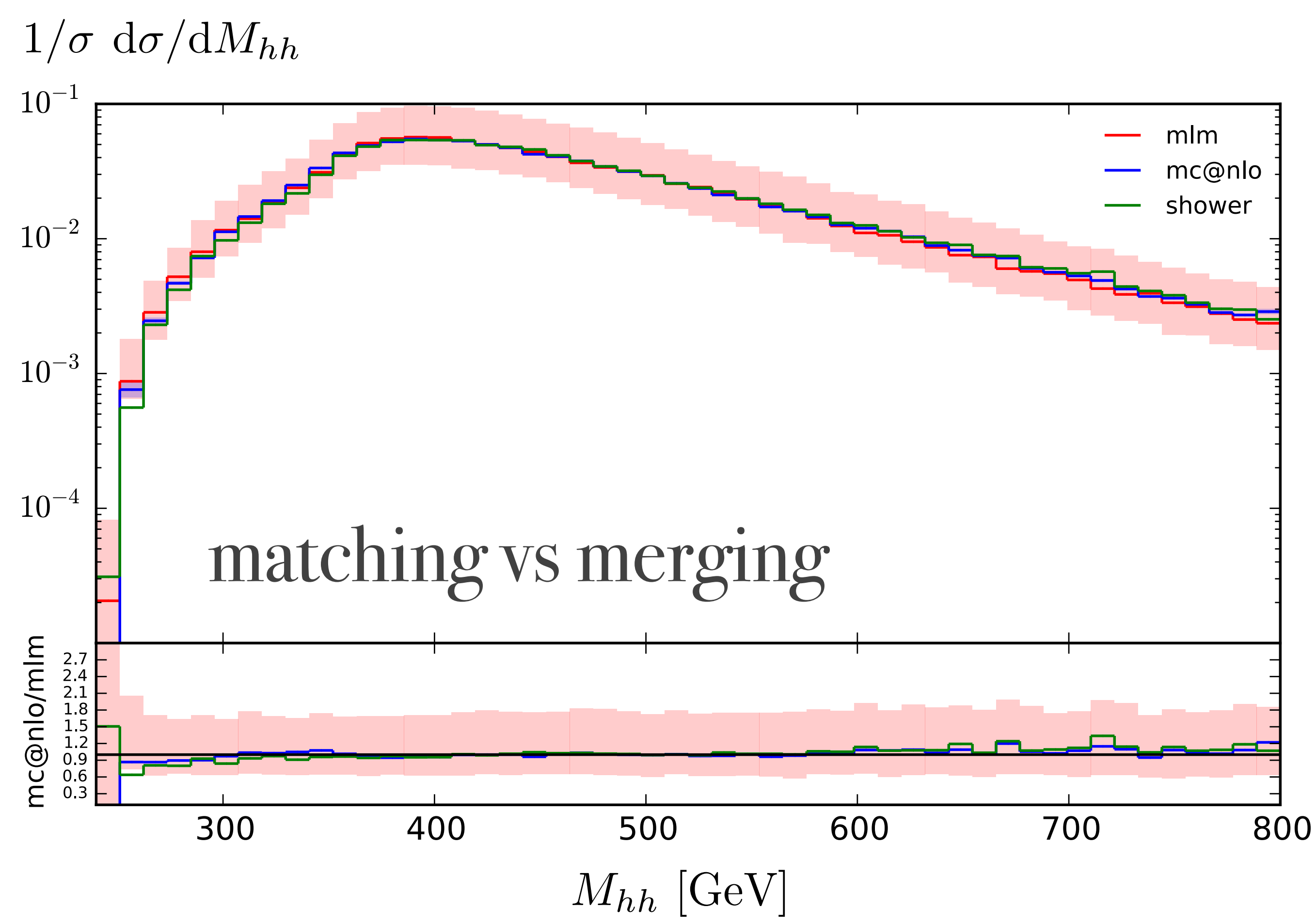
