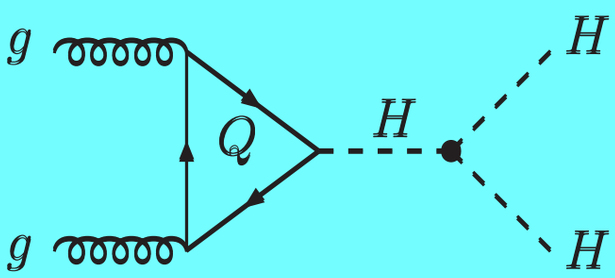
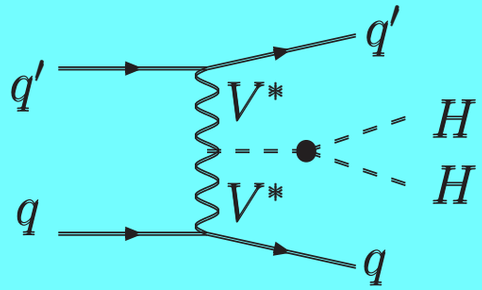
XVII Roma Tre Topical Seminar on Subnuclear Physics:

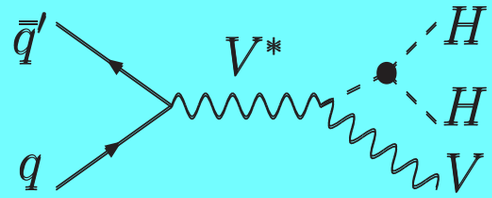
The Higgs potential and physics at future colliders

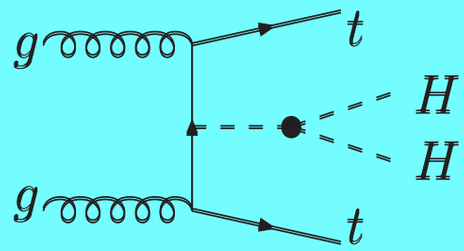
10 December 2014, Università di Roma Tre, Italy

Measurement of the Higgs self-coupling at the HL-LHC and future colliders









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Roma, 10 December 2014

Outline

- SM Higgs potential and Higgs self-coupling λ_{HHH}
- pp → HH cross sections vs λ_{HHH}
- a challenge for HH production → TH uncertainties
- HH production BSM
- searches for HH in Run 1
- HH production at HL-LHC : present projections
- HH production at Linear Colliders : present projections
- Outlook

updated discussion in LHC Higgs-XSections Working Groups :

https://indico.cern.ch/category/5847/

(with all relevant references…)

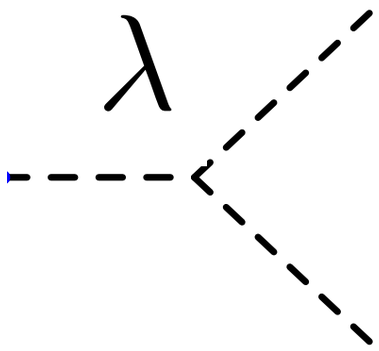
Higgs self-couplings in the SM

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

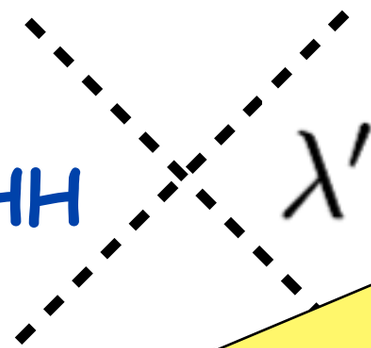
- in the SM : $\lambda = \lambda' = M_H^2/(2v^2)$ = 0.13

m_H directly related to Higgs dynamics !

- needs HH in final states



needs HHH



out of reach !

- BSM : Max λ deviations compatible with no other BSM observation: few % to ~20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

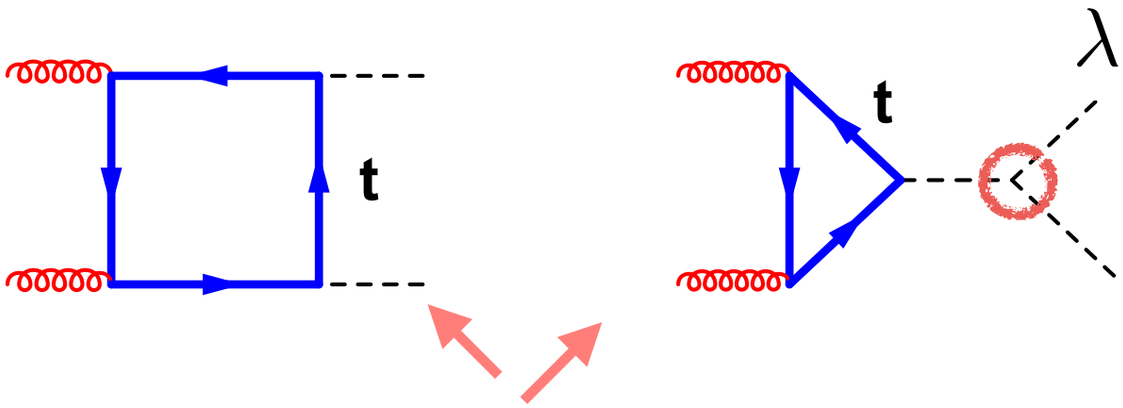
- target for both TH and EXP accuracies !

bad news ! ➜ tiny SM HH rates !

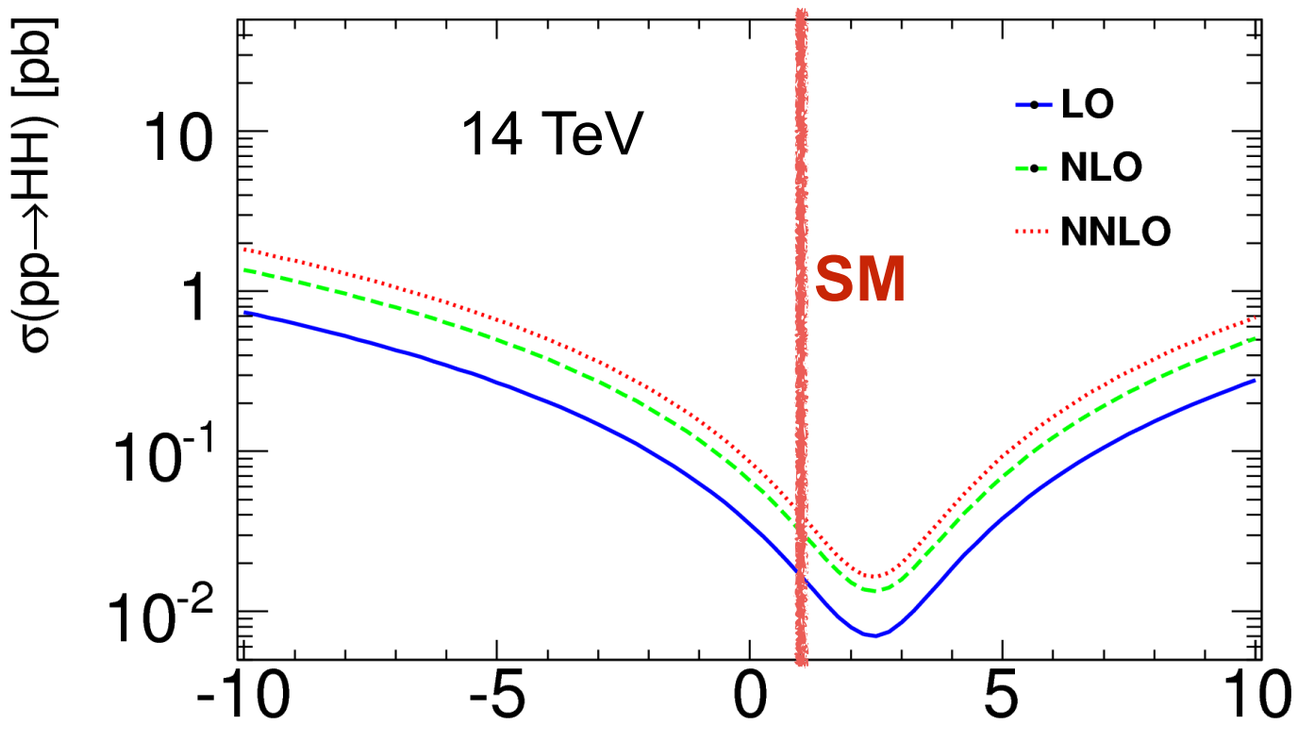
- dominant production in pp collisions :

$\sigma(HH)_{SM} \sim 10^{-3}\ \sigma(H)_{SM}$

$gg \to HH$



destructive interference
ruled by Y_t and λ



[$\lambda^{SM} = (m_H/v)^2/2 = 0.13$]

- other production channels have σ < 1/10 $\sigma(HH)$:

$qq' \to HHqq'$ $\quad q\bar{q}' \to ZHH/WHH$ $\quad q\bar{q}, gg \to t\bar{t}HH$

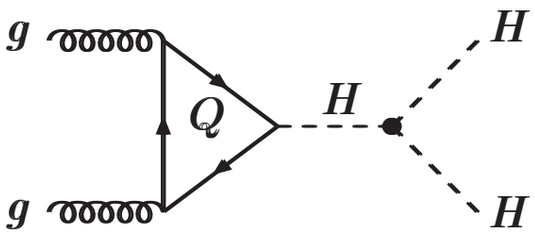
tiny σ's !

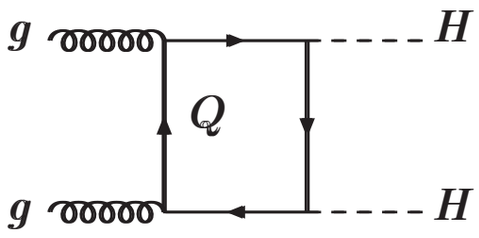
$\sqrt{s}$ (TeV)	Cross sections (fb) and theoretical uncertainties (%)				
	$gg \to HH$	$qq \to qqHH$	$q\bar{q} \to WHH$	$q\bar{q} \to ZHH$	$q\bar{q}/gg \to t\bar{t}HH$
	NLO	NLO	NNLO	NNLO	LO
14	$33.89^{+37.2\%}_{-29.8\%}$	$2.01^{+7.6\%}_{-5.1\%}$	$0.57^{+3.7\%}_{-3.3\%}$	$0.42^{+7.0\%}_{-5.5\%}$	1.02
33	$207.29^{+33.0\%}_{-26.7\%}$	$12.05^{+6.1\%}_{-4.2\%}$	$1.99^{+3.5\%}_{-3.1\%}$	$1.68^{+7.9\%}_{-6.7\%}$	7.91
100	$1417.83^{+29.7\%}_{-24.7\%}$	$79.55^{+6.2\%}_{-4.1\%}$	$8.00^{+4.2\%}_{-3.7\%}$	$8.27^{+8.4\%}_{-8.0\%}$	77.82

