Higgs Boson self-coupling measurements @ the LHC

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aims:

- provide summary of ‘recipe’ of the electroweak sector of the Standard Model.
- provide overview of status of Higgs Boson self-coupling measurements.*
- consider the prospects for the future.

* concentrate on the SM: I will only briefly mention BSM.

electroweak cooking

- ingredients:

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

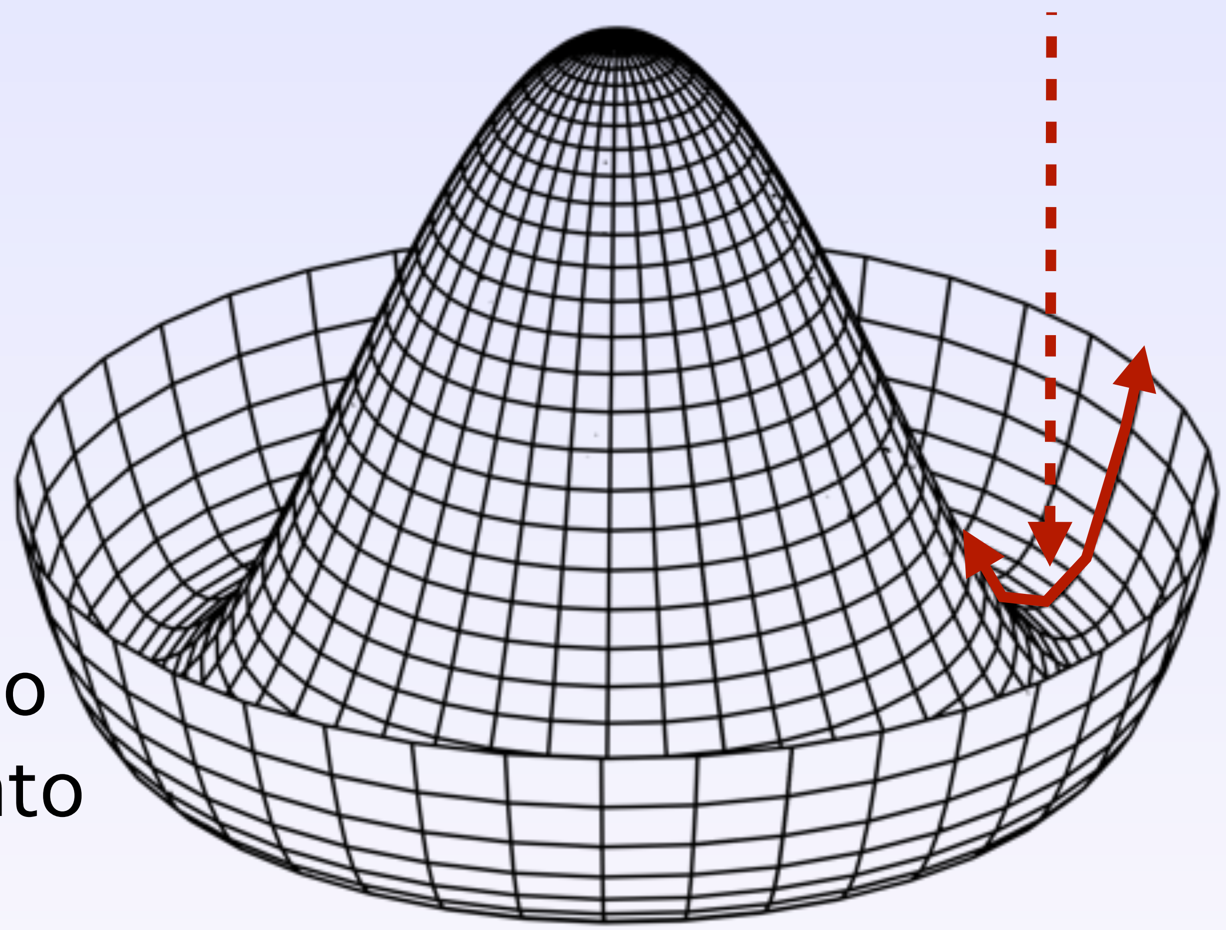
+ complex doublet scalar, ϕ

+ 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.

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



- consider fluctuations of the scalar field about the minimum:

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

- make a gauge transformation to absorb the Goldstone modes into the gauge bosons.

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

Higgs potential

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

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

- M_H, the Higgs mass, has been measured in July 2012 ~125 GeV.
- v, the vacuum expectation value, from the 4-fermion interaction at low energies ~ 246 GeV.
- two 'unknowns': λ, the triple self-coupling; $\tilde{\lambda}$, the quartic self-coupling — not measured directly

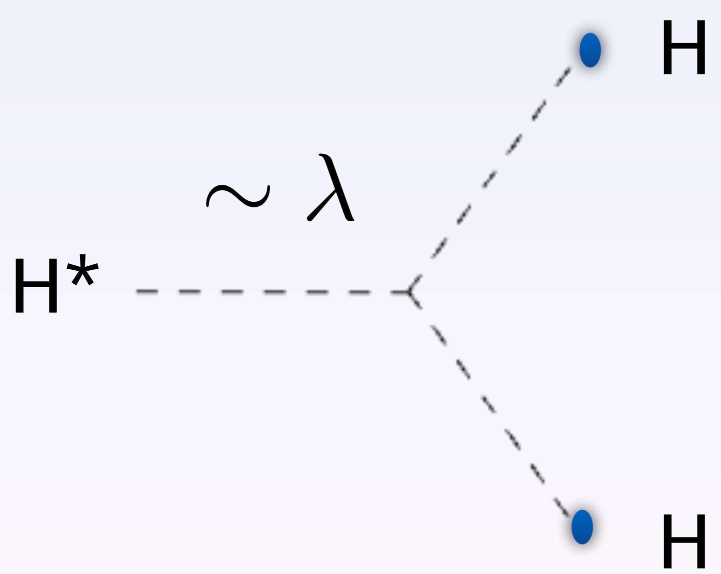
why should we care?

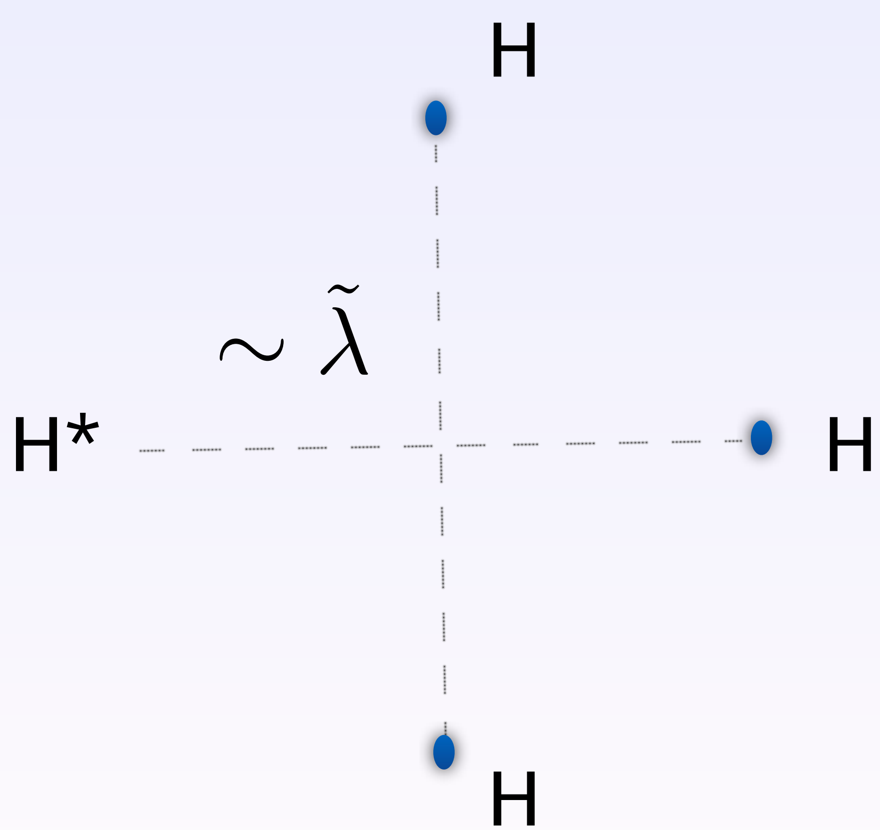
- standard model prediction: $\tilde{\lambda} = \lambda = \frac{M_H^2}{2v^2} \simeq 0.13$.
- here: regard SM as an effective theory, with the self-couplings as per se free parameters.
- direct confirmation of the standard model relation probes new physics effects, e.g.
  - extended Higgs sectors.
  - heavy particles running in loops.
  - + other higher-dimensional operators.
- + probes the general consistency of the standard model.

probing Higgs boson self-interactions

- determination of λ and $\tilde{\lambda}$: through multi-Higgs boson production @ colliders:

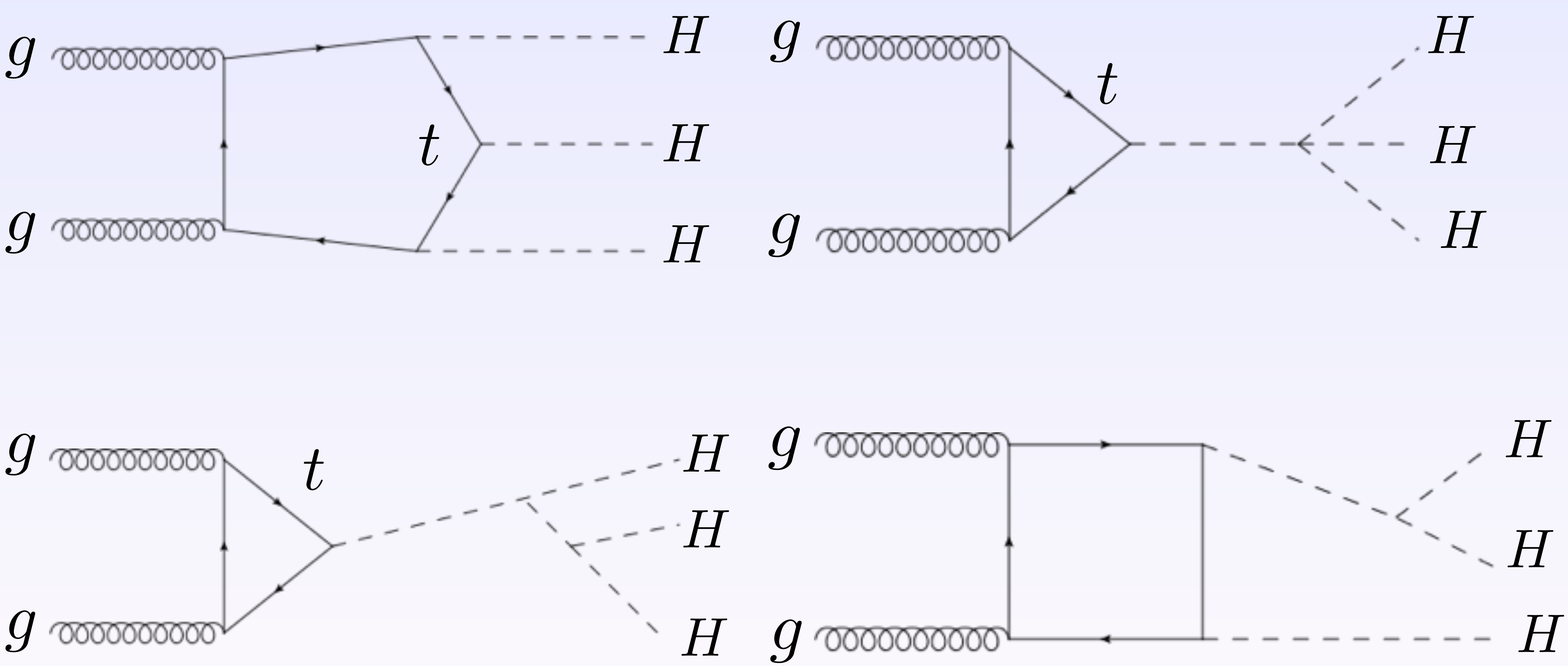
- triple coupling, λ, $\longrightarrow$ **Higgs pair production.**
- quartic coupling, $\tilde{\lambda}$, $\longrightarrow$ **Higgs triple production.**





quartic Higgs coupling (I)

- consider <u>triple</u> Higgs boson production at hadron colliders,
- contributing diagrams: $gg \to HHH$



[Plehn, Rauch, hep-ph/0507321]

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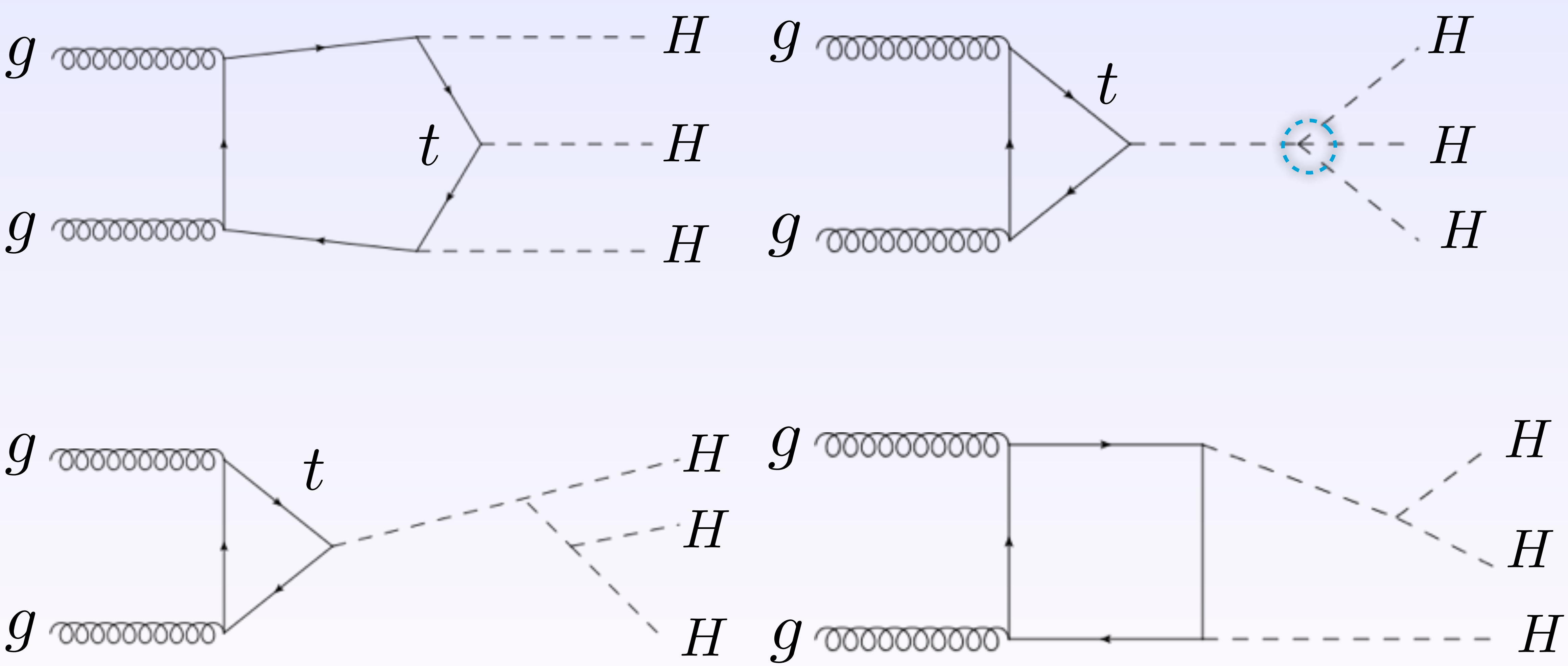

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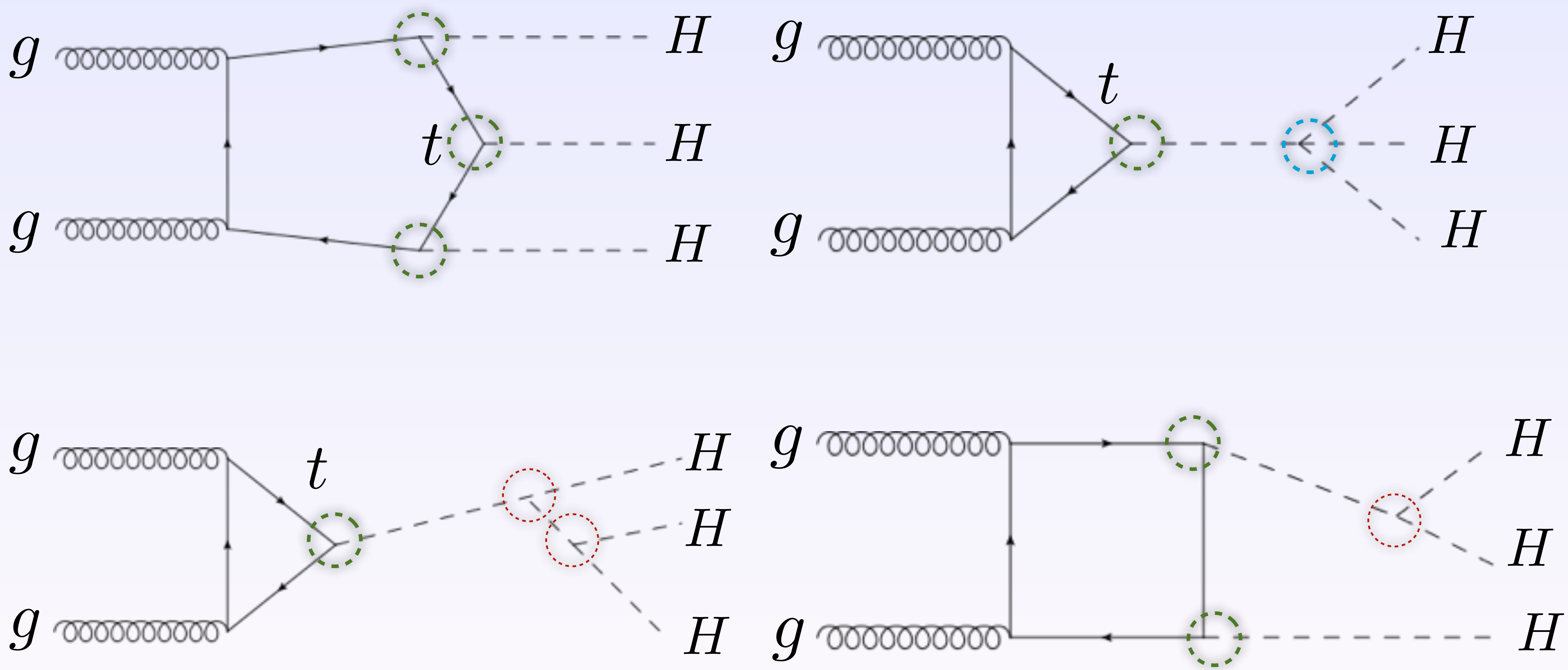