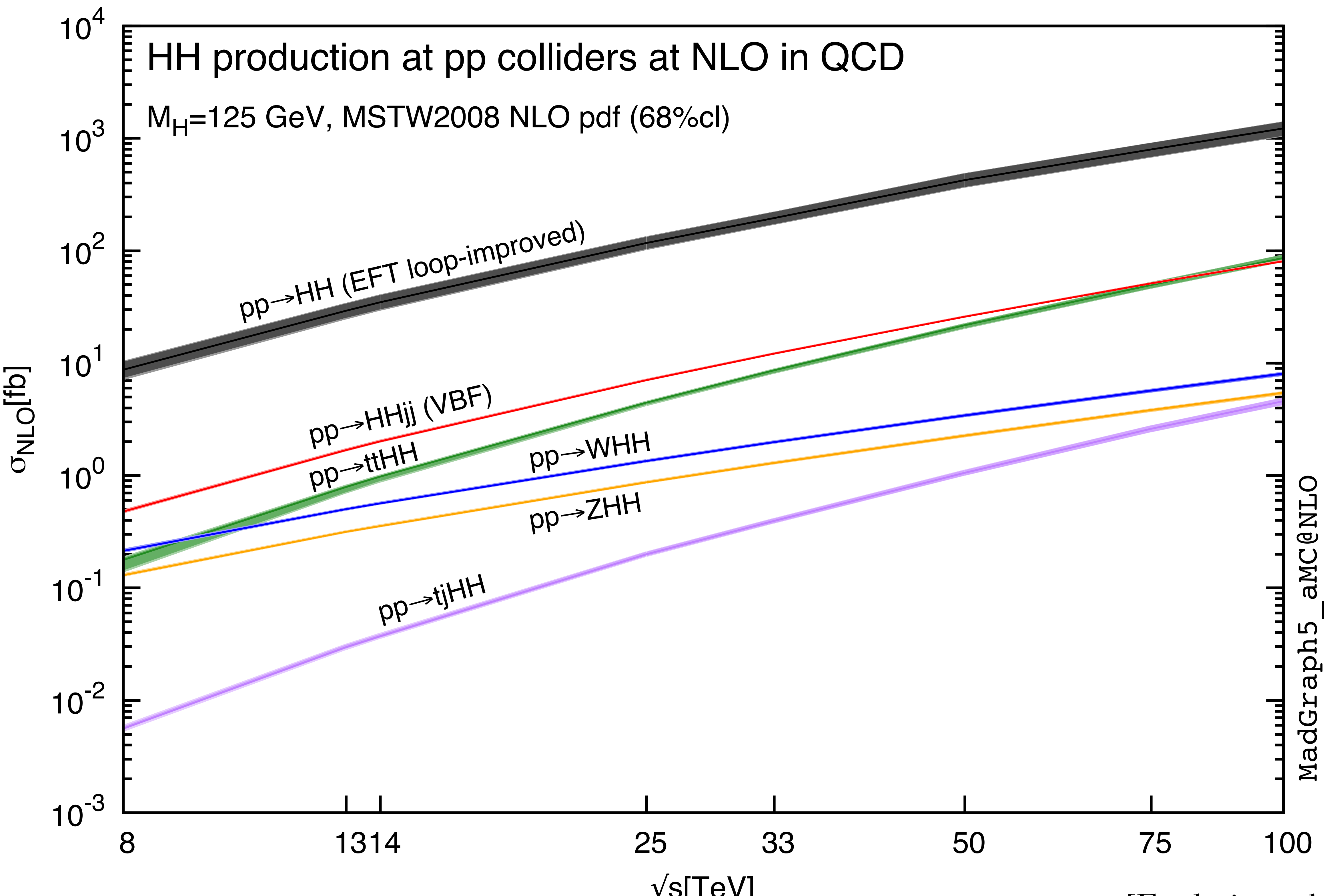


