Higgs boson self-coupling measurements at the LHC (and beyond)

Andreas Papaefstathiou

Physik-Institut
Universität Zürich

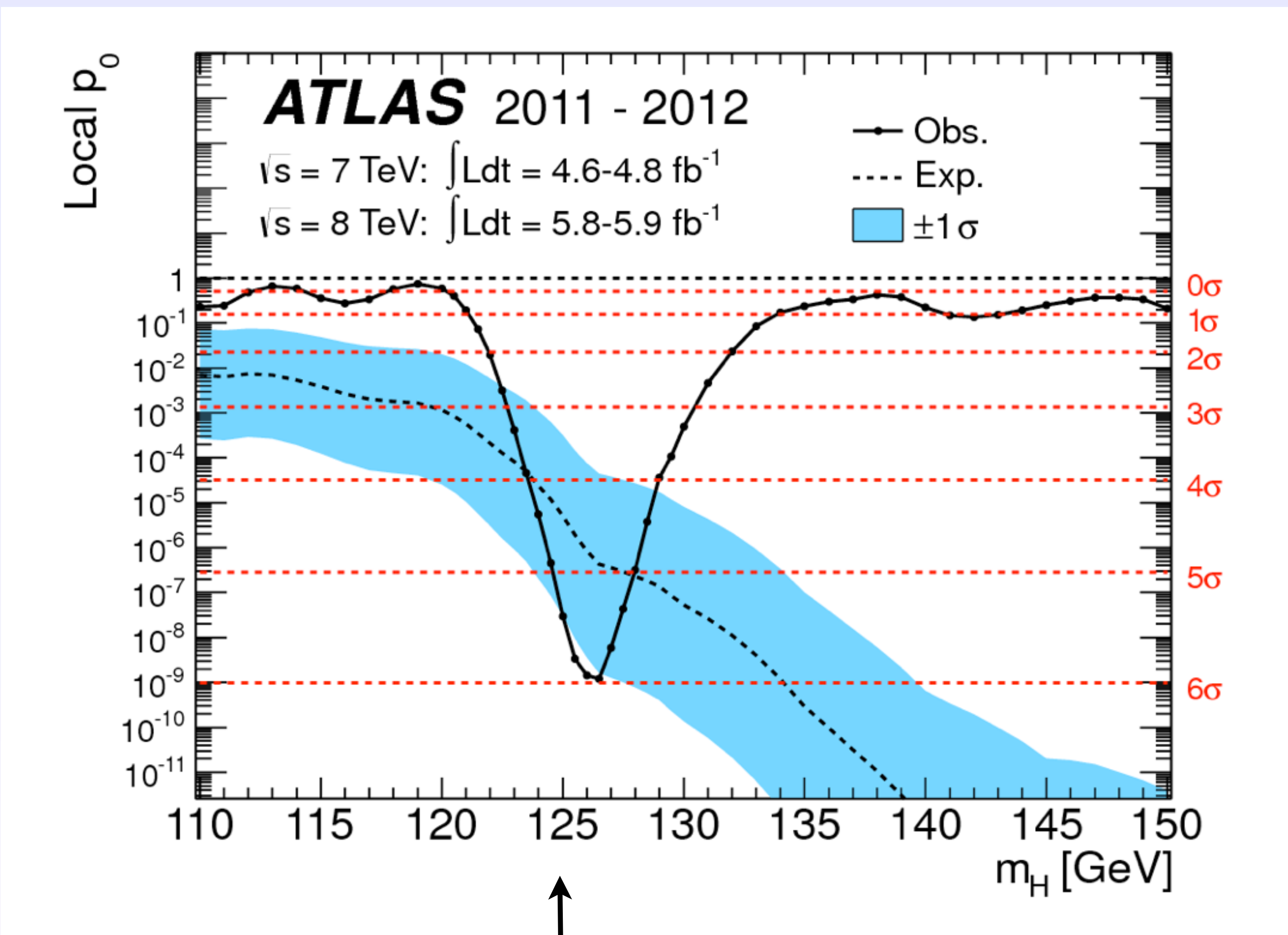
DESY,
Hamburg, 5th May 2014.

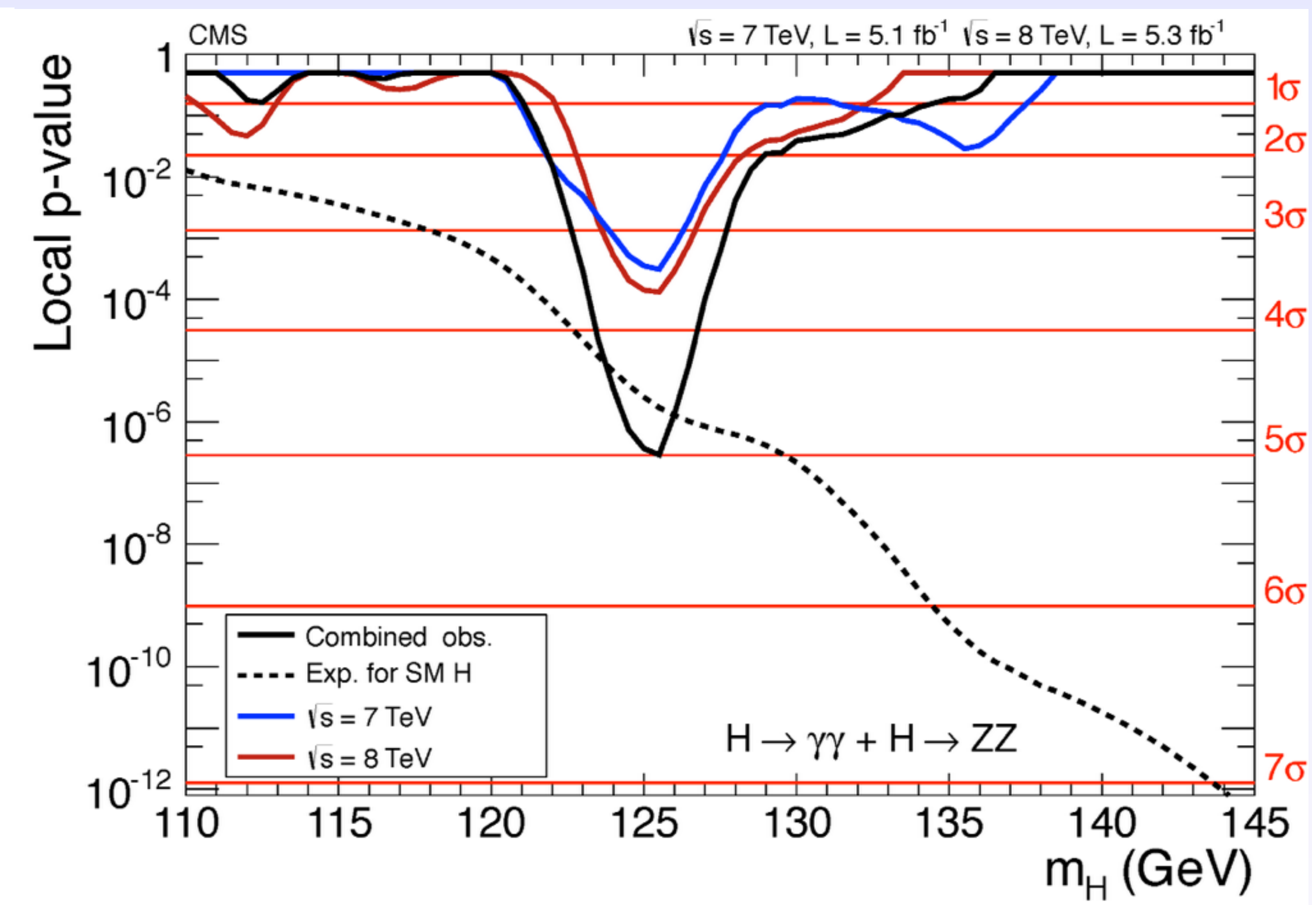
aims:

- what could we hope to learn from multi-Higgs production @ LHC?
- examine multi-Higgs processes.
- search strategies @ (HL)-LHC.
- self-coupling: beyond ggHH@LHC.

Higgs Boson discovery

- p-values, left: **ATLAS**, right: **CMS**.