[Plehn, Rauch, hep-ph/0507321]

quartic Higgs coupling (II)

- <u>total</u> HHH production @ LHC:

$$\sigma_{HHH}(\text{LHC@14 TeV}) \simeq 0.04 \text{ fb}$$

- even for V^nLHC:

$$\sigma_{HHH}(\text{V}^{\text{n}}\text{LHC@200 TeV}) \simeq 10 \text{ fb}$$

- <u>AND</u>: must know the triple coupling <u>and</u> top Yukawa well.

$\Rightarrow$ <u>extremely</u> difficult to measure this coupling @ LHC or even any future hadron collider. [Plehn, Rauch, hep-ph/0507321]

(compare to: $\sigma_{gg\to H}(\text{LHC@14 TeV}) \simeq 50 \times 10^3 \text{ fb}$)

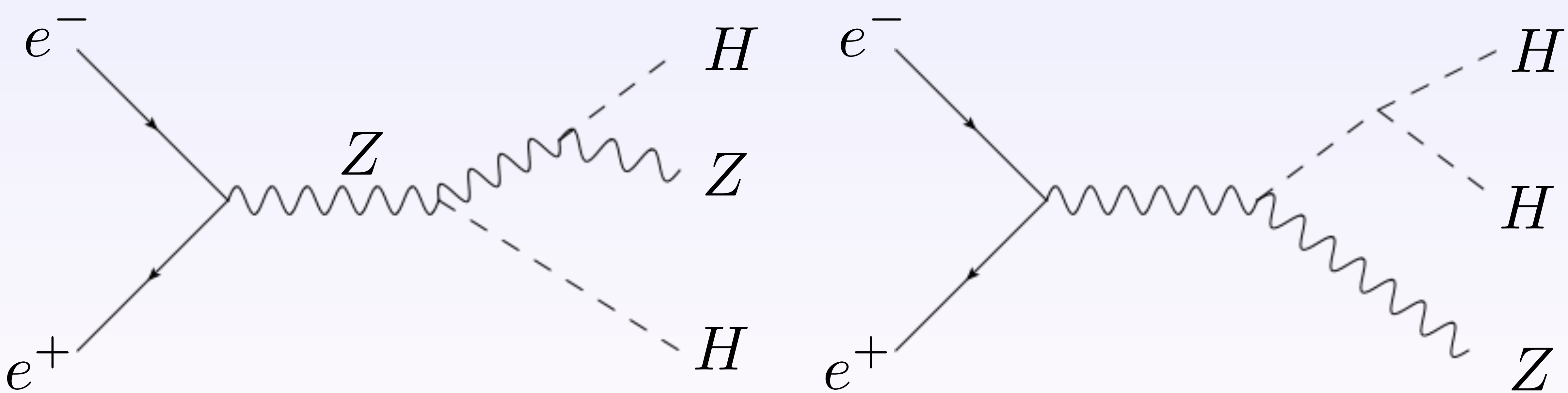
$$\Rightarrow$$

focus on triple Higgs coupling
(through HH production)

triple coupl. @ lin. colliders (I)

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

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



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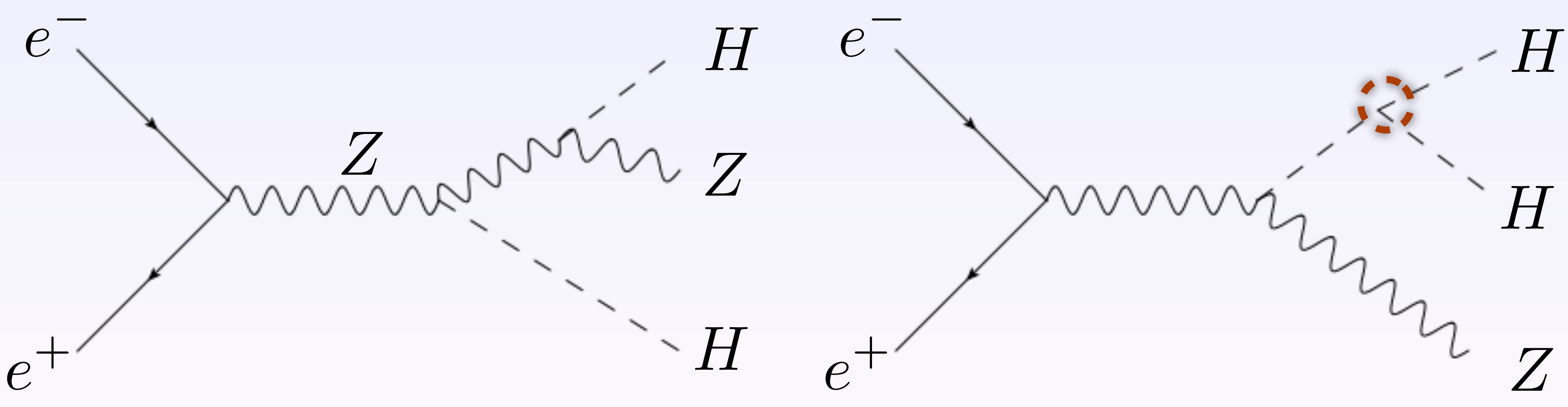


triple coupl. @ lin. colliders (II)

- 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:

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

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

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

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

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

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

$\Downarrow$

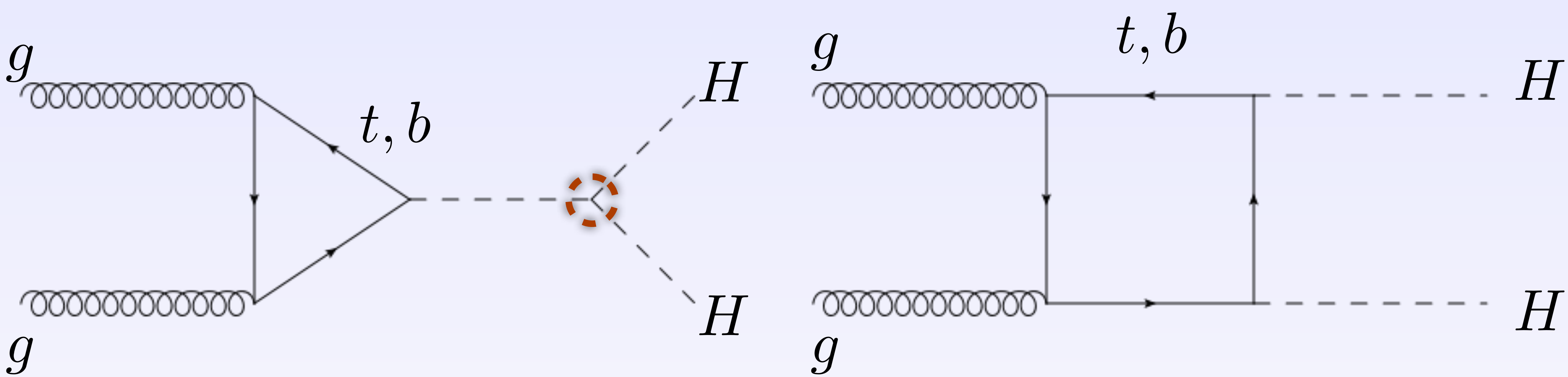
'A new jet clustering algorithm is now being developed.'

what about HH @ LHC (14 TeV)?

first: dissection of the production cross section.

