Higgs Boson Self-Coupling Measurements Using Ratios of Cross Sections

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Exploring TeV Scale New Physics with LHC Data
KITP
June 10, 2013

FG, Papaefstathiou, Yang, Zurita, 1301.3492,
accepted for publication in JHEP

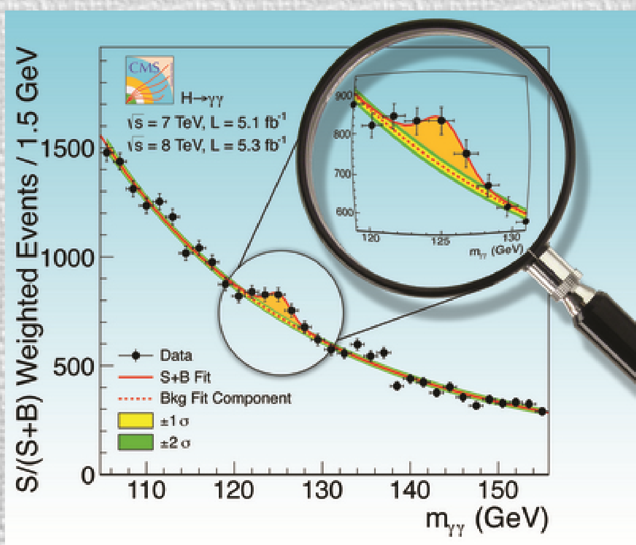
Outline

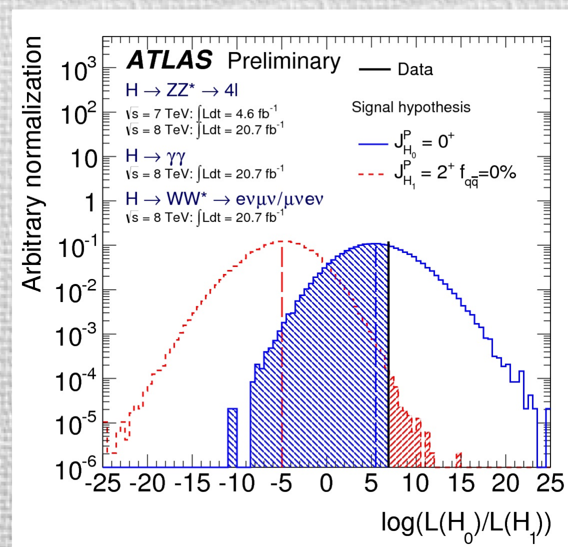
- Motivation
- Higgs-Pair Production Analysis
  - ➔ Different decay channels
  - ➔ Dissection of the cross section
  - ➔ Theoretical Errors – Ratio of cross sections
  - ➔ Variation with self coupling and top yukawa
- Expected Constraints on Trilinear Self Coupling
- Outlook and Conclusions

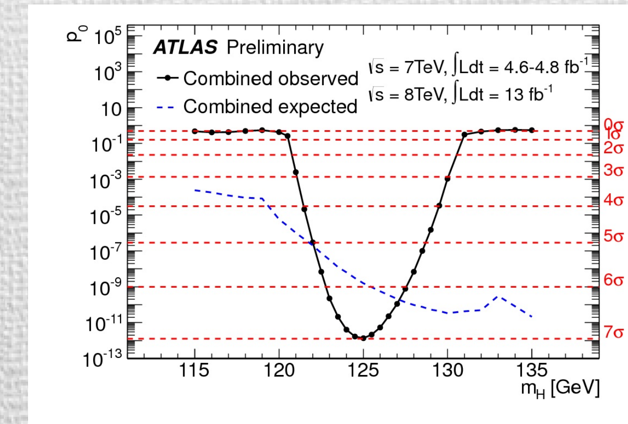
Motivation

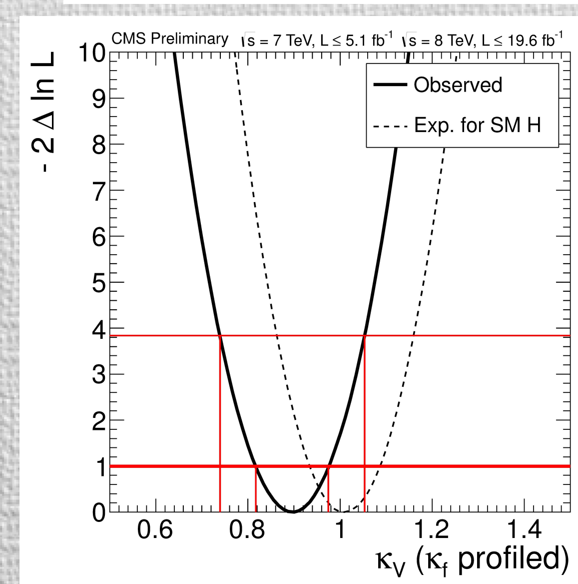
Motivation

- Have discovered *a Higgs boson*









...

Motivation

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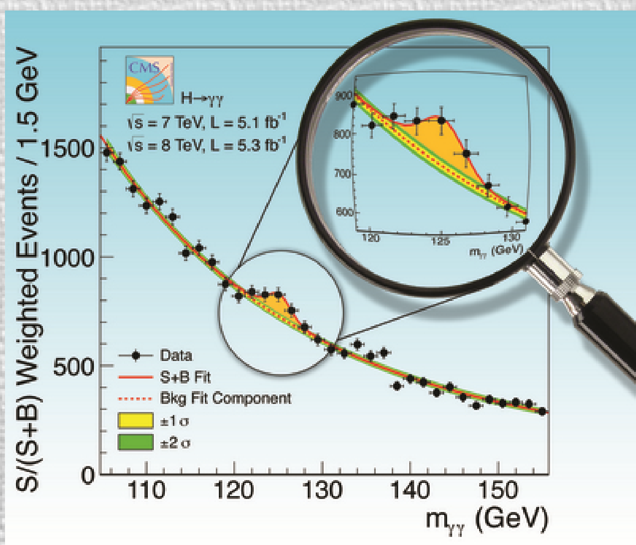
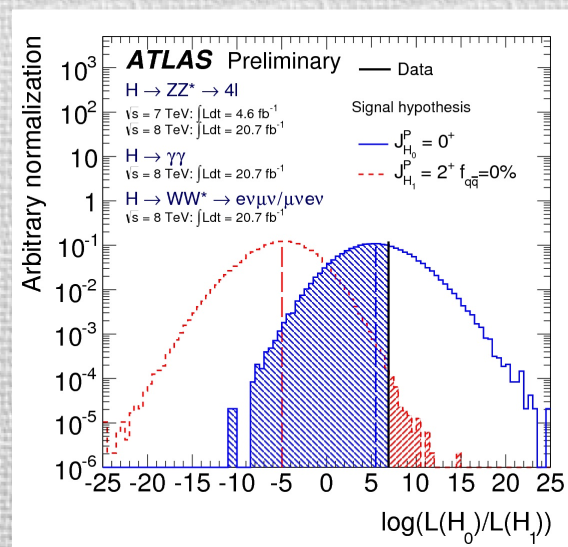
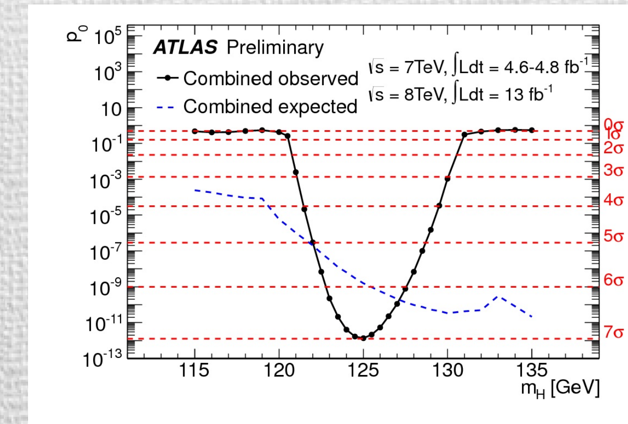
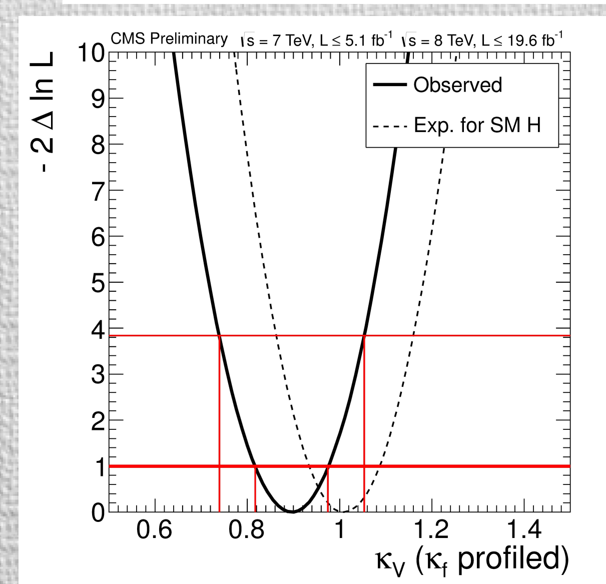








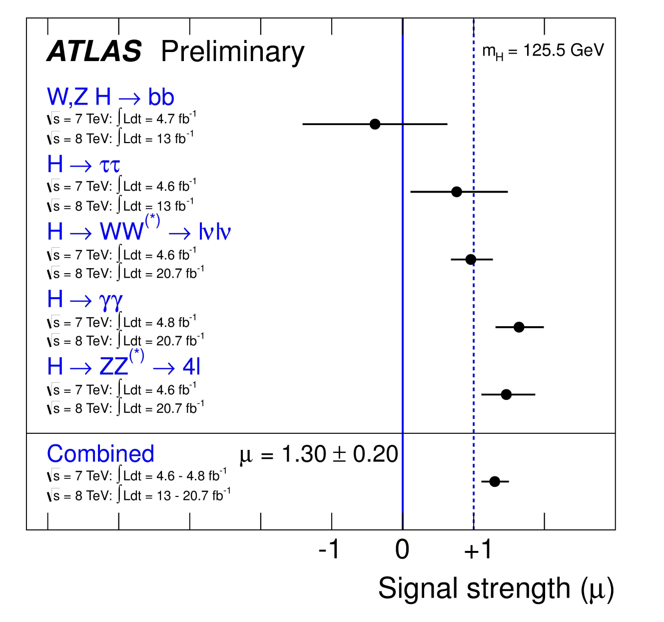
- Is it *the* SM-Higgs Boson?

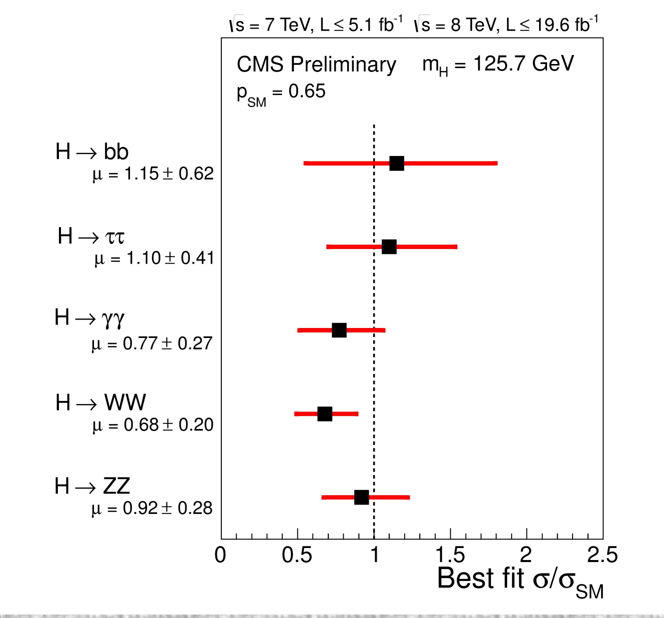
...

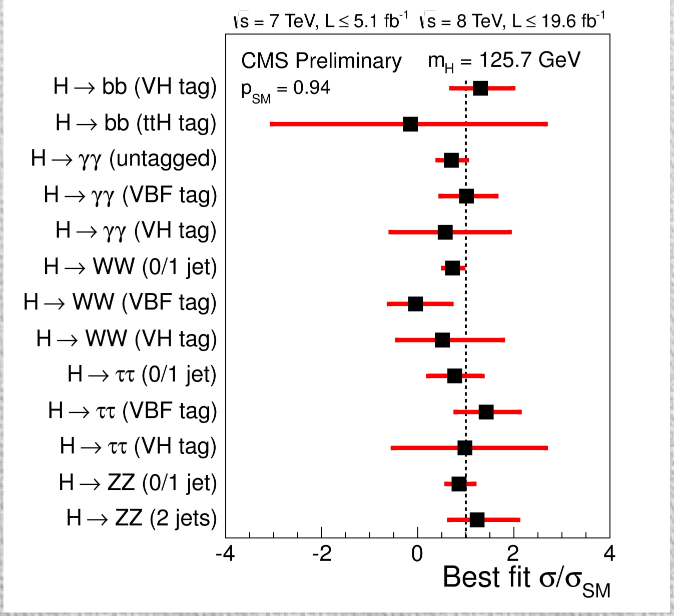
Motivation

Is it *the* SM-Higgs Boson?

Measure further properties like its decay rates to other SM fields







Motivation

Is it *the* SM-Higgs Boson?

Measure further properties like its decay rates to other SM fields

Couplings to gauge bosons and fermions

Motivation

Is it *the* SM-Higgs Boson?

Measure self couplings!

Motivation

Is it *the* SM-Higgs Boson?

↓

Measure self couplings!

↳ test Higgs potential

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

Motivation

Is it *the* SM-Higgs Boson?

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↳ test Higgs potential

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

Only remaining free SM parameter $\mathrm{M}_H \simeq 125\,\mathrm{GeV}$ measured @LHC

Motivation

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Measure self couplings!

↳ consistent with SM predictions or signs of NP?