Maltoni, Papaefstathiou, Vryonidou, Zaro

- comparison with MLM-matched Herwig calculation: hh system stable in comparison, shower systematics remain

Recommendation: under discussion

Other Production Cross Sections



[Frederix et al ` 14]

[Frederix et al ` 14]
[Maltoni, Vryonidou, Zaro ` 14]

Other Processes: NLO Recommendations

Hespel, Vryonidou, Zaro

$hhjj$ (WBF)

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
124.5	$0.320^{+3.2\%}_{-3.7\%} \pm 2.7\%$	$0.470^{+2.4\%}_{-3.1\%} \pm 2.6\%$	$1.65^{+2.4\%}_{-2.7\%} \pm 2.3\%$	$1.97^{+2.3\%}_{-2.6\%} \pm 2.3\%$	$81.9^{+0.2\%}_{-0.2\%} \pm 1.8\%$
125	$0.316^{+3.7\%}_{-4.1\%} \pm 2.7\%$	$0.468^{+2.8\%}_{-3.3\%} \pm 2.6\%$	$1.64^{+2.0\%}_{-2.5\%} \pm 2.3\%$	$1.94^{+2.3\%}_{-2.6\%} \pm 2.3\%$	$80.3^{+0.5\%}_{-0.4\%} \pm 1.7\%$
125.09	$0.313^{+3.2\%}_{-3.8\%} \pm 2.6\%$	$0.459^{+3.2\%}_{-3.6\%} \pm 2.6\%$	$1.62^{+2.3\%}_{-2.7\%} \pm 2.3\%$	$1.95^{+1.8\%}_{-2.3\%} \pm 2.4\%$	$80.8^{+0.8\%}_{-0.8\%} \pm 1.8\%$
125.5	$0.312^{+3.6\%}_{-4.0\%} \pm 2.7\%$	$0.458^{+2.9\%}_{-3.4\%} \pm 2.6\%$	$1.63^{+2.0\%}_{-2.5\%} \pm 2.3\%$	$1.94^{+1.3\%}_{-1.9\%} \pm 2.3\%$	$80.7^{+0.7\%}_{-0.7\%} \pm 1.8\%$

$t\bar{t}hh$

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
124.5	$0.112^{+3.5\%}_{-12.5\%} \pm 4.2\%$	$0.176^{+2.9\%}_{-10.7\%} \pm 3.9\%$	$0.786^{+1.3\%}_{-4.5\%} \pm 3.2\%$	$0.968^{+1.7\%}_{-4.6\%} \pm 3.1\%$	$87.2^{+7.9\%}_{-7.3\%} \pm 1.6\%$
125	$0.110^{+3.5\%}_{-12.5\%} \pm 4.2\%$	$0.174^{+2.9\%}_{-10.6\%} \pm 3.9\%$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$	$0.949^{+1.7\%}_{-4.5\%} \pm 3.1\%$	$82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$
125.09	$0.109^{+3.5\%}_{-12.8\%} \pm 4.2\%$	$0.174^{+2.8\%}_{-10.6\%} \pm 3.9\%$	$0.772^{+1.7\%}_{-4.5\%} \pm 3.2\%$	$0.949^{+1.8\%}_{-4.8\%} \pm 3.2\%$	$82.1^{+8.3\%}_{-7.6\%} \pm 1.6\%$
125.5	$0.107^{+3.3\%}_{-12.9\%} \pm 4.2\%$	$0.172^{+2.9\%}_{-10.4\%} \pm 4.0\%$	$0.762^{+1.3\%}_{-4.5\%} \pm 3.2\%$	$0.937^{+1.5\%}_{-4.5\%} \pm 3.1\%$	$81.9^{+8.2\%}_{-7.6\%} \pm 1.6\%$

$hhtj$

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
124.5		$0.00551^{+5.6\%}_{-3.2\%} \pm 5.8\%$	$0.0289^{+5.4\%}_{-3.4\%} \pm 4.6\%$	$0.0365^{+4.4\%}_{-1.6\%} \pm 4.7\%$	$4.44^{+5.2\%}_{-5.6\%} \pm 2.3\%$
125		$0.00538^{+5.3\%}_{-3.0\%} \pm 5.6\%$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$	$0.0367^{+4.2\%}_{-1.8\%} \pm 4.6\%$	$4.27^{+5.0\%}_{-5.5\%} \pm 2.3\%$
125.09		$0.00540^{+5.4\%}_{-3.1\%} \pm 5.6\%$	$0.0281^{+5.2\%}_{-3.2\%} \pm 4.5\%$	$0.0364^{+3.7\%}_{-1.3\%} \pm 4.7\%$	
125.5		$0.00521^{+5.5\%}_{-3.4\%} \pm 5.8\%$	$0.0279^{+6.1\%}_{-4.6\%} \pm 6.4\%$	$0.0359^{+3.8\%}_{-1.6\%} \pm 4.7\%$	

currently finalised

currently finalised

hhh (GF)