TH accuracies

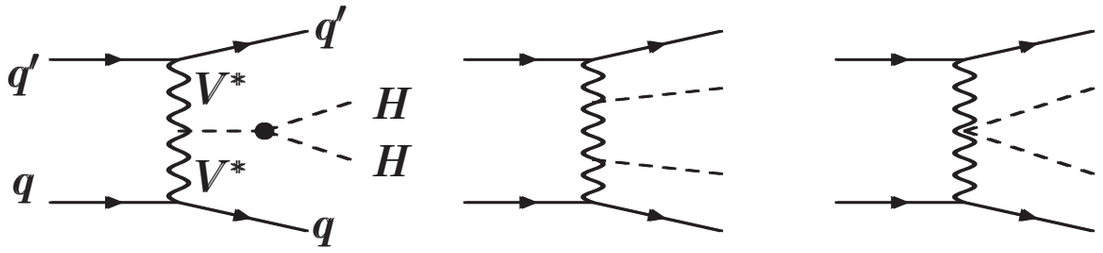
~ qqHH

gg double-Higgs fusion: $gg \to HH$

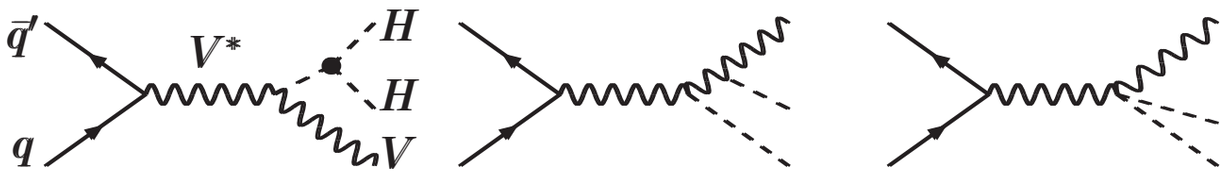




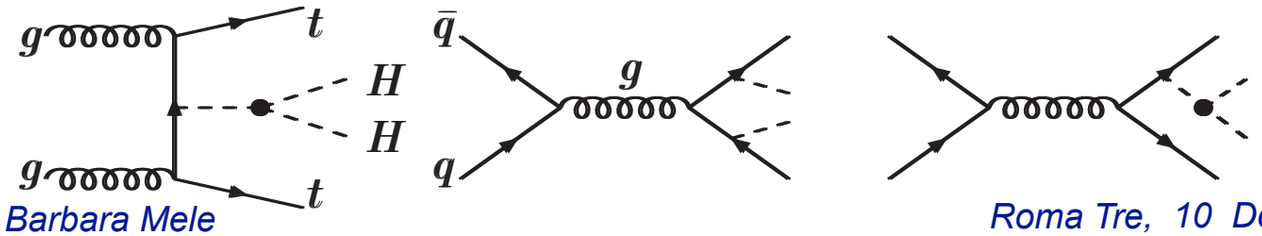
WW/ZZ double-Higgs fusion: $qq' \to HHqq'$