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$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$$\lambda_{HHH}^{SM} = \lambda_{HHHH}^{SM} = \frac{M_H^2}{2v^2} \approx 0.13$$

Motivation

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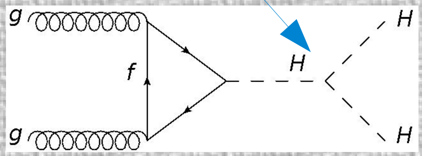
$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

λ_{HHH} can be measured in *Higgs-pair production*



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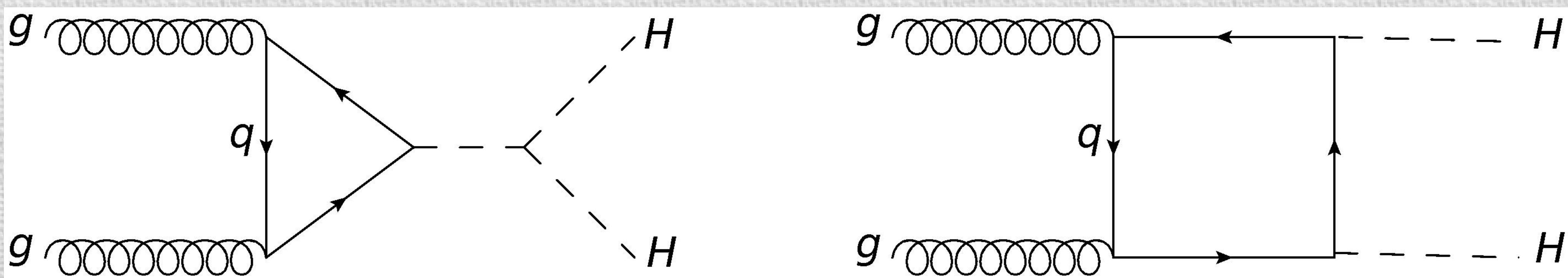
$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

Triple Higgs production
-Extremeley challenging @(V)LHC-
0.06 fb @ LHC14
9.45 fb @ VLHC (200 TeV)
Plehn, Rauch, hep-ph/0507321

Higgs-Pair Production Analysis

Higgs-Pair Production

- Most important production mechanism: $\mathrm{gg} \to HH$



Eboli, Marques, Novaes, Natale, PLB 197(1987)269; Glover, van der Bij, NPB 309(1988)282
Dawson, Dittmaier and M. Spira, PRD 58(1998)115012

$$\sigma(gg \to HH)_{\mathrm{LO}} \sim 17\,\mathrm{fb}$$

$$\sigma(gg \to HH)_{\mathrm{NLO}} \sim 33\,\mathrm{fb}$$

14TeV LHC
M_H~125 GeV

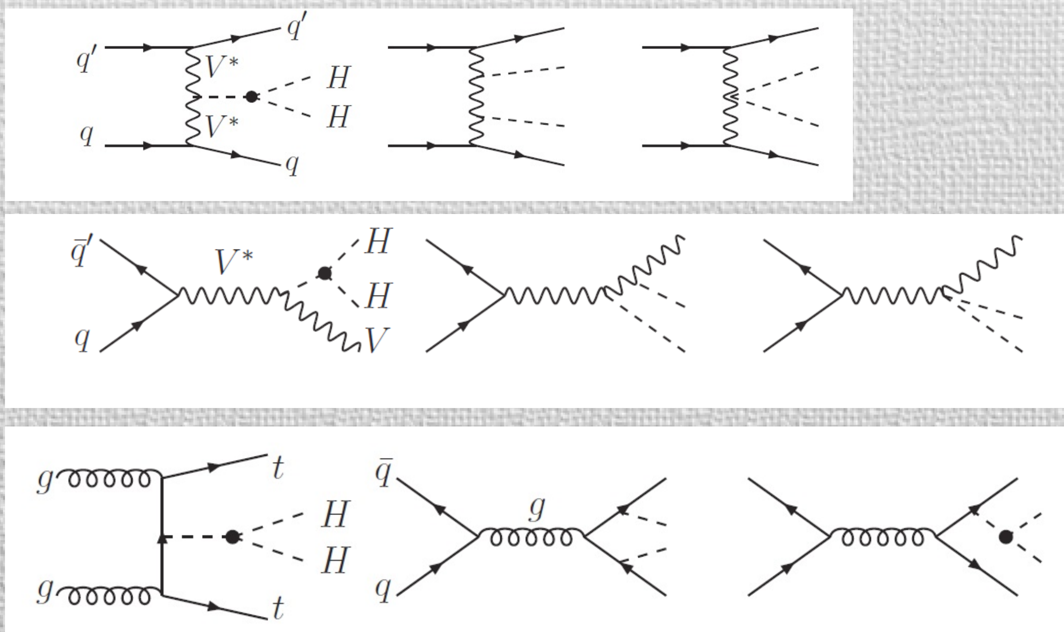
Theoretical error (mostly scale variation): ~ 20% @NLO, large m_t

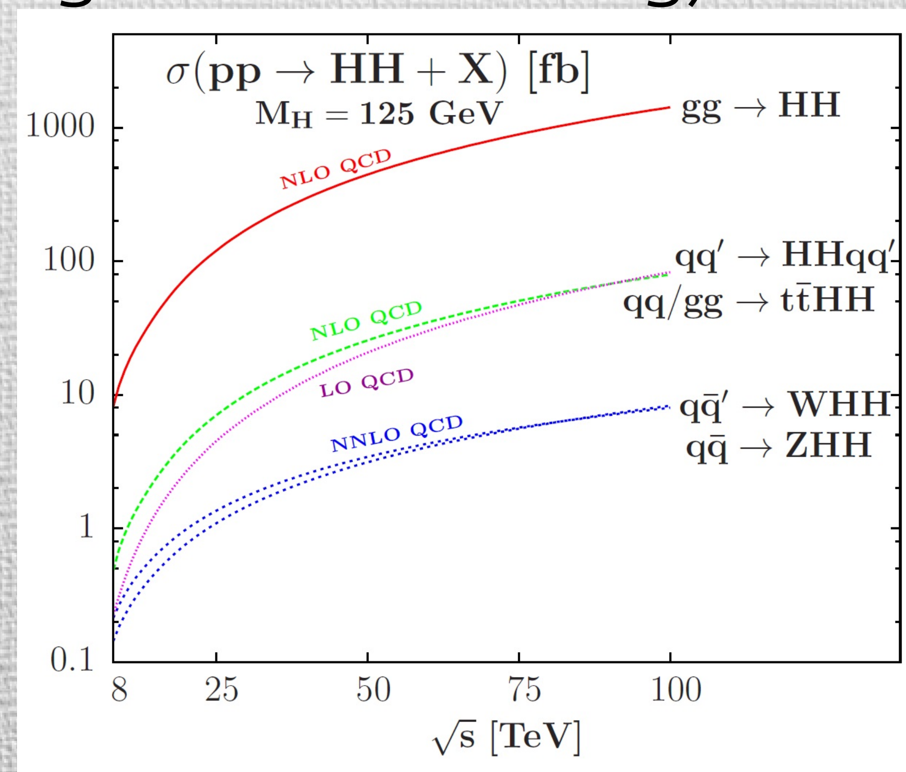
recent
Grigo,Hoff,Melnikov,
Steinhauser,1305.7340
[$1/mt^n$ corrections]

Higgs-Pair Production

- Other production channels $qq' \to HHqq', VHH, t\bar{t}HH$

  ~10-30 times smaller (neglect in following)

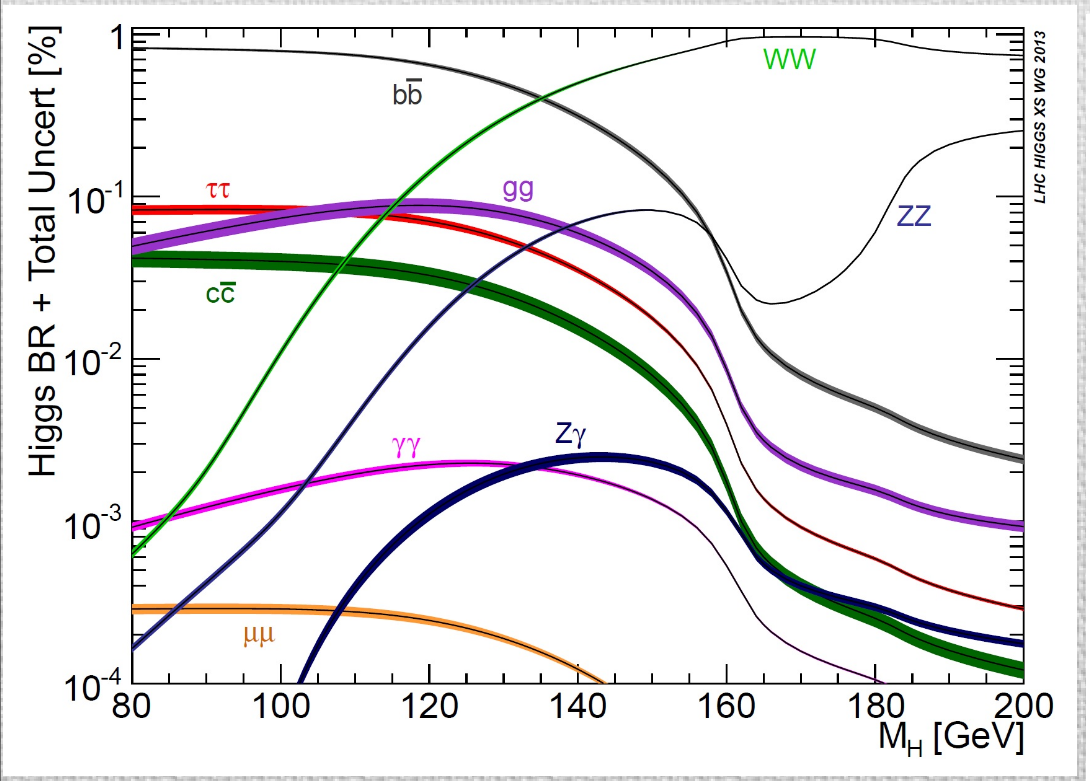




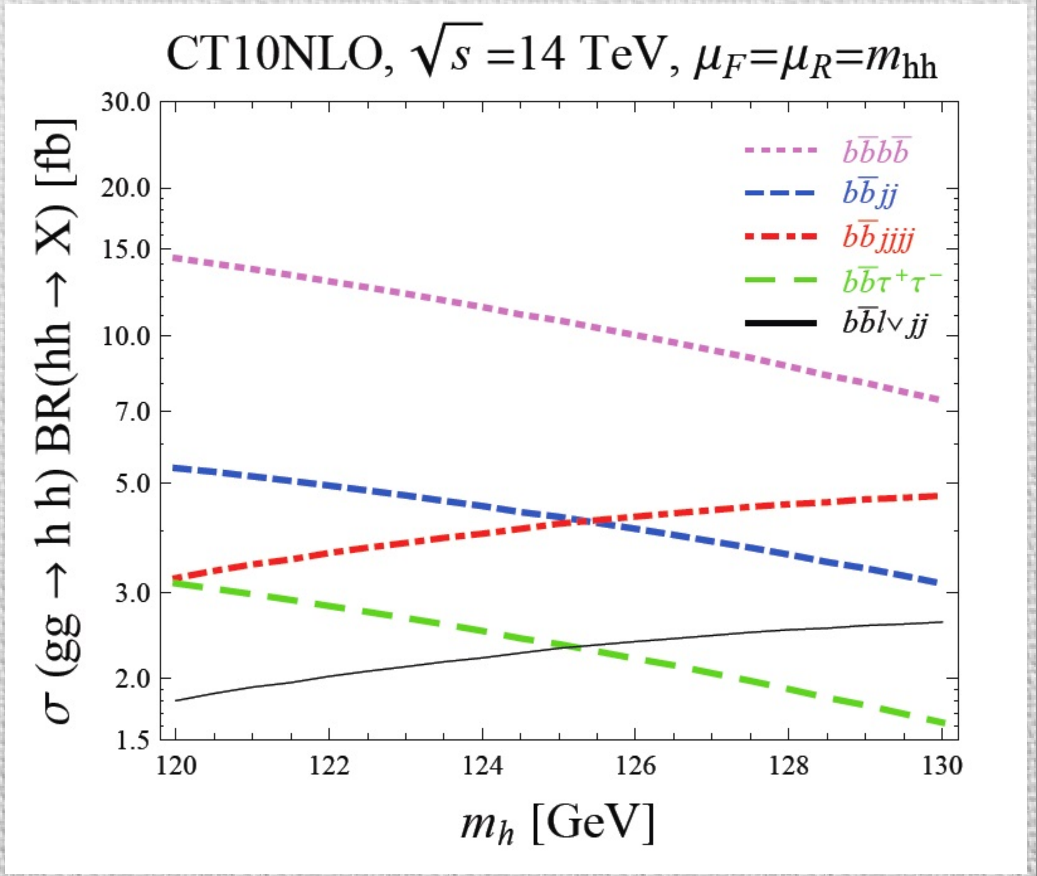
See [e.g.] Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581, and refs. therein

Decay Channels

Discovery potential for LHC studied in different channels



Baur, Plehn, Rainwater, hep-ph/0310056



Papaefstathiou, Yang, Zurita, 1209.1489

Hadronic modes dominate

Decay Channels

Discovery potential for LHC studied in different channels

- Before 2008: @600fb^{-1}

  only $HH \to b\bar{b}\gamma\gamma$ promising (for M_H~120 GeV): S/B=6/12.5 ➡ $1.5\,\sigma$

Baur, Plehn, Rainwater, hep-ph/0310056

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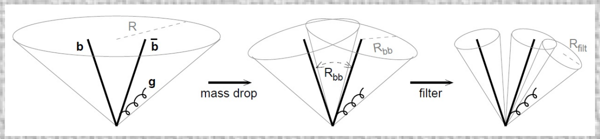
  Baur, Plehn, Rainwater, hep-ph/0310056

- After 2008:
  Boosted jet+substructure techniques



Butterworth, Davison, Rubin, Salam, 0802.2470

→ $HH \to b\bar{b}\tau^+\tau^-$

Dolan, Englert, Spannowsky, 1206.5001

S/B=57/119 → $4.85\,\sigma$

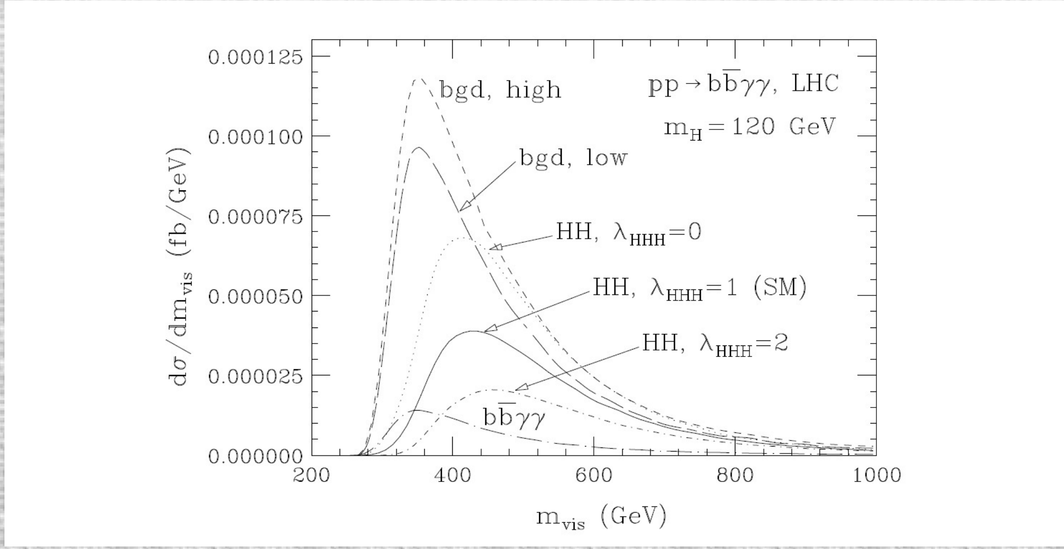
$HH \to b\bar{b}W^+W^-$

Papaefstathiou, Yang, Zurita, 1209.1489

S/B=12/8 → $3.3\,\sigma$

Decay Channels

- In $b\bar{b}\gamma\gamma$ analysis, expected LHC constraints on λ have been derived, using fits to the visible mass distribution