μ_0	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
$M_{hhh}/2$	$12.1^{+17.9\%}_{-16.4\%} \pm 5.2\%$	$18.4^{+17.1\%}_{-15.7\%} \pm 4.8\%$	$75.2^{+15.5\%}_{-14.1\%} \pm 3.3\%$	$89.2^{+14.8\%}_{-13.6\%} \pm 3.2\%$	$4819^{+12.3\%}_{-11.9\%} \pm 1.8\%$
M_{hhh}	$10.0^{+19.5\%}_{-16.7\%} \pm 5.2\%$	$15.3^{+18.7\%}_{-16.1\%} \pm 4.7\%$	$63.8^{+16.2\%}_{-14.2\%} \pm 3.3\%$	$76.9^{+16.2\%}_{-14.1\%} \pm 3.2\%$	$4300^{+14.0\%}_{-12.3\%} \pm 1.8\%$

Other Processes: NLO Recommendations

hhZ

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 100 TeV
124.5	$0.103^{+2.6\%}_{-2.2\%} \pm 2.7\%$	$0.135^{+2.4\%}_{-2.0\%} \pm 2.4\%$	$0.323^{+2.0\%}_{-1.5\%} \pm 1.8\%$	$0.364^{+2.0\%}_{-1.4\%} \pm 1.7\%$	$5.33^{+3.9\%}_{-5.8\%} \pm 1.9\%$
125	$0.102^{+2.6\%}_{-2.2\%} \pm 2.7\%$	$0.133^{+2.4\%}_{-2.0\%} \pm 2.4\%$	$0.319^{+2.1\%}_{-1.5\%} \pm 1.8\%$	$0.358^{+2.1\%}_{-1.5\%} \pm 1.7\%$	$5.28^{+3.8\%}_{-5.7\%} \pm 1.9\%$
125.09	$0.102^{+2.7\%}_{-2.4\%} \pm 2.7\%$	$0.132^{+2.7\%}_{-2.2\%} \pm 2.4\%$	$0.316^{+2.1\%}_{-1.5\%} \pm 1.8\%$	$0.357^{+1.8\%}_{-1.3\%} \pm 1.7\%$	$5.24^{+4.0\%}_{-5.8\%} \pm 1.9\%$
125.5	$0.101^{+2.5\%}_{-2.2\%} \pm 2.7\%$	$0.131^{+2.6\%}_{-2.1\%} \pm 2.4\%$	$0.314^{+2.3\%}_{-1.6\%} \pm 1.8\%$	$0.355^{+2.2\%}_{-1.6\%} \pm 1.7\%$	$5.23^{+3.9\%}_{-5.7\%} \pm 1.9\%$

hhW^-

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 100 TeV
124.5	$0.0531^{+2.8\%}_{-2.4\%} \pm 3.4\%$	$0.0714^{+2.4\%}_{-2.0\%} \pm 3.1\%$	$0.180^{+1.9\%}_{-1.4\%} \pm 2.3\%$	$0.205^{+1.9\%}_{-1.4\%} \pm 2.2\%$	$3.35^{+4.0\%}_{-5.7\%} \pm 2.0\%$
125	$0.0527^{+2.5\%}_{-2.2\%} \pm 3.4\%$	$0.0697^{+2.9\%}_{-2.3\%} \pm 3.1\%$	$0.177^{+1.9\%}_{-1.4\%} \pm 2.3\%$	$0.202^{+2.0\%}_{-1.4\%} \pm 2.2\%$	$3.32^{+4.1\%}_{-5.8\%} \pm 2.0\%$
125.09	$0.0524^{+2.7\%}_{-2.3\%} \pm 3.4\%$	$0.0698^{+2.7\%}_{-2.2\%} \pm 3.1\%$	$0.177^{+2.4\%}_{-1.7\%} \pm 2.3\%$	$0.201^{+2.1\%}_{-1.4\%} \pm 2.2\%$	$3.33^{+4.0\%}_{-5.7\%} \pm 2.0\%$
125.5	$0.0515^{+2.6\%}_{-2.2\%} \pm 3.4\%$	$0.0691^{+2.6\%}_{-2.1\%} \pm 3.1\%$	$0.175^{+2.3\%}_{-1.6\%} \pm 2.3\%$	$0.199^{+1.9\%}_{-1.3\%} \pm 2.2\%$	$3.25^{+3.7\%}_{-5.5\%} \pm 2.0\%$