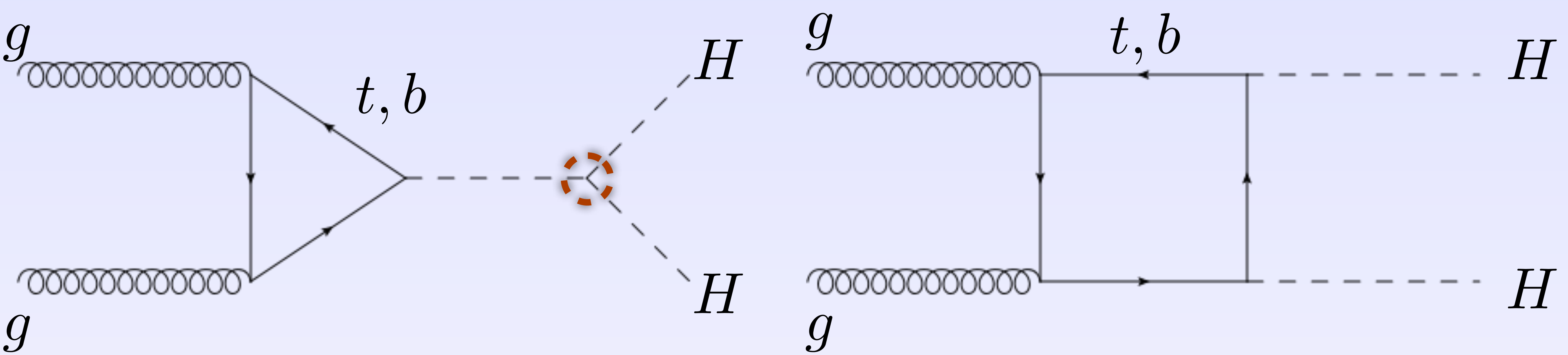
(LO) HH production @ LHC

- focus on dominant initial state: gluon-gluon fusion.
- leading order, two diagrams:



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

(LO) HH production @ LHC



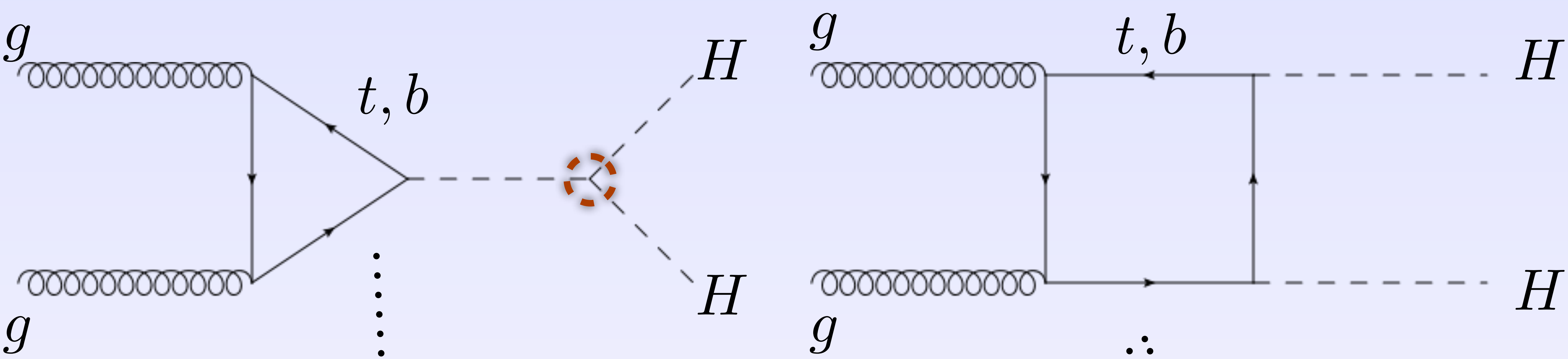
box and triangle topologies, Lorentz structures corresponding to spin-0 and spin-2 gg configurations.

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

(sum over quarks q = t, b)

(couplings normalized to SM)

(LO) HH production @ LHC



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HH production @ LHC

- NLO calculation is only available in the infinite top mass limit. [Dawson, Dittmaier, Spira, [hep-ph/9805244]].
- K-factor in this limit ~ 2.
- recently, corrections in inverse powers of the top quark mass have been computed, found to be significant. [Grigo, Hoff, Melnikov, Steinhauser, [1305.7340]].
- interesting fact: gg box and triangle contributions exactly cancel at the partonic threshold at LO. This causes a large enhancement of the K-factor in the threshold region.

HH production @ LHC

- using HPAIR (M. Spira), fits: Florian Goertz, AP, Li Lin Yang, and José Zurita [1301.3492]

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

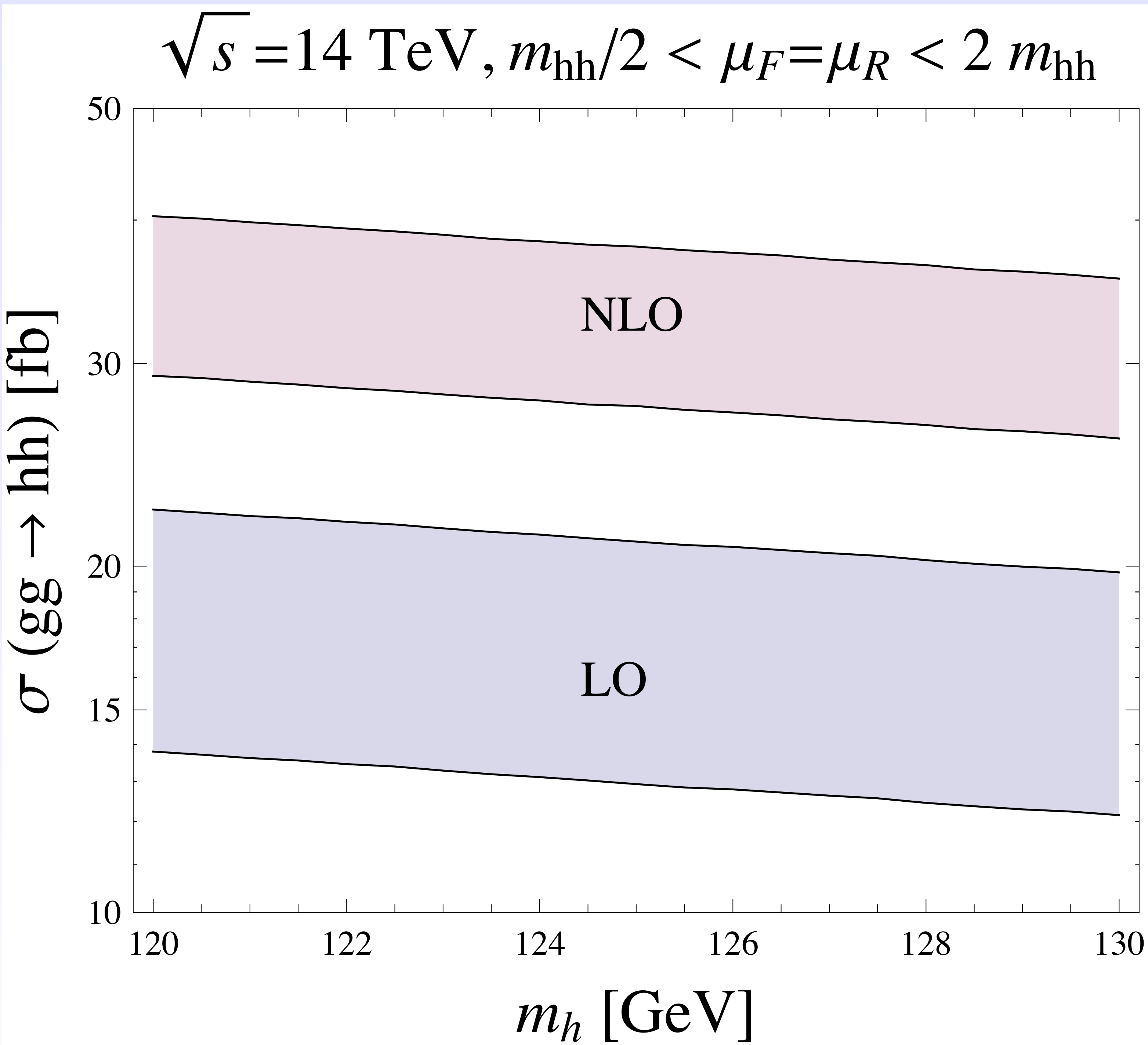
$$\sigma_{HH}^{\rm NLO}[\rm fb] = 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4$$

(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)].