- Optimistic assumptions for background subtraction
- Need good knowledge of shapes, low number of events...

define $\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{SM}$

$$\lambda \in (0.26, 1.94) @ 600\,\text{fb}^{-1}, \quad \lambda \in (0.54, 1.52) @ 6000\,\text{fb}^{-1} (\text{SLHC})$$

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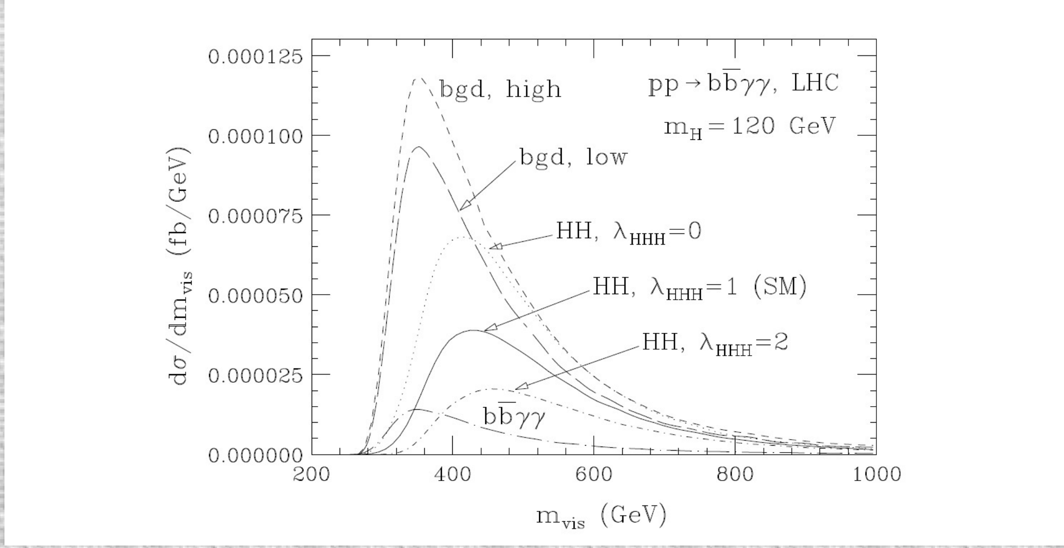

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- In promising $b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$ only established these channels for discovering HH production, no limits on λ

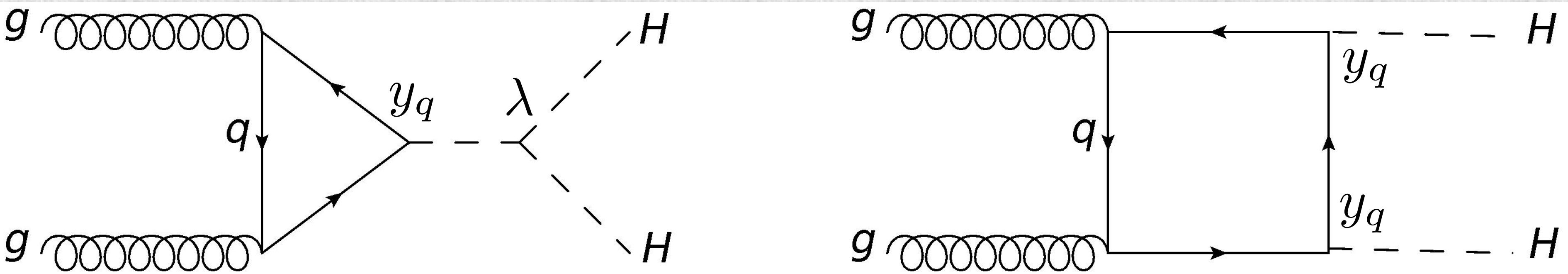
Higgs-Pair Production

- In the following derive expected constraints on λ for M_H~125 GeV, using the most promising channels at the 14TeV LHC @600fb^{-1}, 3000fb^{-1}

- Relatively low number of signal events (or difficult final states), control shapes of backgrounds/signal?
  ➡ Use *total* cross section,
  try to reduce theoretical error

- Study dependence on y_t

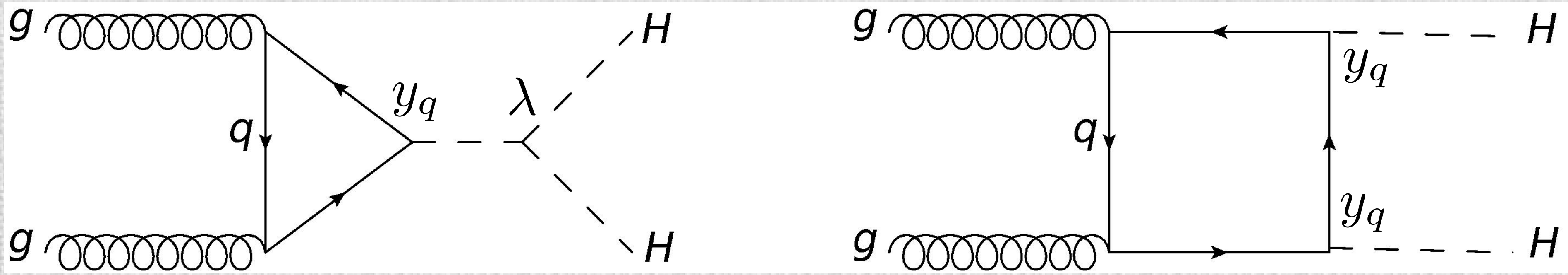
The Cross Section



$$\sigma_{HH}^{LO} = |\sum_{q=t,b}(\alpha_q C_{q,\mathrm{tri}}^{(1)} + \beta_q C_{q,\mathrm{box}}^{(1)})|^2 + |\sum_{q=t,b} \gamma_q C_{q,\mathrm{box}}^{(2)}|^2$$

In the SM: $\alpha_q = \lambda\, y_q\,, \quad \beta_q = \gamma_q = y_q^2$

The Cross Section



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In the SM: $\alpha_q = \lambda\, y_q\,, \quad \beta_q = \gamma_q = y_q^2$

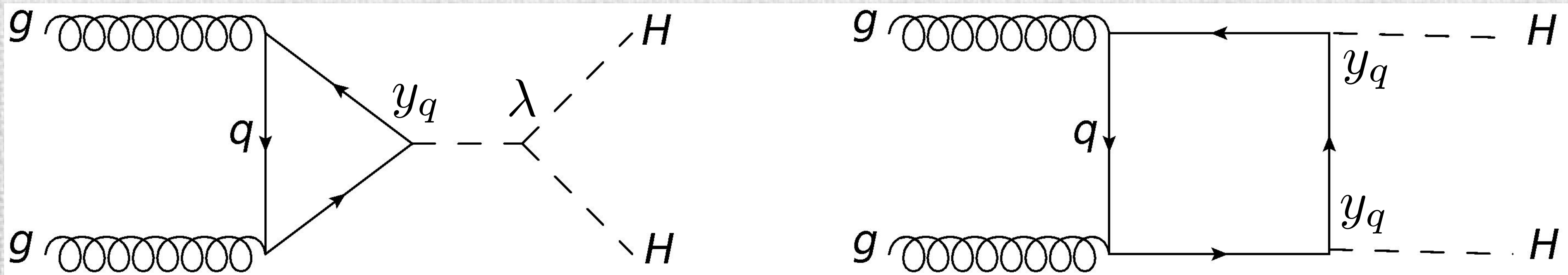
$$\sigma_{HH}^{\text{LO}}[\text{fb}] = \quad 5.22\lambda^2 y_t^2 - 25.1\lambda y_t^3 + 37.3 y_t^4 + \mathcal{O}(\mathrm{y}_b \mathrm{y}_t^2 \lambda_{HHH})$$

$$\sigma_{HH}^{\text{NLO}}[\text{fb}] = \quad 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(\mathrm{y}_b \mathrm{y}_t^2 \lambda_{HHH})$$

Fits obtained from *hpair, http://people.web.psi.ch/spira/hpair/*, using MSTW2008lo68cl and MSTW2008nlo68cl pdfs

$y_t \equiv \mathrm{y}_t/\mathrm{y}_t^{SM}$

The Cross Section



off-shell Higgs!

~0.2% effect (in SM)

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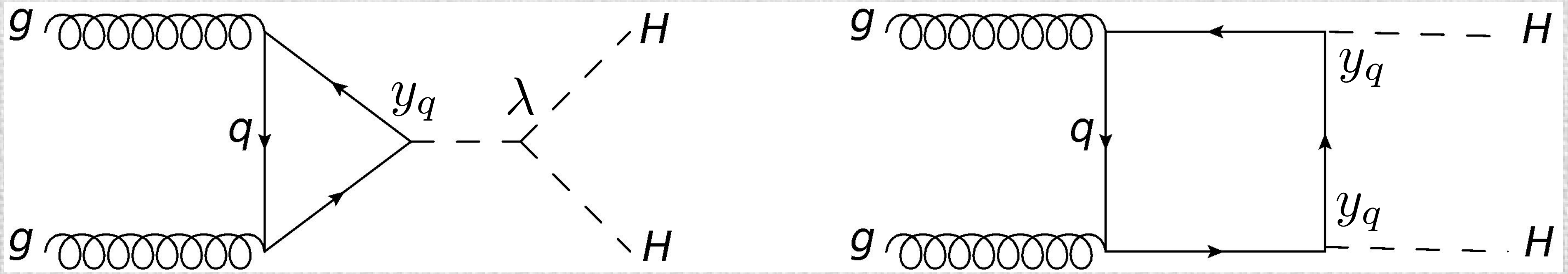

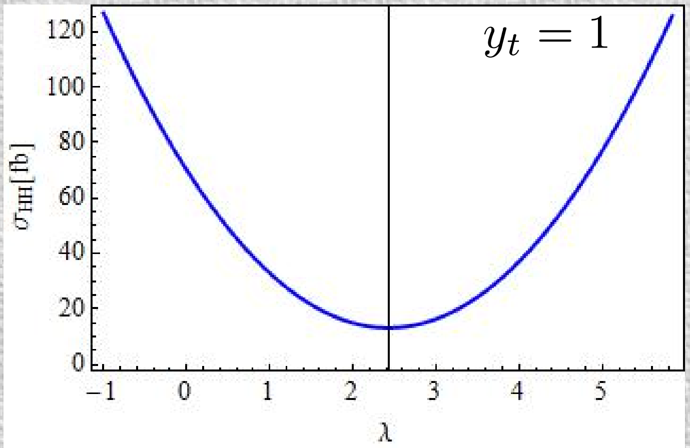

$\lambda_{min} \approx 2.5\, y_t$

Symmetric about minimum

Focus on $\lambda \in (-1.0, \lambda_{min})$

$$\sigma_{HH}^{\mathrm{NLO}}[\mathrm{fb}] = \quad 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(\mathrm{y}_b \mathrm{y}_t^2 \lambda_{HHH})$$

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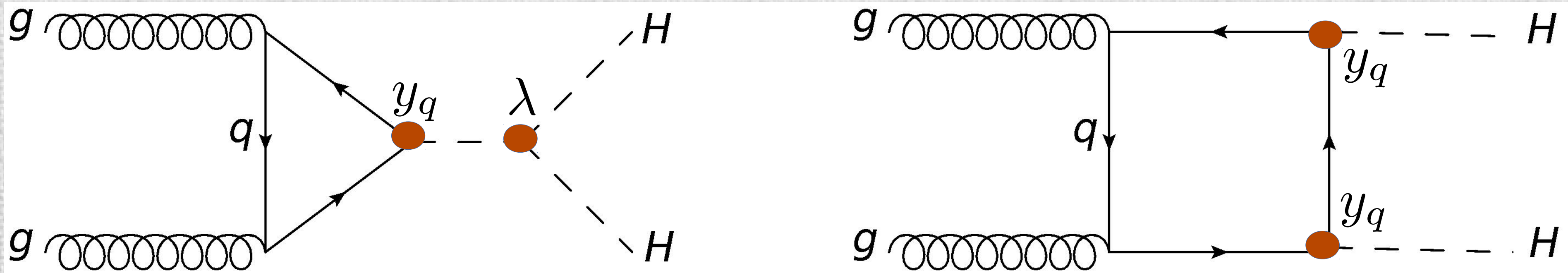


- Model dependence of analysis? Beyond consistency check of SM?
- Assume $\mathcal{L} = \mathcal{L}_{\text{SM}}$ everywhere to leading approximation besides potentially in the ($D \leq 4$) Higgs potential and the (SM-like) Yukawa couplings, where allow for $\lambda \neq 1, y_t \neq 1$
- Realized e.g. in 2HDM, Higgs-Portal models in certain parts of parameter-space