hhW^+

$\mu_0 = M_{hh}/2$

m_h (GeV)	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 100 TeV
124.5	$0.117^{+2.6\%}_{-2.3\%} \pm 2.8\%$	$0.149^{+2.6\%}_{-2.2\%} \pm 2.6\%$	$0.333^{+1.9\%}_{-1.3\%} \pm 2.1\%$	$0.371^{+2.0\%}_{-1.4\%} \pm 2.0\%$	$4.57^{+4.2\%}_{-5.9\%} \pm 1.9\%$
125	$0.116^{+2.5\%}_{-2.2\%} \pm 2.8\%$	$0.149^{+2.4\%}_{-2.0\%} \pm 2.6\%$	$0.330^{+1.9\%}_{-1.4\%} \pm 2.0\%$	$0.367^{+2.1\%}_{-1.5\%} \pm 2.0\%$	$4.47^{+4.1\%}_{-5.7\%} \pm 1.9\%$
125.09	$0.115^{+2.6\%}_{-2.2\%} \pm 2.8\%$	$0.147^{+2.7\%}_{-2.3\%} \pm 2.6\%$	$0.329^{+1.9\%}_{-1.4\%} \pm 2.1\%$	$0.368^{+2.1\%}_{-1.5\%} \pm 2.0\%$	$4.47^{+4.2\%}_{-5.8\%} \pm 1.9\%$
125.5	$0.114^{+2.5\%}_{-2.2\%} \pm 2.8\%$	$0.146^{+2.6\%}_{-2.2\%} \pm 2.6\%$	$0.327^{+2.3\%}_{-1.7\%} \pm 2.1\%$	$0.365^{+1.8\%}_{-1.3\%} \pm 2.0\%$	$4.44^{+3.9\%}_{-5.6\%} \pm 1.9\%$

[Frederix et al ` 14] [Maltoni, Vryonidou, Zaro ` 14]

... will be updated to NNLO for YR4 with different scale choice

[Baglio et al. ` 12]

BSM: Effective Field Theory

- dominant CP-even interactions gluon fusion [WG 2]

$$L = L_{SM} + \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right) \frac{g_s^2}{4} G^A_{\mu\nu} G^{A,\mu\nu} - \frac{h}{v} \Sigma_f \Sigma_i m_{f_i} [\delta y_f]_i \overline{f}_i f_i$$
$$- \frac{h^2}{2v^2} \Sigma_f \Sigma_i m_{f_i} [y_f^{(2)}]_i \overline{f}_i f_i + \delta\lambda_3 h^3 \, .$$

- production not sensitive to bottom Yukawa, relevant parameters

$$c_g, \; c_{gg}, \; \delta y_t, \; y_t^{(2)}, \; \delta\lambda_3$$

- phenomenological fit to (isomorphic to WG2 parametrisation)

[Dall'Osso et al. `15]

$$L' = \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{m_h^2}{2} h^2 - \kappa_\lambda \lambda_{SM} v h^3$$
$$- \frac{m_t}{v} \left(v + \kappa_t h + \frac{c_2}{v} h h \right) \left(\bar{t}_L t_R + h.c. \right) + \frac{\alpha_s}{12\pi v} \left(c_{1g} h - \frac{c_{2g}}{2v} h h \right) G^A_{\mu\nu} G^{A,\mu,\nu}$$

[details available in separate LHCXSWG-INT-2015-007]

BSM: Effective Field Theory

- NLO QCD corrections available and flat [Gröber, Mühlleitner, Spira, Streicher `15]

[HPair]

$$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = A_1\kappa_t^4 + A_2c_2^2 + (A_3\kappa_t^2 + A_4c_g^2)\kappa_\lambda^2 + A_5c_{2g}^2 + (A_6c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9c_g\kappa_\lambda)c_2 + A_{10}c_2c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_gc_{2g}\kappa_\lambda\,.$$