HH production @ LHC



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

<u>AP</u>, Li Lin Yang, and José Zurita

[arXiv:1209.1489]

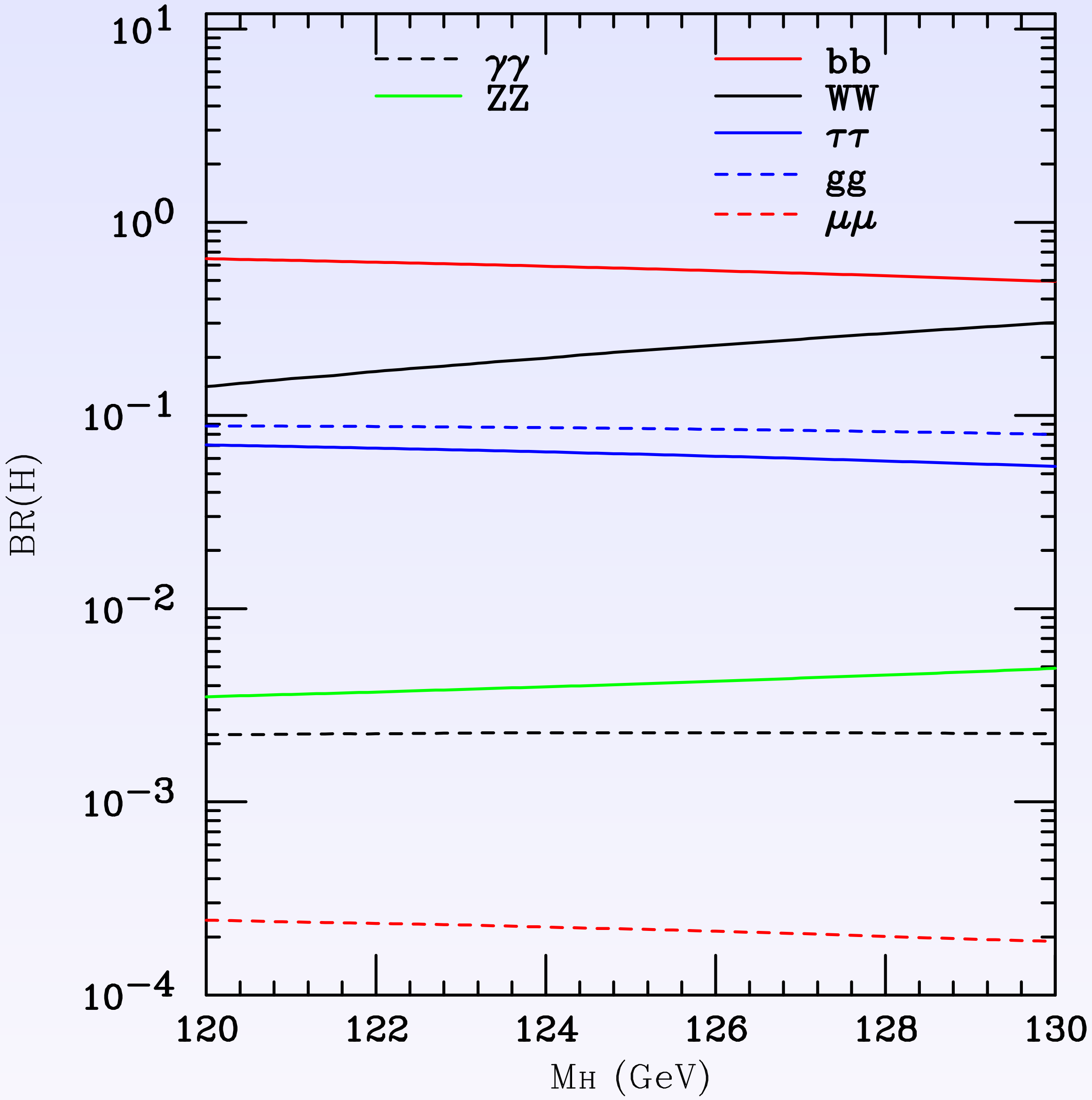
(using HPAIR)

(NLO calculation exists only in the **heavy top limit**)

$$\Rightarrow$$

the decay channels

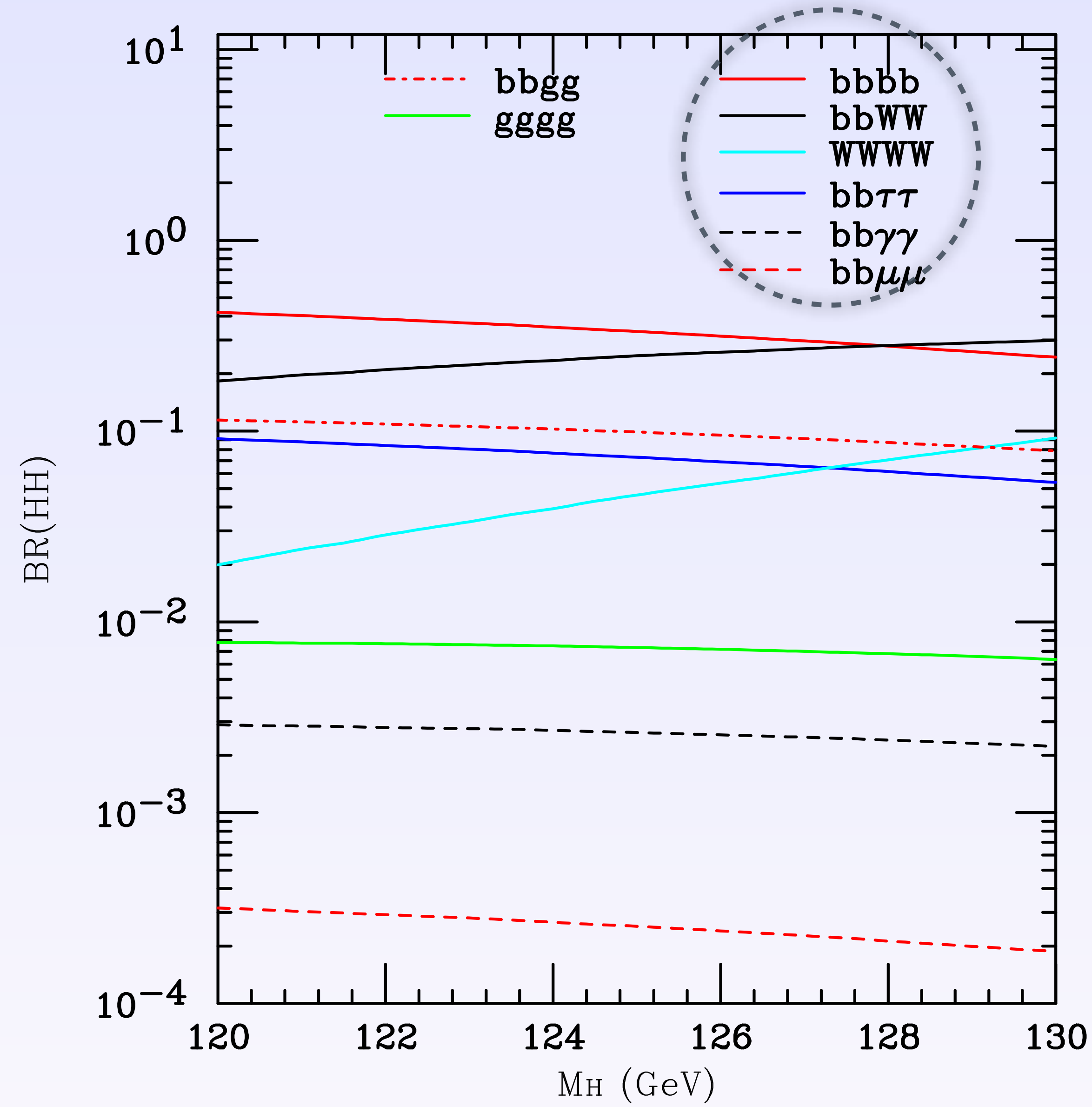
branching ratios



single production

2

=



pair production

branching ratios (M_H = 125 GeV)

pair production

$$BR[b\bar{b}b\bar{b}] = 33.3\%$$

$$BR[b\bar{b}WW] = 24.8\%$$

$$BR[b\bar{b}\tau\tau] = 7.29\%$$

$$BR[WWWW] = 4.62\%$$

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

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

$$BR[b\bar{b}ZZ] = 0.305\%$$

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

$$BR[b\bar{b}Z\gamma] = 0.178\%$$

$$BR[b\bar{b}\mu\mu] = 0.025\%$$

note: each 1% corresponds to ~100 events per 300 fb^{-1} of luminosity.

branching ratios (M_H = 125 GeV)

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shown to be potentially viable (in the SM)

establishment of HH process

- first step towards constraining the triple coupling: **establishing** (i.e. discovering) the HH process @ LHC.
- need **large** integrated luminosity: 600 fb^{-1} (certain) and 3000 fb^{-1} (possible).
- first: look at the channels that are considered to be ‘viable’.

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

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]
- 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).

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

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, Li Lin Yang, and José Zurita [arXiv:1209.1489]]
- S = 11 versus B = 7 at 600 fb^{-1} (~4σ).

more HH channels?

- $\underline{b\bar{b}b\bar{b}}$: highest BR, but fully hadronic (triggering?) and huge QCD backgrounds (σ ~ 10.8 fb).
- $\underline{b\bar{b}\mu\bar{\mu}}$: small initial cross section, essentially found to be impossible (σ ~ 0.008 fb). [Baur, Plehn, Rainwater [hep-ph/0304015]].
- $\underline{WWWW}$: good for high-mass Higgs. for low mass seems to be hard due to BR of Ws (σ ~ 1.5 fb).
- $\underline{\tau\tau\tau\tau}$: low rate and τ-tagging (σ ~ 0.13 fb).
- $\underline{WW\tau\tau}$: τ-tagging, W BRs (σ ~ 0.86 fb)
- $\underline{b\bar{b}Z\gamma}$, $\underline{b\bar{b}ZZ}$: low rates and BR for Zs (σ < 0.1 fb).

other production modes?

- several associated production modes exist:

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

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

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

summary of HH 'searches':

- 3 channels shown to be potentially viable.

- these should be looked at by experimentalists.

- some others could be investigated again.

Now: what about measuring λ?

first: how well do we need to measure λ?

