Two Aspects of Di-Higgs Production:
NLO Predictions for HH
Di-Higgs Relation to Baryogenesis

M. Margarete Mühlleitner
Karlsruhe Institute of Technology

MultiHiggs '22: 30 Aug - 2 Sep 2022
Lisbon, Portugal

Talks and some of the workshops are broadcasted.

Online participation fee: 10 Euros

Also men can register.

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24-27 November 2022
Karlsruhe Institute of Technology
Europe/Berlin timezone

Overview
Abstract Submission
Timetable
Registration
Venue
Social Program
Hotel Booking Link
Sponsoring
German Poster Download
English Poster Download
Wilhelm und Else Heraeus-Förderprogramm

Contact
dpt2022org@lists.kit.edu

Abstract submission has opened!
The deadline for abstract submission is 9 September 2022.

Fees for the conference and dinner:
Conference Fee for early bird registration:
Bachelor or Master student: 25 Euro
With Master's degree: 35 Euro.
End of early bird registration: 30 September 2022.

Conference Dinner fee: 20 Euro.

Information on payment instructions will be sent via email after registration.

Information on financial support:
Members of the DPG that are eligible according to the criteria (see here) can ask for travel allowance within the „Wilhelm und Else Heraeus-Förderprogramm". More details are given in the menu. Note that the deadline for applications is 13 October 2022.

Some advice: In case you are not eligible for this support you can try with the various CRCs, excellence clusters, graduate schools, ... at your university. They have money for equal opportunity. If you are a member of these scientific programs you can ask for support. You can also ask the equal opportunity offices of your universities if they can support you. If you are already affiliated with an institute you can ask the director of the institute or your supervisor for support.

Child care:
If you need child care during DPT2022 please fill in the corresponding fields in the registration form.

The German Conference of Women in Physics (Deutsche Physikerinnentagung), taking place annually since 1997, is supported by the German Physical Society (Deutsche Physikalische Gesellschaft DPG) and by its Working Group on Equal Opportunities (AKC). This year's conference will be hosted by the Karlsruhe Institute of Technology (KIT).

The conference offers female physicists of different areas and at different career levels - from student to professor as well as physicists in industry - the possibility for networking and professional exchange. The program of the conference covers scientific talks from different areas of physics with special focus on the research performed at KIT, the presentation of professional perspectives for physicists, school and didactic events as well as events on topics like equal opportunity, work-life balance, or career management.

The scientific program will consist of keynote talks and a selection of registered talks. If you are interested in giving a talk (oral or in a poster session) you will have the possibility to send an abstract once the registration will be open. The talks will be selected by the scientific organization committee. You will also have the possibility to register for various workshops and events in due time.

The conference will take place in person (if the then current Covid rules allow for it). A good part of the program will also be broadcasted online. - Should it turn out that Covid rules will not allow for an in person format in November we will switch to the online format. The majority of the talks and events will be in English (details will be given in due time).

www.physikerinnentagung.de

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Patron of the conference is Frau Bettina Stark-Watzinger, Federal Minister for Education and Research.

Confirmed speakers include:

- Prof. Cornelia Denz, University of Münster
- Prof. Monica Dunford, University of Heidelberg
- Prof. Claudia Felser, Director Max-Planck Dresden, Prizewinner of the Max Born Award 2022
- Dr. Elisabeth Fischer-Friedrich, TU Dresden, Prizewinner of the Hertha-Sponer Award 2022
- Prof. Franziska Glassmeier, TU Delft
- Prof. Ramona Gröber, University of Padova
- Dr. Edda Gschwendtner, CERN
- Prof. Céline Hadziioannou, University of Hamburg
- Prof. Stephanie Hansmann-Menzemer, University of Heidelberg
- Prof. Erica Lilleodden, Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen IMWS
- Prof. Elisa Resconi, TU Munich
- Prof. Roser Valenti, Goethe Universität Frankfurt am Main
- Prof. Annette Zippelius, University of Göttingen, Prizewinner of the Max-Planck-Medal 2022

For further questions or help contact the local organization committee at dpt2022org@lists.kit.edu.