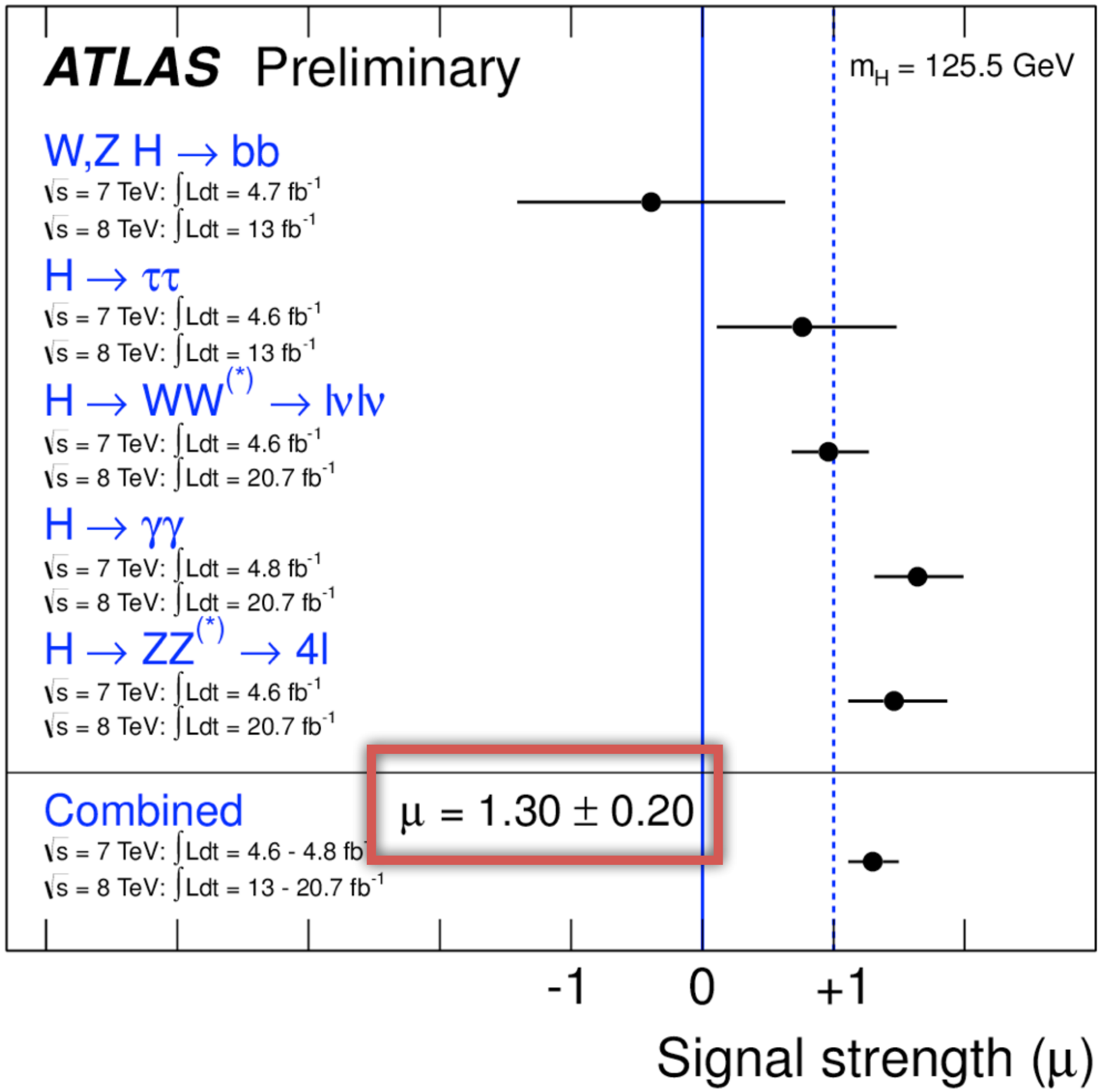


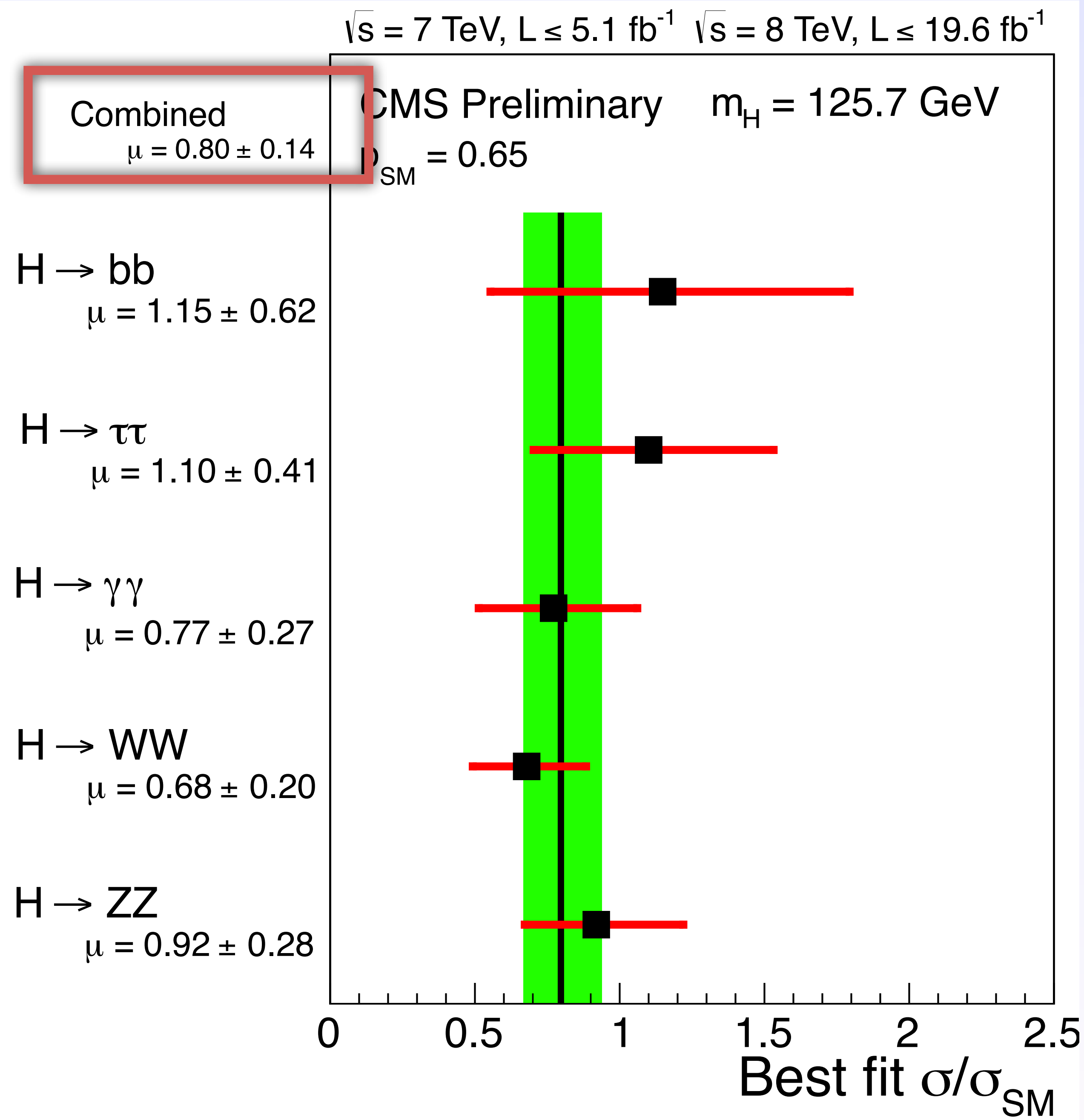


~ 125 GeV

Higgs Boson signal strengths

$$\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}}$$





What about HH, HHH?

i. what could we hope to learn from multi-Higgs production @ LHC?

electroweak cooking

- ingredients:

$SU(2) \times U(1)$ gauge symmetry

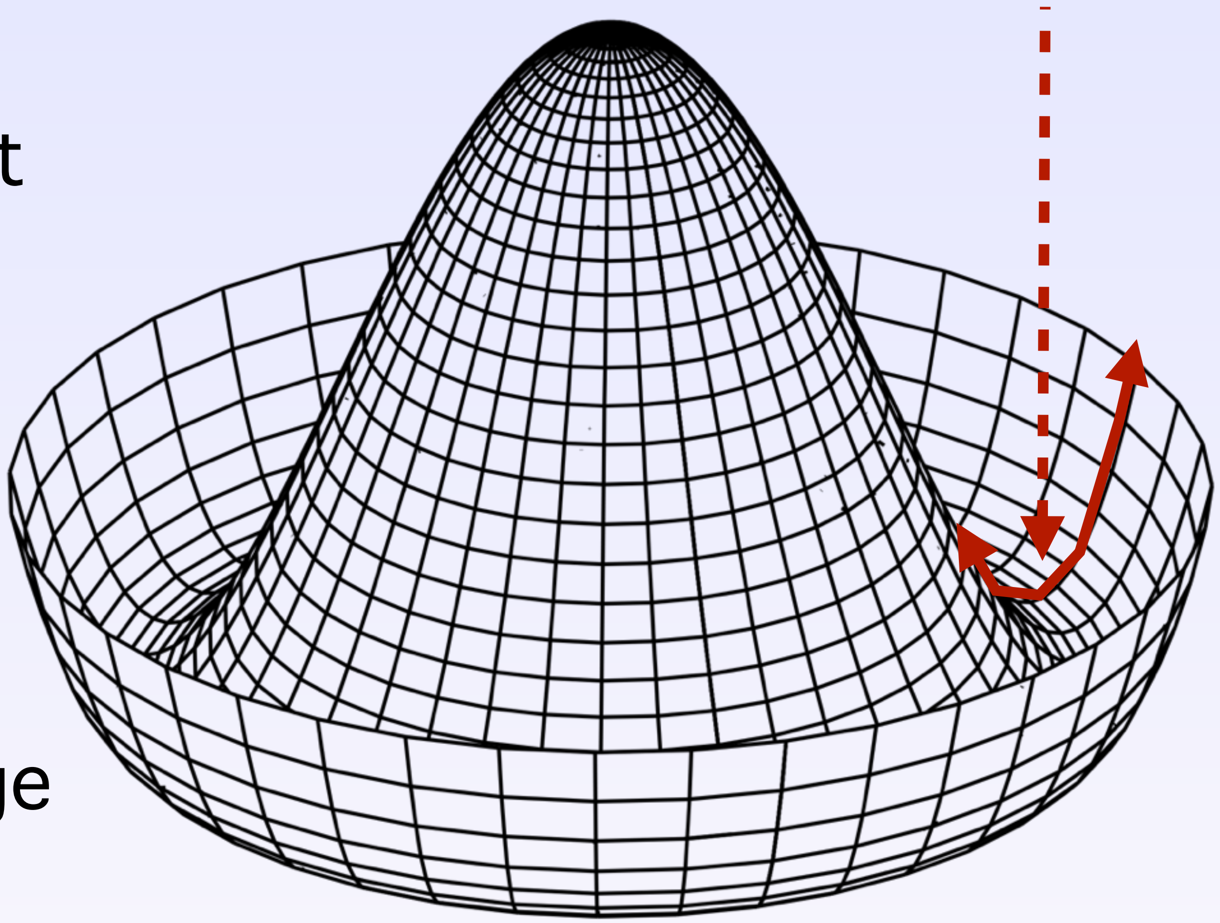
+ complex doublet scalar, ϕ

+ potential for ϕ : $\mathcal{V}(\phi^\dagger \phi)$

electroweak cooking, steps

- choose a minimum in a particular direction, maintaining U(1) invariance $\hookrightarrow$ symmetry breaking.

$$\phi_{\mathrm{min.}} \propto (0, v)$$



- fluctuations of scalar field about minimum:

$$\phi \propto (0, v + H)$$

- gauge transformation: absorb Goldstone modes into the gauge bosons.

- recipe makes massive W, Z, massless photons and the Higgs scalar (H). Topped with QCD and served with fermions to complete the SM.

Higgs potential

- focus on the resulting potential for the scalar field H:

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

$$M_H^2 = (2\lambda v^2) \simeq 125 \text{ GeV}$$

- assuming the SM: we already know everything!
- SM prediction: $\lambda = \dfrac{M_H^2}{2v^2} \simeq 0.13$.
- but one wishes to verify the form of the potential in a model-independent way.

anomalous couplings

$$\mathcal{V} = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{\tilde{\lambda}}{4} H^4$$

- we may consider anomalous values for these couplings, i.e. free parameters.
- their measurement would be a consistency test for the standard model.
- HH can probe λ and the top Yukawa.
- (**SPOILER ALERT:** forget about $\tilde{\lambda}$ through HHH.)

the meaning of anomalous couplings

$$\mathcal{V} = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{\tilde{\lambda}}{4} H^4$$

- let's assume we measure $\lambda = (1+\delta) \times \lambda_{\rm SM}$ via HH at the LHC, e.g. through μ(HH):

  1. if δ is **small**, we may conclude that the SM is self-consistent.

  2. if δ is **large**, there may be some new physics in action.

- (but in reality, this is "only" a consistency test.)

- other options for HH: [e.g. Gupta, Rzehak, Wells, 1305.6397]

  - use concrete models: constraints on param. space.

  - use an effective theory: constraints on coefficients.

an example: dimension-6 EFT (I)

[see: e.g. T. Plehn, 0910.4182]

- add dimension-6 Higgs operators, e.g.:

$$\mathcal{O}_1 = \frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) \quad \text{and} \quad \mathcal{O}_2 = -\frac{1}{3}(\phi^\dagger\phi)^3$$

- parametrised by an unknown mass scale Λ:

$$\mathcal{L}_{\mathrm{D6}} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

- go through electroweak "cooking" again...

- ...find new minima, expand Φ, generate W/Z masses, massless photon, etc.

an example: dimension-6 EFT (II)

- the twist is that we have to canonically normalise the Higgs boson kinetic term, i.e.

$$\hookrightarrow \alpha\, \partial_\mu H' \partial^\mu H' \to \frac{1}{2}\partial_\mu H \partial^\mu H$$

- one possibility (to avoid momentum-dependent interactions in self-couplings):

$$H \to aH + bH^2 + cH^3 + \mathcal{O}(H^4) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- but: this choice introduces new interactions everywhere in the SM Lagrangian related to f_1. [again, see T. Plehn, 0910.4182]

an example: dimension-6 EFT (III)

- let's drop f_1 for the sake of simplicity...
- resulting expressions: (f_1=0)

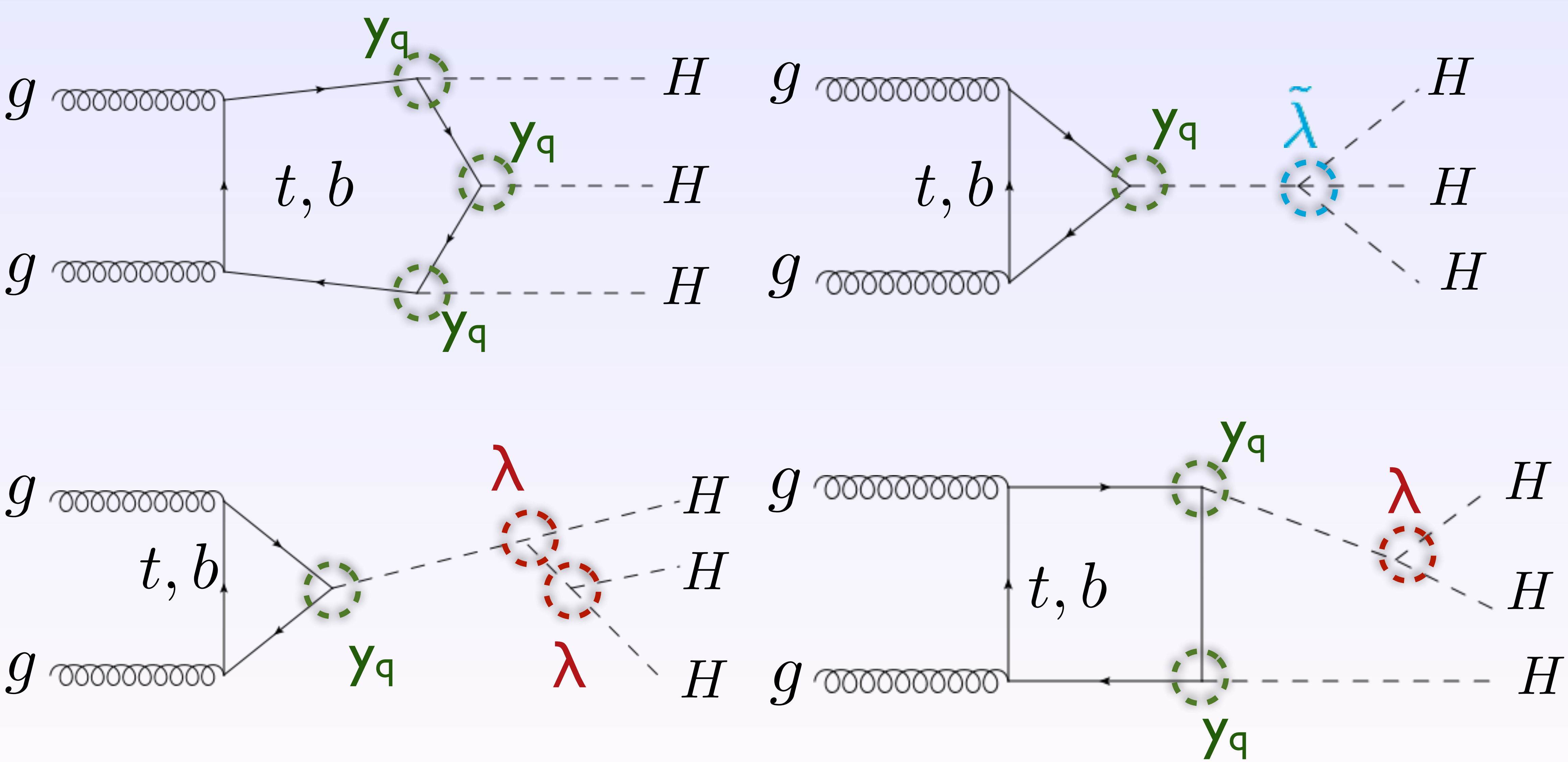
$$M_H^2 = 2\lambda v^2 \left(1 + \frac{f_2 v^2}{2\Lambda^2 \lambda}\right) \quad \text{and} \quad \lambda' = \left(1 + \underbrace{\frac{2 f_2 v^4}{3\Lambda^2 M_H^2}}_{\delta}\right) \times \lambda_{\rm SM}$$

- measuring "effective" self-coupling through HH signal strength would constrain: $\frac{f_2}{\Lambda^2}$ and λ
- had we kept f_1, simple picture of "effective" self-coupling through HH production no longer holds due to additional interactions.
- for a complete study, add more operators f_i & use other experimental results.