$\sqrt{s}$	8 TeV	13 TeV	14 TeV	100 TeV
A_1^H	0.86	0.82	0.81	0.72
A_2^H	0.32	0.29	0.29	0.22
A_3^H	-4.86	-4.82	-4.81	-4.72
A_4^H	8.92	8.76	8.73	8.38
A_5^H	-3.24	-3.04	-3.01	-2.60
A_6^H	-5.68	-5.70	-5.69	-5.78
A_7^H	9.91	10.16	10.19	11.27
A_8^H	14.41	14.27	14.24	14.08
A_9^H	-3.05	-2.88	-2.85	-2.51
A_{10}^H	-9.5E-02	-8.7E-02	-8.6E-02	-6.1E-02
A_{11}^H	8.2E-03	9.3E-03	9.4E-03	2.0E-02
A_{12}^H	-3.3E-02	-3.0E-02	-3.0E-02	-2.4E-02
A_{13}^H	8.2E-04	7.3E-04	7.2E-04	5.5E-04
A_{14}^H	4.2E-03	4.0E-03	4.0E-03	3.8E-03
A_{15}^H	1.7E-03	2.4E-03	2.5E-03	3.1E-03
A_{16}^H	-7.8E-02	-7.1E-02	-7.1E-02	-5.8E-02
A_{17}^H	9.7E-02	8.8E-02	8.7E-02	6.8E-02
A_{18}^H	0.27	0.25	0.24	0.18
A_{19}^H	0.13	0.12	0.12	0.10
A_{20}^H	0.43	0.41	0.41	0.36

Higgs Basis
Dorigo, Goertz, Tosi, Gouzevich, Oliveira
LHCXSWG-INT-2015-007

recommendations

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.55	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

[Dall'Osso et al. `15]
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BSM: Effective Field Theory

- NLO QCD corrections available and flat [Gröber, Mühlleitner, Spira, Streicher ` 15]

[HPair]

$$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = A_1\kappa_t^4 + A_2c_2^2 + (A_3\kappa_t^2 + A_4c_g^2)\kappa_\lambda^2 + A_5c_{2g}^2 + (A_6c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9c_g\kappa_\lambda)c_2 + A_{10}c_2c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_gc_{2g}\kappa_\lambda\,.$$

recommendations

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- particularly relevant: Higgs selfcoupling
K* factors for NNLO+NNLL available

	$\sigma_{NNLL}/\sigma_{NNLL,SM}(\delta\lambda_3)$				
$\delta\lambda_3/\lambda_{SM}$	-2	-1.5	-1	-0.5	1
$\sqrt{s}=7$ TeV	4.17	3.12	2.24	1.53	0.452
$\sqrt{s}=8$ TeV	4.09	3.06	2.21	1.52	0.455
$\sqrt{s}=13$ TeV	3.85	2.92	2.13	1.49	0.466
$\sqrt{s}=14$ TeV	3.82	2.90	2.12	1.49	0.467
$\sqrt{s}=100$ TeV	3.39	2.62	1.97	1.43	0.492

de Florian, Mazzitelli

- multi-Higgs phenomenology most transparently reflected in singlet extension scenario

$$V = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3\Phi^\dagger\Phi S^2$$

$$\begin{aligned} h &= \quad \cos\alpha\,\phi_0 + \sin\alpha\; s \\ H &= -\sin\alpha\,\phi_0 + \cos\alpha\, s \end{aligned}$$