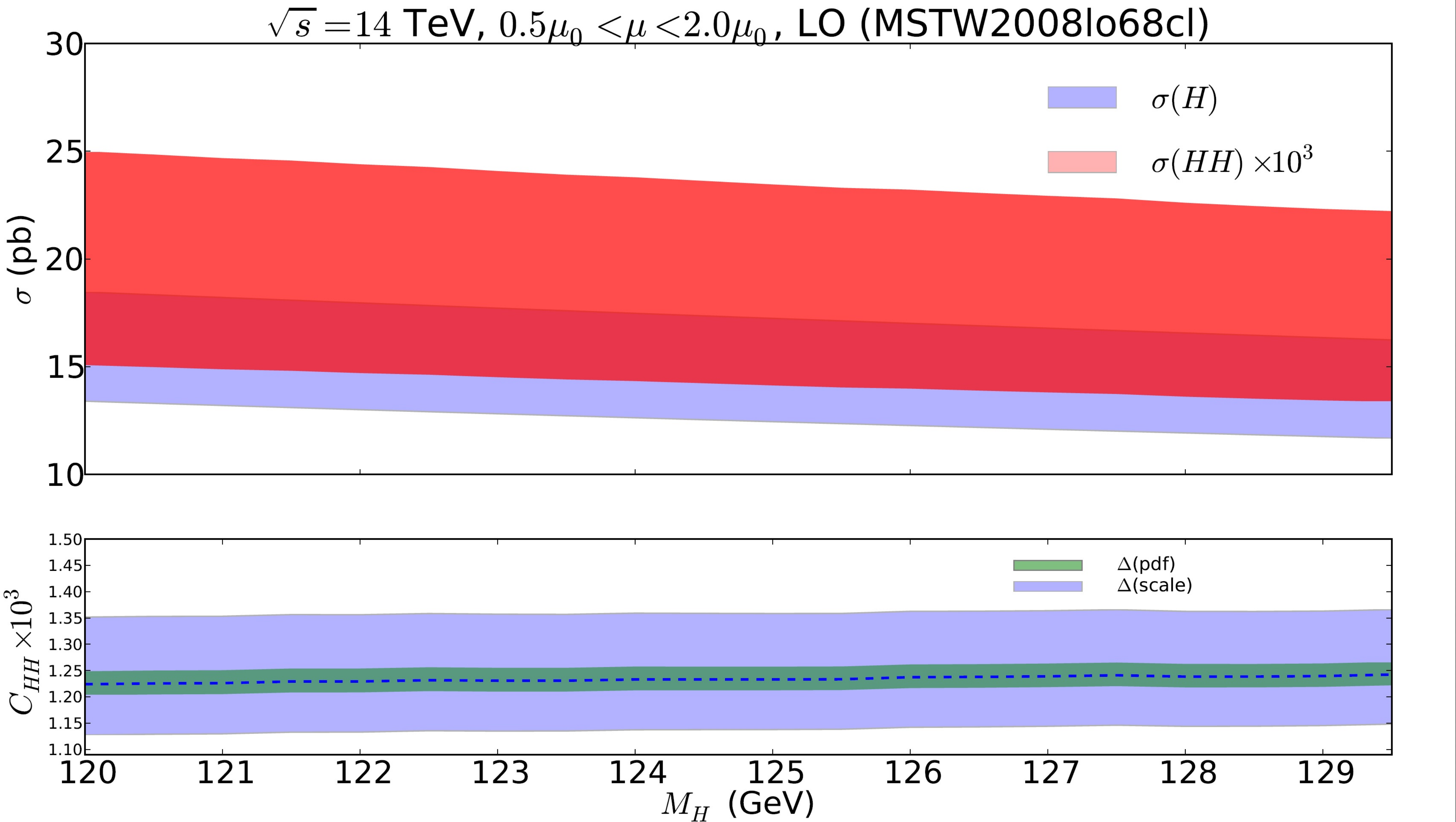
Theoretical Errors and Ratios

- Ratio of cross sections $\mathrm{C}_{HH} = \frac{\sigma(gg \to HH)}{\sigma(gg \to H)} \equiv \frac{\sigma_{HH}}{\sigma_H}$ expected to be more accurately determined theoretically than double-Higgs cross section itself

  A. Djouadi, 1208.3436

- Both gluon-gluon initiated and expected to feature similar higher order QCD corrections (initial state gluon radiation)
  → QCD uncertainties drop out to some extent

- Check in following



used: M. Spira, *hpair*, *HIGLU*, hep-ph/9510347

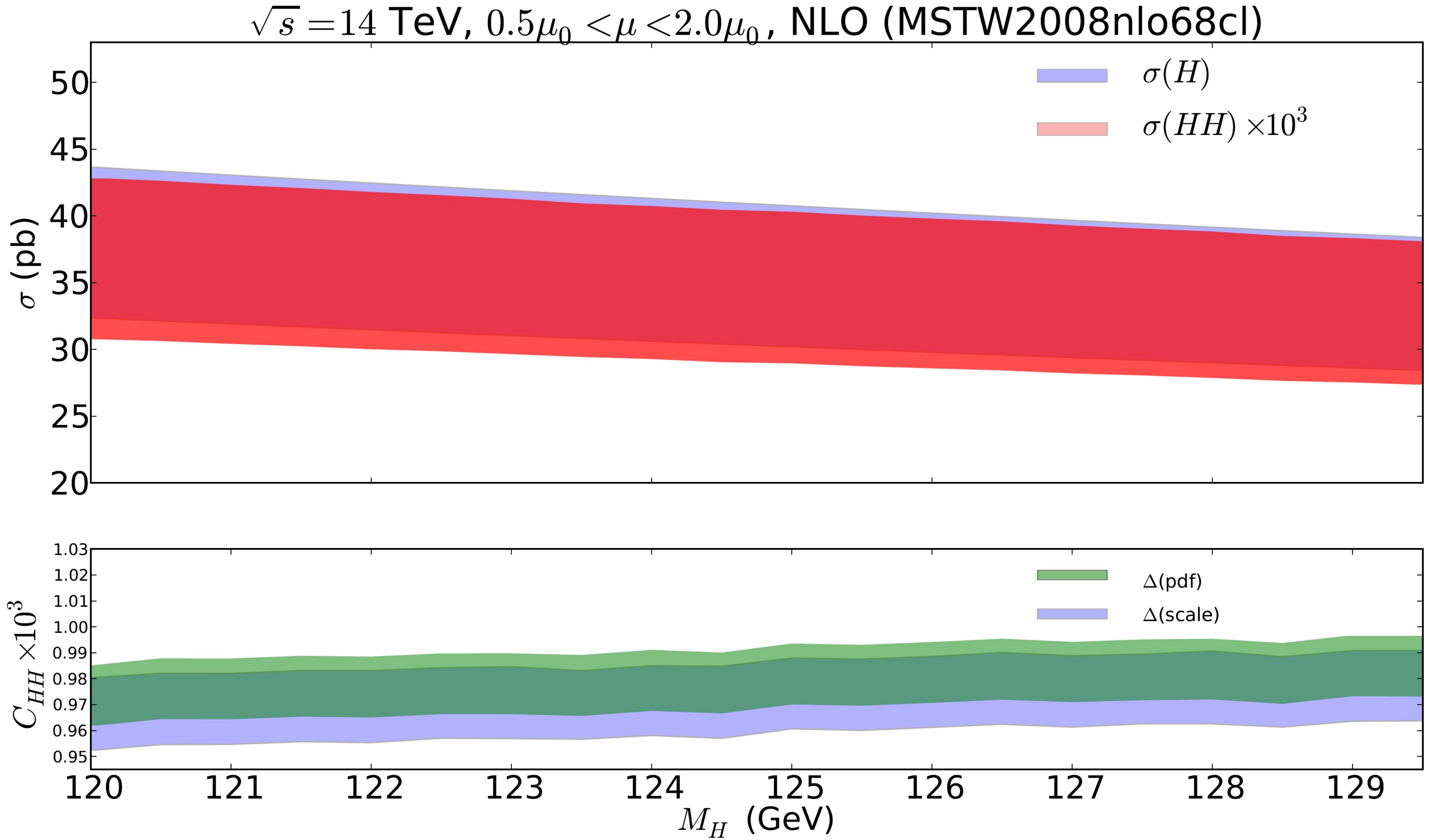
- Error due to scale variation significantly reduced in ratio

$\mu \in [0.5\mu_0, 2\mu_0]$

$\mu_0 = M_H(M_{HH})$

(similar results if $M_{HH} \to M_H$)

$$\Delta_{\sigma^{\rm LO}} = \pm(20-25)\% \to \Delta_{C_{HH}^{\rm LO}} \simeq \pm 9\%$$



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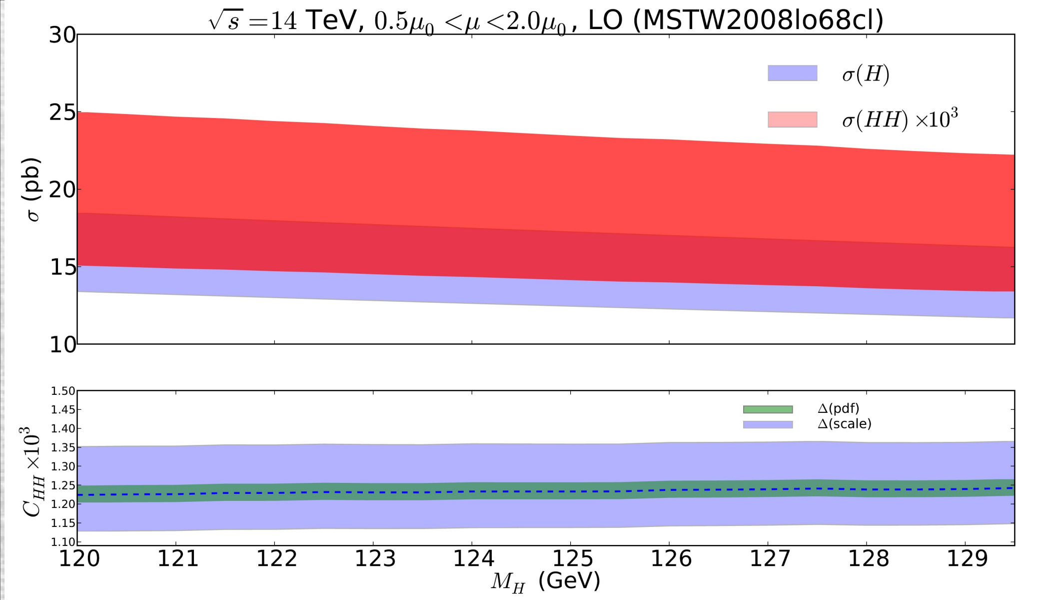
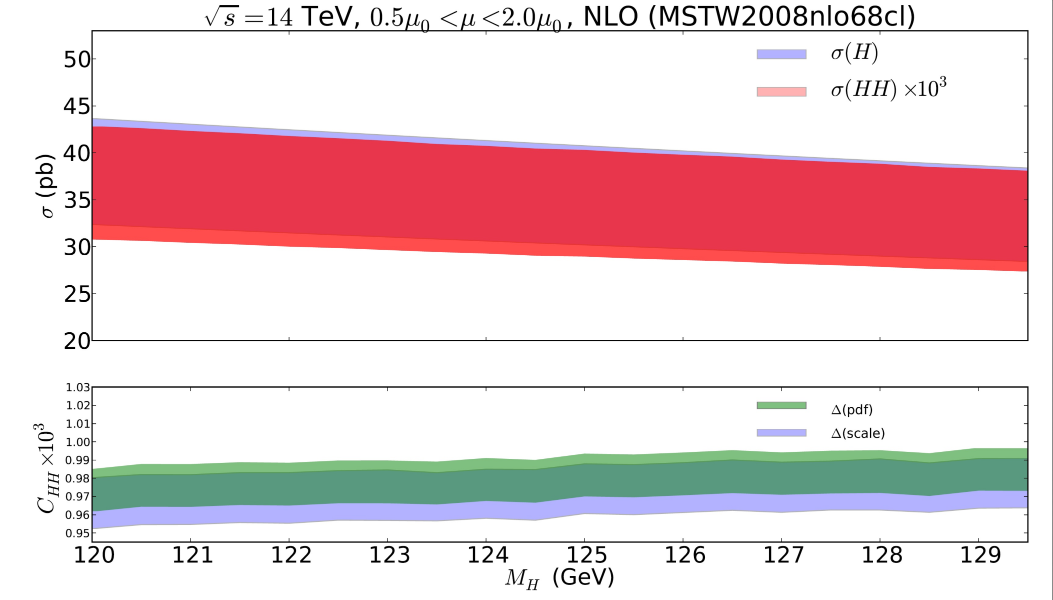
$\mu_0 = M_H(M_{HH})$

$$\Delta^{\text{scale}}_{\sigma^{\text{NLO}}} \simeq \pm 17\% \rightarrow \Delta^{\text{scale}}_{C^{\text{NLO}}_{HH}} \simeq \pm 1.5\%$$

(similar results if $M_{HH} \rightarrow M_H$)

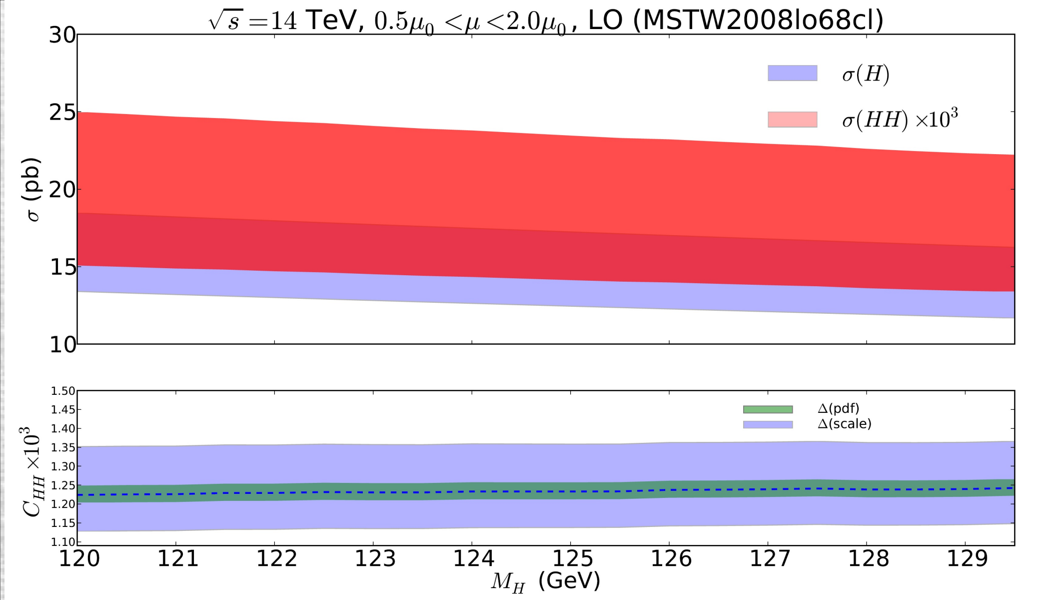


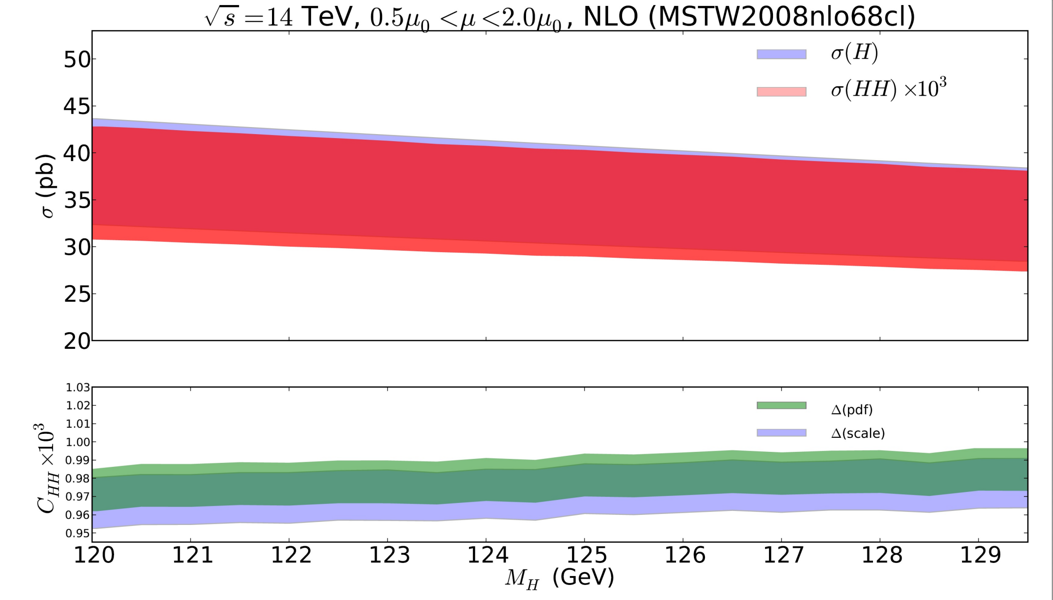


- Verification that uncertainty due to the QCD corrections (partially) cancels: K-factors in the individual cross sections are large, but also very similar ~2
  - Central value of the ratio only decreases by small amount from LO (~1.25) to NLO (~1.0)
- Indication that higher order corrections (NNLO) are likely to change ratio by an even smaller fraction, whereas single Higgs production cross section has K-factor of ~1.5 when compared to NLO