- recent study estimates that λ will likely need to be measured to better than 20% to see a deviation from the SM expectation. [Gupta, Rzehak, Wells [1305.6397]]
- (considers new mixed-in singlets, MSSM Higgses and composite models.)
- other studies of HH in relation to BSM:
  - in composite Higgs models, e.g. [Gillioz, Gröber, Grojean, Mühlleitner, Salvioni, 1206.7120],
  - in warped extra-dimensional models, e.g. [Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz, 1303.6636],
  - Higgs portal/MSSM/pseudo-Nambu-Goldstone boson, e.g. [Dolan, Englert, Spannowsky, 1210.8166],
  - + many more...

how well can we measure λ?

- large theoretical uncertainties: scale, PDF, α_s & effective theory (EFT) uncertainty: ~30-40%. [Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581]].
- note: cross section has been shown to be larger than NLO EFT:
  - including top mass corrections: ~10% increase. [Grigo, Hoff, Melnikov, Steinhauser, [1305.7340]]. Moreover, the scale dependence reduced (~5%).
  - in the effective theory at NNLO: ~20% increase. [de Florian, Mazzitelli, [1305.5206]]

how well <u>can</u> 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: use rates instead. [Goertz, <u>AP</u>, Yang, Zurita [arXiv:1301.3492]].

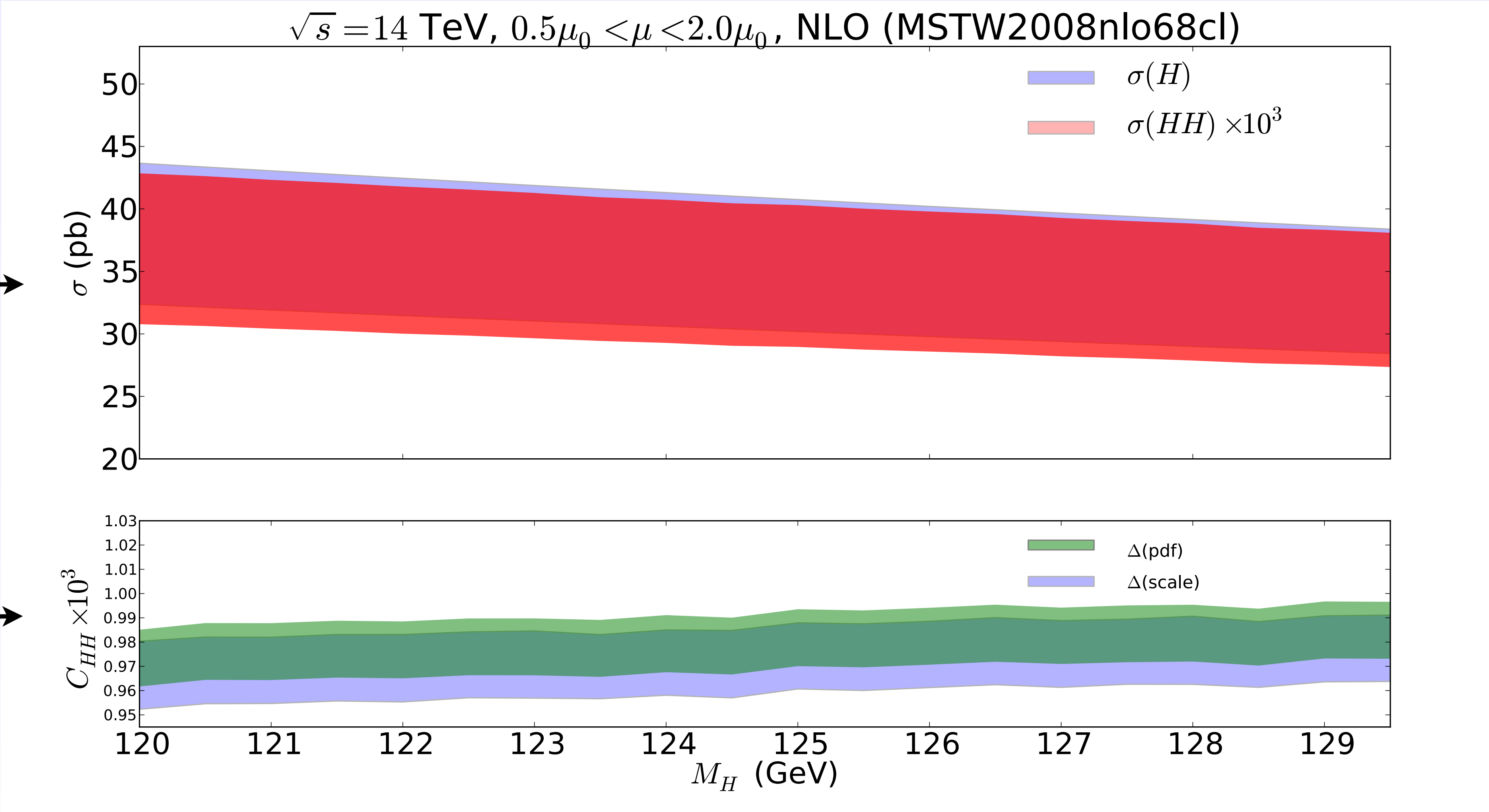
how well can we measure λ?

- claim: single H and double H production possess similar topologies and hence QCD corrections could be also similar.
- can use ratios of cross section of HH to single H to cancel out part of the theoretical uncertainties.

σ_{HH}x1000

σ_H

$C_{HH}=\sigma_{HH}/\sigma_H$



Goertz, AP, Yang, Zurita [arXiv:1301.3492]

how well <u>can</u> we measure λ?

- 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

[Goertz, <u>AP</u>, Yang, Zurita [arXiv:1301.3492]]

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

- with this method, to get down to e.g. O(10%), we would need an extra 3-4 channels with an error of ~40%-50% each.

outlook: theoretical improvements

- a better NLO calculation could be performed. hard: two loops with two mass scales (H and top mass).
- then this could be matched with the parton shower (MC@NLO/POWHEG) to provide better description of kinematical distributions.
- until then perhaps resummed calculations?
- or an improved Monte Carlo with the real emission matrix elements?
- with an improvement on the kinematical description, shape analyses could improve the limits from each channel.

outlook: ‘other’ improvements

- use ‘improved’ boosted jet techniques to push the channels further: e.g. Shower deconstruction or Q-jets. [Soper, Spannowsky, [1102.3480, 1211.3140], Ellis, Hornig, Roy, Krohn, Schwartz [1201.1914]].
- other channels could be made viable.
- further ‘technological’ improvements in jet sub-structure techniques?
- long-term (& expensive!): an LHC energy upgrade will allow for more events to ‘play with’. e.g. σ(HH@33TeV) ~ 210 fb.

summary (I)

- with the discovery of the Higgs boson, an important next step is to determine the form of its potential.
- this can be done via measurement of the self-couplings.
- the triple Higgs coupling, λ, can be probed via Higgs pair production (HH).
- total cross section is low and the HH process is challenging.

summary (II)

- several investigations performed so far,
- but more work needs to be done:
- **theoretically:** improving description of the kinematics and the total cross section,
- in **phenomenology:** re-examine channels, search new,
- **experimentally:** to assess the viability of the promising channels.

special thanks

- special thanks to my collaborators: Florian Goertz, José Zurita, Li Lin Yang.

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- ...and thanks for your attention!