ii. multi-Higgs processes @ hadron colliders

SM HHH production @ LHC

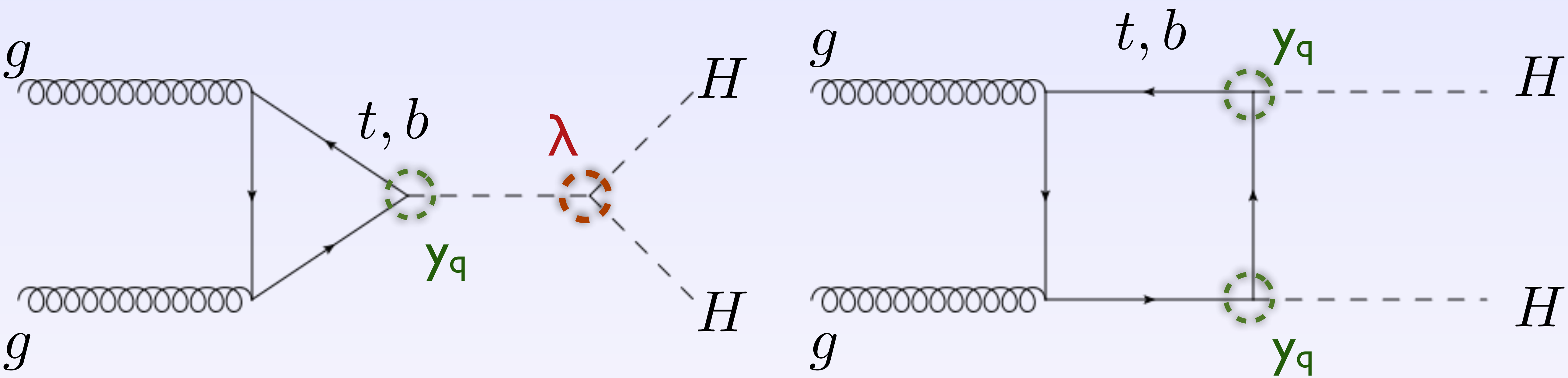
- **triple** Higgs boson production at hadron colliders,
- contributing diagrams: $gg \to HHH$



[Plehn, Rauch, hep-ph/0507321]

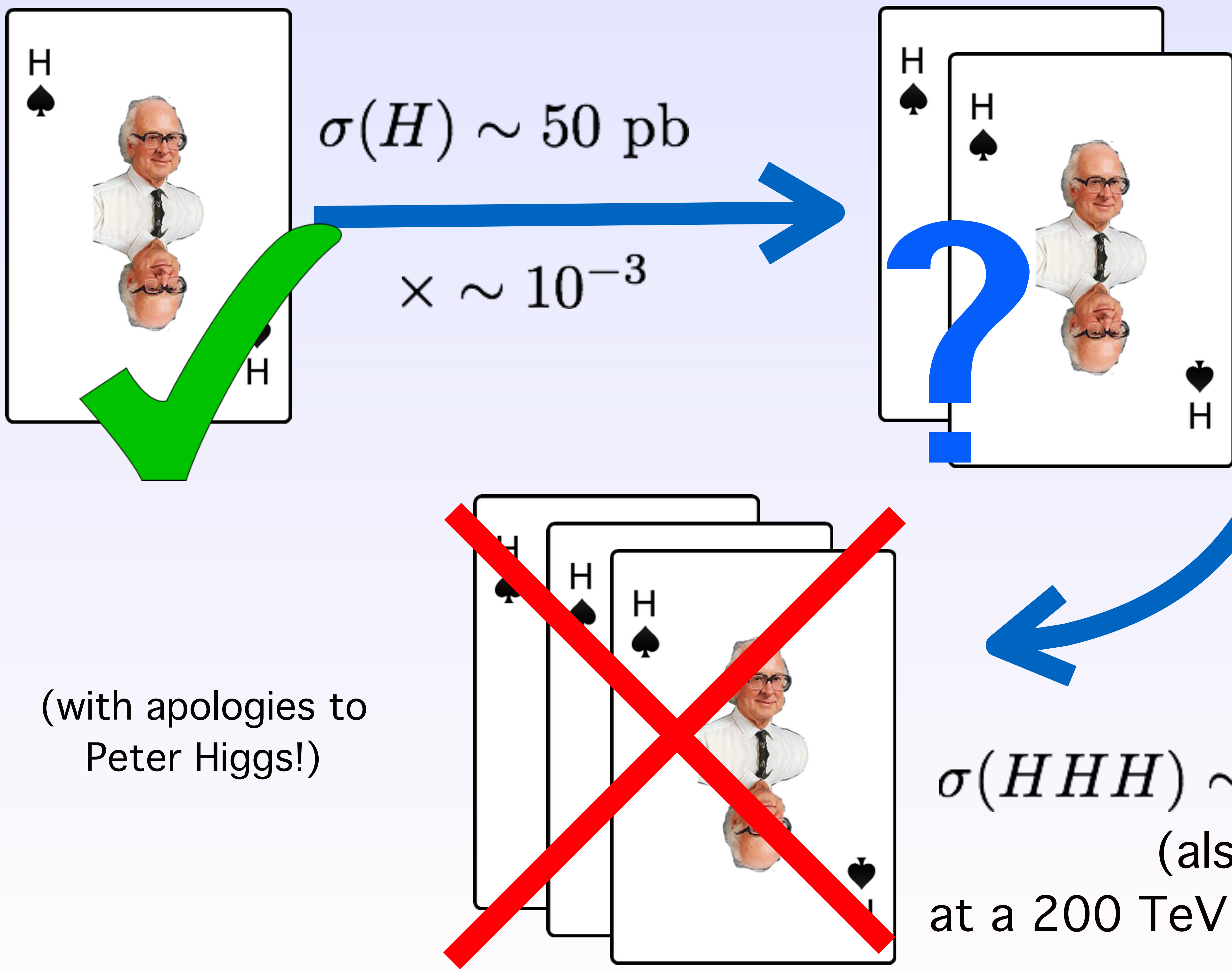
SM HH production @ LHC

- dominant initial state: gluon-gluon fusion.
- <u>leading order</u>, two diagrams:



- effective theory (infinite top mass) insufficient: $Q^2 \gtrsim M_{\rm top}^2$.
- loop calculation necessary to reproduce kinematical properties.

multi-Higgs cross sections (14 TeV LHC)



$\sigma(H) \sim 50$ pb

$\times \sim 10^{-3}$

$\sigma(HH) \sim 40$ fb

$\times \sim 10^{-3}$

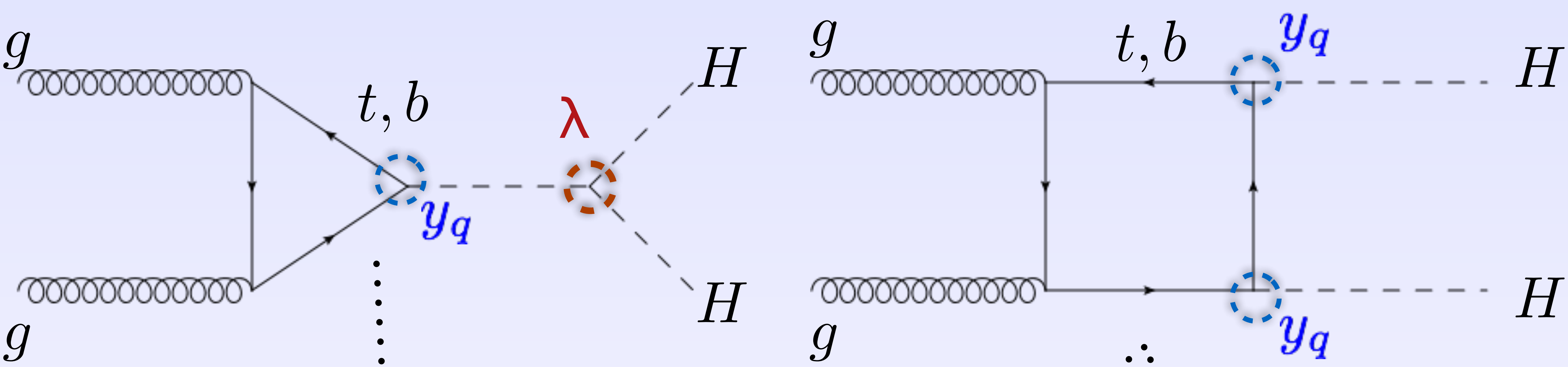
$\sigma(HHH) \sim 0.04$ fb

(also tiny:
at a 200 TeV collider: ~10 fb)

(with apologies to
Peter Higgs!)

iii. HH production @ LHC, in gory detail

HH production @ LO



box and triangle topologies,

Lorentz structures for spin-0 and spin-2 gg configurations.

$$\sigma_{HH}^{LO} = |\sum_q (\lambda y_q C_{q,\mathrm{tri}}^{(\mathrm{spin}-0)} + y_q^2 C_{q,\mathrm{box}}^{(\mathrm{spin}-0)})|^2 + |\sum_q y_q^2 C_{q,\mathrm{box}}^{(\mathrm{spin}-2)}|^2$$

(sum over quarks q = t, b)

(couplings normalized to SM: $\lambda = 1$, $y_q = 1$ is the SM)

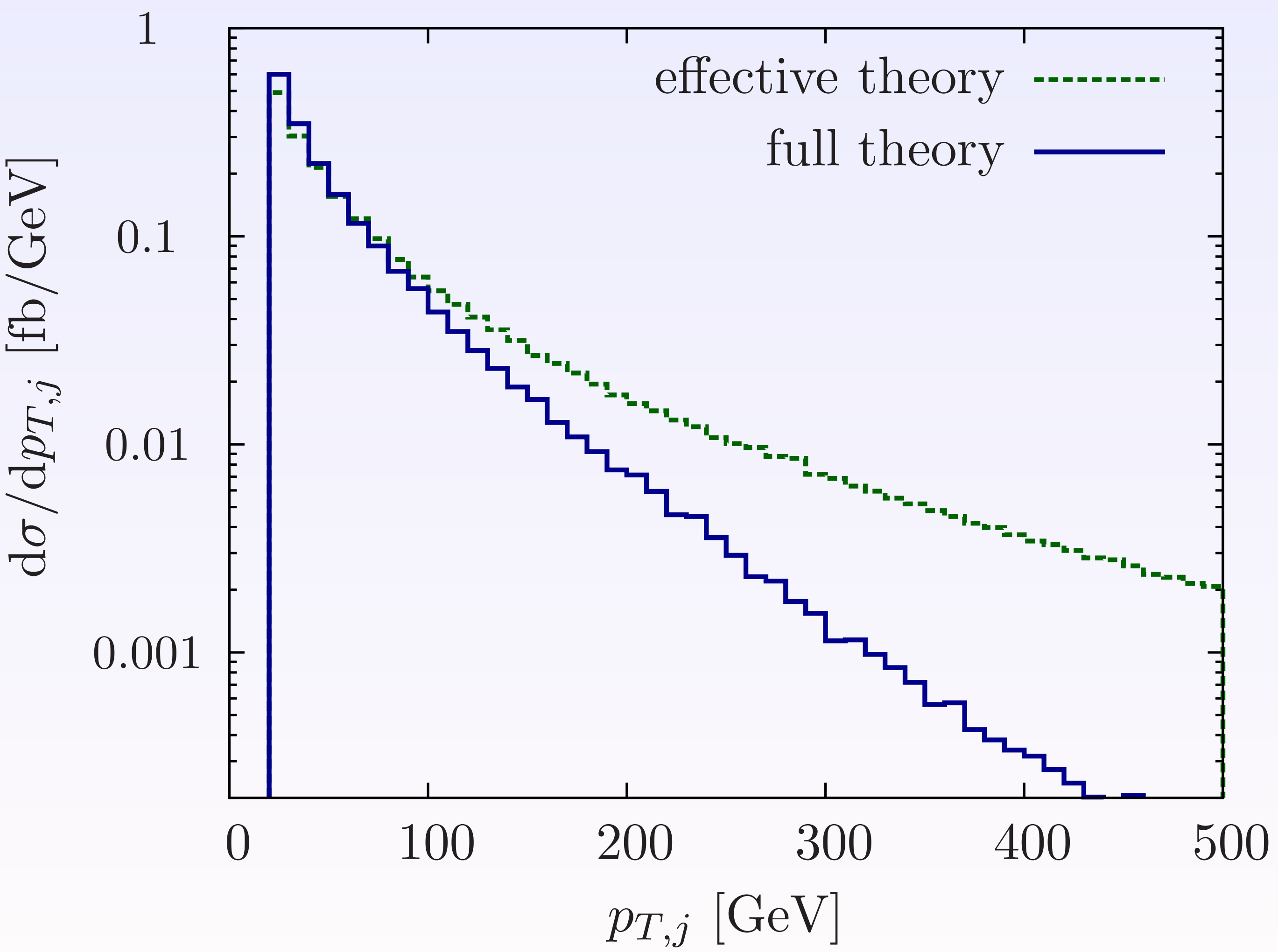
effective theory gone wild

- **<u>for HH:</u>** FAILS since $Q^2 \gtrsim 4M_H^2 > M_t^2$.
- the K-factor (NLO/LO) at HH threshold is strongly affected by power-suppressed $1/M_{\rm top}$ terms. [Grigo, Hoff, Melnikov, Steinhauser, 1305.7340]
- does not describe the kinematics of the process properly:

e.g., spectrum of the hardest jet in

$$pp \to HH + j + X$$

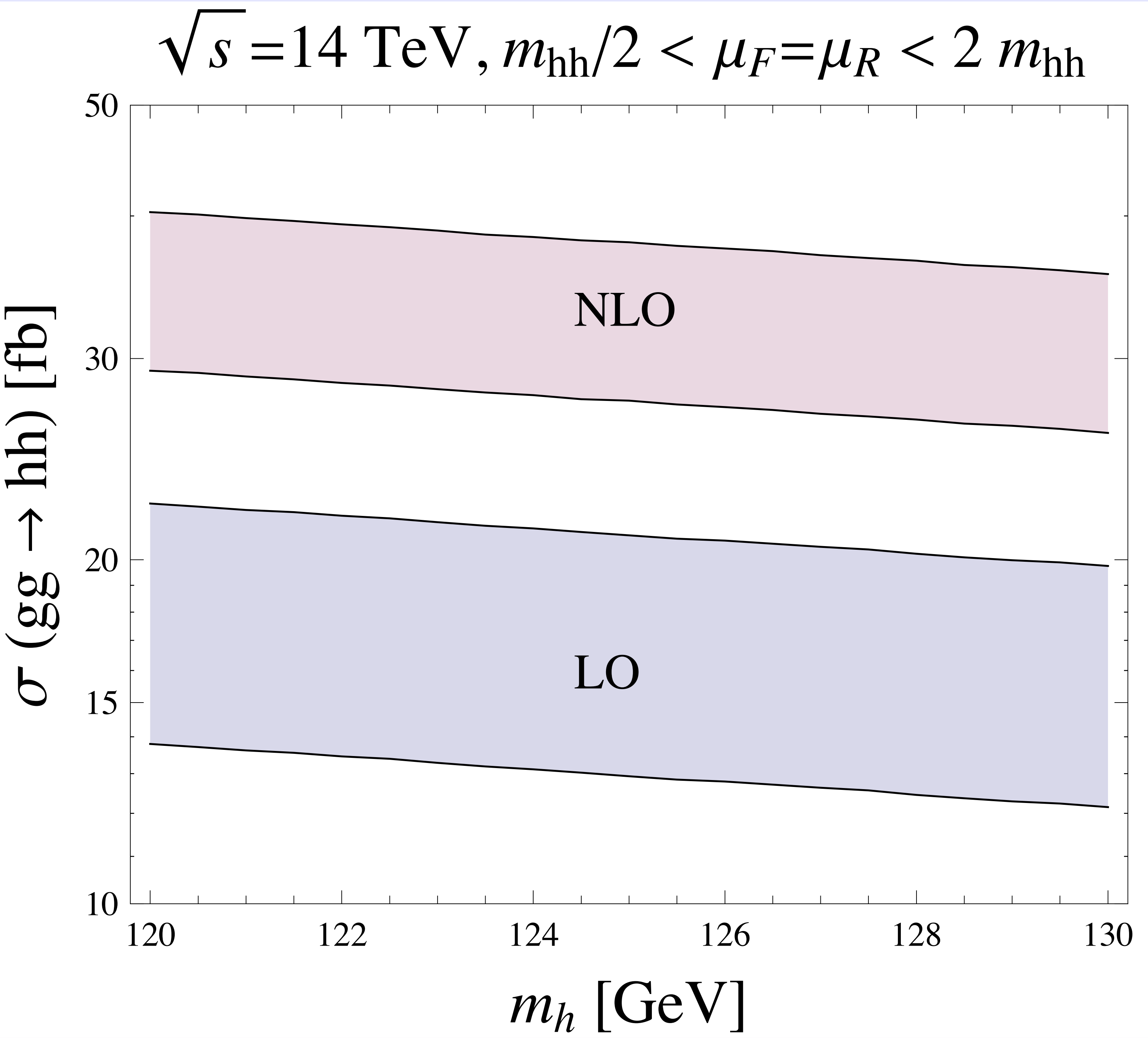
[Dolan, Englert, Spannowsky 1206.5001]



HH production @ (N)NLO

- (N)NLO calculations only available in the infinite top mass limit. [Dawson, Dittmaier, Spira, [hep-ph/9805244]], [de Florian, Mazzitelli, 1309.6594]
- K-factor (w.r.t. LO) in this limit ~ 2.
- $\sigma_{NNLO}/\sigma_{NLO} \sim 1.2$

HH cross section @ 14 TeV



$$\sigma^{NLO}_{(M_H=125\ \text{GeV})} = 32.3^{+5.6}_{-4.7}\ \text{fb}$$

(using HPAIR by M. Spira)

[**AP**, Li Lin Yang, and José Zurita, 1209.1489]

improving the Monte Carlo (I)

- go beyond LO + parton shower
- merging/matching (e.g. MLM or CKKW/MC@NLO or POWHEG)
- HH production, no full NLO calculation: use the effective theory NLO or merge to higher-multiplicities.

P. Maierhöfer, **AP**, 1401.0007

Q. Li, Q. Yan, X. Zhao, 1312.3830

→ MLM merging up to 1 extra parton.

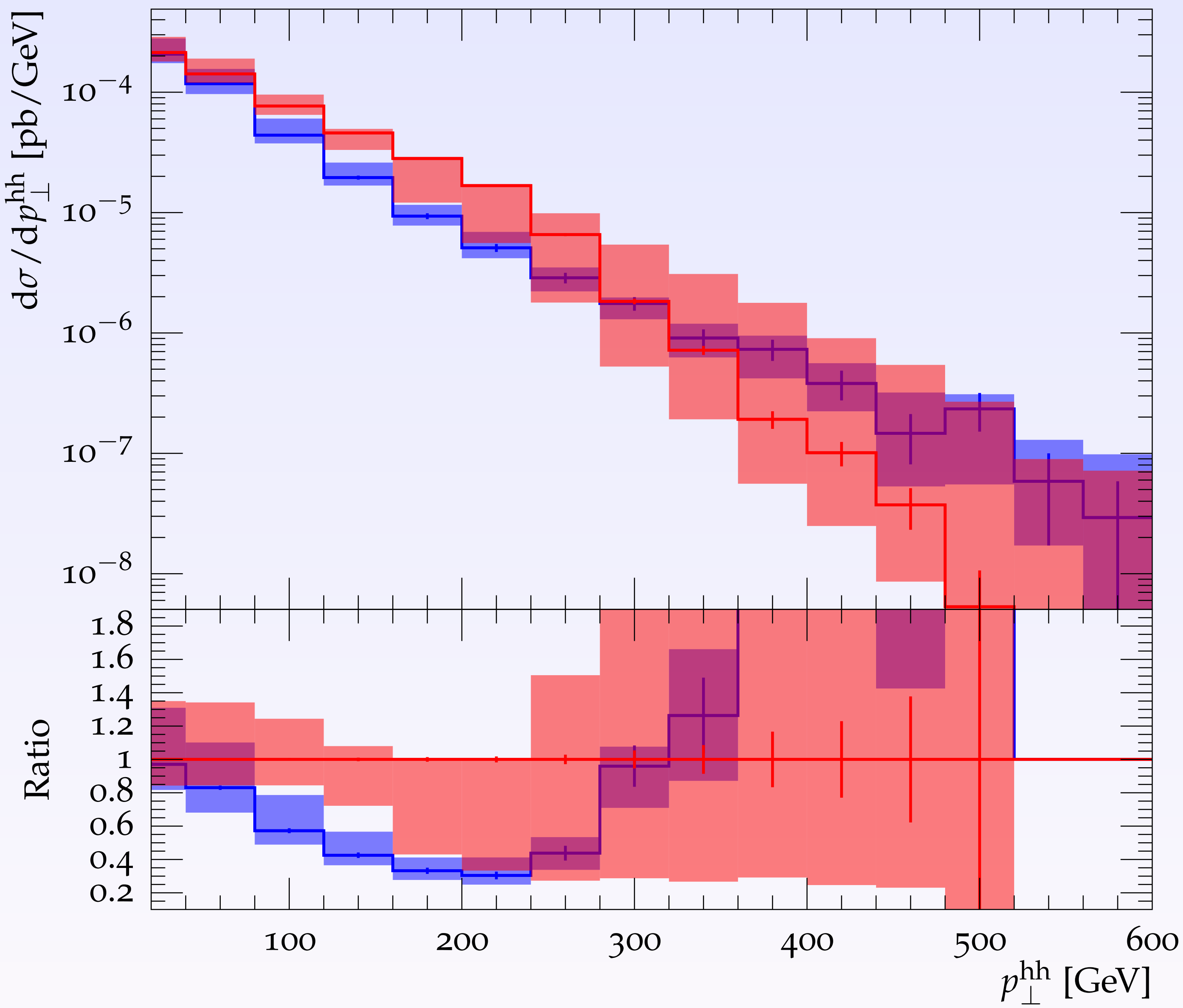
R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, 1401.7340 → MC@NLO with NLO EFT.

- using these improved samples, systematic uncertainties can be reduced.

improving the Monte Carlo (II)

- (leading log to LO in first jet p_T: similar to improvement in scale uncertainty from LO to NLO.)

- e.g., transverse momentum of Higgs pair (red: parton shower, blue: merged sample)

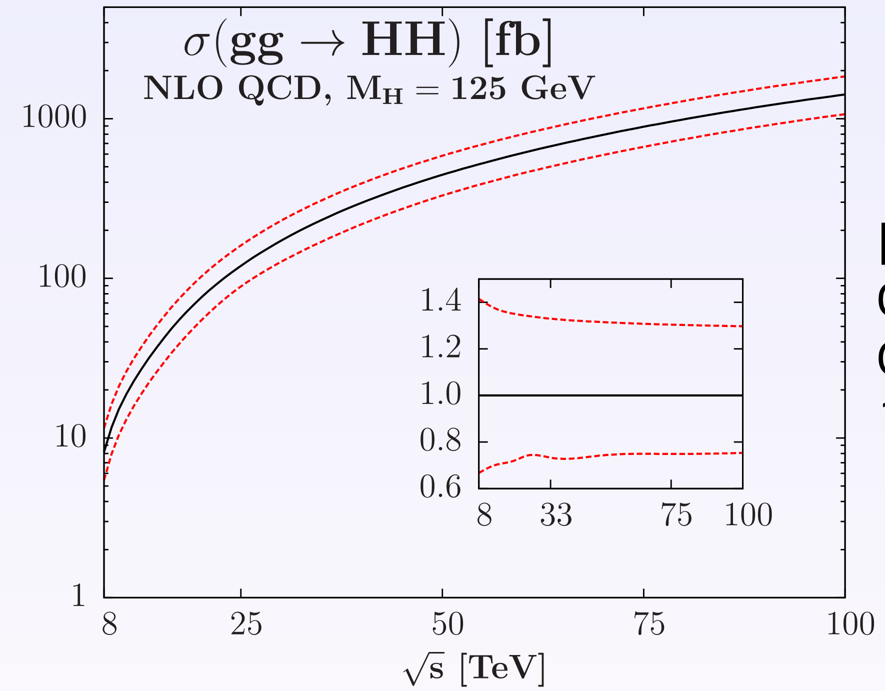


[P. Maierhöfer, **AP**, 1401.0007]

iv. searching for HH @ LHC14

challenges

- small cross section, implying high luminosity (600/fb or 3000/fb: end-of-lifetime or HL-LHC).
- + large theoretical uncertainties on this cross section.
- generating sufficiently large Monte Carlo background samples:
  - N_{events} = O(1000/fb) x O(100 pb) = O(10^8)
- simulating experimental efficiencies,
  - jet-to-γ mis-tagging,
  - τ-tagging, b-tagging.



[Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira, 1212.5581]

Figure 10: The total cross section (black/full) of the process $gg \to HH + X$ at the LHC for $M_H = 125$ GeV as a function of $\sqrt{s}$ including the total theoretical uncertainty (red/dashed). The insert shows the relative deviation from the central cross section.

branching ratios (M_H = 125 GeV)

$BR[b\bar{b}b\bar{b}] = 33.3\%$ ✓

$BR[b\bar{b}WW] = 24.8\%$ ✓

$BR[b\bar{b}\tau\tau] = 7.29\%$ ✓

$BR[WWWW] = 4.62\%$?

$BR[WW\tau\tau] = 2.71\%$?

$BR[\tau\tau\tau\tau] = 0.399\%$?

$BR[b\bar{b}ZZ] = 0.305\%$ ✗

$BR[b\bar{b}\gamma\gamma] = 0.263\%$ ✓

$BR[b\bar{b}Z\gamma] = 0.178\%$ ✗

$BR[b\bar{b}\mu\mu] = 0.025\%$ ✗

<u>note</u>: each 1% corresponds to ~100 events per 300 fb^{-1} of luminosity @ LHC14.

may provide constraints

$HH \to b\bar{b}\tau\tau$

Dolan, Englert, Spannowsky, [1206.5001], Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581].

- BR = 7.29%, cross section ~ 2.4fb (~700 events @ 300 fb^{-1}).
- reconstruction of τ leptons experimentally delicate.
- backgrounds relatively low: electroweak and top decays with taus in the final states.
- Higgses naturally boosted: use a fat jet: sub-structure of the two b-quark system: like in Higgs+vector boson.
  [Butterworth, Davison, Rubin, Salam, 0802.2470] --→ **"BDRS"**
- results promising given a high τ-tagging efficiency (80%), b-tagging assumed 70%, low fake rates.
- S ~ 50 versus B = 100 at 600 fb^{-1} (~5σ).

$HH \to b\bar{b}\gamma\gamma$

Baur, Plehn, Rainwater, [hep-ph/031005], Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581].

- BR = 0.263%, cross section = 0.09 fb, (~27 events @ 300 fb^{-1}).
- low rate but ‘clean’. backgrounds generally low and mostly coming from reducible backgrounds due to mis-identification of b-jets or photons (jet-to-γ).
- S ~ 30 versus B ~ 60 at 3000 fb^{-1} (~4σ).