LHC Higgs Cross Section Working Group, 1101.0593

- Supports reduced size of theoretcial error found in scale variation





- Combining scale variation and pdf errors in quadrature

$$\Rightarrow \Delta_{C_{HH}^{\rm NLO}} \sim \mathcal{O}(\pm 3\%)$$

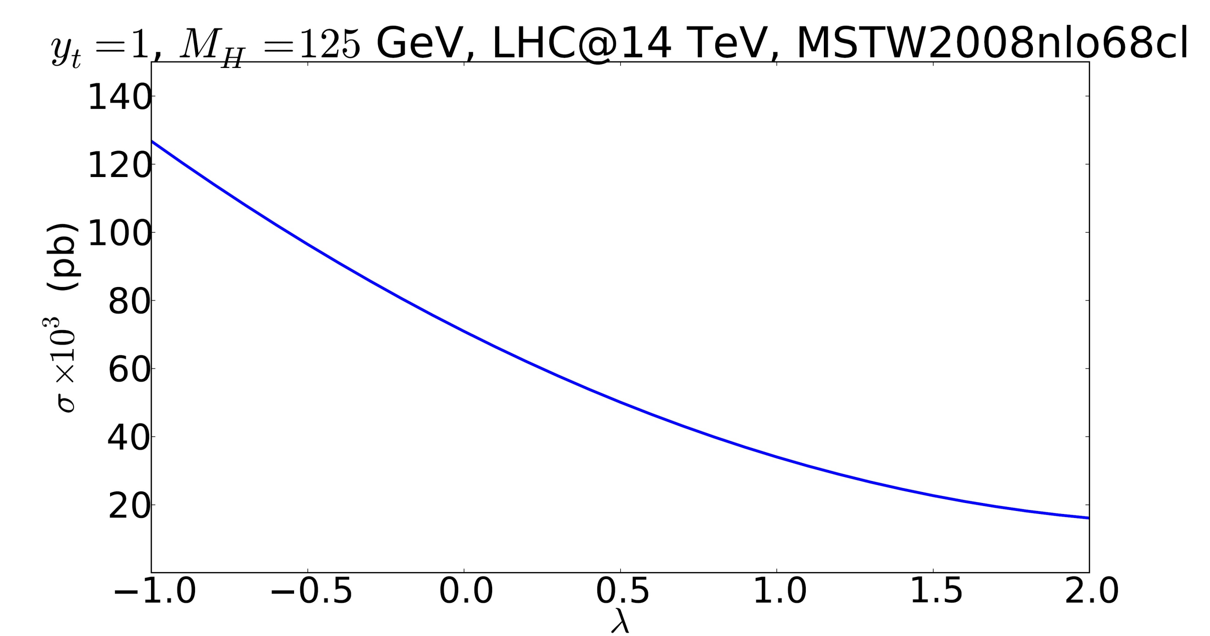
See also recent
Shao, Li, Li, Wang, 1301.1245 : [threshold resummation in SCET]
Grigo, Hoff, Melnikov, Steinhauser, 1305.7340 [$1/m_t^n$ corrections]

- To be compared with $\Delta_{\sigma_{HH}^{\rm NLO}} \simeq \pm 17\%$

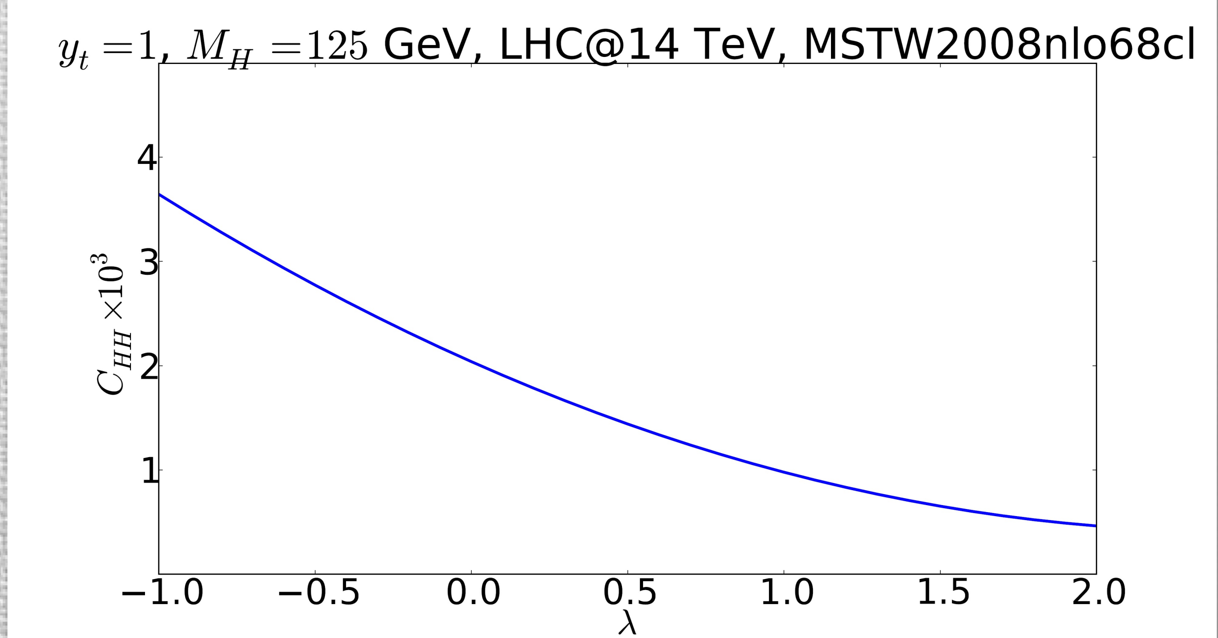
- Conservative assumption for the following:

$$\Delta_{C_{HH}^{\rm NLO}} = \pm 5\%\,,\ \Delta_{\sigma_{HH}^{\rm NLO}} = \pm 20\%$$

Variation with Self-Coupling and Top-Quark Yukawa



- Negative values of λ can be excluded sooner



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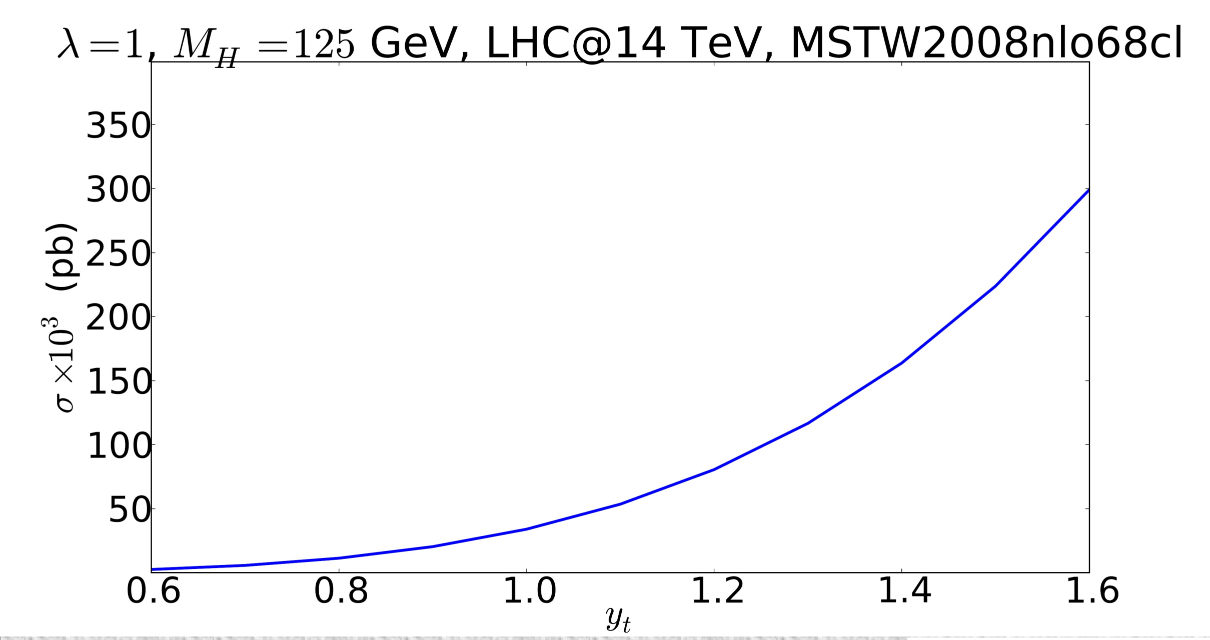
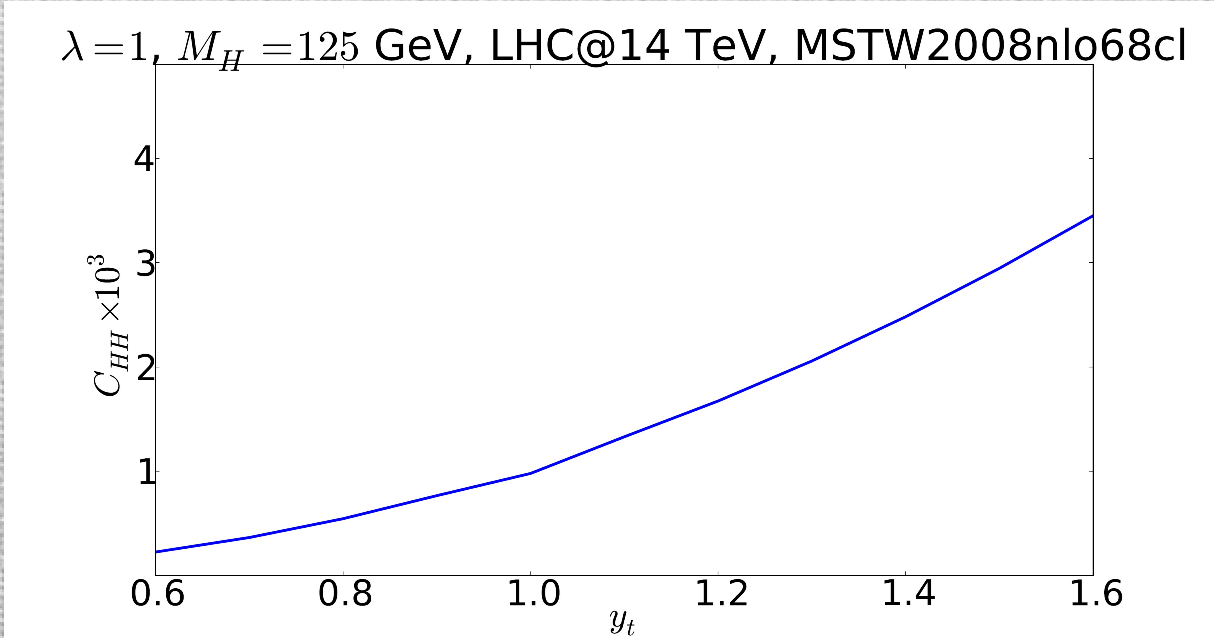
Variation with Self-Coupling and Top-Quark Yukawa



- Strong variation with top yukawa
- … which is only expected to be known up to 15% at LHC after 300fb[-1] @14 TeV Peskin, 1207.2516

$$y_t \to -y_t \text{ via } \lambda \to -\lambda$$



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Expected Constraints on Trilinear Self Coupling

Constraining the Self-Coupling

- Use theoretically more stable ratio of cross sections C_{HH} to derive expected constraints on λ
- Furter benefit when using C_{HH}:
  Experimental uncertainties can also be reduced, e.g. some systematic uncertainties are expected to cancel (Luminosit uncertainty)

Assumptions for Experimental Uncertainties

$$\sigma_{HH}^{b\bar{b}xx} \equiv 2\,\sigma_{HH} \times \mathrm{BR}(b\bar{b}) \times \mathrm{BR}(xx)$$

$$\sigma_{H}^{b\bar{b}} \equiv \sigma_{H} \times \mathrm{BR}(b\bar{b})$$

$$C_{HH}^{\mathrm{exp.}} = \left.\frac{\sigma_{HH}^{b\bar{b}xx}}{2\,\sigma_{H}^{b\bar{b}} \times BR(xx)}\right|_{\mathrm{exp.}}$$

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta\mathrm{BR}(xx)}{\mathrm{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

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$$\sigma_{H}^{b\bar{b}} \equiv \sigma_{H} \times \mathrm{BR}(b\bar{b})$$

$$C_{HH}^{\mathrm{exp.}} = \left.\frac{\sigma_{HH}^{b\bar{b}xx}}{2\,\sigma_{H}^{b\bar{b}} \times BR(xx)}\right|_{\mathrm{exp.}}$$

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta \mathrm{BR}(xx)}{\mathrm{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

Add 5% theoretical error in quadrature

Actually better to access than error on BR alone, which enters the cross section itself

Assumptions for Experimental Uncertainties

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta \mathrm{BR}(xx)}{\mathrm{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

$\Delta\sigma_{HH}^{b\bar{b}xx}/\sigma_{HH}^{b\bar{b}xx}$ obtained from $b\bar{b}\tau^+\tau^-$ $b\bar{b}W^+W^-$ $b\bar{b}\gamma\gamma$ analyses via $\Delta S = \sqrt{N+B}$ after bringing channels to equal footing

$$\Delta\sigma_H^{b\bar{b}} \sim \pm 20\%$$
$$\Delta \mathrm{BR}(\tau^+\tau^-) \sim \pm 12\%$$
$$\Delta \mathrm{BR}(W^+W^-) \sim \pm 12\%$$
$$\Delta \mathrm{BR}(\gamma\gamma) \sim \pm 16\%$$