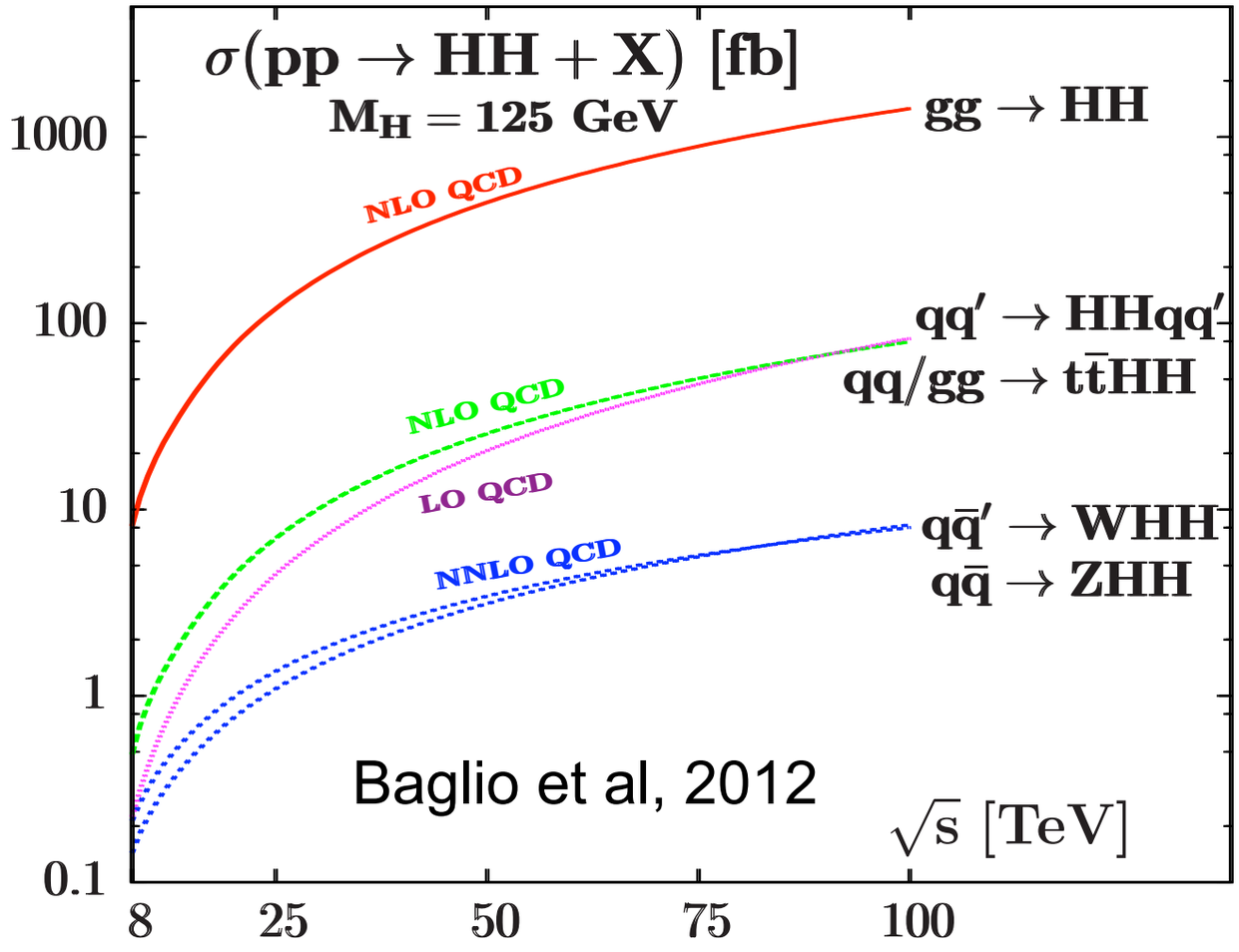


Double Higgs-strahlung: $q\bar{q}' \to ZHH/WHH$

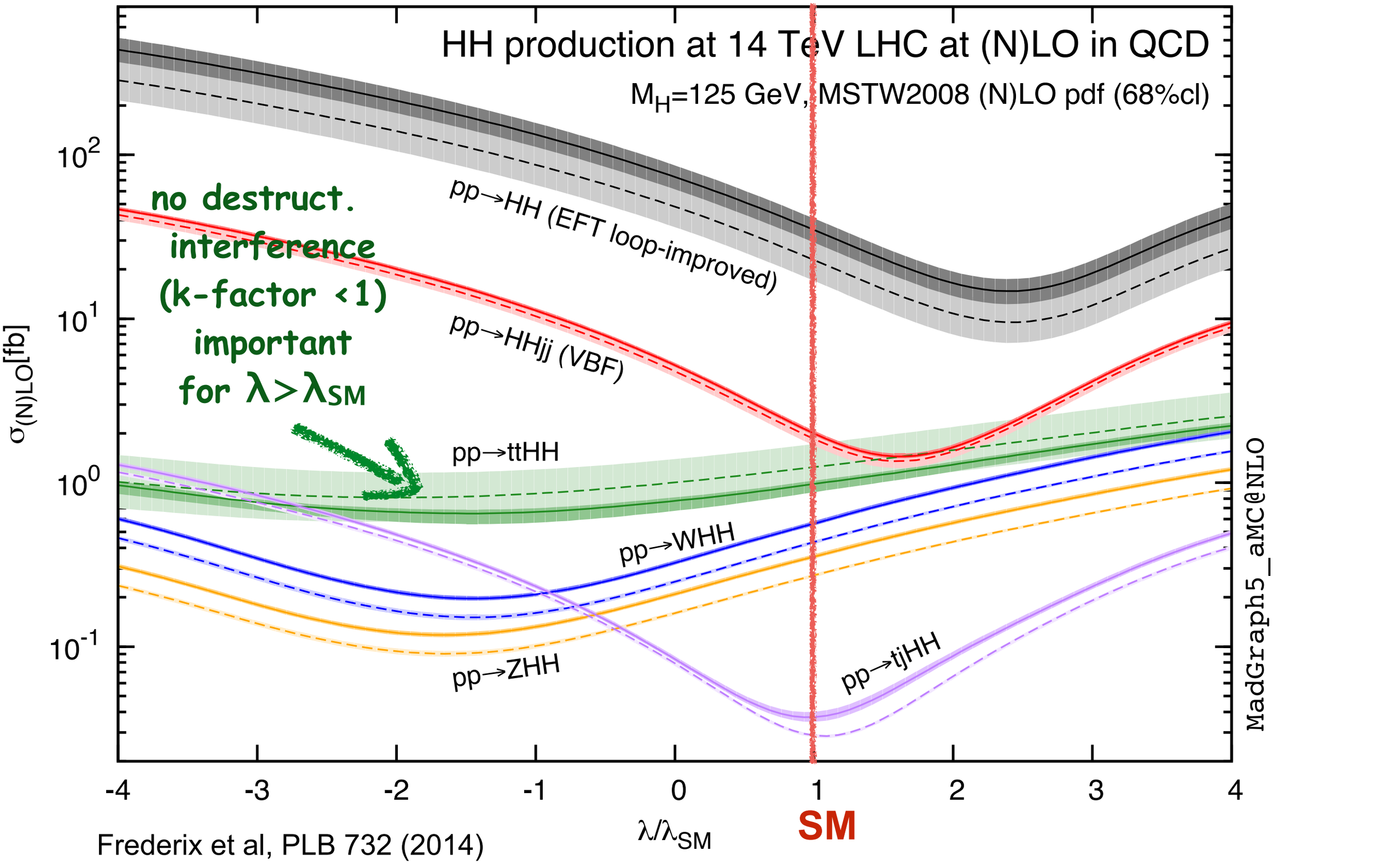


Associated production with top-quarks: $q\bar{q}/gg \to t\bar{t}HH$



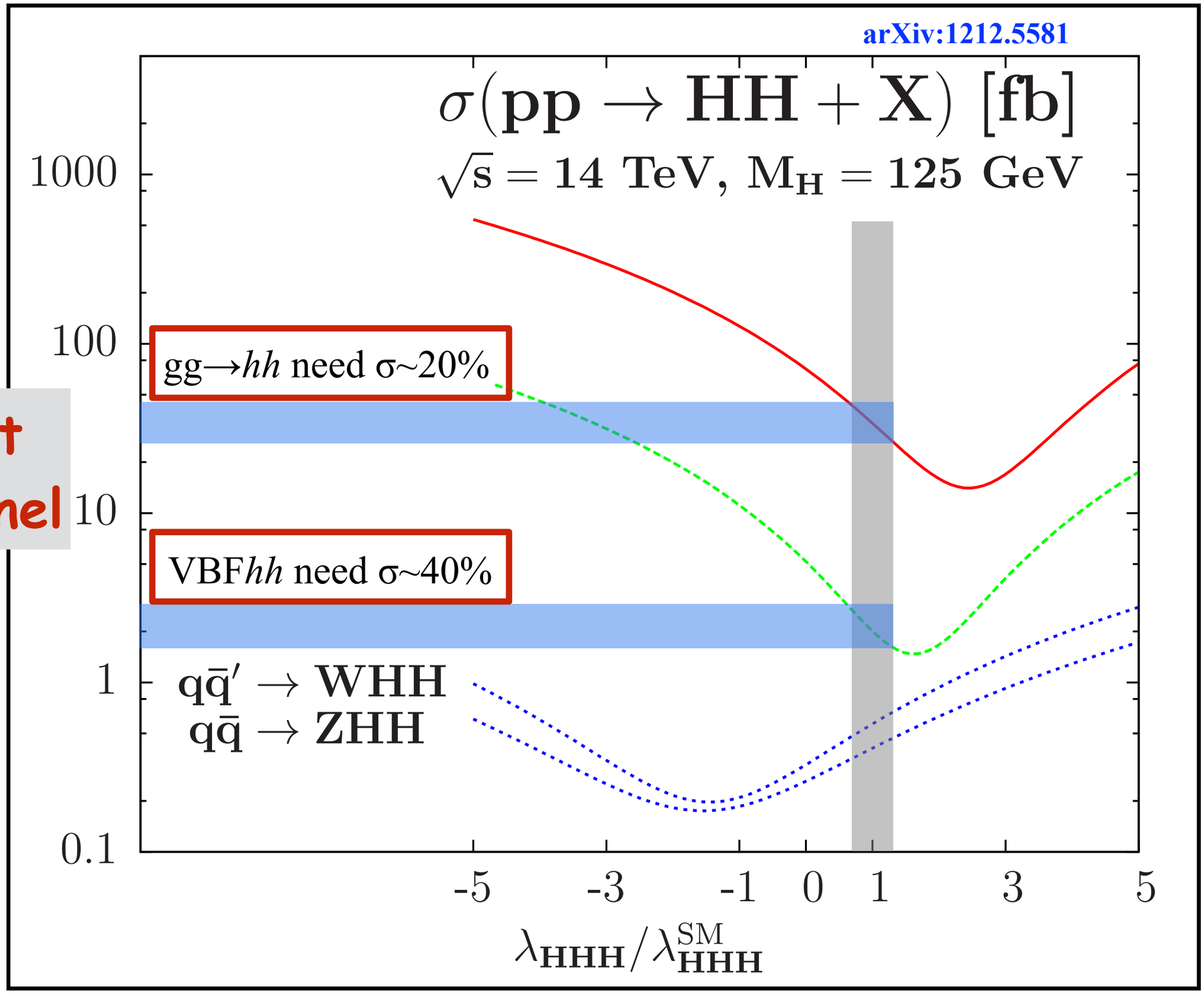


σ sensitivity to λ H^3 coupling at 14 TeV



Target: ~ 20% constrain on λ_{HHH}

VBF HH most sensitive channel

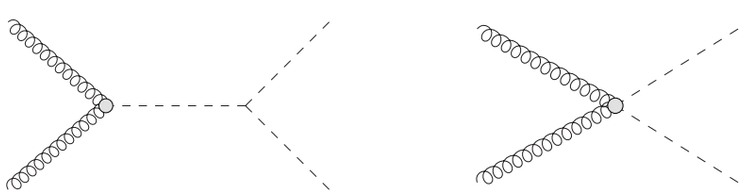


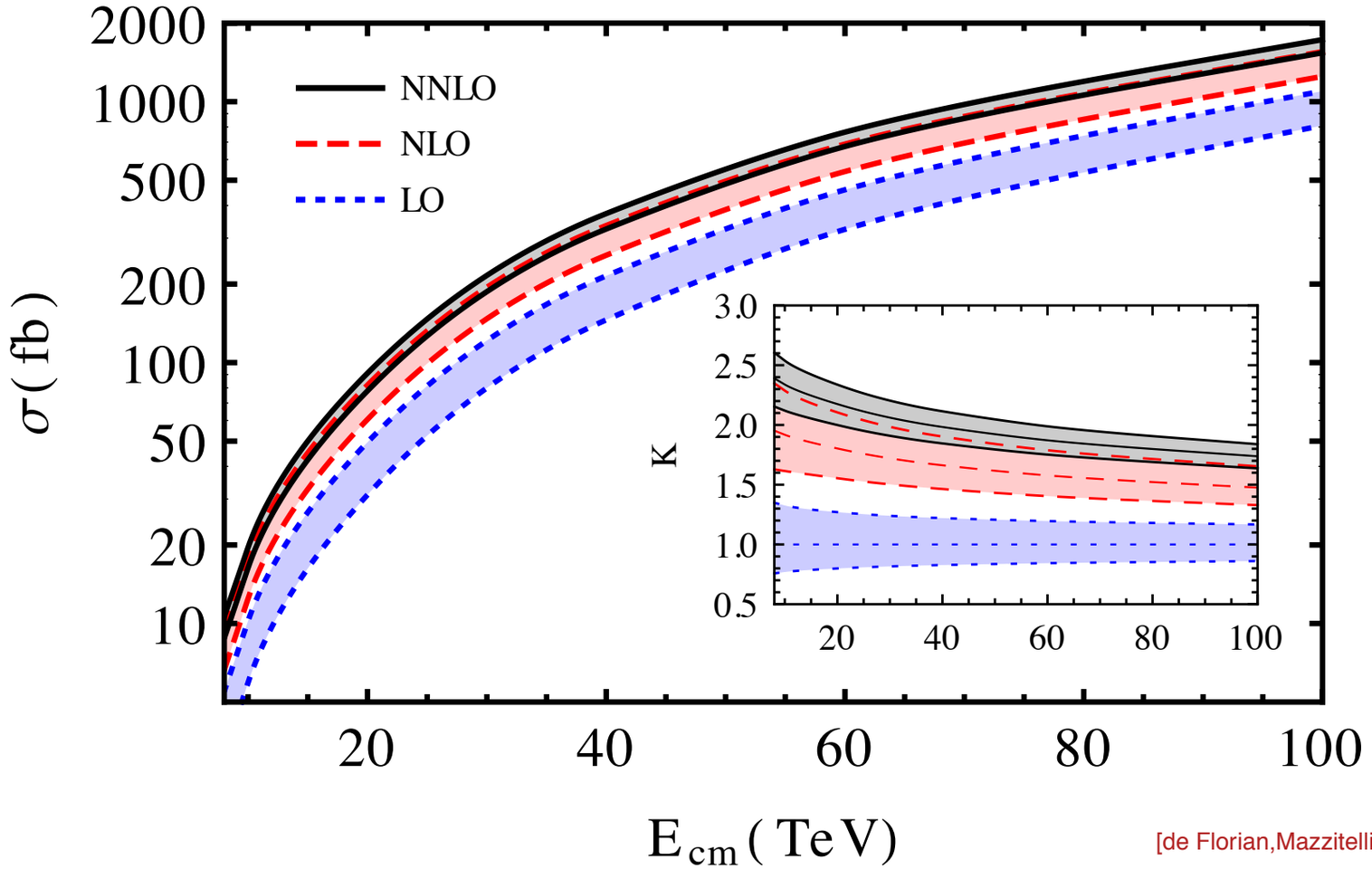
gg → HH (TH): known results

- LO cross section ~ 18 fb ($\sqrt{S}$=14 TeV)
- NLO ($m_t \to \infty$) ~ +100%
- NLO including $1/m_t$ terms ~ +10%
- NNLO ($m_t \to \infty$) ~ +20%
- NNLL soft-gluon resumm. ~ NLO +20%

Effective Lagrangian (EFT) used in the large m_t limit

$$\mathcal{L}_{\rm eff} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} \left(C_H \frac{H}{v} - C_{HH} \frac{H^2}{v^2} \right)$$





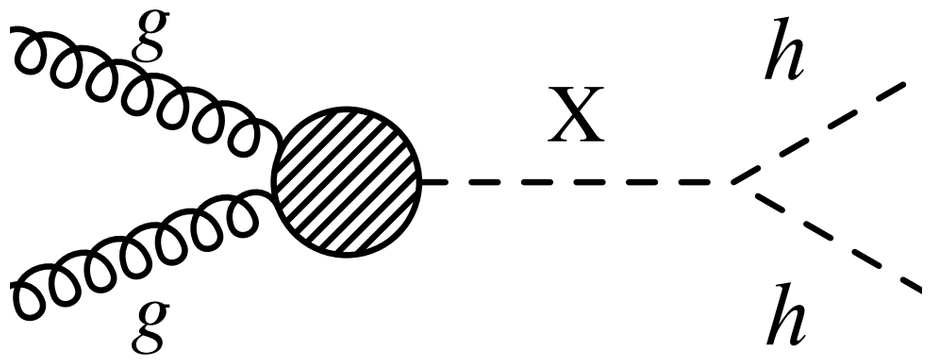
[de Florian,Mazzitelli'13

TH uncertainties on gg → HH

- scale uncertainty : ~ 20% at NLO (EFT)
  ~ 10% at NNLO (EFT)
- PDF + α_S : ~ 10%
- finite m_{top} effects : ~ 10 % (?)
- m_{top} uncertainties: $\frac{\Delta\sigma}{\sigma} \simeq 0.6\% \frac{\Delta m_t}{1\mathrm{GeV}}$
- Total → ~ 30% ?
- full two-loop calculation (hard) would help…

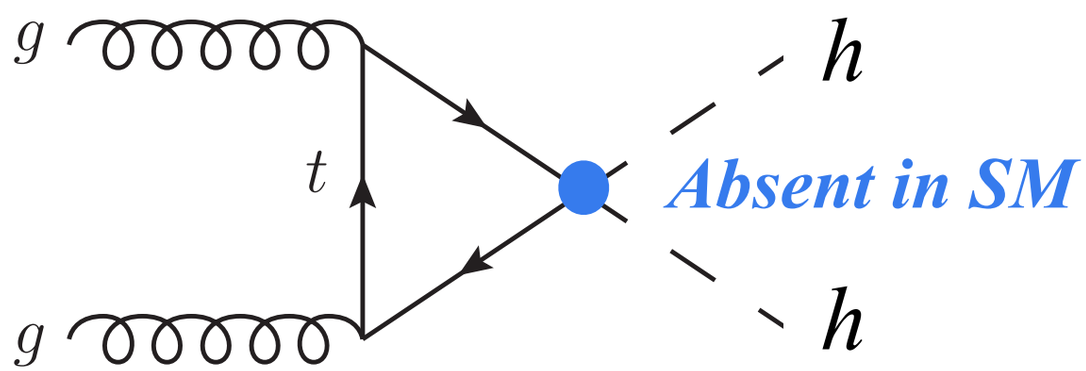
HH production in BSM

- significant **enhancement** in many BSM frameworks
  - HH resonant production (KK-gravitons, 2HDM, (N)MSSM,….)
    - potentially large cross section (up to pb)
    - m_X shape helps with bckgrs