KIT
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Outline

- Introduction
- NLO QCD Corrections to Higgs Pair Production
- Top-Yukawa Induced EW Corrections to Higgs Pair Production
- Higgs Pair Production and Baryogenesis

Introduction

Motivation

✦ Higgs Discovery ⤳ New Era of Particle Physics: structurally completes the SM

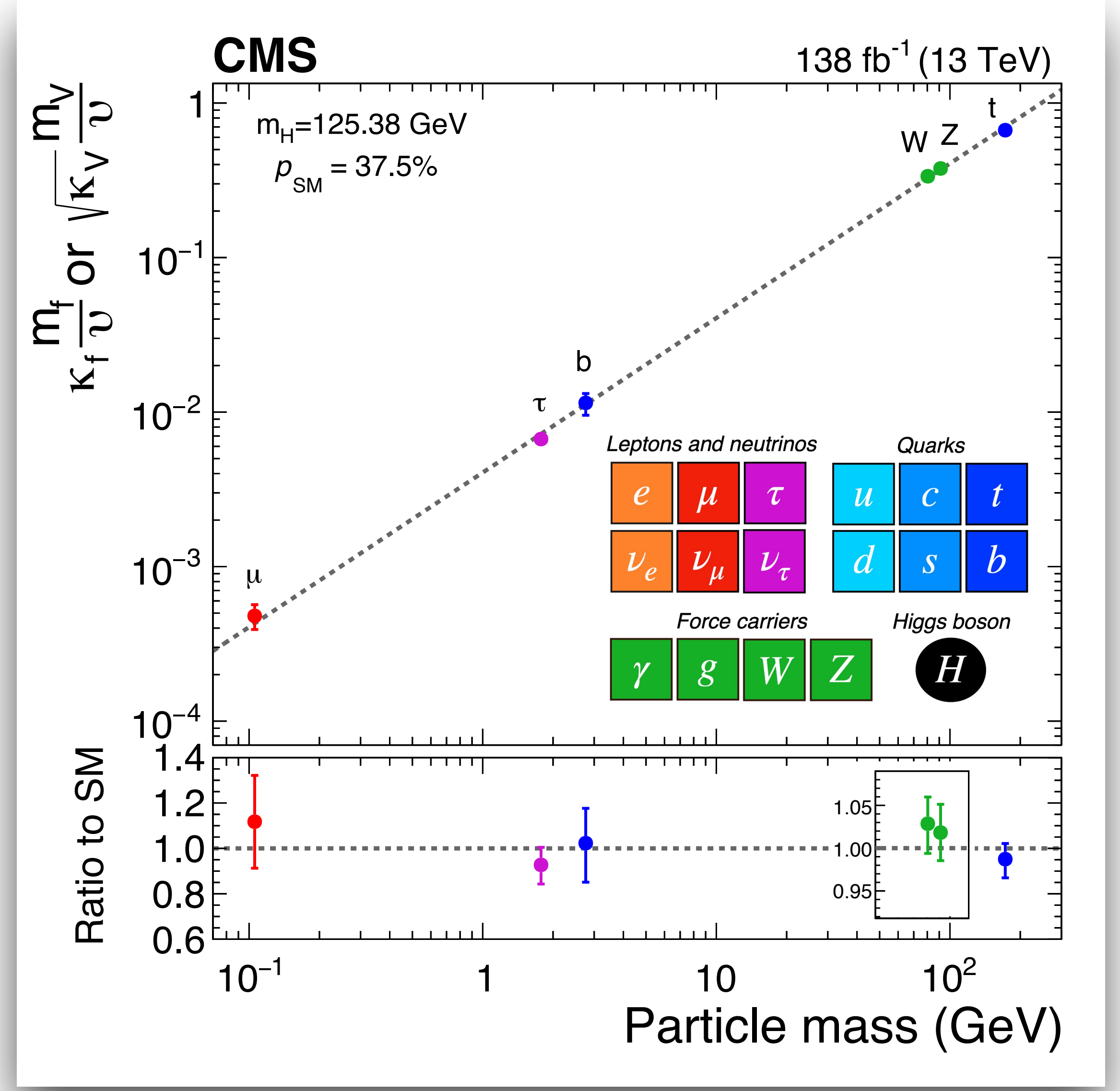
- self-consistent framework to describe physics up to cosmologically relevant scales
- extended Higgs sectors: answers to generation of baryon asymmetry, nature of DM