„European Strategy for Particle Physics" https://indico.cern.ch/contributionDisplay.py?contribId=144&confId=175067, 2012

Assume no improvement beyond 300 fb^{-1}

SM:

Process	S/B(600 fb^{-1})	$\Delta C_{HH}/C_{HH}$ (600 fb^{-1})	$\Delta C_{HH}/C_{HH}$ (3000 fb^{-1})
$b\bar{b}\tau^+\tau^-$	50/104	0.400	0.279
$b\bar{b}W^+W^-$	11.2/7.4	0.513	0.314
$b\bar{b}\gamma\gamma$	6/12.5	0.964	0.490

Deriving Constraints

- We now want to use C_{HH} to constrain the parameters $\{p_i\}$ of a model
- Expected exclusion in parameter-space depends on true parameters of the model

Deriving Constraints – General Strategy

- Calculate C_{HH} as a function of the set of parameters {p_i} (e.g. new couplings/Wilson coefficients, masses) as well as theoretical error
- Estimate expected experimental errors arising from measurements of components that comprise $C_{HH}^{\rm exp.}$

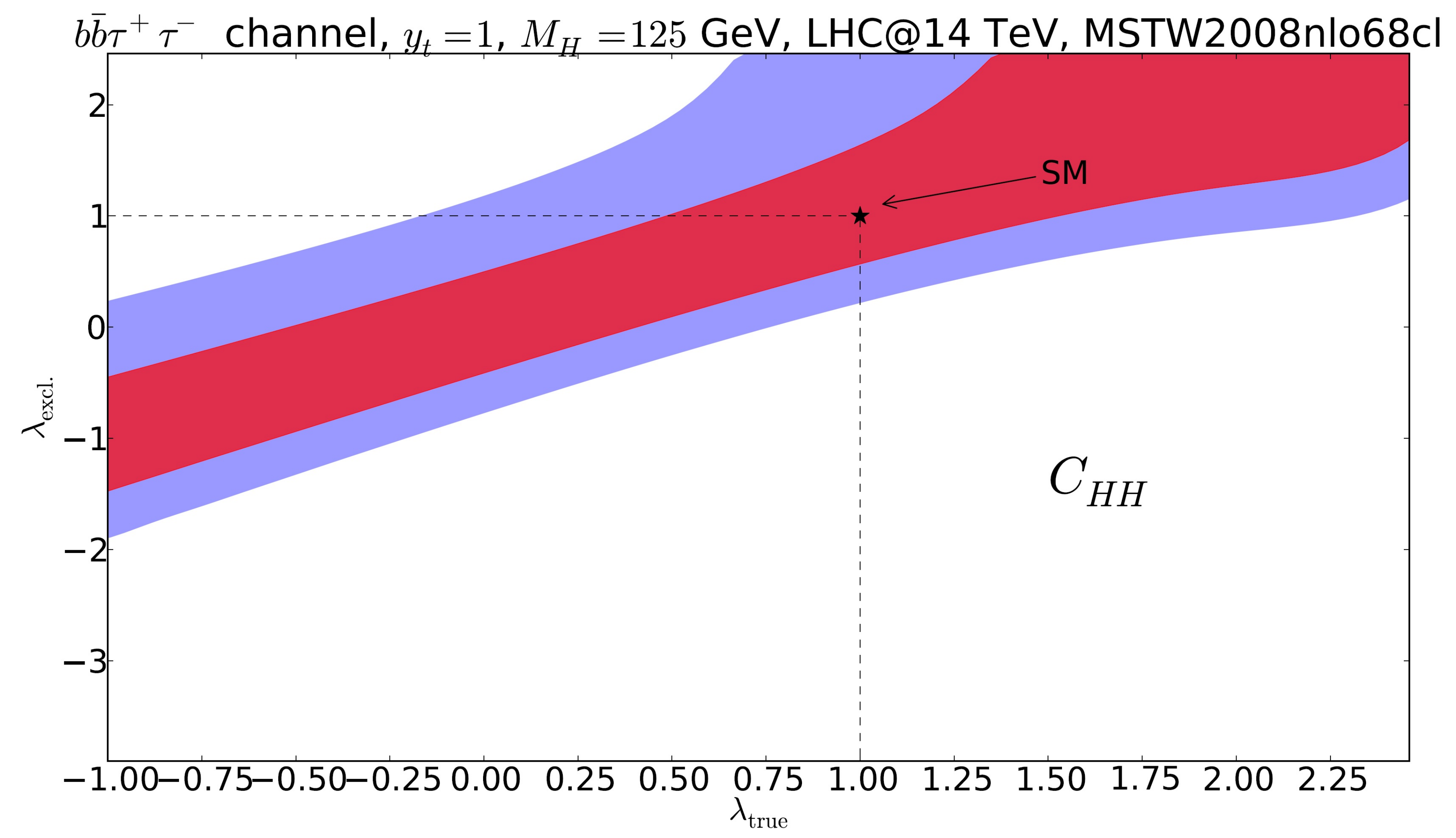
Deriving Constraints – General Strategy

- Calculate C_{HH} as a function of the set of parameters $\{p_i\}$ (e.g. new couplings/Wilson coefficients, masses) as well as theoretical error
- Estimate expected experimental errors arising from measurements of components that comprise $C_{HH}^{\text{exp.}}$
- Question to address: Given an assumption for the 'true' values of the model parameters, what is the constraint we *expect* to impose on the parameters through Higgs-pair production?

Deriving Constraints

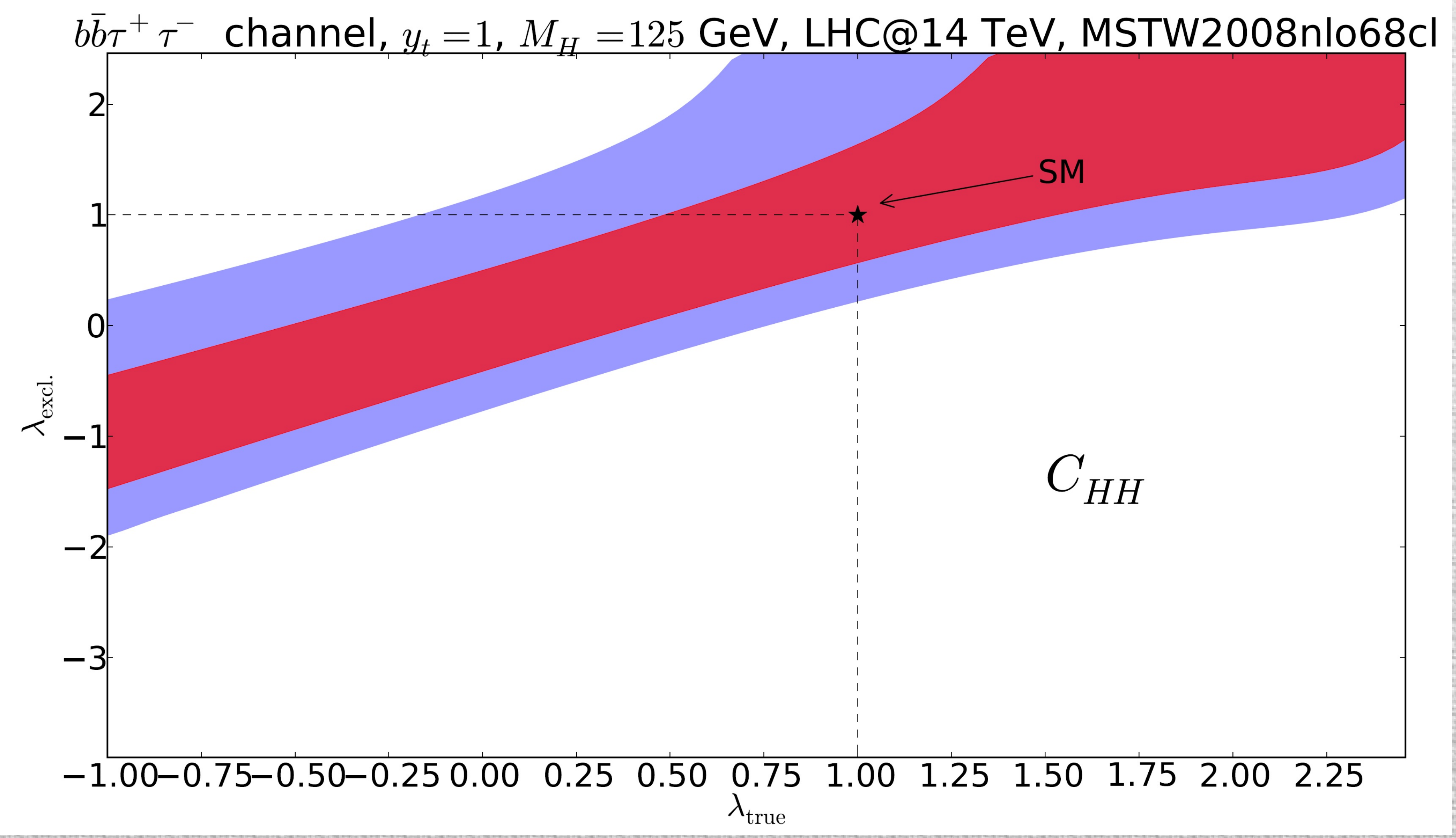
- In the following: simplified framework $\{p_i\} = \{\lambda, y_t\}$
- Start with assuming $y_t = y_{t,\mathrm{true}} = 1$
- Draw curves of λ that lead to a theoretically predicted cross section of one or two standard deviations away from the true cross section, derived with the underlying true λ_{true}
- In the following focus on $\lambda \in (-1.0, \lambda_{min} \sim 2.5)$

Deriving Constraints



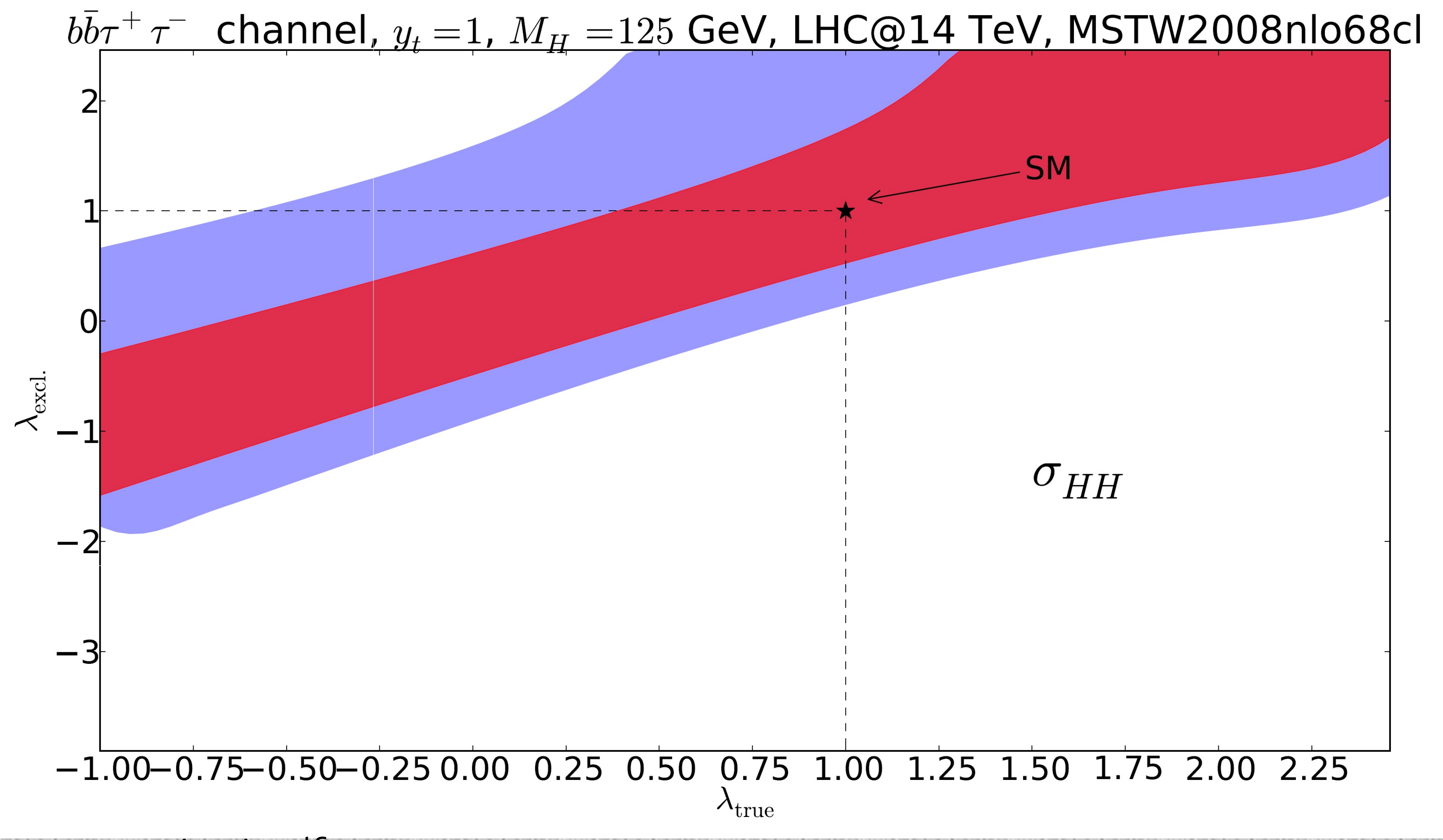
Expect to exclude values outside regions at 1σ (2σ)

Deriving Constraints



e.g. $\lambda_{\rm true}=1 \Rightarrow$ expect to constrain $\lambda \in (0.57, 1.64)$ @ 68%CL $(600\,{\rm fb}^{-1})$