$HH \to b\bar{b}WW$

Dolan, Englert, Spannowsky, [1206.5001], Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581], **AP**, Li Lin Yang, and José Zurita [arXiv:1209.1489]

- BR = 24.8%, cross section = 8.0 fb, (~2400 events @ 300 fb^{-1}).
- high rate, can have leptons + missing energy in the final state.
- **but**: huge backgrounds from top-anti-top production.
- with one leptonic W and one hadronic W was shown to be viable using jet sub-structure techniques. [**AP**, L. L. Yang, and J. Zurita, 1209.1489]
- S = 11 versus B = 7 at 600 fb^{-1} (~4σ).

more HH channels? (I)

- $b\bar{b}b\bar{b}$: highest BR (σ ~ 10.8 fb), but fully hadronic (triggering an issue) and huge QCD backgrounds.
- one may use boosted jet techniques to dig out this mode from the QCD background.

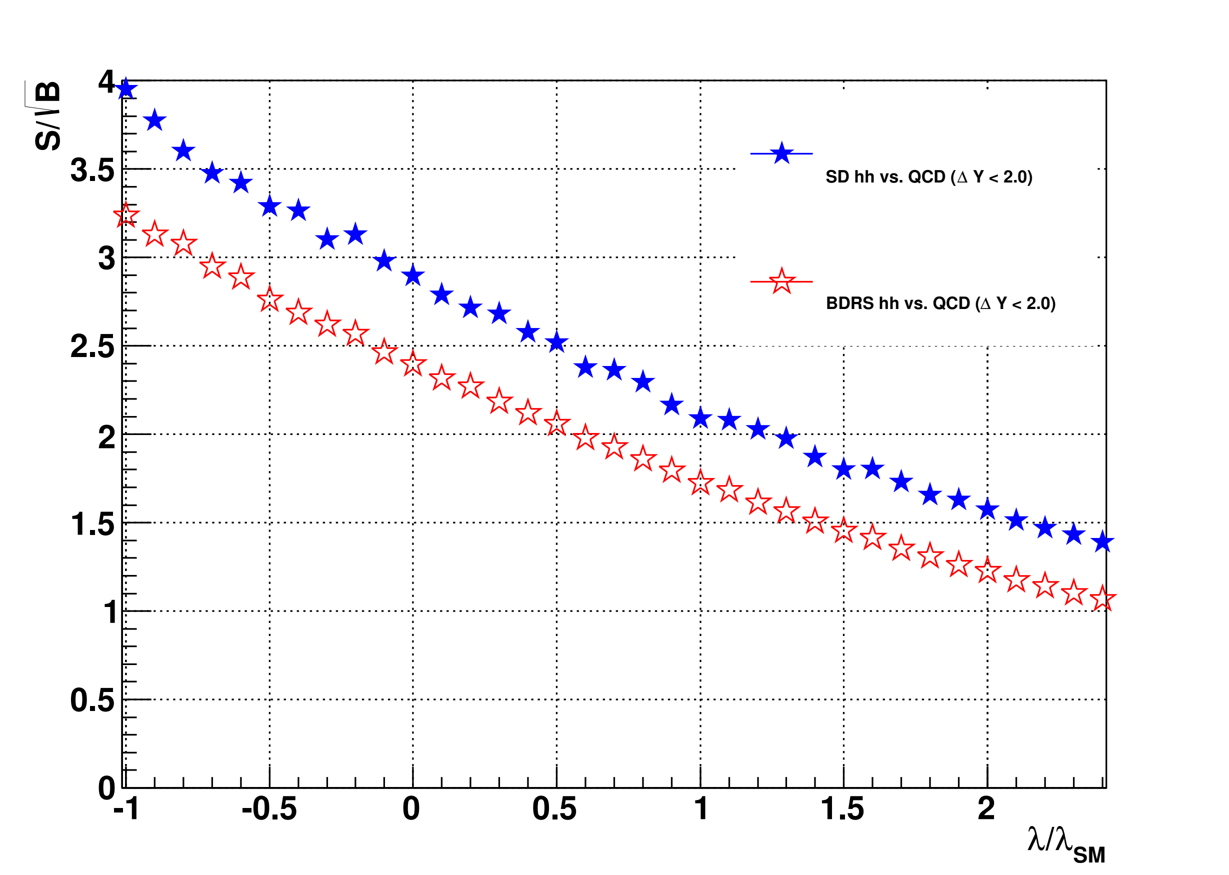


Figure 8: The best expected significance of the different Higgs tagger methods for different values of λ at 3000 fb^{-1} for a 14 TeV LHC.

- improved triggering strategies <u>necessary</u>!

[Danilo E. Ferreira de Lima, **AP**, Michael Spannowsky,1404.7139]

more HH channels? (II)

- $b\bar{b}\mu\bar{\mu}$: small initial cross section, essentially found to be impossible (σ ~ 0.008 fb). [Baur, Plehn, Rainwater [hep-ph/0304015]].
- $WWWW$: good for high-mass Higgs. for low mass seems to be hard due to BR of Ws (σ ~ 1.5 fb).
- $\tau\tau\tau\tau$: low rate and τ-tagging (σ ~ 0.13 fb).
- $WW\tau\tau$: τ-tagging, W BRs (σ ~ 0.86 fb)
- $b\bar{b}Z\gamma$, $b\bar{b}ZZ$: low rates and BR for Zs (σ < 0.1 fb).

v. how can we use HH to constrain the self-couplings?

(focus on anomalous coupling picture)

how can we measure λ?

- older studies considered analysis of shapes of distributions. [e.g. Baur, Plehn, Rainwater [hep-ph/0310056]].
- shapes may not be so well predicted at the moment.
- moreover, low number of events: must exploit all differences in shapes of distributions to dig signal VS background.
- to start with: use measured rates instead. [F. Goertz, **AP**, L.L. Yang, J. Zurita, arXiv:1301.3492].

how can we measure λ?

- e.g. using the three channels shown to be potentially viable, at 3000 fb^{-1}, LHC@14 TeV:

$$HH \to b\bar{b}\tau\tau \quad \Rightarrow \quad \lambda = 1.00^{+0.40}_{-0.31}$$

$$HH \to b\bar{b}\gamma\gamma \quad \Rightarrow \quad \lambda = 1.00^{+0.87}_{-0.52}$$

$$HH \to b\bar{b}WW \quad \Rightarrow \quad \lambda = 1.00^{+0.46}_{-0.35}$$

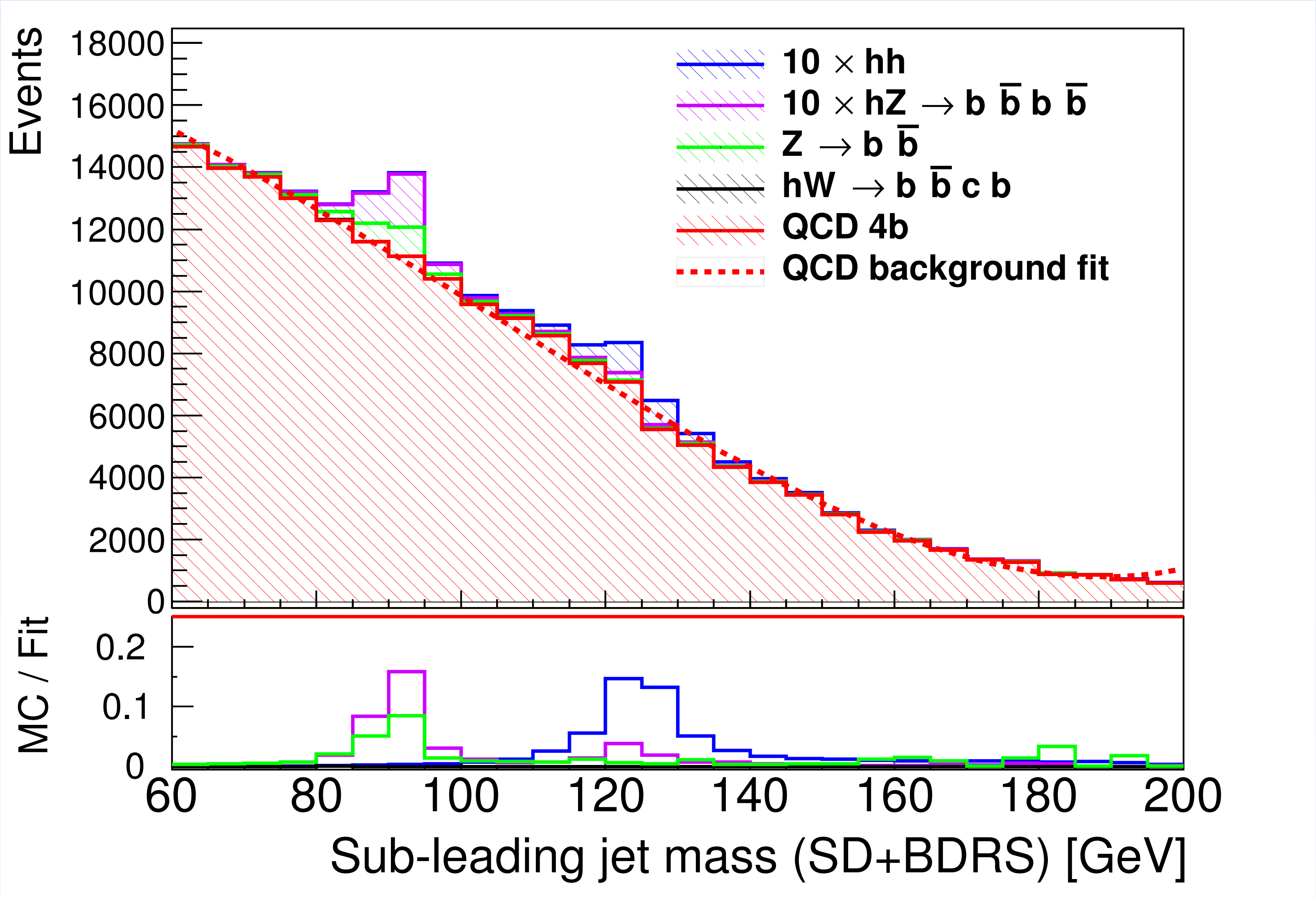
times the SM value

[F. Goertz, **AP**, L. L. Yang, J. Zurita, 1301.3492]

- "naively" combining: ~+30%, ~-20% error.

how can we measure λ?

- using the ratio with hZ/ZZ peak in the 4b mode.



[Danilo E. Ferreira de Lima, **AP**, Michael Spannowsky, 1404.7139]

Figure 9: A fit of a side band region using a 5th-order polynomial, performed with looser selection requirements, using Shower Deconstruction for the leading-p_T Higgs boson identification and BDRS for the sub-leading Higgs mass reconstruction.

vi. (… and beyond)

other production modes?

- several associated production modes exist:

	cross section@14 TeV
$qq \to qqHH$	~1.8 fb
$qq \to WHH$	~0.4 fb
$qq \to ZHH$	~0.3 fb

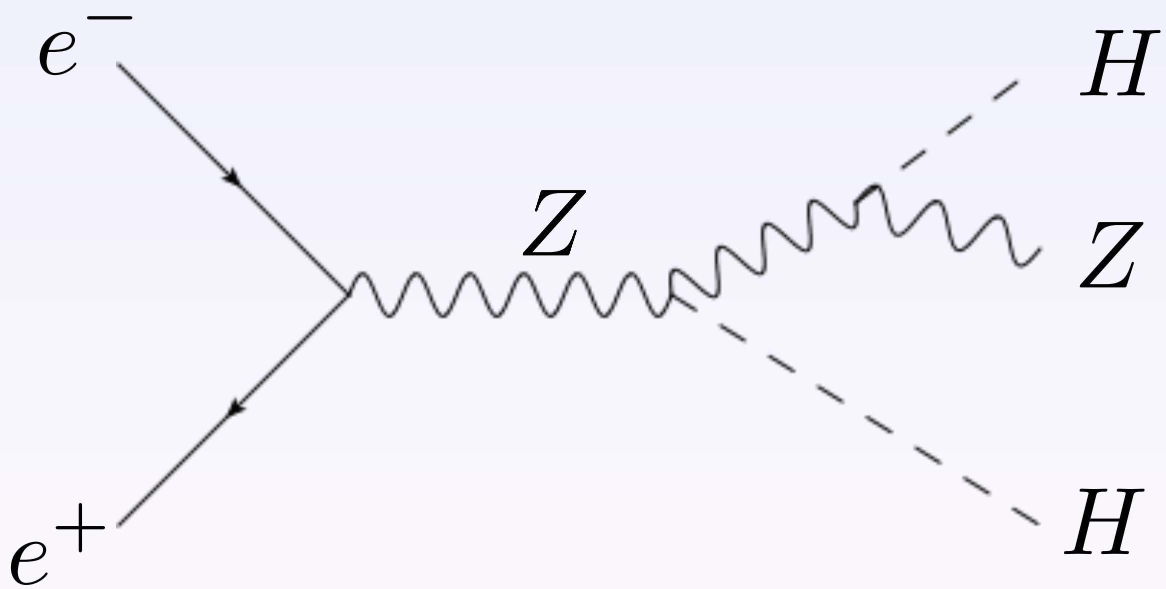
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581]