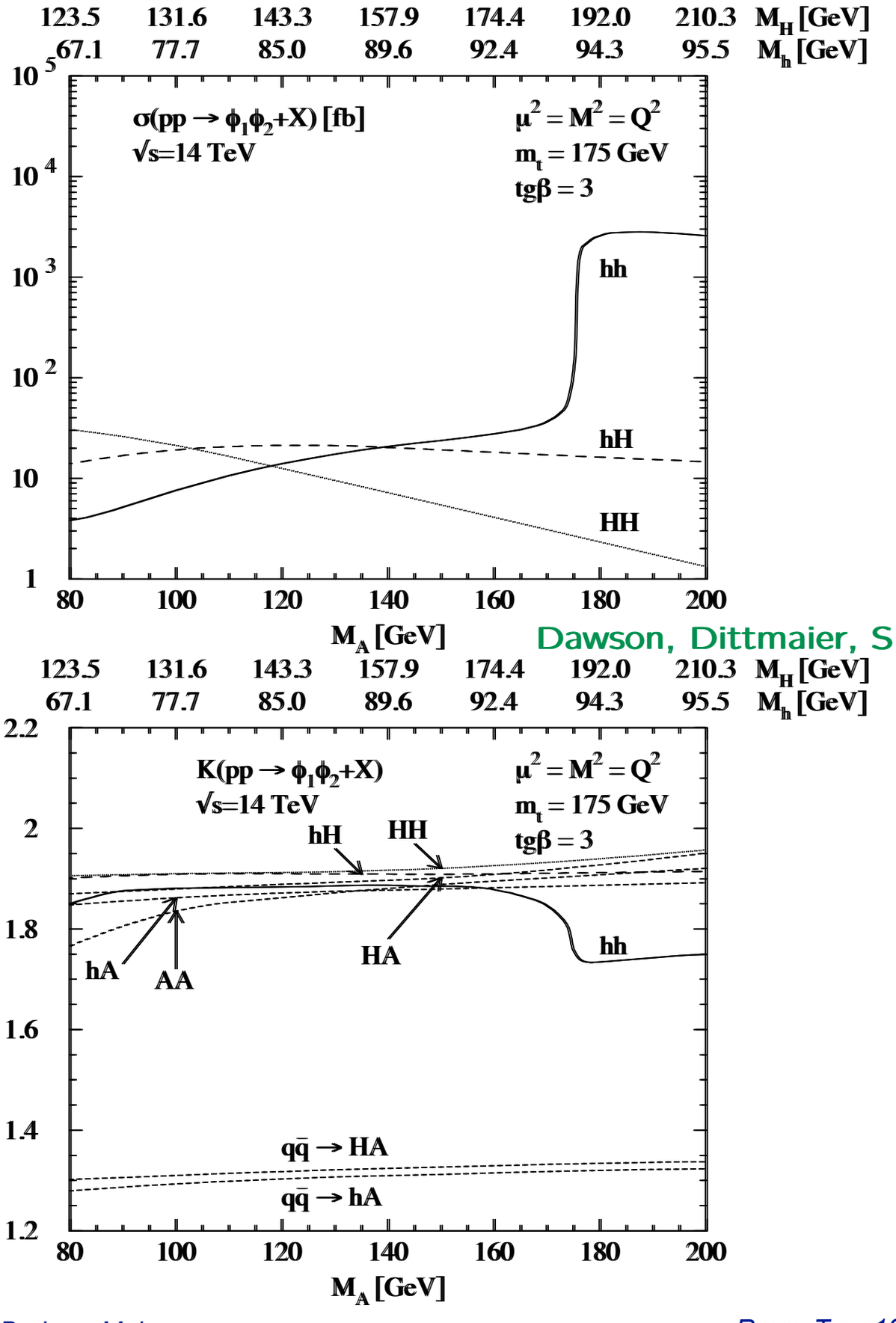
  - HH non-resonant enhancement
    - Composite Higgs/Little Higgs/…
    - can modify λ or/and give rise to new couplings
    - can give strong enhancement at large $p_T(H)$

- analysis relevant also for Run 1

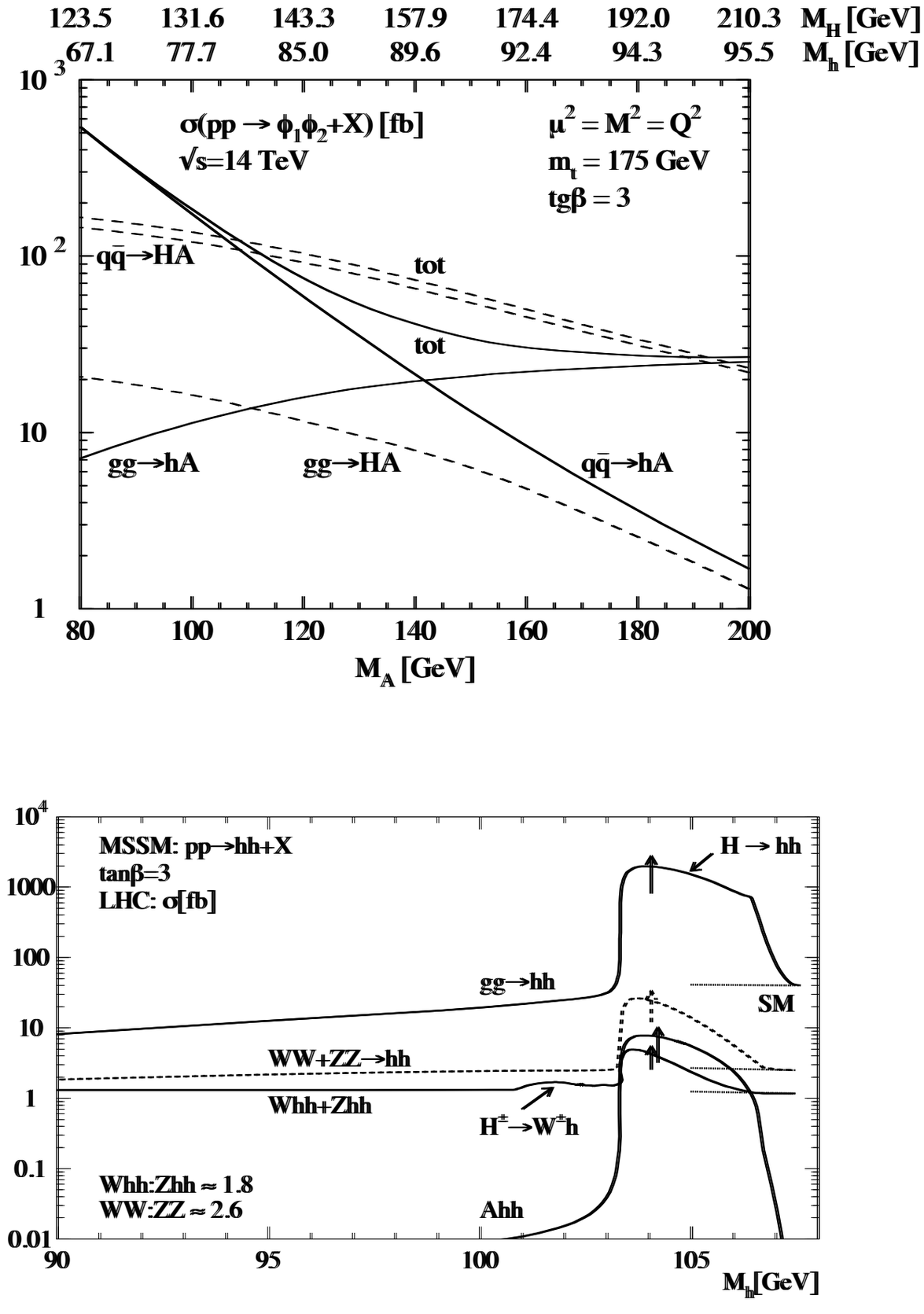


anomalous Higgs-top quartic coupling

MSSM $gg \to hh, hH, HH, hA, HA, AA$ and $q\bar{q} \to hA, HA$



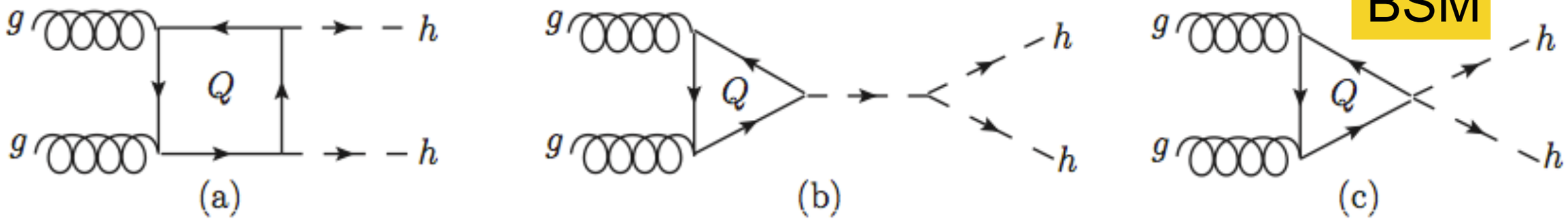
Dawson, Dittmaier, S.



Djouadi, Kilian, Mühlleitner, Zerwas

Spira HXS

non-resonant HH enhancement



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \left(c_{tri} \frac{3m_h^2}{\hat{s} - m_h^2} + c_{nl} \right) F_\triangle + c_{box} F_\square \right|^2 + \left| c_{box} G_\square \right|^2 \right]$$

$$c_{box}^{(\mathrm{SM})} = 1 \,, \qquad c_{tri}^{(\mathrm{SM})} = 1 \,, \qquad c_{nl}^{(\mathrm{SM})} = 0$$

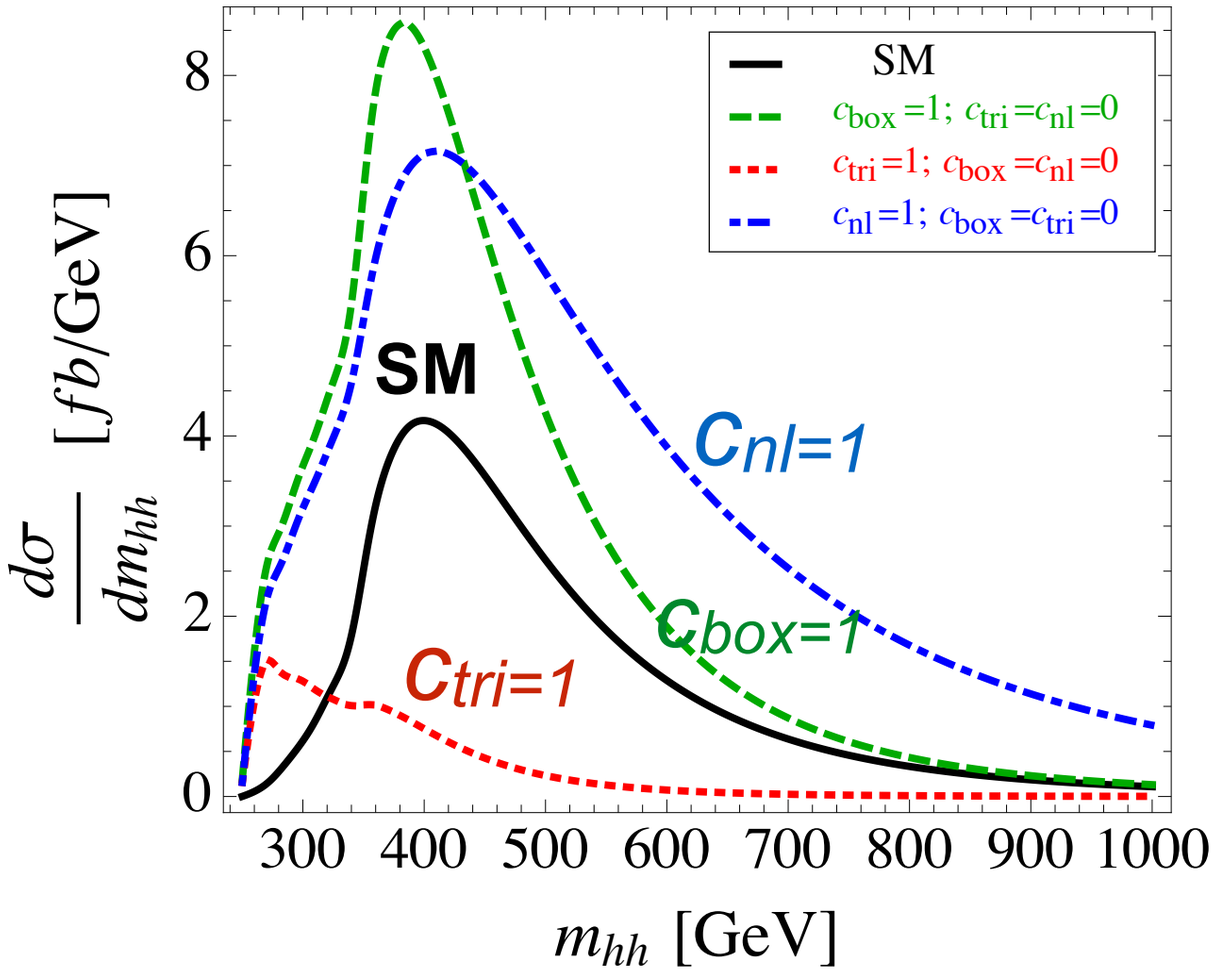
interferences between graphs ➜ degeneracies in σ's