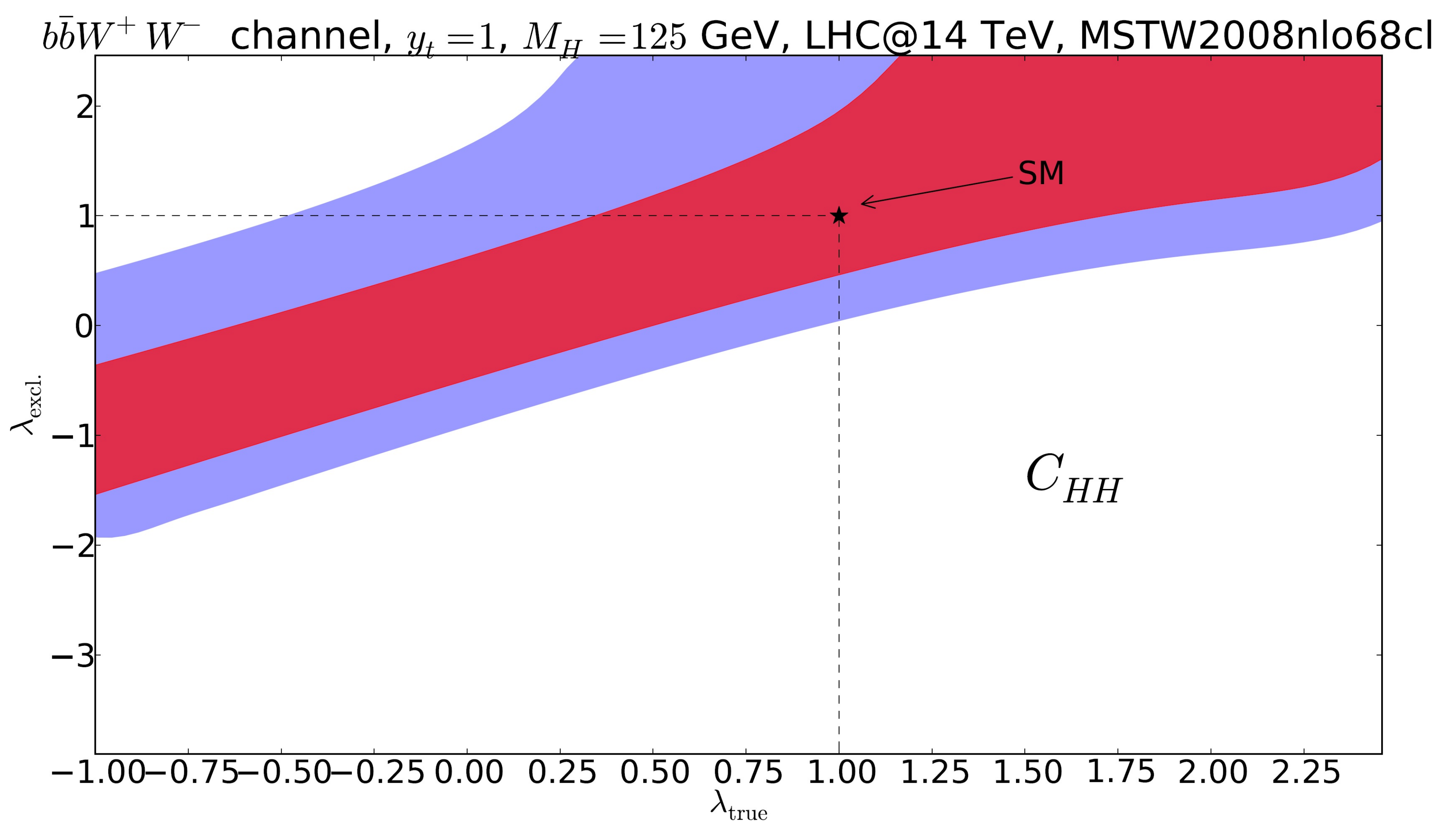
Deriving Constraints



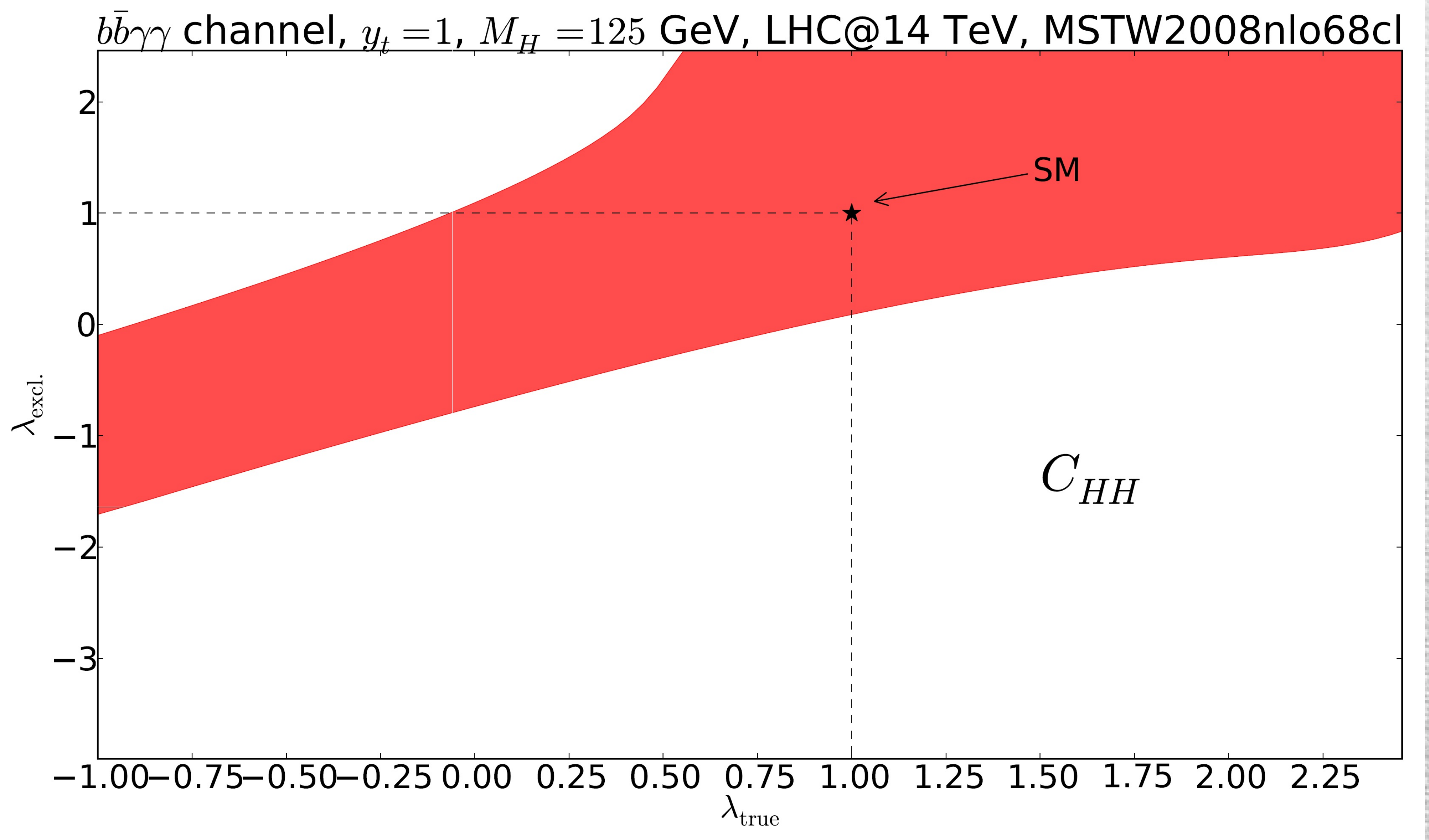
cross section itself:
20 % theoretical Error

Expect additional errors - not present in C_{HH}

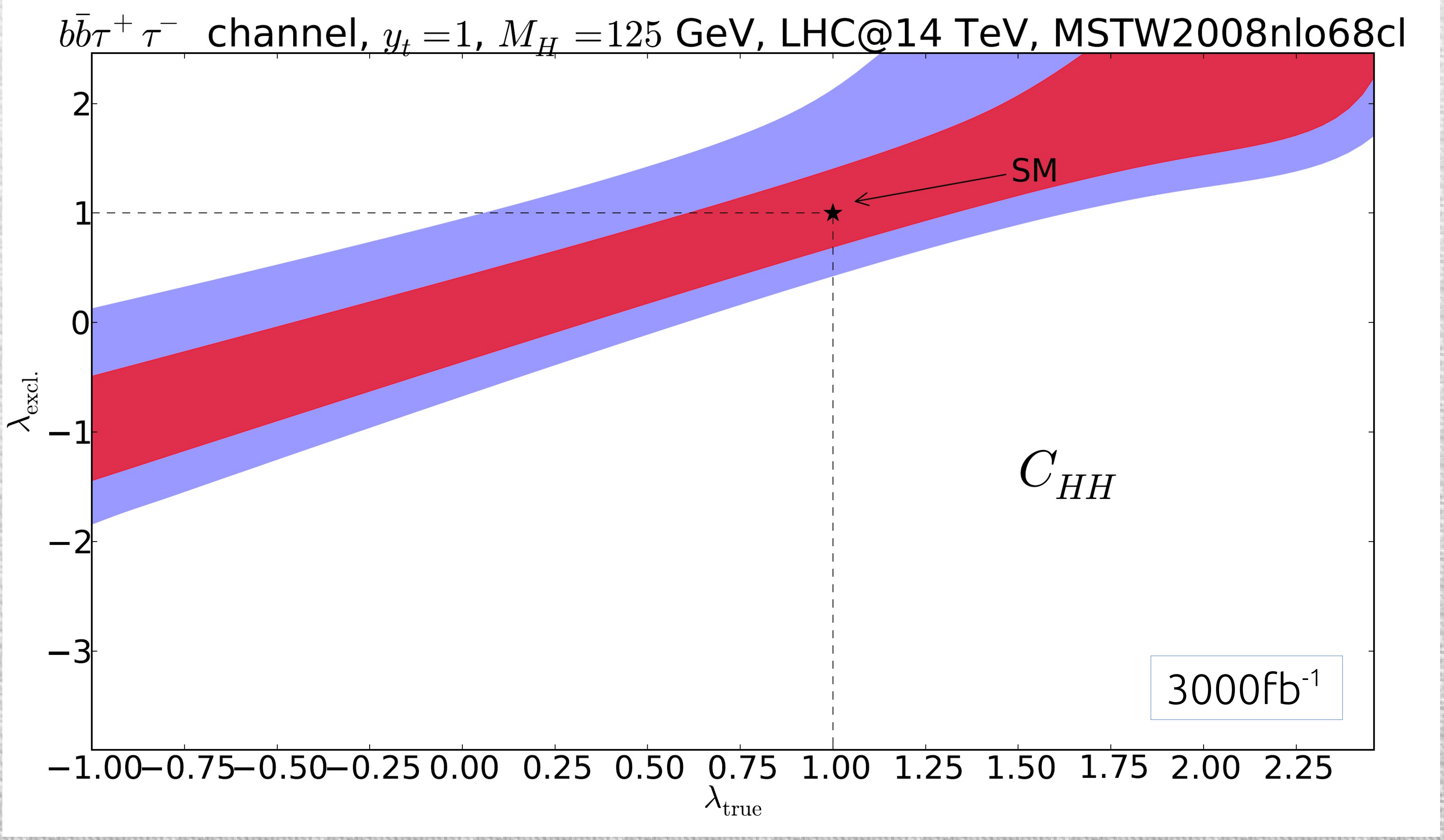
Deriving Constraints



Deriving Constraints



Deriving Constraints



Deriving Constraints

Process	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} 2σ	3000 fb^{-1} 1σ
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
$b\bar{b}W^+W^-$	(0.04, 4.88)	(0.46, 1.95)	(0.36, 4.56)	(0.65, 1.46)
$b\bar{b}\gamma\gamma$	(-0.56, 5.48)	(0.09, 4.83)	(0.08, 4.84)	(0.48, 1.87)

assume $\lambda_{\text{true}}=y_{t,\text{true}}=1$, for disconnected regions only show below $\lambda_{\text{min}} \simeq 2.43$

- Possible to constrain trilinear self coupling to be positive at 95% CL with 600fb^{-1} using C_{HH}
- Comparable for $b\bar{b}\gamma\gamma$ to shape analysis $\lambda \in (0.26, 1.94)$ @ 600 fb^{-1}

Baur, Plehn, Rainwater, hep-ph/0310056

actually also $\lambda \in (2.98, 4.66)$, optimistic asmpt

Deriving Constraints

Process	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} 2σ	3000 fb^{-1} 1σ
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
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assume $\lambda_{\rm true}$=$y_{t,\rm true}$=1, for disconnected regions only show below $\lambda_{\rm min} \simeq 2.43$.

- Possible to constrain trilinear self coupling to be positive at 95% CL with 600fb^{-1} using C_{HH}
- Comparable for $b\bar{b}\gamma\gamma$ to shape analysis $\lambda \in (0.26, 1.94)$ @ 600 fb^{-1}

Baur, Plehn, Rainwater, hep-ph/0310056

actually also $\lambda \in (2.98, 4.66)$, optimistic asmpt

- Improve predictions due to new channels
- Combination of channels yields ~ +30% and ~ -20% accuracy with 3000fb^{-1}

Deriving Constraints

Process	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} 2σ	3000 fb^{-1} 1σ
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
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assume $\lambda_{\text{true}}=y_{t,\text{true}}=1$, for disconnected regions only show below $\lambda_{\text{min}} \simeq 2.43$.

- Combination of channels yields ~ +30% and ~ -20% accuracy with 3000fb^{-1}

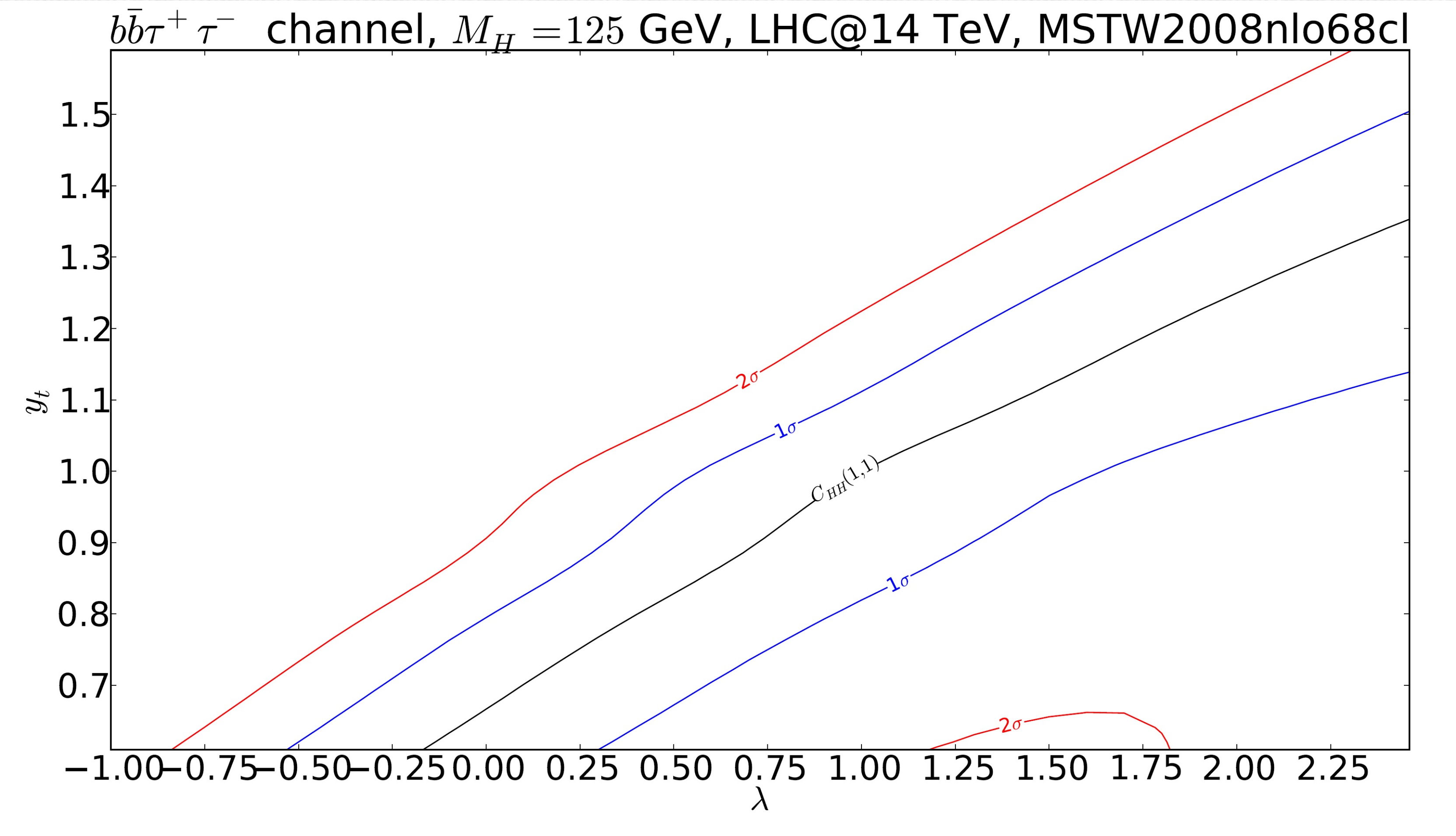
- Compare to ILC ILC-TDR (2012, to be published)