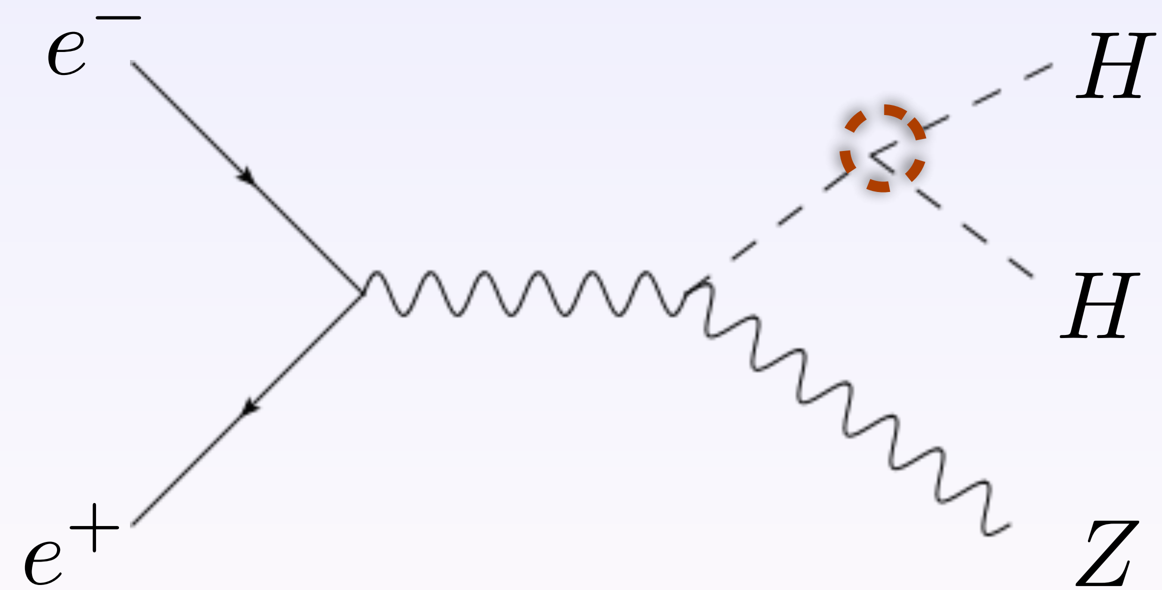
- (note: behaviour w.r.t. λ is different for each channel.)
- with decays $HH \to b\bar{b}b\bar{b}$, could be looked into with sub-structure techniques, but initial cross section low.

triple coupl. @ lin. colliders (I)

- at a linear collider, a few studies exist,
- based on processes such as:

$$e^+e^- \to ZHH$$





triple coupl. @ lin. colliders (II)

- e.g. ILC [1306.6352] or TESLA TDR [hep-ph/0106315]:

$$e^+e^- \to ZHH \quad \text{(and both } H \to b\bar{b}\text{)}$$

with:

$$\sigma(\sqrt{S} = 500\ \mathrm{GeV}) \simeq 0.15\ \mathrm{fb} \quad \text{for: } M_H \simeq 125\ \mathrm{GeV}$$

TESLA TDR (2001): cross section with ~20% error,

and λ with accuracy ~20%: at $1000\ \mathrm{fb}^{-1}$.

ILC TDR (2013): cross section with ~27% error,

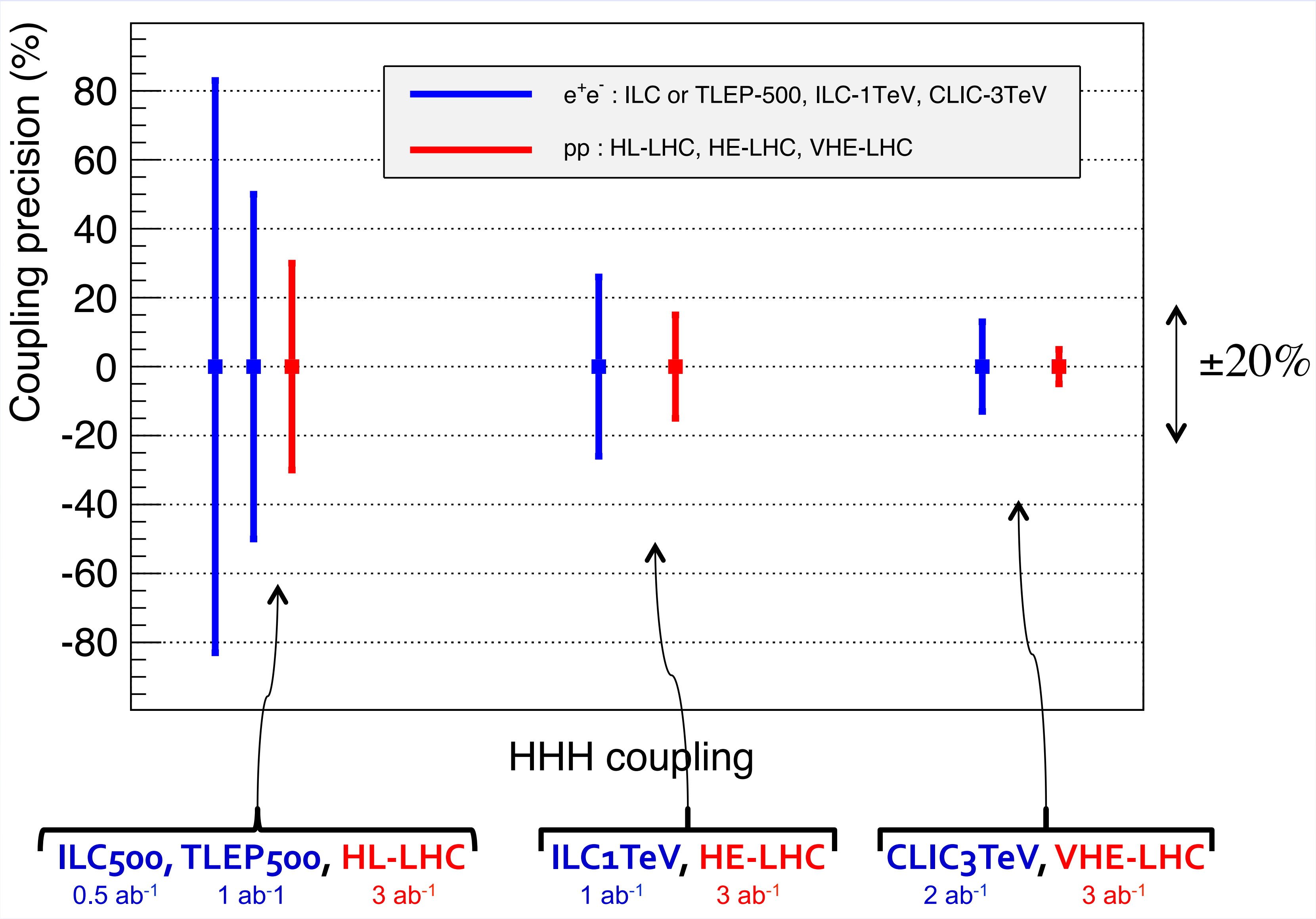
and λ with accuracy ~44%: at $2000\ \mathrm{fb}^{-1}$.

ILC discrepancy:
'mis-clustering of color-singlet groups'

$\Downarrow$

'A new jet clustering algorithm is now being developed.'

triple coupl. @ future colliders



HE-LHC: 33 TeV

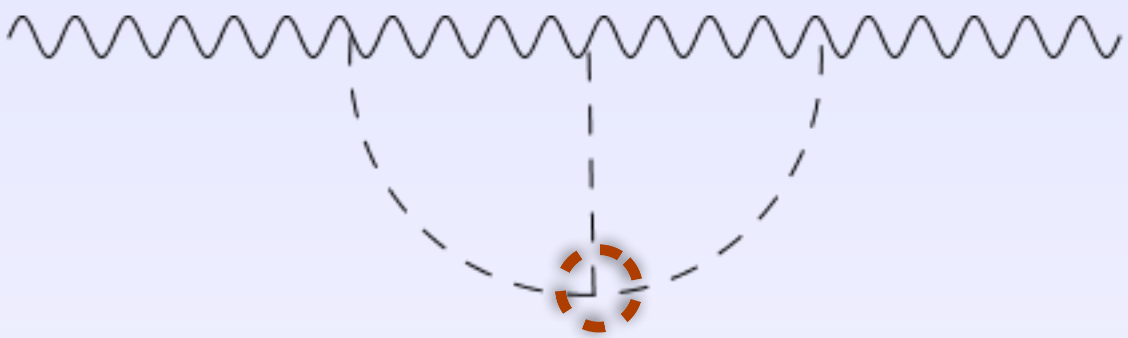
VHE-LHC: 100 TeV

[TLEP Design WG, 1308.6176]

Fig. 18: Expected relative statistical accuracy in % on the trilinear Higgs self-coupling for e^+e^- (blue) and pp (red) colliders at the high-energy frontier. The accuracy estimates are given, from left to right, for ILC500, TLEP500, HL-LHC, ILC1000, HE-LHC, CLIC and VHE-LHC, for integrated luminosities of 0.5, 1, 3, 1, 3, 2, and 3 ab^{-1}, respectively.

indirect constraints? (I)

- e.g. contributions to observables such as the W mass @ two loops via:



- but SUM of **all** the bosonic contributions only has (in the SM): [e.g. Awramik, Czakon, Freitas, Weiglein, hep-ph/0311148]

$$(\Delta M_W)^{2-\text{loop}}_{\text{bos.}} = \mathcal{O}(0.1\ \text{MeV})$$

- compare to ~15 MeV, current experimental uncert. (or factor of 2-3 better in future experiments).

- can never provide constraints (?).

indirect constraints? (II)

- e.g. contributions to **single Higgs observables** through higher-order corrections.
- e.g. e+e- @ 240 GeV:

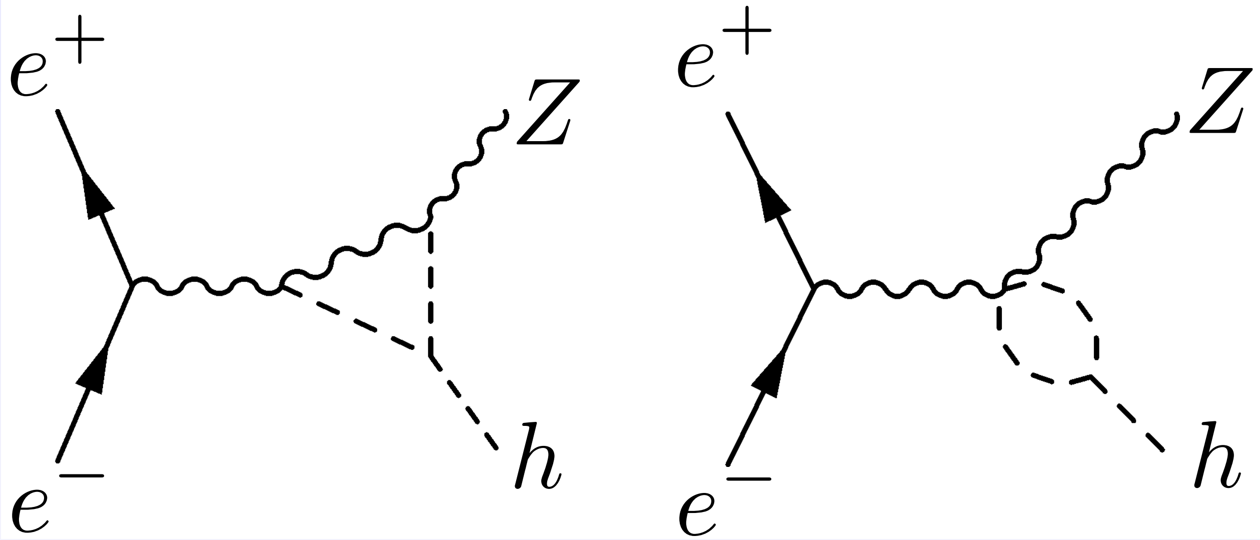


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h.

[M. McCullough, 1312.3322]

- may determine triple coupling within ~30% at 10/ab.

summary/conclusions

- I have discussed...

  i. multi-Higgs processes at the LHC,

  ii. and what we would hope to learn.

  iii. specifically: HH production,

  iv. how to go about searching for it, and what possible constraints we could expect.

  v. prospects for going beyond gluon fusion HH@LHC.

- HH is a “flagship” channel for HL-LHC and future colliders!
- further work:
    - **theoretically:** improving description of the kinematics and the total cross section (full NLO?), investigate effective theory description,
    - in **phenomenology:** re-examine channels, search new, or use indirect constraints,
    - **experimentally:** assess the viability of the promising channels/methods, improve triggering for this channel!

special thanks

- special thanks to my collaborators: Florian, José, Li Lin, Philipp, Michael, Danilo.

- ...and thanks for your attention!