✦ SM Higgs couplings:

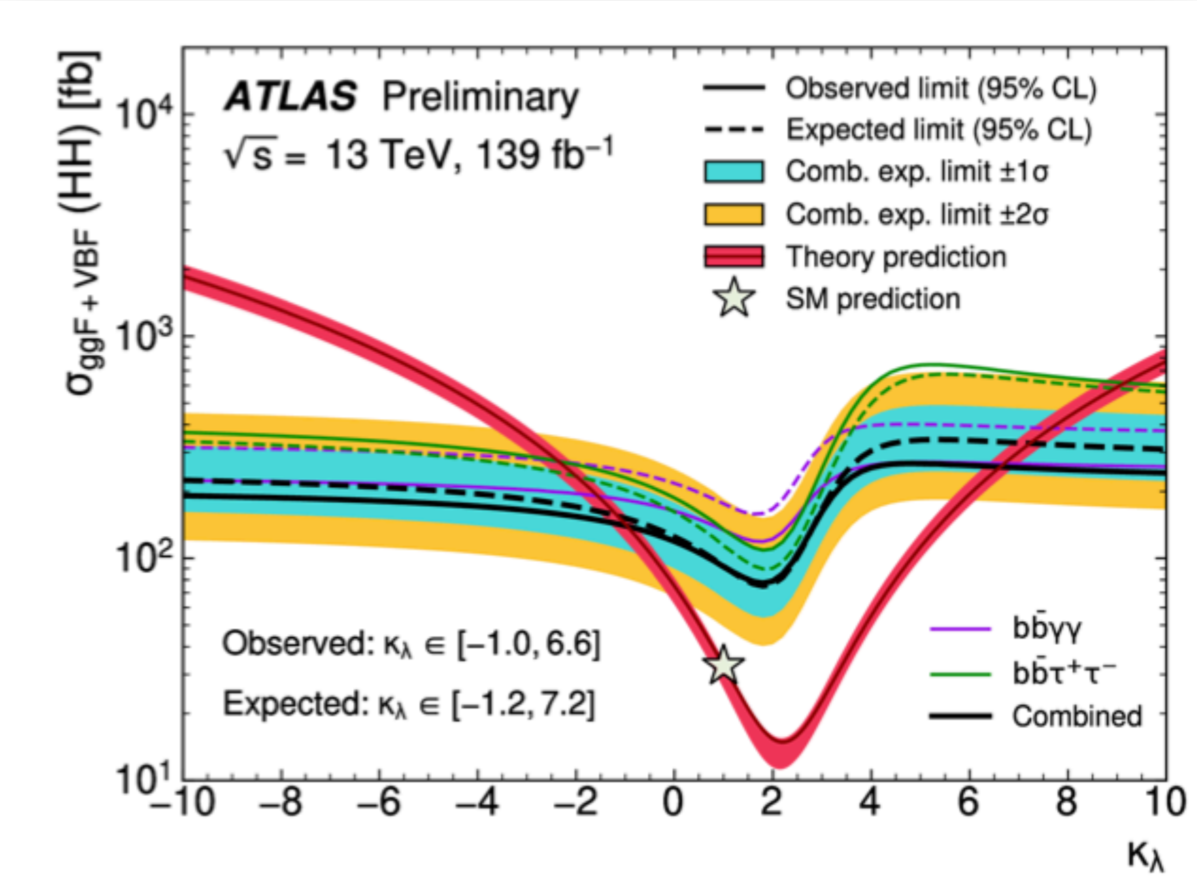
- proportional to masses/masses² of the corresponding SM particle
  $g_{hff} \sim m_f/v$, $g_{hVV} \sim m_V^2/v^2$

✦ Higgs self-coupling strengths:

- still unknown



Experimental Results - Limits on Trilinear Higgs Self-Coupling



[Rui Zhang, ATLAS, HH Workshop´22]