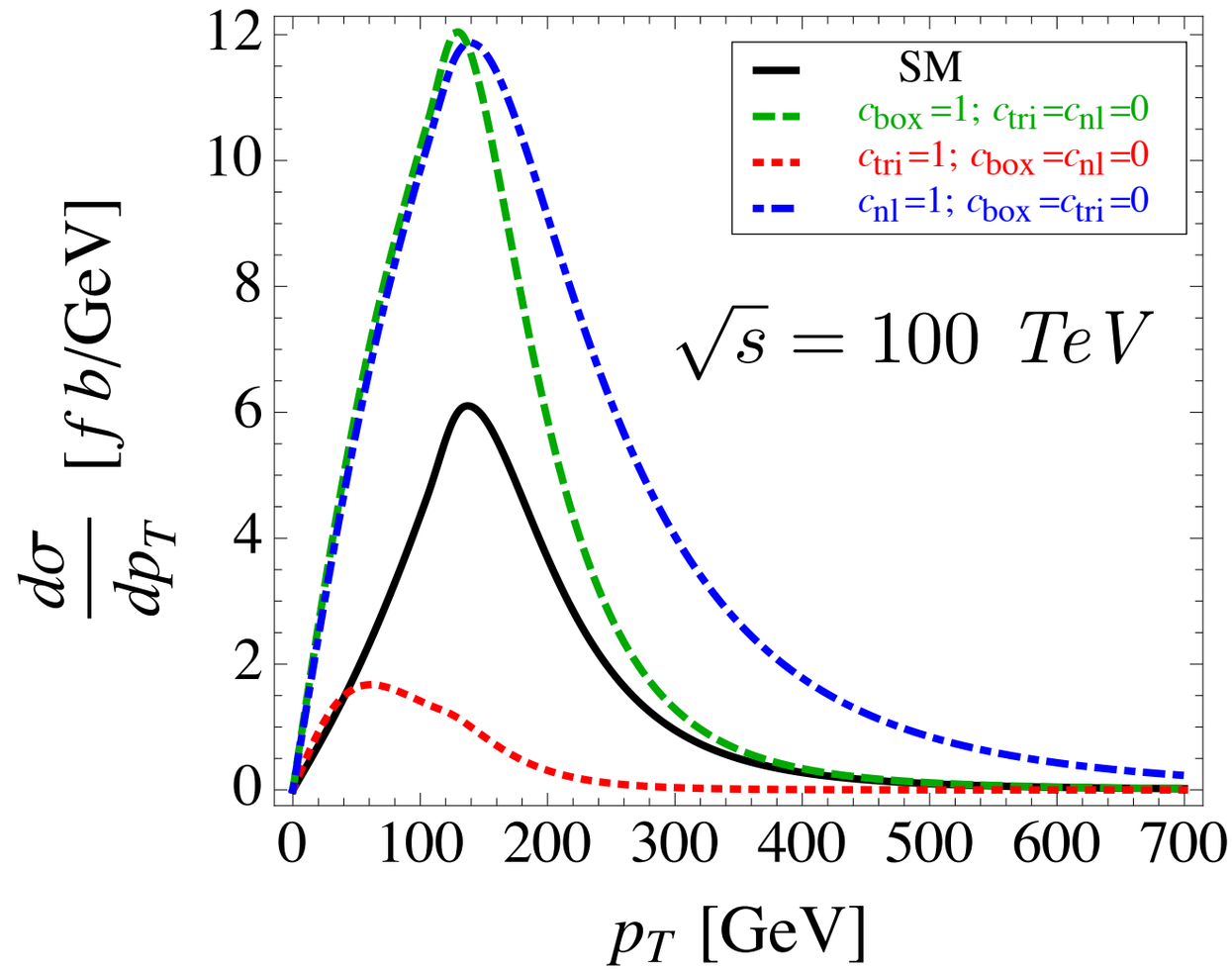
$$\sigma(gg \to hh) = \sigma^{SM}(gg \to hh)[1.849\ c_{box}^2 + 0.201\ c_{tri}^2 + 2.684\ c_{nl}^2$$

$$-1.050\ c_{box}c_{tri} - 3.974\ c_{box}c_{nl} + 1.215\ c_{tri}c_{nl}].$$

Chen, Low, arXiv:1405.7040

kinematic. distributions can help

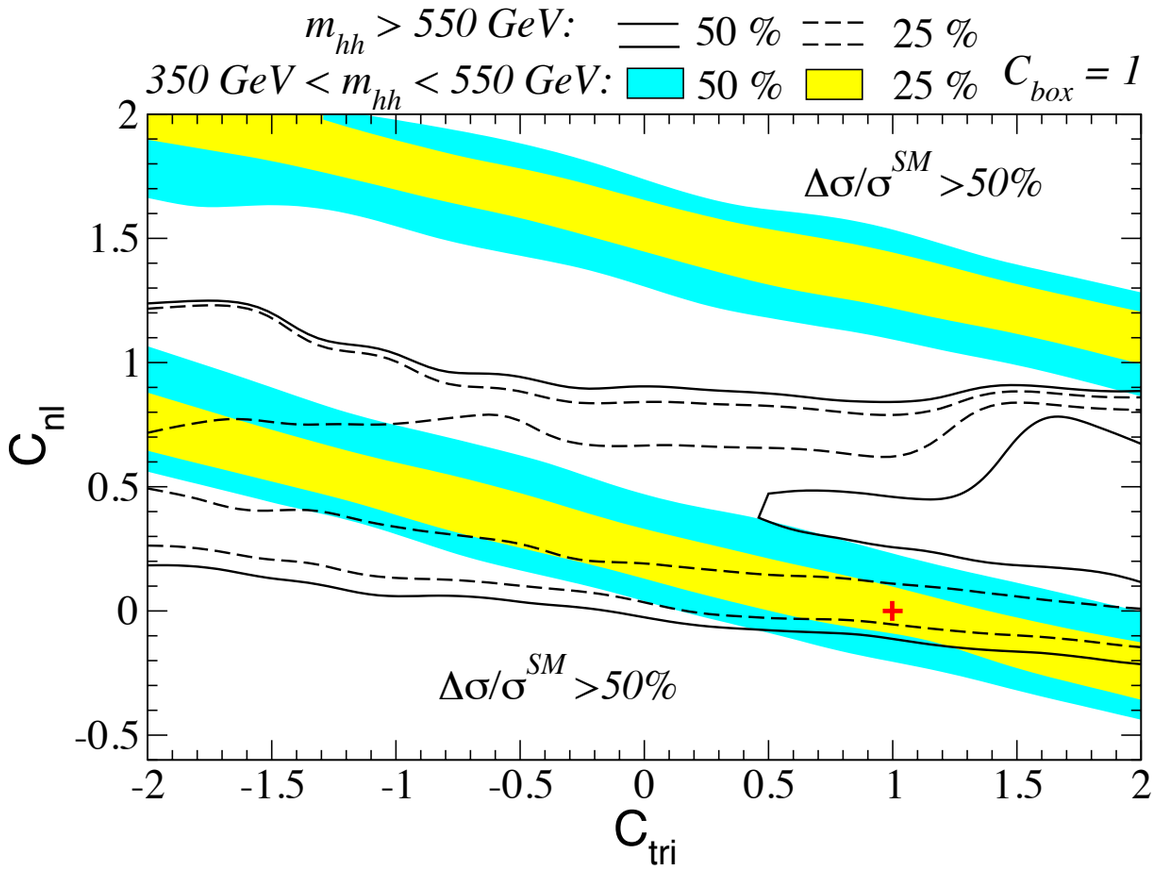




Warning : a small c_{nl} could mimic effects from BSM c_{tri}

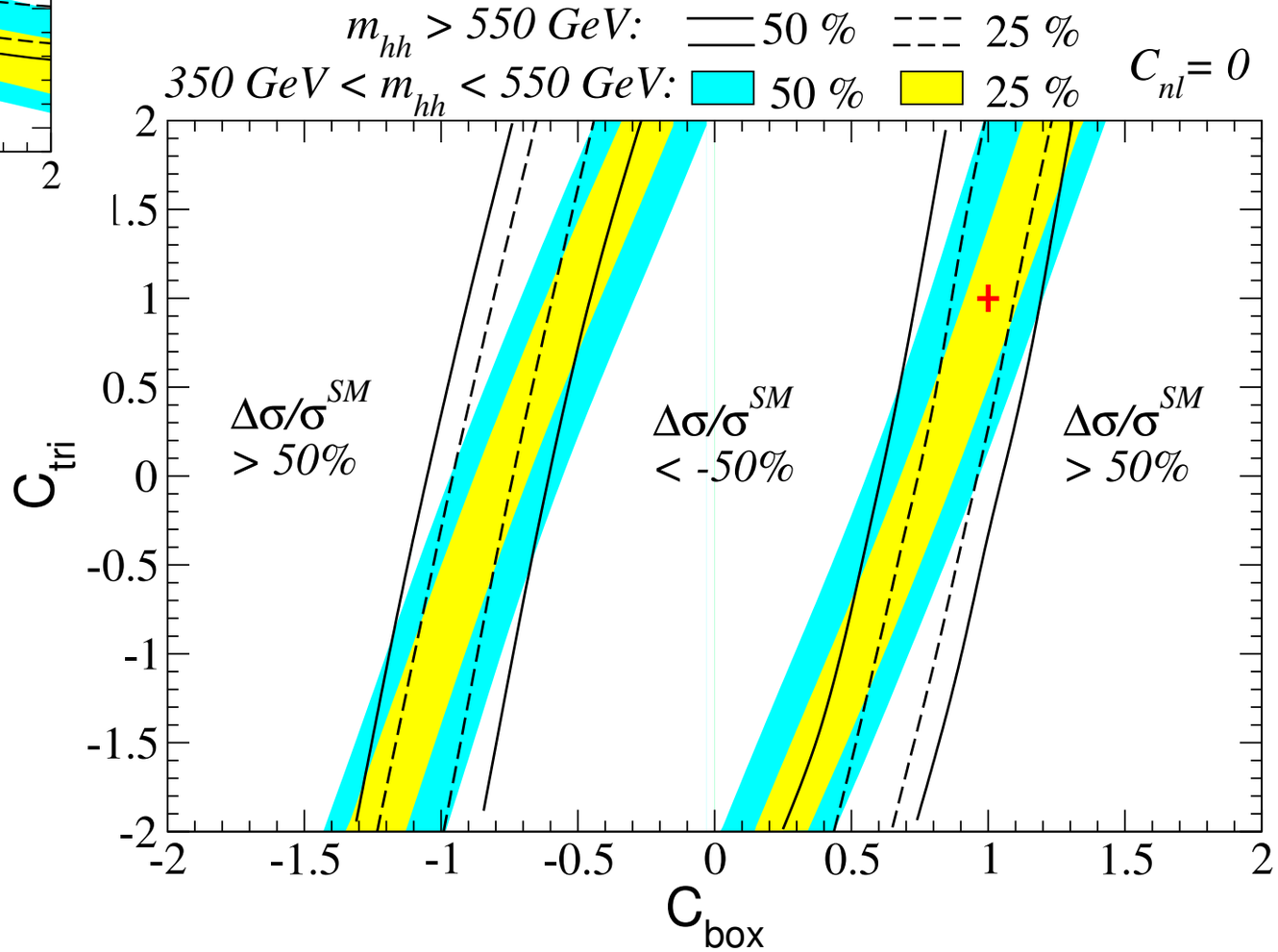
Chen, Low, arXiv:1405.7040

moderate sensitivity to C_{tri} (λ)



$$\sqrt{s} = 100\ TeV$$

sensitivity on self-coupling still the least !



kinem information from two different m_{hh} bins allows for a significant improvement in constraining c_{tri} wrt using the σ measurement alone.