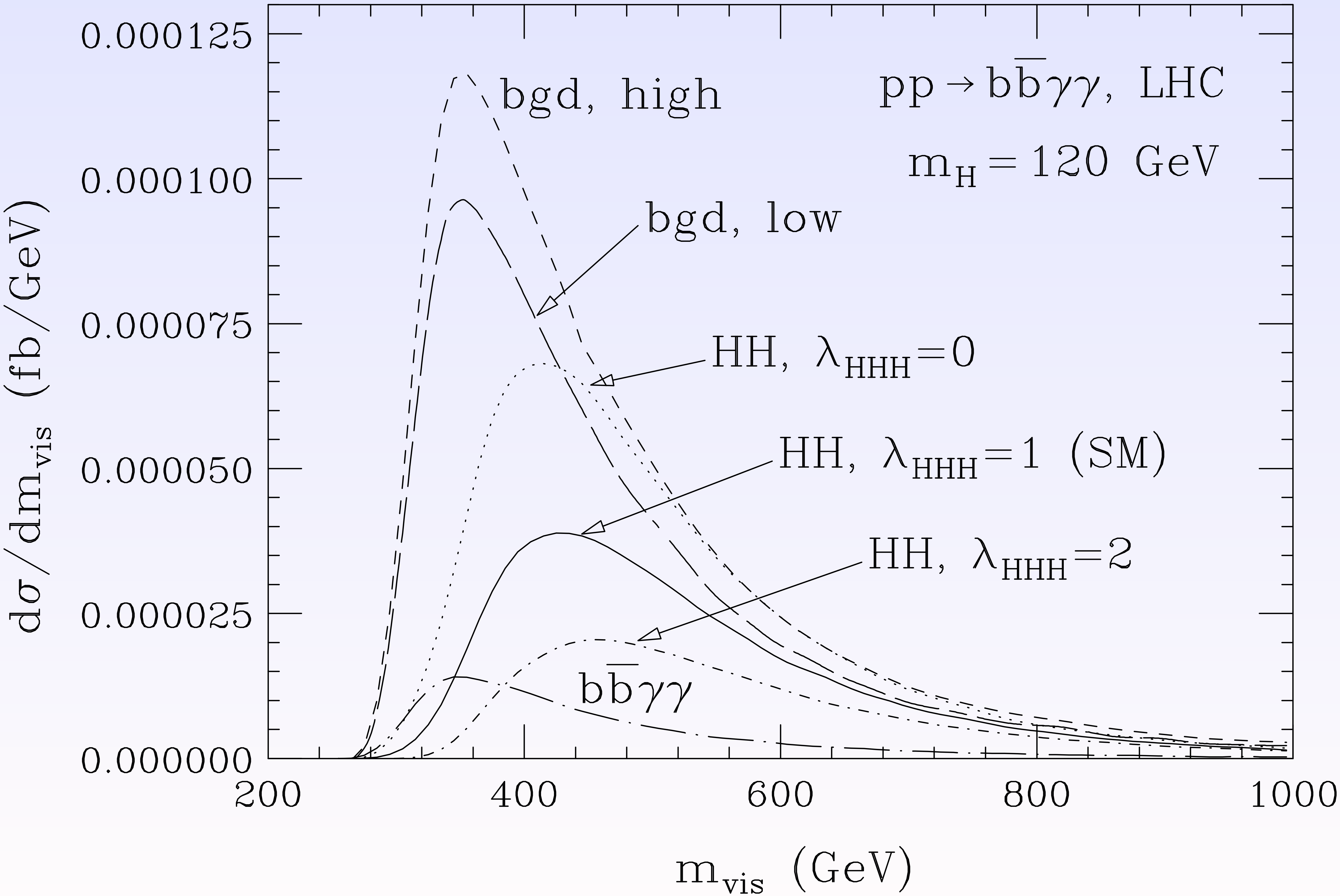
auxiliary slides

how do we (actually) measure the triple coupling λ?

using differential distributions

- (as seen in: Baur, Plehn, Rainwater [hep-ph/0310056])
- perform the analysis, e.g. for $b\bar{b}\gamma\gamma$.
- construct a differential distribution for signal and background using Monte Carlo.
- compare to Monte Carlo events to get expected bounds on the self-coupling.

using differential distributions (an example from Baur, Plehn, Rainwater):



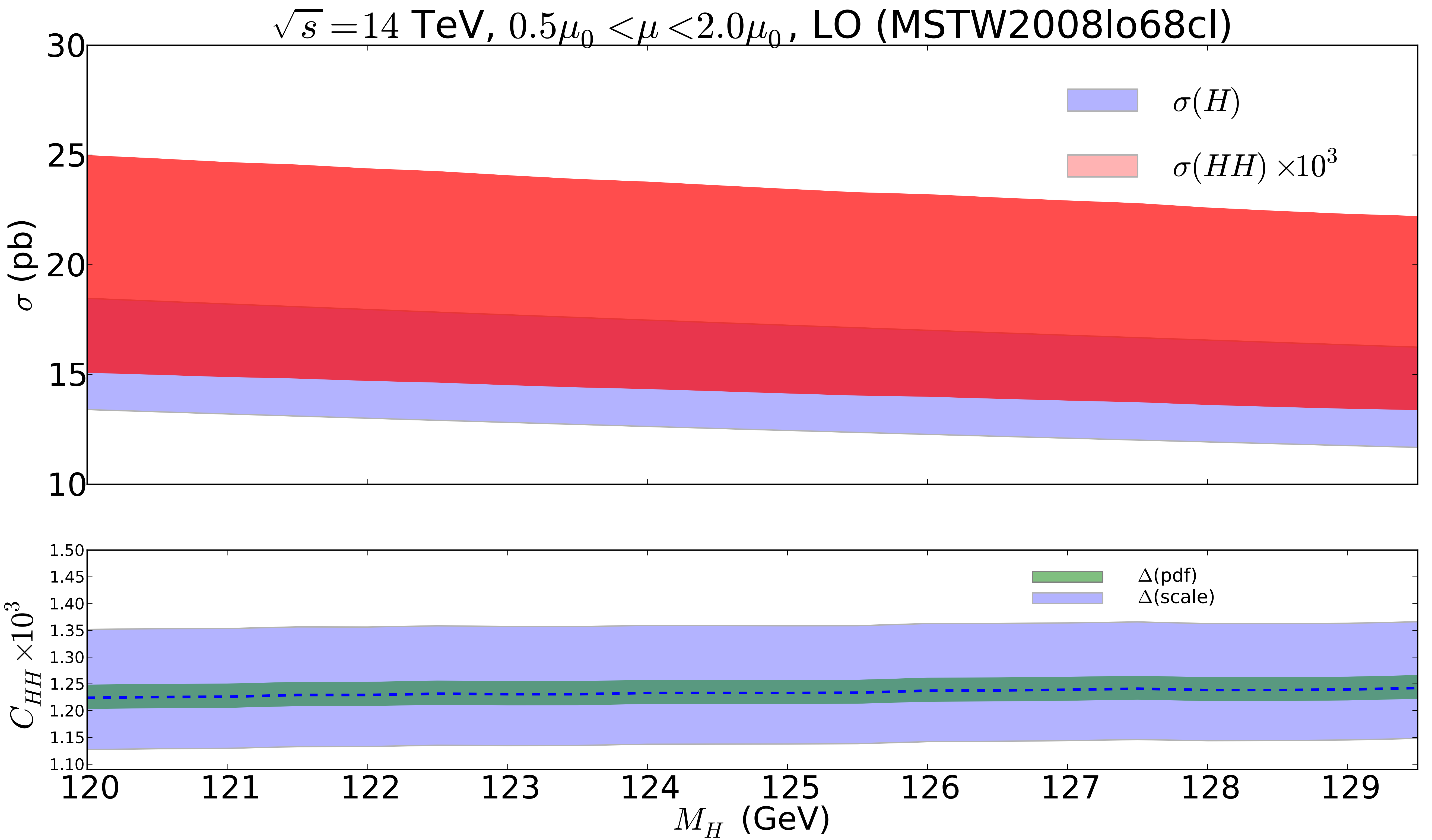
using rates (i.e. cross sections)

- differential distributions for both signal and background may not be very well modeled.
- we can use the **total rate** predictions for signal and background instead.
- BUT: these can be dominated by large systematic uncertainties, originating either from:
  - unknown higher-order corrections,
  - parton density function uncertainties,
  - experimental errors,
  - + more.

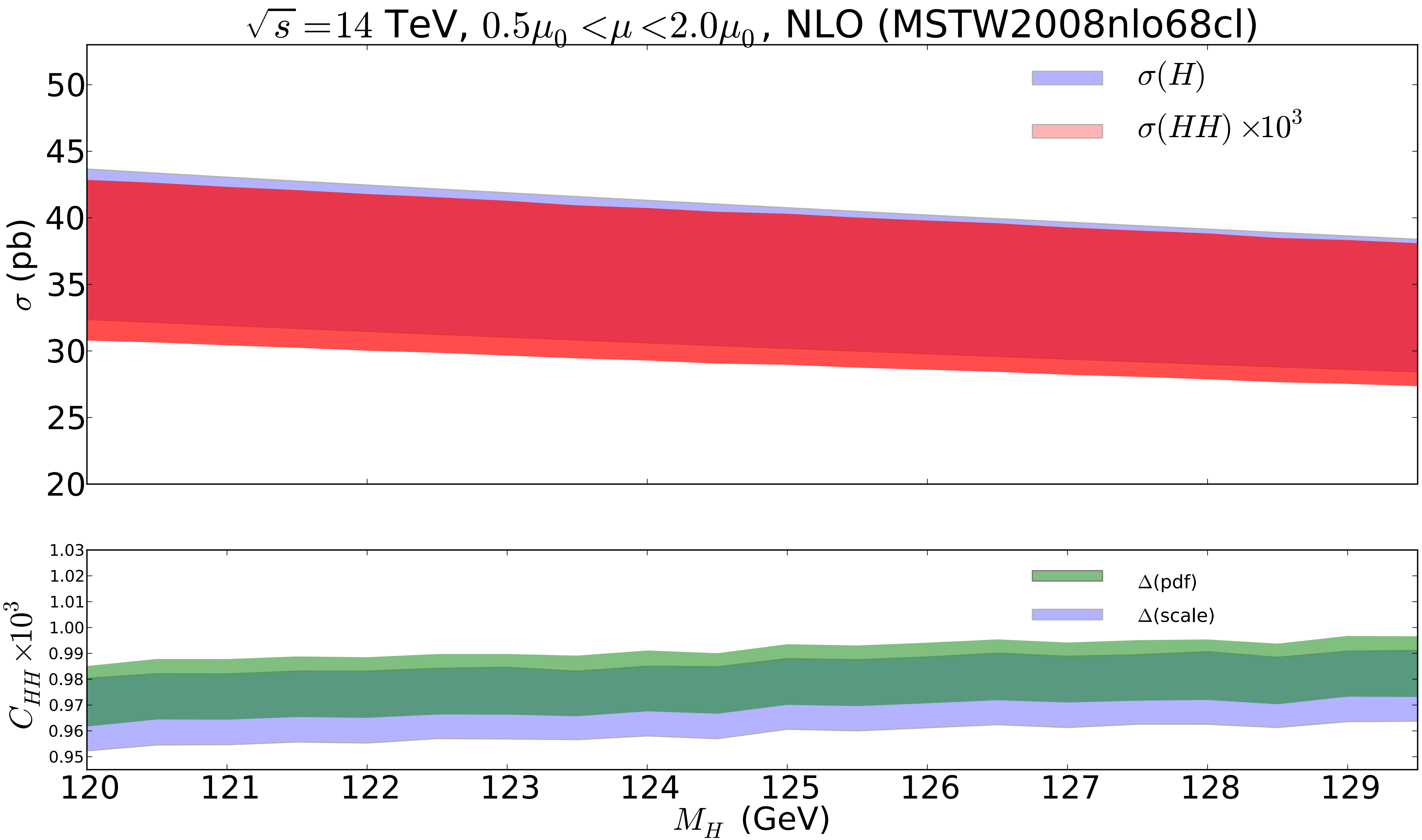
using ratios of cross sections

- consider: $$C_{HH} = \frac{\sigma(gg \to HH)}{\sigma(gg \to H)} \, ,$$
- **single** Higgs production may possess similar higher-order QCD corrections to Higgs pair production.
- these may cancel out in the ratio, leading to a more stable prediction.
- moreover, experimental systematic uncertainties may cancel out, e.g. the luminosity uncertainty.
- we can check the degree to which extent the scale and pdf uncertainties cancel out.

leading order



next-to-leading order



comments on ratio

- assuming that the scale uncertainties are correlated is a reasonable assumption.
- ratio goes from ~1.25 to ~1.0 from LO to NLO even though the K-factor is ~2.
- a total theoretical uncertainty of ~5% is not unreasonable for the ratio, as opposed to ~20% for the cross section itself.
- we used the ratio, along with **conservative** expected experimental uncertainties to construct expected exclusion regions.

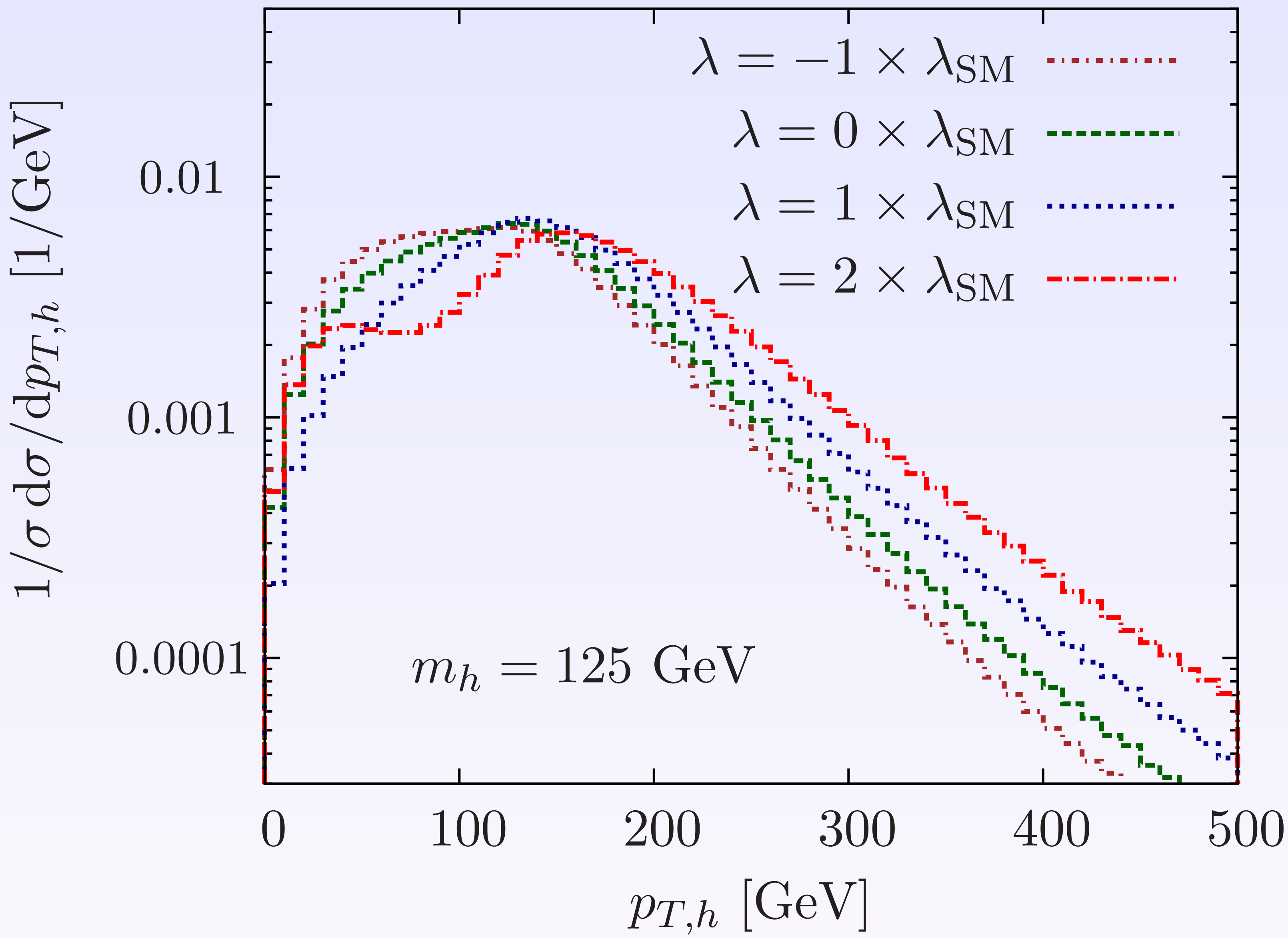
H+V, BDRS Analysis

[Butterworth, Davison, Rubin, Salam, 0802.2470]