$\sqrt{s} = 500\,\text{GeV}, \quad \mathcal{L} = 2000\,\text{fb}^{-1}$ ~40%

$\sqrt{s} = 1000\,\text{GeV}, \mathcal{L} = 1000\,\text{fb}^{-1}$ ~25%

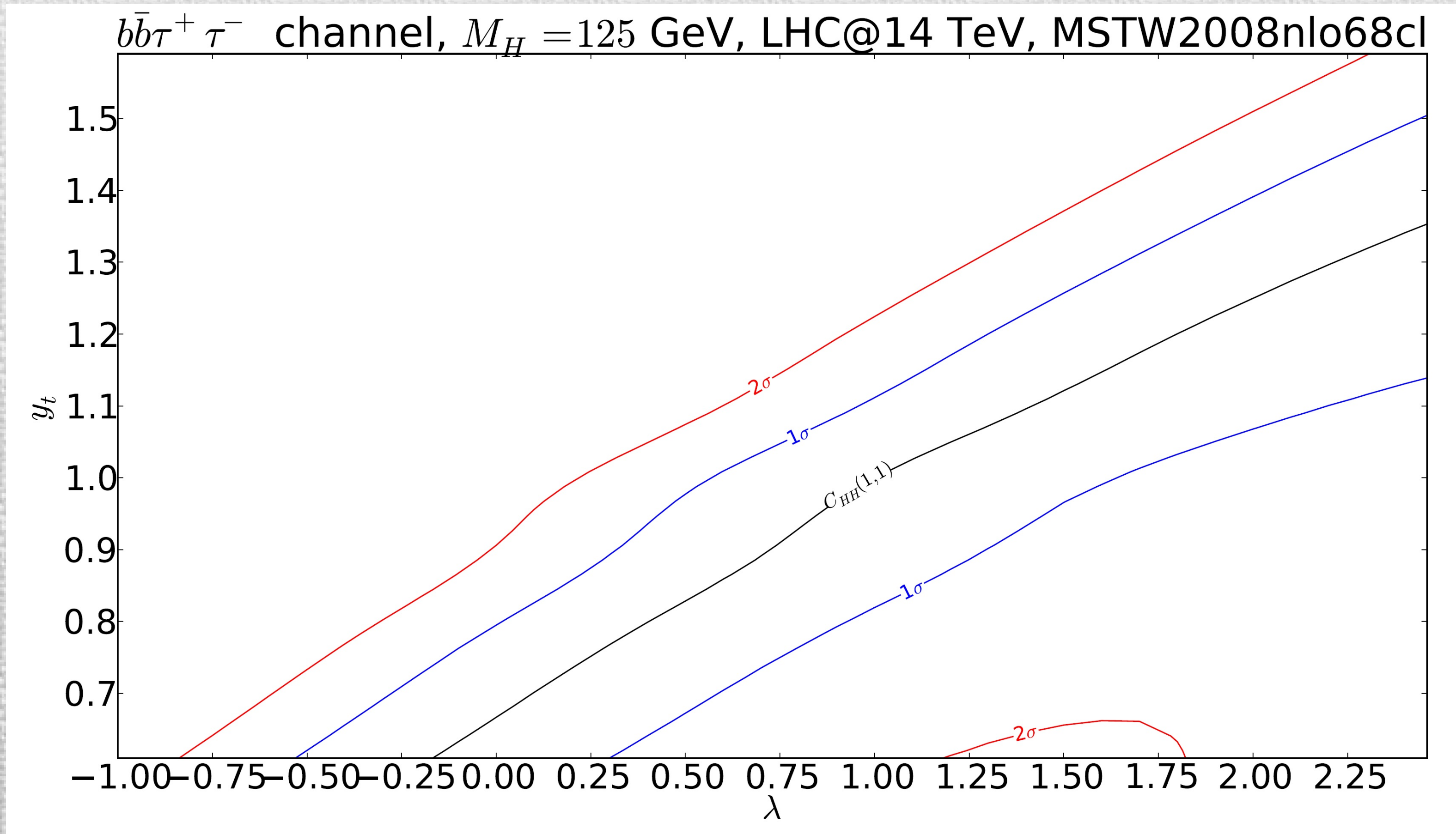
Variation with y_t

- y_t only known to O(15%) after 300fb^{-1} @14 TeV Peskin, 1207.2516



assume $y_{t,\mathrm{true}} = \lambda_{\mathrm{true}} = 1$, $\mathcal{L} = 600\ \mathrm{fb}^{-1}$

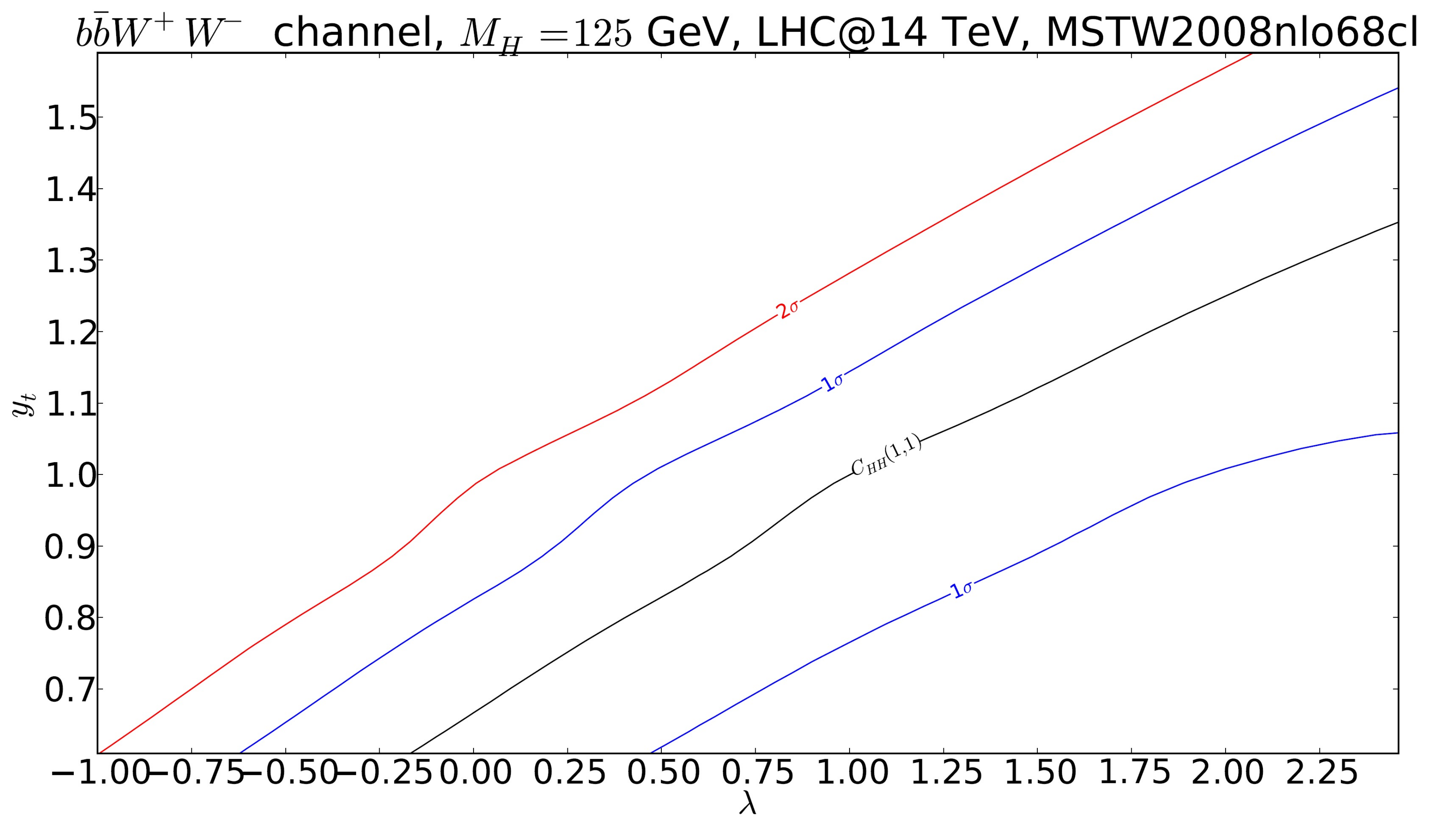
Variation with y_t



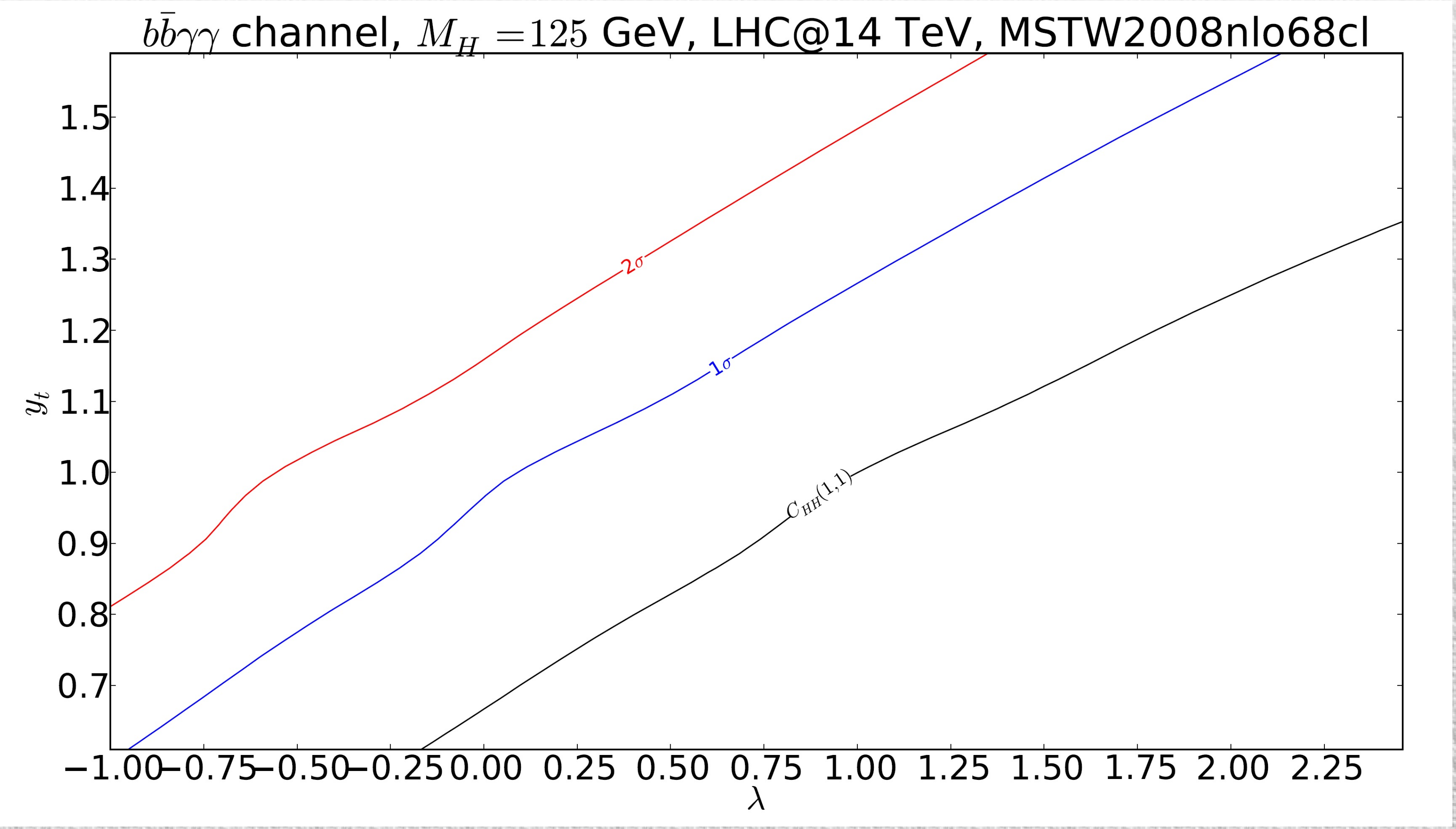
$y_t = 0.85$ yields $\lambda \in (0.2, 1.1)$, whereas $y_t = 1.15$ implies $\lambda \in (1.1, \sim 2.4)$

➡ accurate knowledge of y_t is essential

Variation with y_t



Variation with y_t



Outlook and Conclusions

Outlook

- Do full „model independent“ survey of double Higgs production, supplementing the SM Lagrangian with dimension 6 operators
- Use equations of motion to arrive at most appropriate basis for the analysis

Outlook

- Employ precision constraints to further reduce the operator basis
- Use information from single Higgs production to constrain operators and derive expectations for double-Higgs production
- Study different scenarios

Conclusions

- Examined theoretical error on ratio of dobule-to-single Higgs production cross section C_{HH}
- Using this ratio, derived expected exclusions on the trilinear H coupling in the $b\bar{b}\gamma\gamma$, $b\bar{b}W^+W^-$, $b\bar{b}\tau^+\tau^-$ channels
- Obtained the most precise expected determination of the Higgs trilinear self-coupling at the 14TeV LHC: -20/+30% achievable (in the SM)
- Good knowledge of top-quark yukawa important
- Outlook: Full operator analysis of HH production

Thank you for the attention!