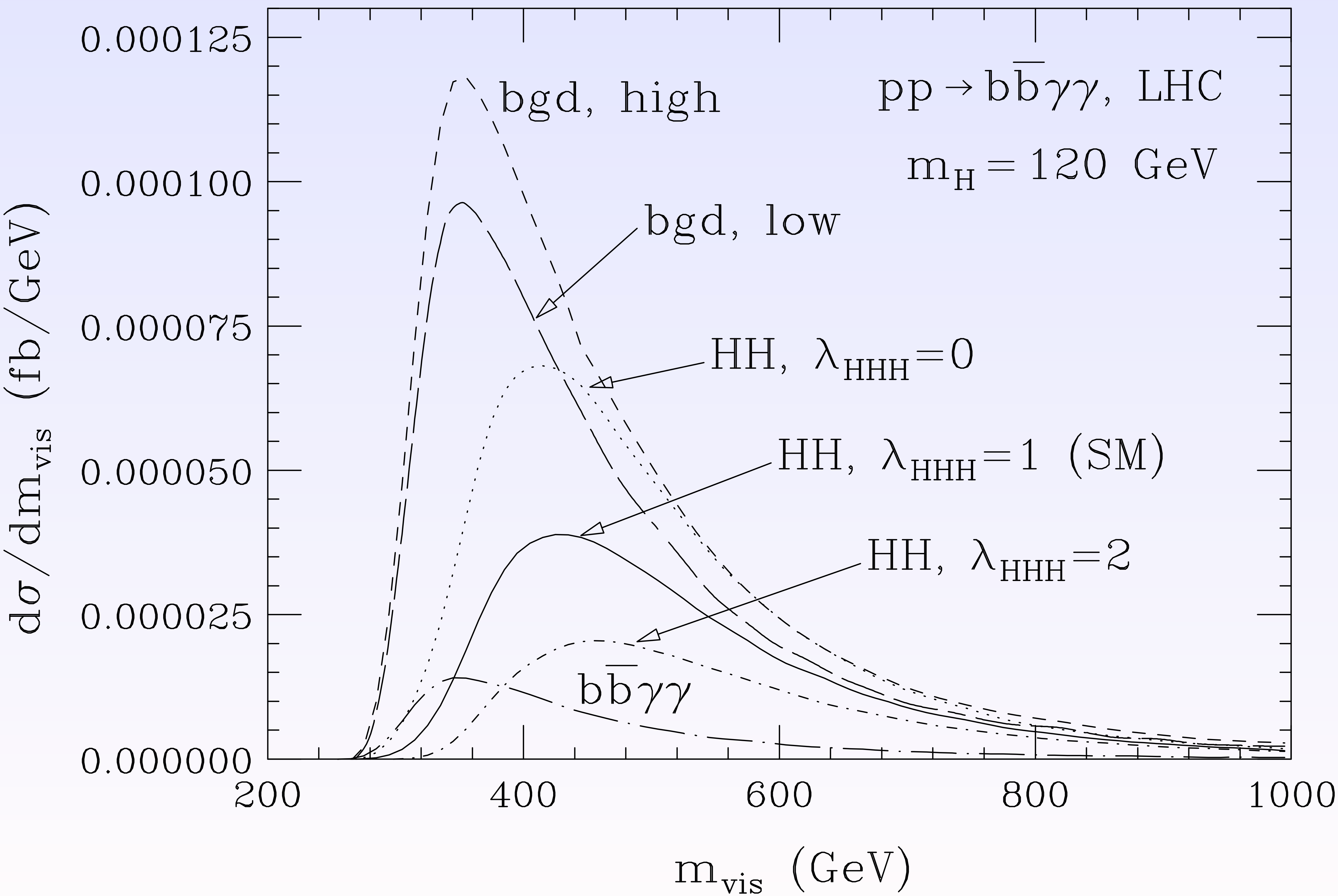
auxiliary slides

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):



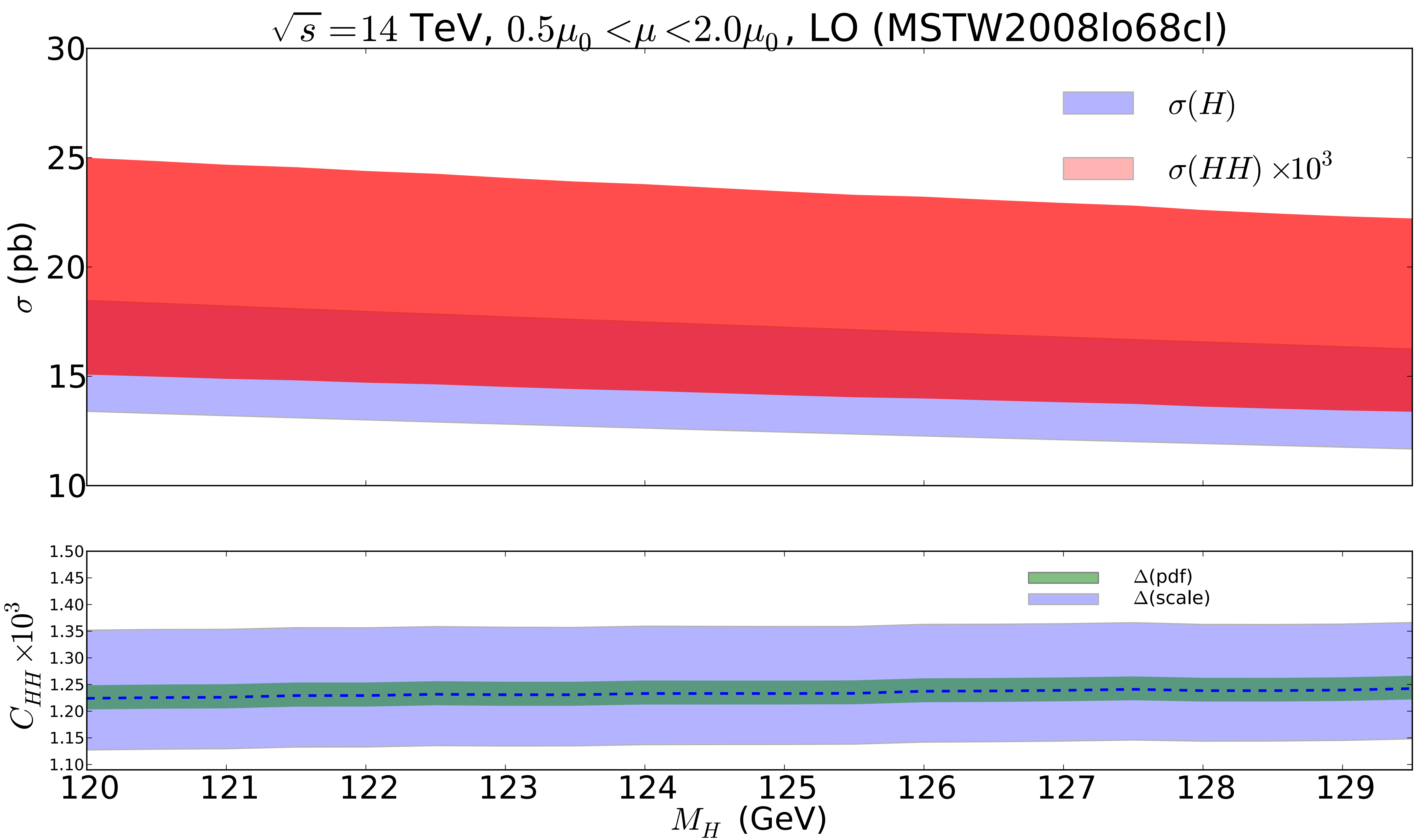
using rates (i.e. cross sections)

- 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.

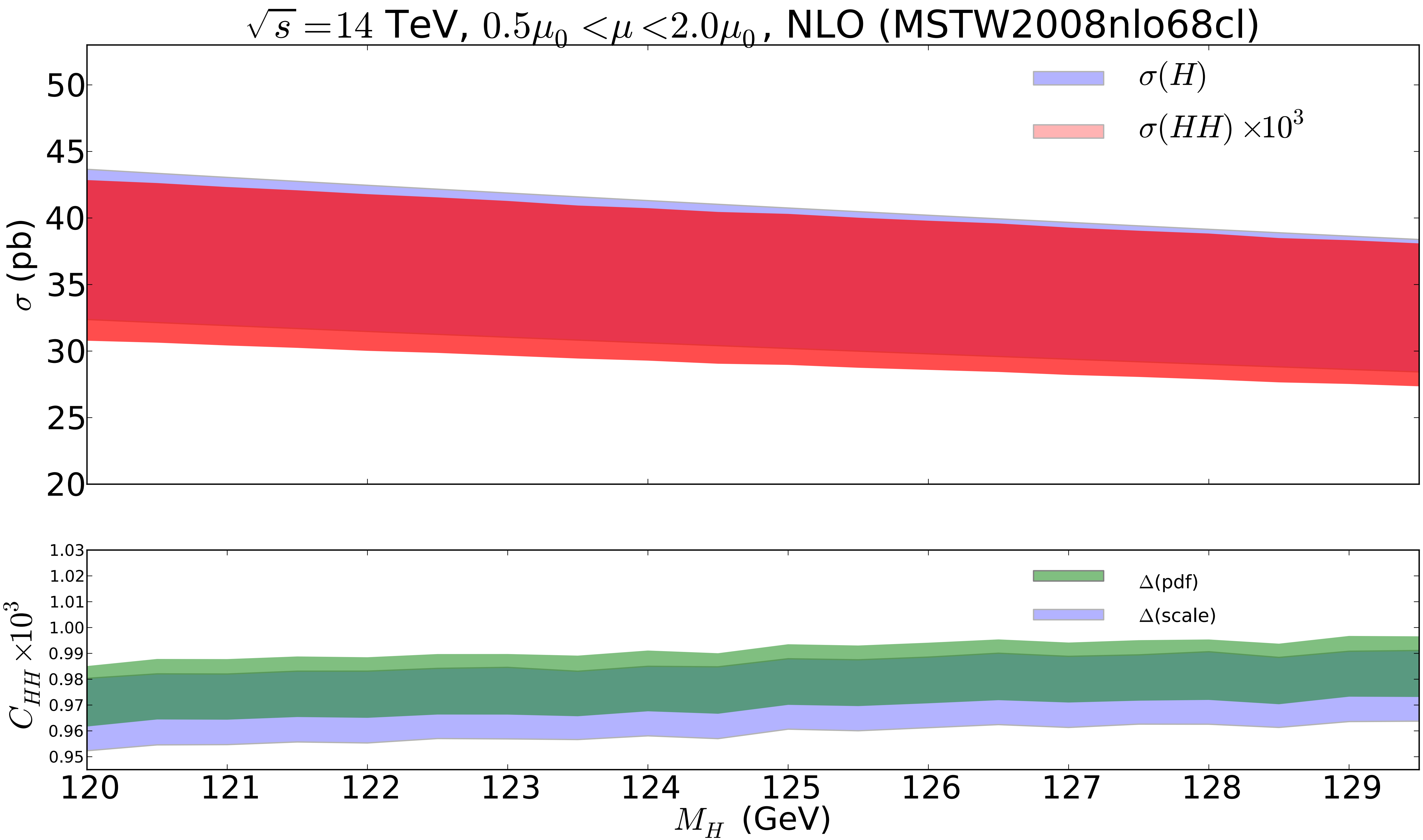
using ratios of cross sections

- 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.