Chen, Low, arXiv:1405.7040

(SM) HH rates at HL-LHC (ev/3000fb^{-1})

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

(40.8 fb NNLO HH)

selection of HH final states has to account for:

- final states experimentally clear and robust
- final states with large enough production rate

HH → bbWW [large rates but S(~10^3)/B(tt pairs)~10^{-4}]

HH → bbγγ [clean but small rates], (also HH → bb[ττ, bb, ZZ, μ μ])

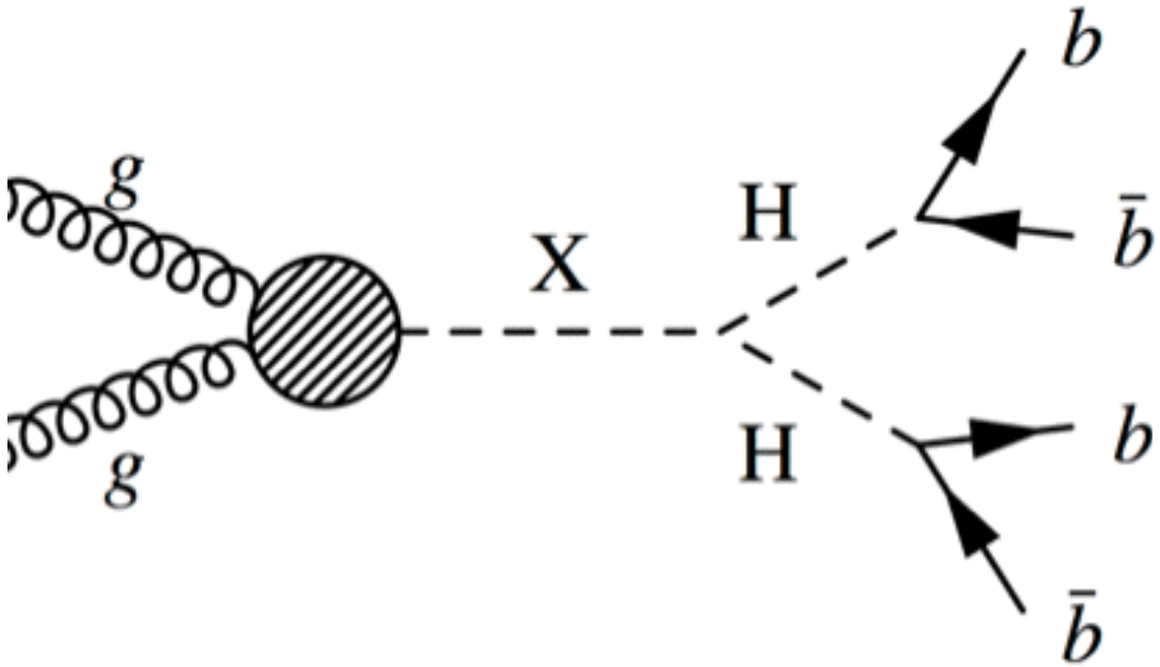
many studies … results not yet robust !

Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

resonant HH : Run 1 results (8 TeV)

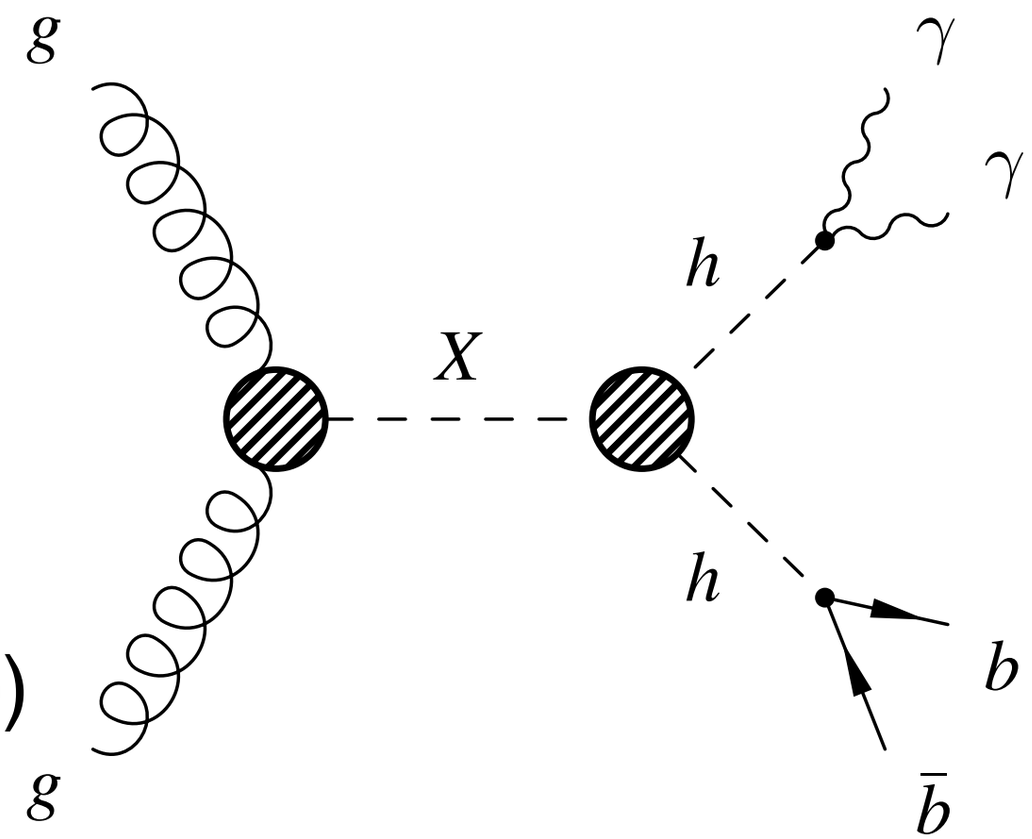
narrow resonances from WED radion/graviton,2HDM

competitive with VV searches



ATLAS-CONF-2014-005 (bbbb)

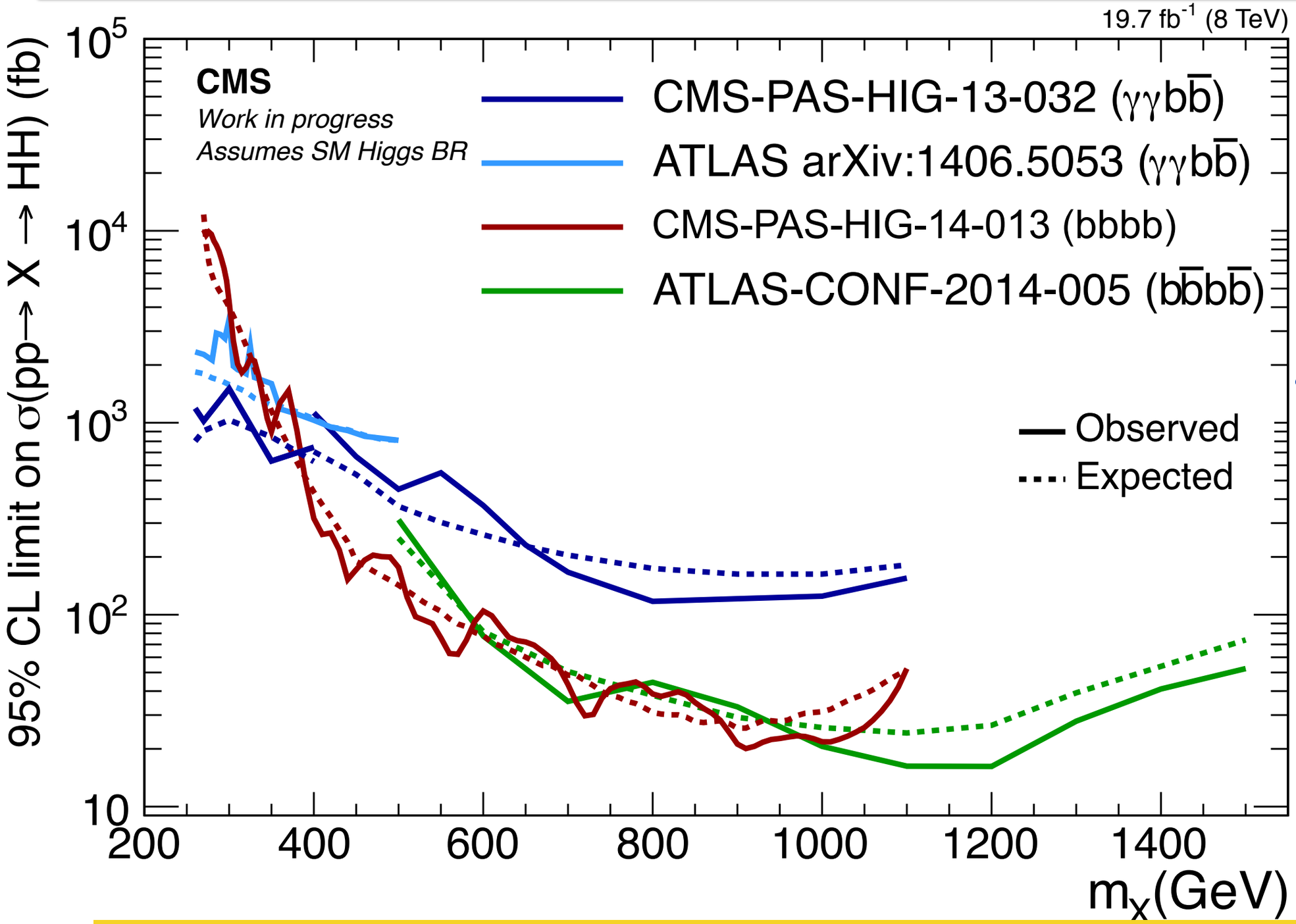
CMS-PAS-HIG-14-013 (bbbb)