- “BDRS” analysis:
  - Higgs decays to two b-quarks.
  - Cambridge/Aachen jet algorithm, R=1.2, get “fat jets”.
  - **apply a “mass-drop” condition** on a hard jet:
    - picks up the decay of a massive particle, e.g. $H \to b\bar{b}$
  - **“filter” the jet:** re-apply the jet algorithm with a smaller R, on the “fat” jet constituents, take **three** hardest “sub-jets”.
  - ask for the two hardest “sub-jets” to contain **b-tags**.
  - “**filtering**” reduces the effective area of the “Higgs”-jet,
  - hence reduces pollution from **Underlying Event.**

BDRS analysis on H+H

- the Higgs bosons in HH are **naturally boosted:**

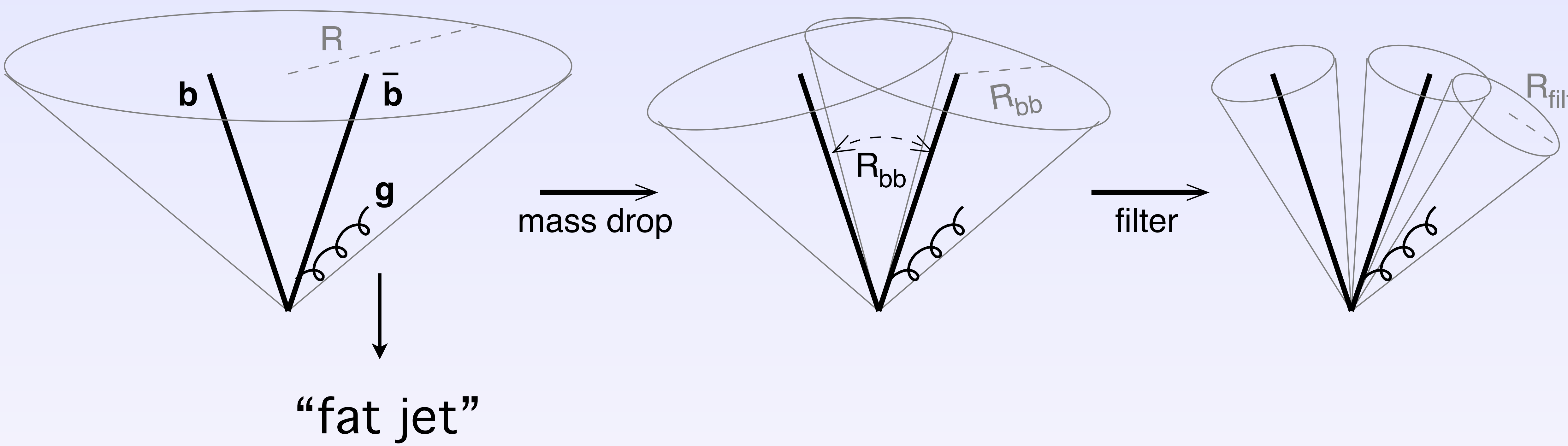


[Dolan, Englert, Spannowsky, 1206.5001]

- + other arguments of BDRS technique apply.

H+V

- "BDRS" analysis, pictorially: [Butterworth, Davison, Rubin, Salam, 0802.2470]



- HV: yields good sensitivity (4.5σ) @ 14 TeV @ 30 fb^{-1}.

- perhaps an improvement of previous HH results can be also achieved!

electroweak Lagrangian (I)

- ingredients of the ‘recipe’:

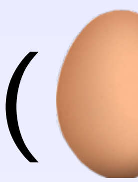
+ (...)

electroweak Lagrangian (I)

- ingredients of the 'recipe':

an $SU(2) \times U(1)$ gauge symmetry ()

+

+ a complex doublet scalar, ϕ. ()

- start by writing (i.e. Higgs boson Lagrangian):

$$\mathcal{L} = (D^{\mu}\phi)(D_{\mu}\phi) - \mathcal{V}(\phi^{\dagger}\phi)$$

the covariant derivative:

$$D^{\mu} = \partial^{\mu} + ig_2(T \cdot W^{\mu}) + iYg_1 B^{\mu}$$

SU(2) coupl. SU(2) gens. U(1) coupl.

electroweak Lagrangian (II)

- with potential:

$$\mathcal{V}(\phi^\dagger\phi) = \lambda(\phi^\dagger\phi)^2 + \mu^2\phi^\dagger\phi,$$

$$(\lambda > 0,\ \ \mu^2 < 0)$$

$\Rightarrow$ vacuum expectation value (vev) at:

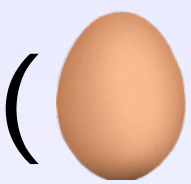
$$|\phi|^2 = -\mu^2/(2\lambda) \equiv v^2/2.$$

(infinite number of degenerate minima)

$\hookrightarrow$ implies symmetry breaking

()

+

()

+

(...)

=

()

electroweak Lagrangian

- further steps:
  - choose minimum in particular direction:

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \text{(implies: residual U(1) invariance)}$$

  - consider fluctuations of scalar field about that minimum,
  - and make a gauge transformation to absorb the Goldstone modes into the gauge bosons.

electroweak Lagrangian

- hence, after symmetry breaking, the Higgs + SU(2)xU(1) Lagrangian becomes:

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H - \mathcal{V}(H; \lambda, v) + \frac{(v+H)^2}{8} \begin{pmatrix} 0 & 1 \end{pmatrix} (2g_2 T \cdot W_\mu + g_1 B_\mu) \times (2g_2 T \cdot W^\mu + g_1 B^\mu) \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

fluct. about min. $\phi \propto (0, v+H)$

(recall: **μ**, **λ** and **υ** are related and hence only 2/3 are independent.)

$\hookrightarrow$ **'Free' parameters:** v, g_1, g_2, λ

‘fixing’ free params. (I)

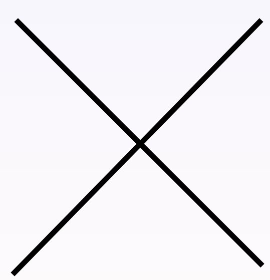
- diagonalize the quadratic terms in vector boson fields,
- and deduce the masses of Z and W bosons:

$$M_W = \frac{1}{2} v g_2 \qquad M_Z = \frac{1}{2} v \sqrt{g_1^2 + g_2^2}$$

Measured!

WARNING: Leading Order!

- 4-fermion interaction at low energies can fix the Fermi constant:



$$\Rightarrow \quad \frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}$$

‘fixing’ free params. (II)

- until very recently, only had 3 out of 4 constraining equations...
- ...in July 2012, we obtained the fourth:

$$M_H = \sqrt{2\lambda} v$$

Measured!

$$\hookrightarrow \sim 125 \text{ GeV}$$

HH SM consistency via anomalous couplings

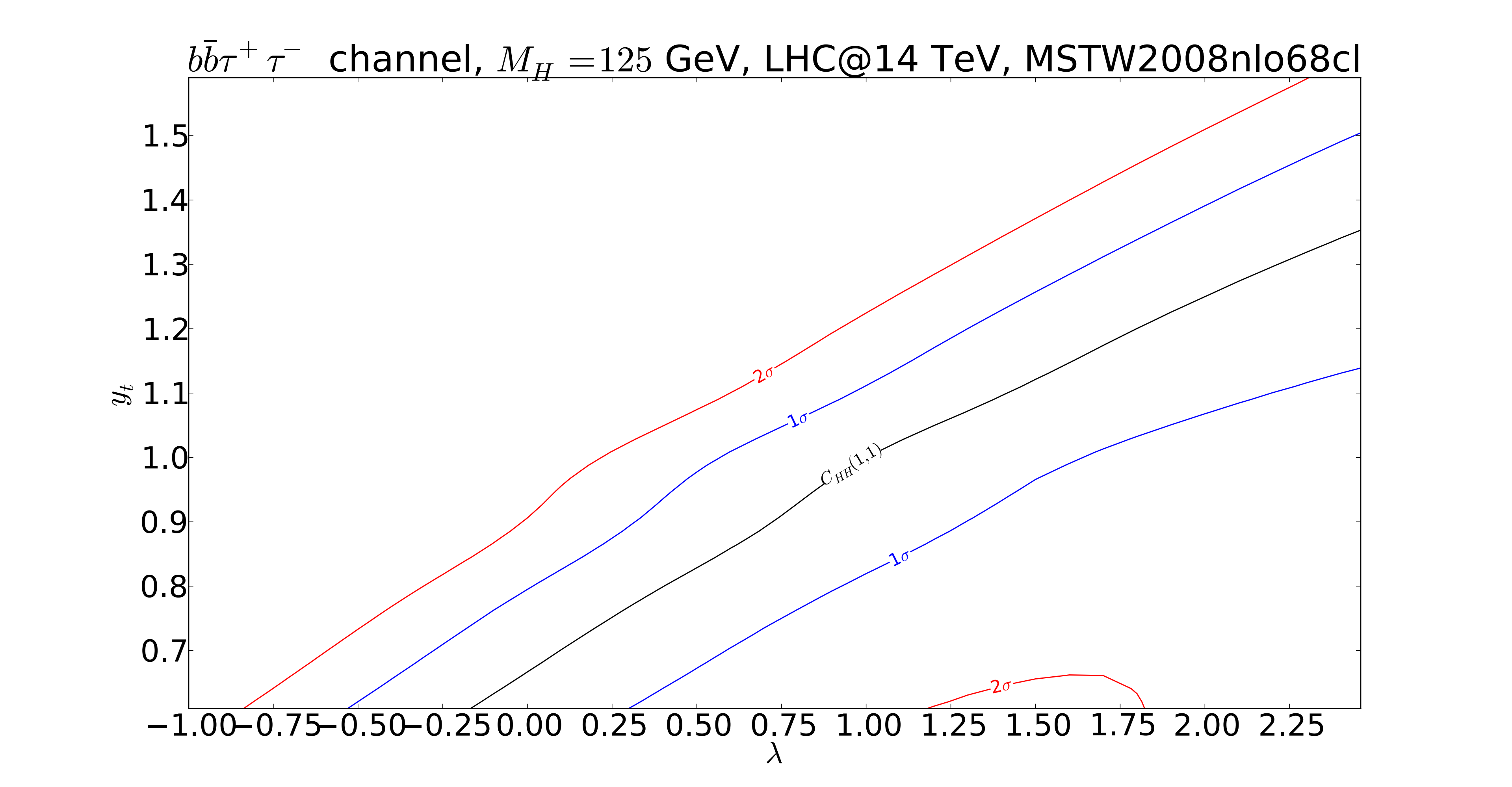


Figure 9: The 1σ and 2σ confidence regions in the $y_t - \lambda$ plane at 600 fb^{-1} for the $b\bar{b}\tau^+\tau^-$ decay mode, derived using C_{HH}, within the SM ($\lambda_{\text{true}} = 1$ and $y_{t,\text{true}} = 1$).

HH production @ LHC: numerically

- using HPAIR (M. Spira), fits:

Florian Goertz, AP, Li Lin Yang, and José Zurita [1301.3492]

$$\sigma_{HH}^{\rm LO}[{\rm fb}] = 5.22\lambda^2 y_t^2 - 25.1\lambda y_t^3 + 37.3 y_t^4$$

$$\sigma_{HH}^{\rm NLO}[{\rm fb}] = 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4$$

(couplings normalized to SM)

neglecting bottom quark contributions:
O(1%) at total cross section

- negative interference term between triangle and box.
- [interesting: a symmetry point exists at $\lambda \sim 2.5\, y_t$ (NLO)].

dim-6 EFT with both operators

$$\lambda' = \lambda_{\rm SM}\left(1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2 f_2 v^4}{3\Lambda^2 M_H^2}\right)$$

$$\mathcal{L}_{m_f} = -\frac{m_f}{v}\bar{f}f(v+H) \rightarrow$$

$$\mathcal{L}'_{m_f} = -\frac{m_f}{v}\bar{f}f\left[v + \left(1 + \frac{f_1 v^2}{2\Lambda^2}\right)H + \frac{f_1 v}{2\Lambda^2}H^2 + \frac{f_1}{6\Lambda^2}H^3 + \mathcal{O}(H^4) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)\right] .$$

$$y_f = \frac{m_f}{v} \rightarrow y'_f = \frac{m_f}{v}\left(1 + \frac{f_1 v^2}{2\Lambda^2}\right)$$