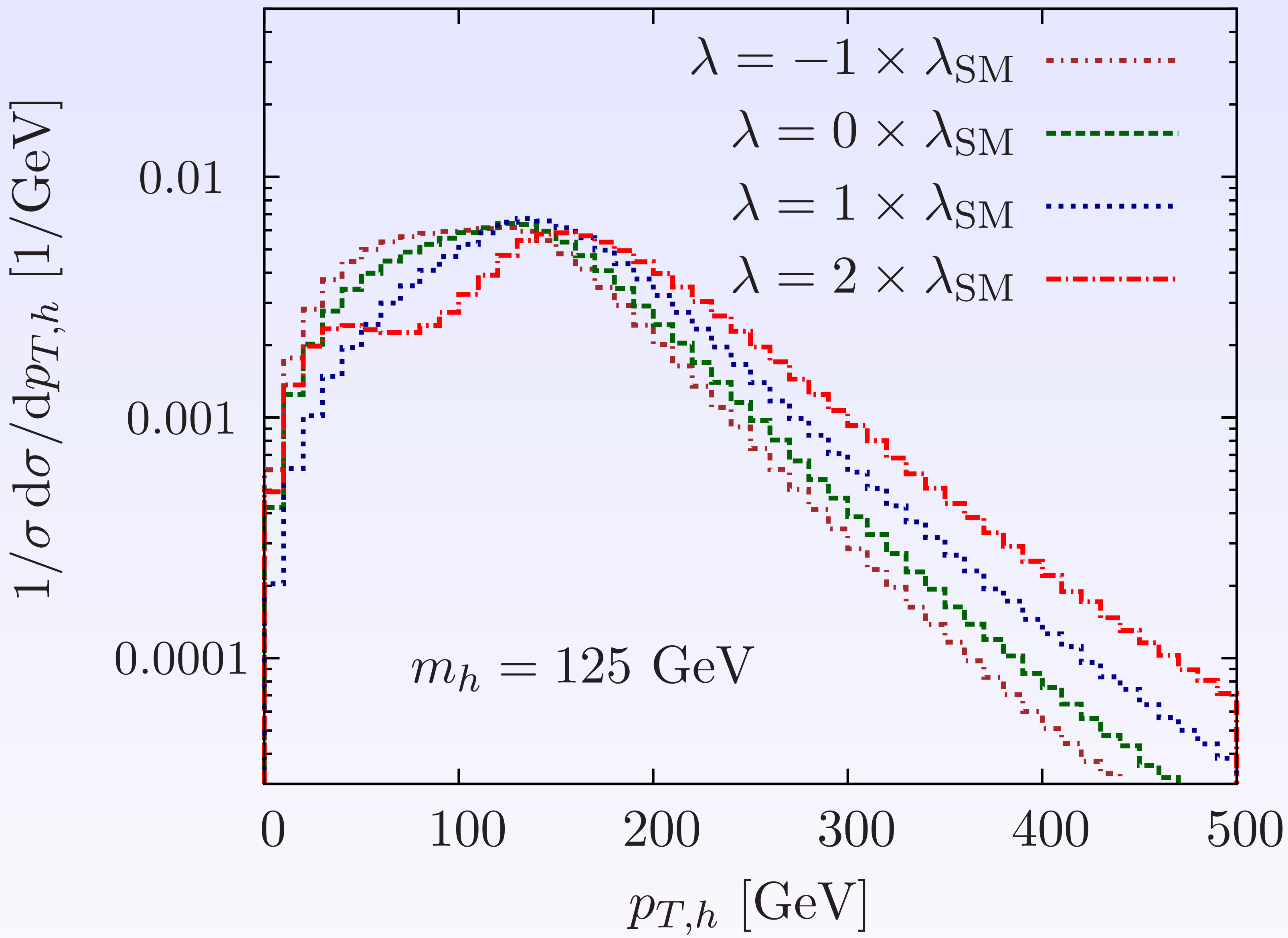
H+V, BDRS Analysis

[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:**

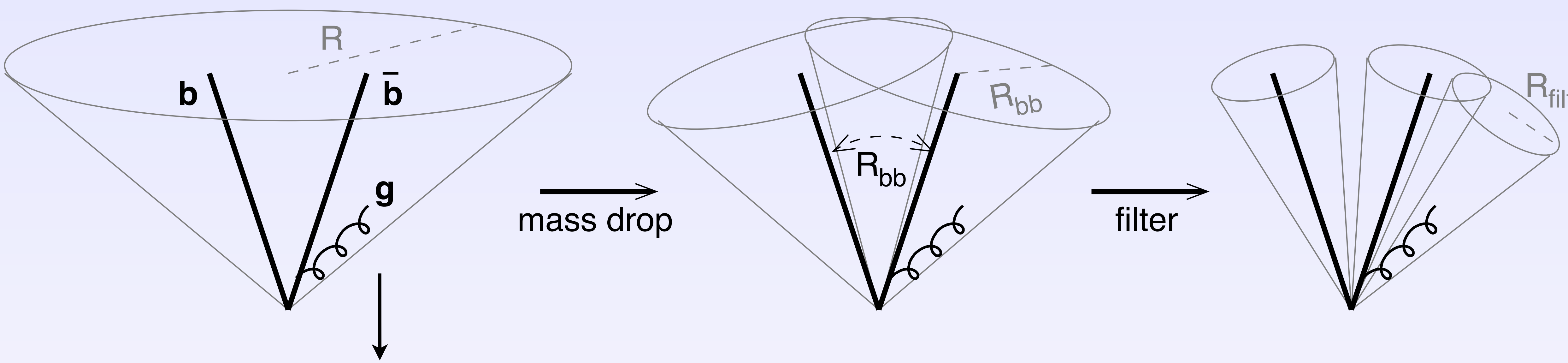


[Dolan, Englert, Spannowsky, 1206.5001]

- + other arguments of BDRS technique apply.

H+V

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



"fat jet"

- 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)

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

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  ()

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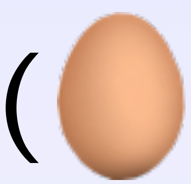
  ()

electroweak Lagrangian (I)

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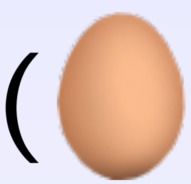
  an $SU(2) \times U(1)$ gauge symmetry ()

  + a complex doublet scalar, ϕ. + ()

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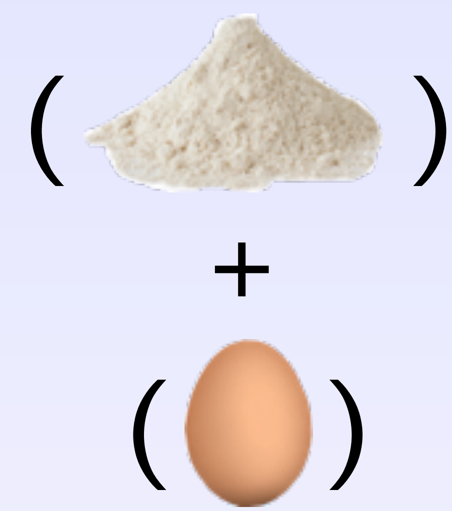

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the covariant derivative:

$$D^\mu = \partial^\mu + i g_2 (T \cdot W^\mu) + i Y g_1 B^\mu$$

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

electroweak Lagrangian (II)

- with potential:

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

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

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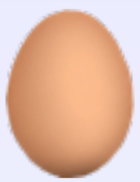
()

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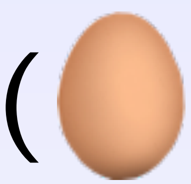
()

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

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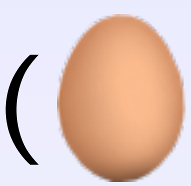
()

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(...)

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electroweak Lagrangian (III)

- 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 (IV)

- 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

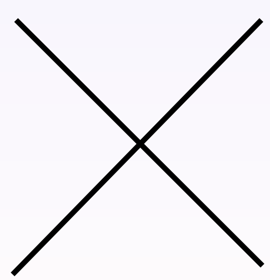
‘fixing’ free params. (I)

- 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!

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



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WARNING: Leading Order!

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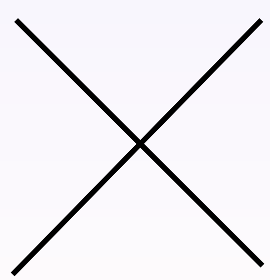

$$\Rightarrow \quad \frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}$$

‘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!

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