CMS-PAS-HIG-13-032 (γγbb)

ATLAS arXiv:1406.5053 (γγbb)

Comparison of sensitivities (ATLAS+CMS)



bbbb and γγbb complementary

Run 1 (8TeV)

best limits on cross section for X→HH in m_X range

380-600 GeV (921-93 fb) 700-970 GeV (136-23 fb)

HH → bbγγ (Snowmass studies)

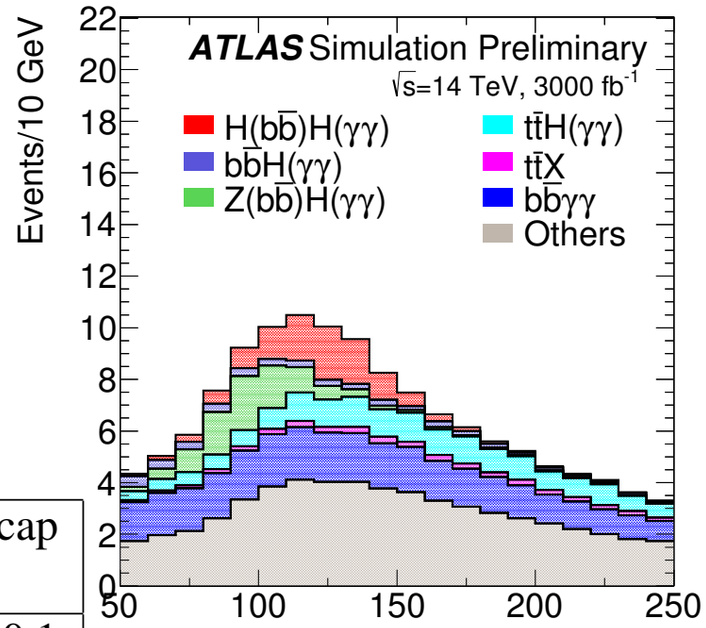
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L} dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

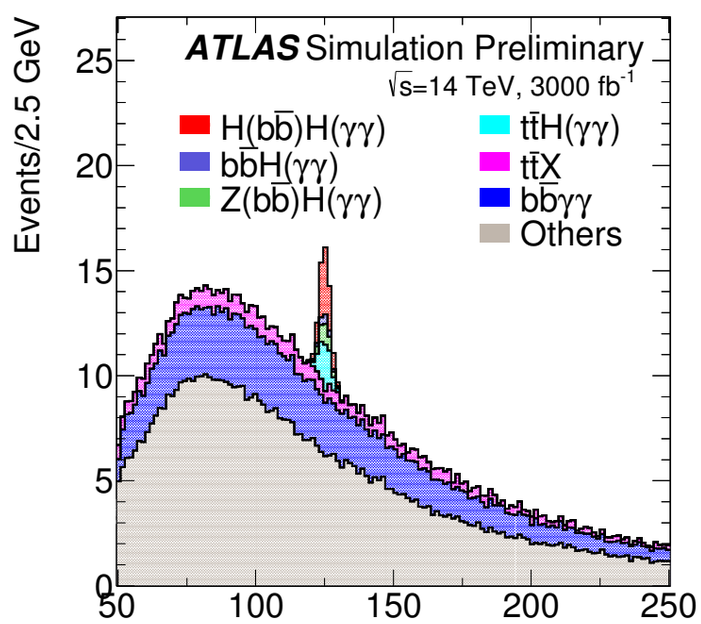
ATLAS at HL-LHC : HH → bbγγ

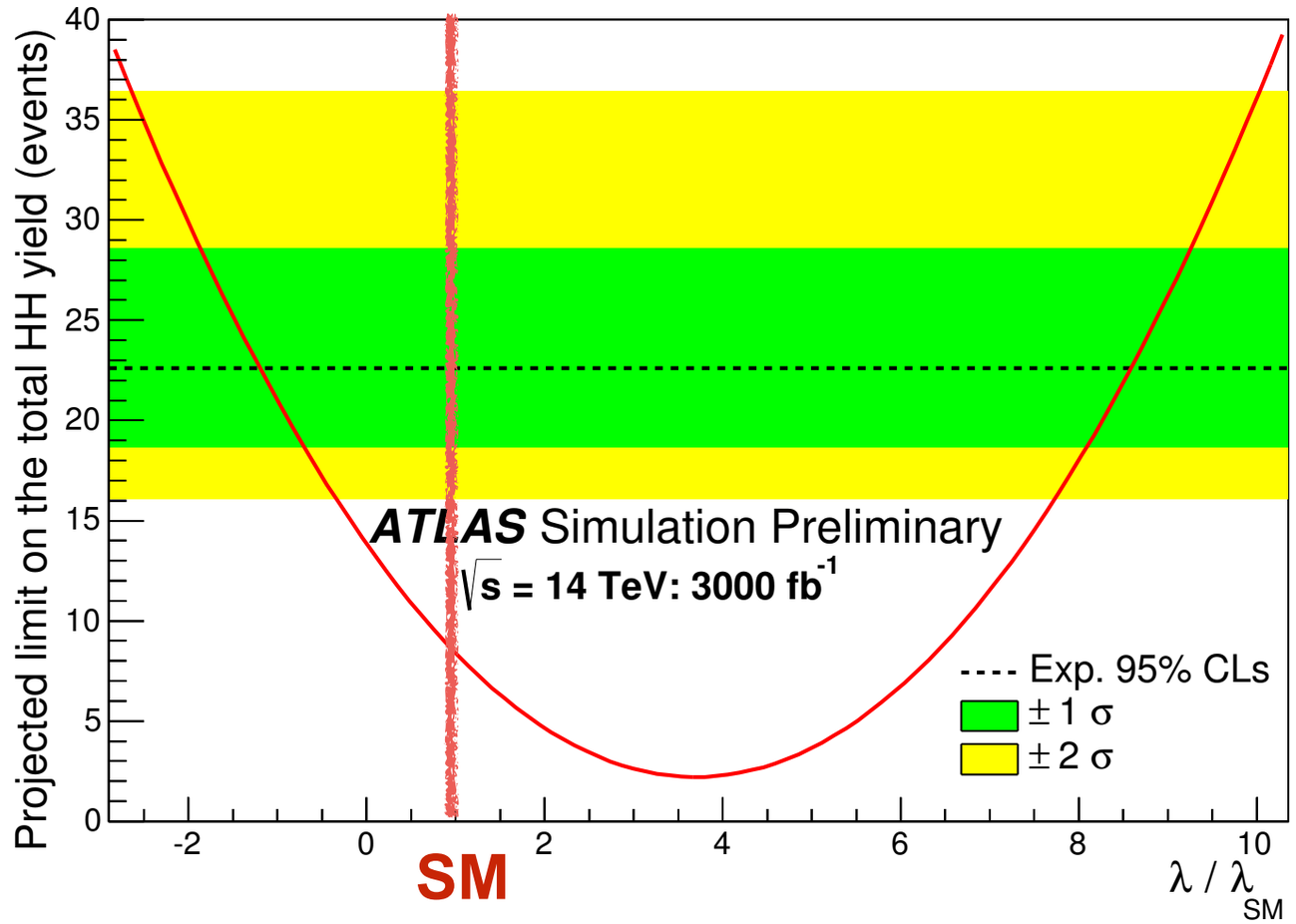
ATL-PHYS-PUB-2014-019

combining "barrel" and "endcap" categories significance reaches ~ 1.3σ

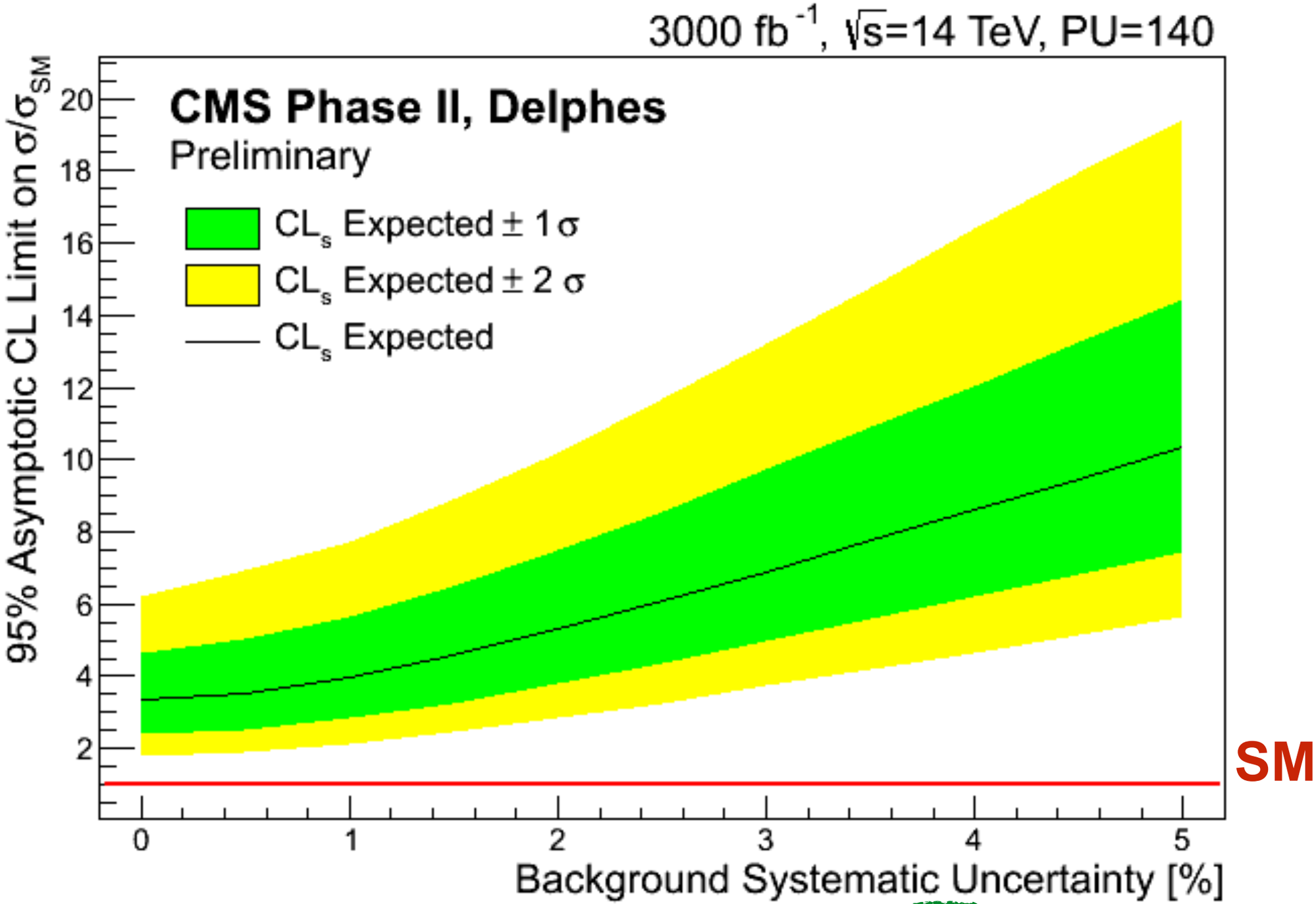
Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4