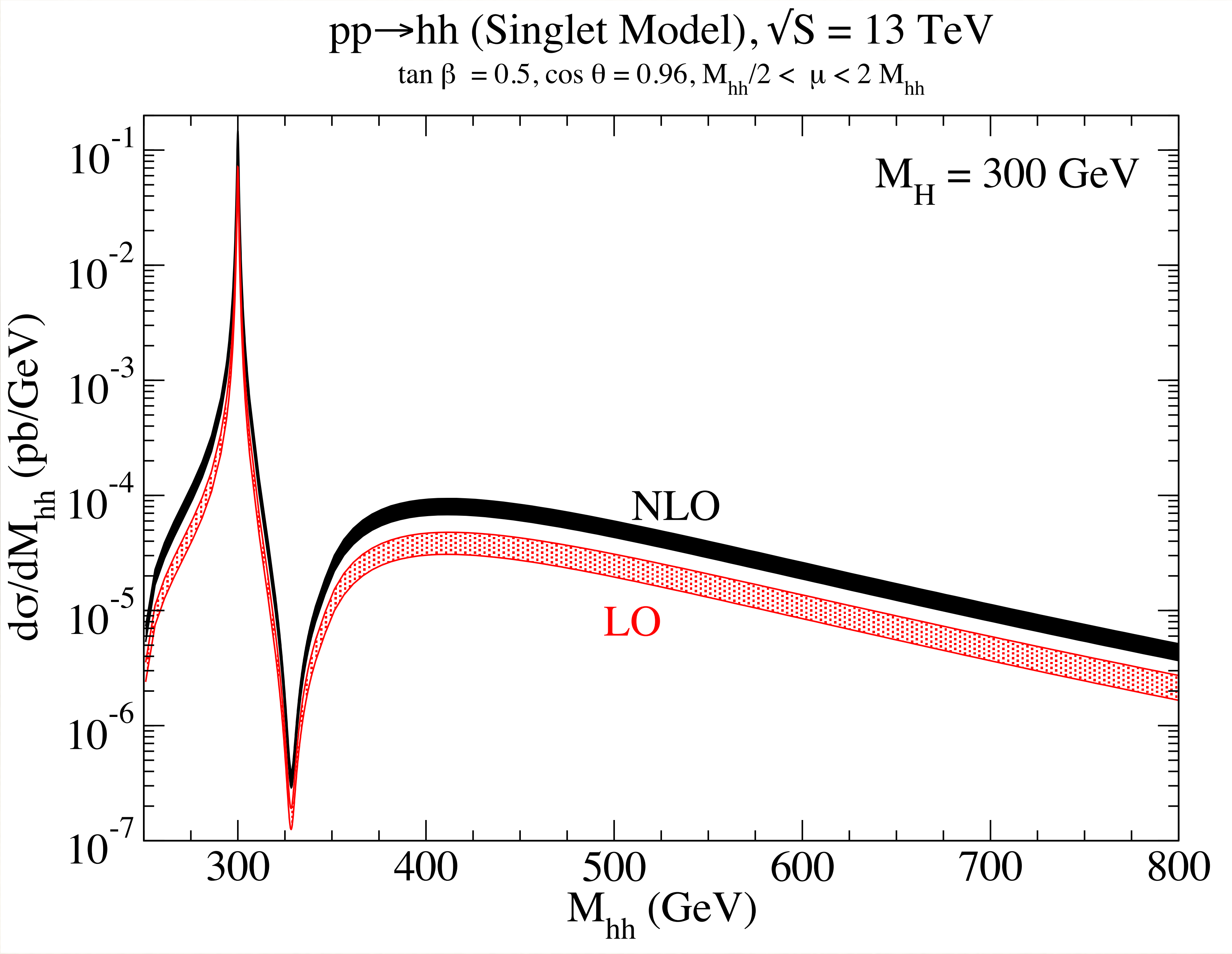
$$m_h = 125\; GeV,\; M_H,\; \cos\alpha,\; v,\; \tan\beta = v/\langle s\rangle$$

$$\begin{aligned} \Gamma(h\to X_{SM}X_{SM}) &= \cos^2\alpha\,\Gamma(h\to X_{SM}X_{SM})_{SM} \\ \Gamma(H\to X_{SM}X_{SM}) &= \sin^2\alpha\,\Gamma(H\to X_{SM}X_{SM})_{SM} \\ \Gamma_H &= \sin^2\alpha\,\Gamma_{H,SM}(M_H) + \Gamma(H\to hh) \\ \Gamma_h &= \cos^2\alpha\,\Gamma_{h,SM}(m_h)\,, \end{aligned}$$

BSM: hh Resonances

- multi-Higgs phenomenology most transparently reflected in singlet extension, NLO QCD corrections available

[Dawson, Lewis ` 15]



cross sections to be included in YR4

- in YR4 (link to internal note)
  - latest recommendations for gluon fusion Higgs pair production as well as for subdominant channels
  - recommendation for gluon fusion distributions
  - transparent and phenomenologically relevant BSM extension recommendations for hh final states

- **final meeting for YR4 : February 1st at 4.30pm CERN time**

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Beyond YR4.....

- further investigate NLO finite top mass effects in gluon fusion
  [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke]
  [first details to be publicised in separate LHCXSWG note]

- shower systematics

- NNLO GF differential distributions and NLO differential distribution recommendations for subdominant production modes

- supplement additional subdominant production cross sections at NLO
  - gluon fusion + 2 jets (similar to gluon fusion hh)
  - gluon fusion induced hhZ production, VVhh…

- specific model-dependent benchmarking of (exotic) multi-Higgs final states in light of improved single Higgs results: (N)MSSM, 2HDM, …