CMS at HL-LHC : HH → bbWW



Data driven technique should constrain this to percent level

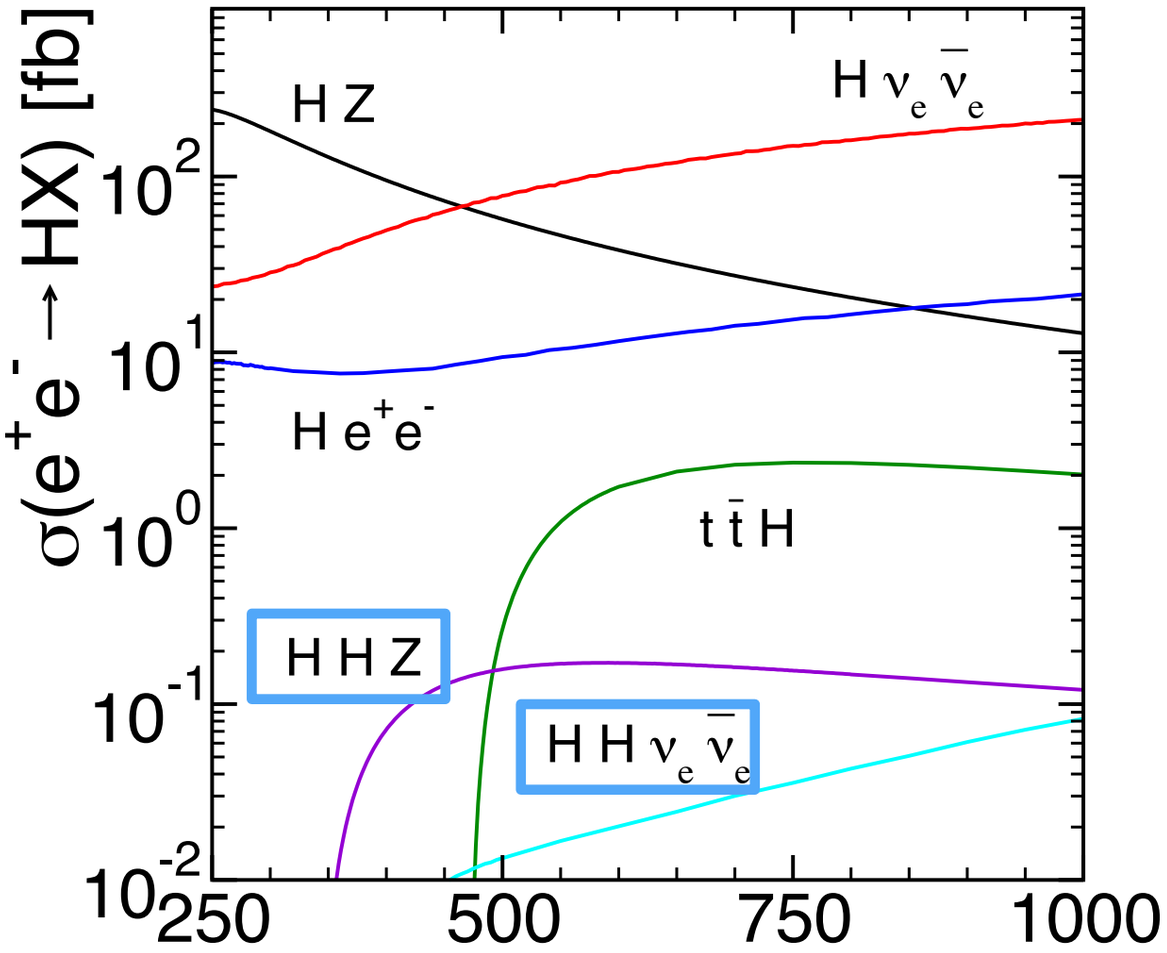
in conclusion…

a lot of work still needed to assess
the actual HL-LHC sensitivity
to λ H^3 coupling !

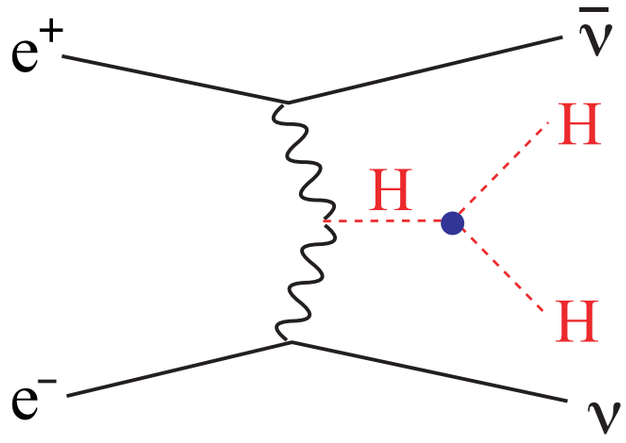
will likely benefit a lot from
new exp strategies developed in Run 2
and knowledge of actual HL detector upgrades

(3σ significance (SM) / 3ab-1 doable ?)

HH production in e^+e^- collisions

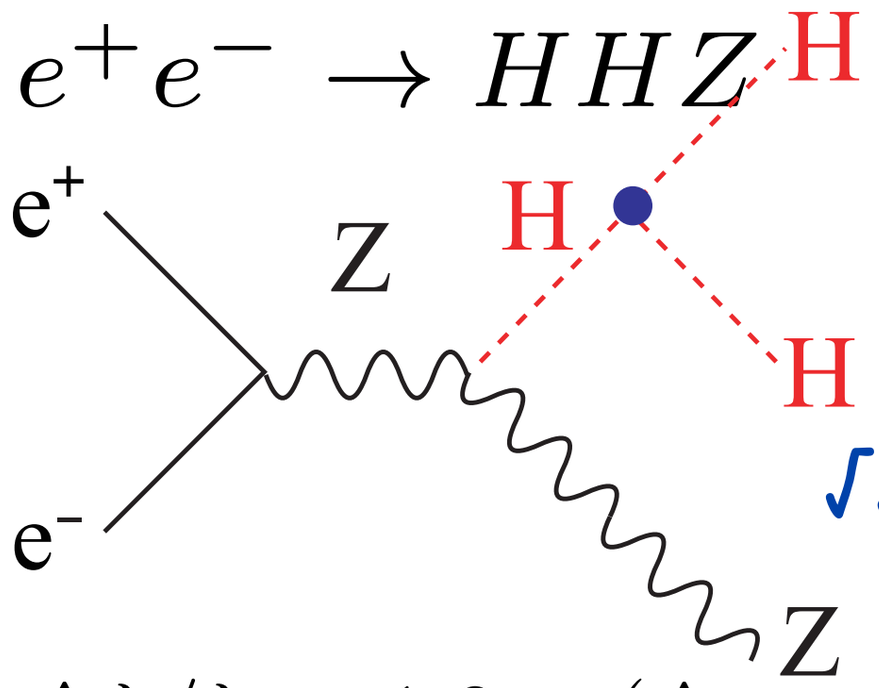


$$e^+e^- \to HH\nu_e\bar{\nu}_e$$



√s ~ 1TeV

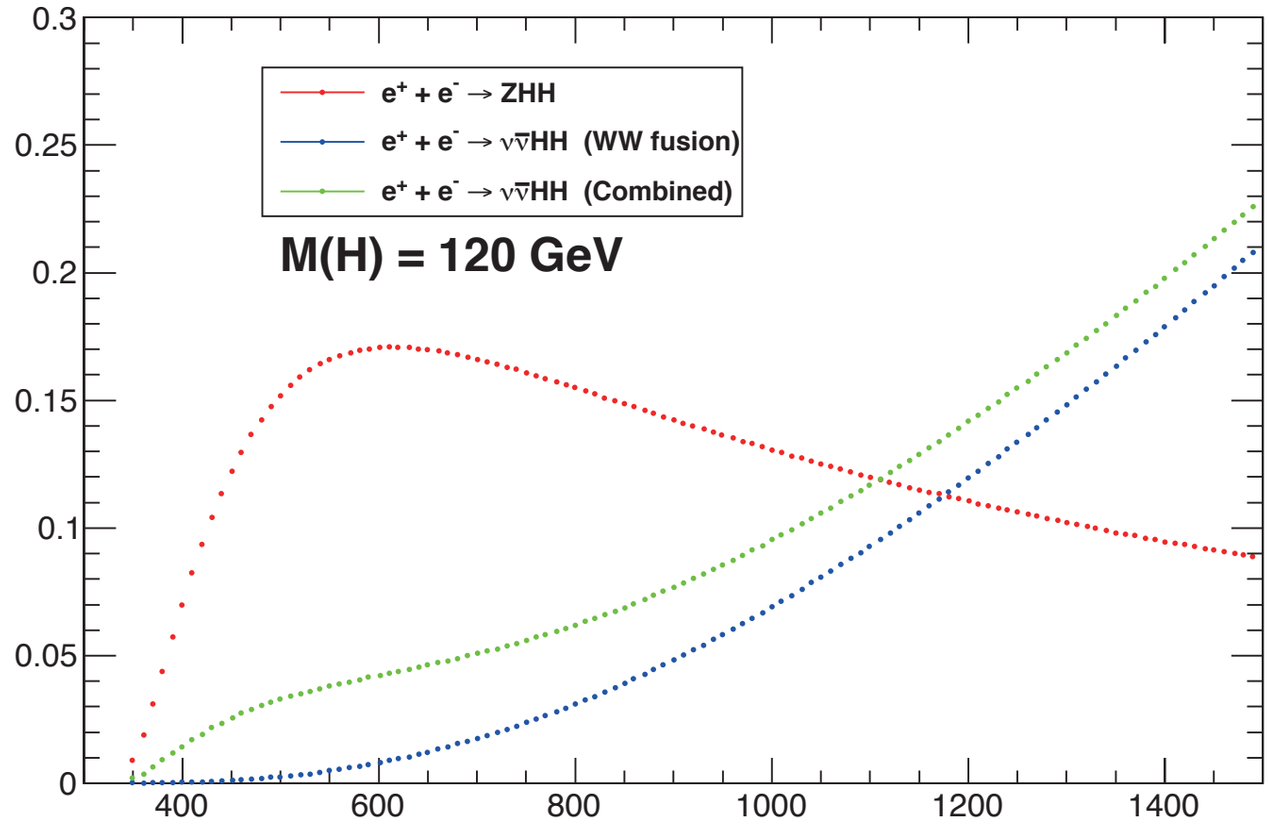
$$\Delta\lambda/\lambda \simeq 0.85 \times (\Delta\sigma_{\nu\bar{\nu}HH}/\sigma_{\nu\bar{\nu}HH})$$



$$e^+e^- \to HHZ$$

√s~0.5TeV

$$\Delta\lambda/\lambda \simeq 1.8 \times (\Delta\sigma_{ZHH}/\sigma_{ZHH})$$



e+e- colliders

ILC TDR + Snowmass projections

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0, 0)/(-0.8, 0)$	$(0, 0)/(-0.8, 0)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

based on bbbb and WWbb simulation at ILC
and bbbb at CLIC
(to be improved - ongoing simulations)

needs full luminosity program !

Outlook

- Higgs self-coupling measurement crucial to characterize Higgs
- tiny rates for HH prod. ➜ very hard EXP (and TH) problem !
- "training" in Run 1 for searches of BSM-resonance signatures
- HL-LHC lumi needed to approach SM signal sensitivity

(HH excellent benchmark for trigger/detector HL-LHC studies !)

- sensitivity to individual channels low ➜ need combination of many
- simulations in different HH decay channels ongoing in ATLAS and CMS to assess the actual potential of HL-LHC
- e+e- excellent potential, needs large cm energies (≥500 GeV) and high luminosities
- mandatory to extend studies to FCC-hh …