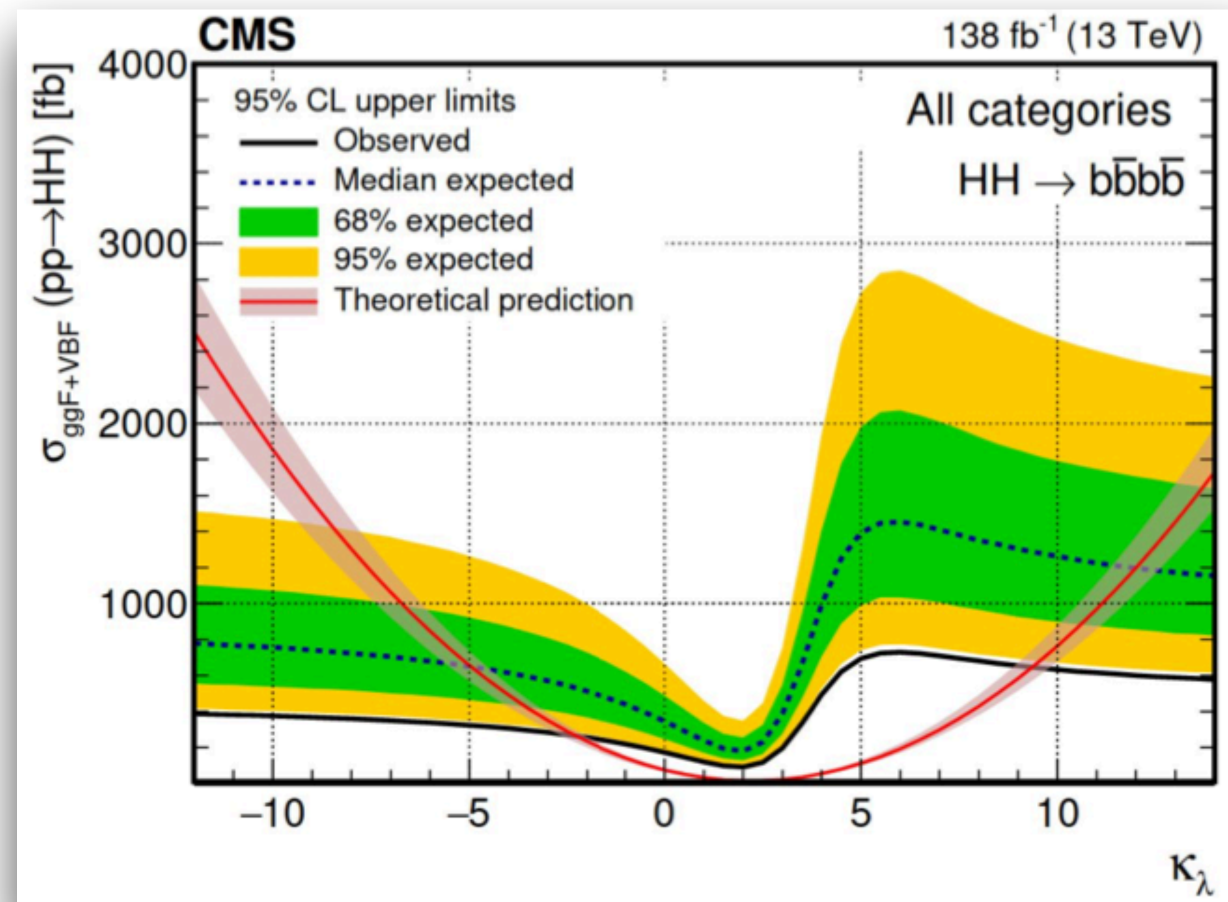
Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

Obs. $k_\lambda \in$ [-2.3, 9.4]

Exp. $k_\lambda \in$ [-5.0, 12.0]

[Fabio Monti, CMS, HH Workshop´22]



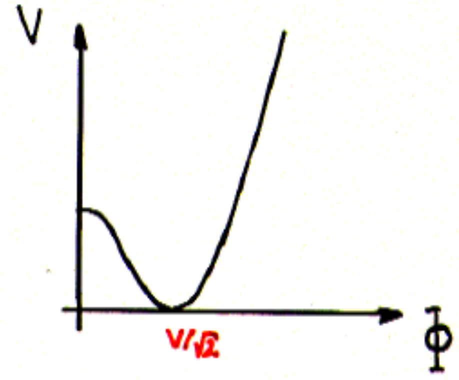
Ultimate Test of the Higgs Mechanism

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

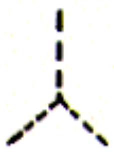
$v = 246$ GeV

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$



Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higg self-coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$



quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)

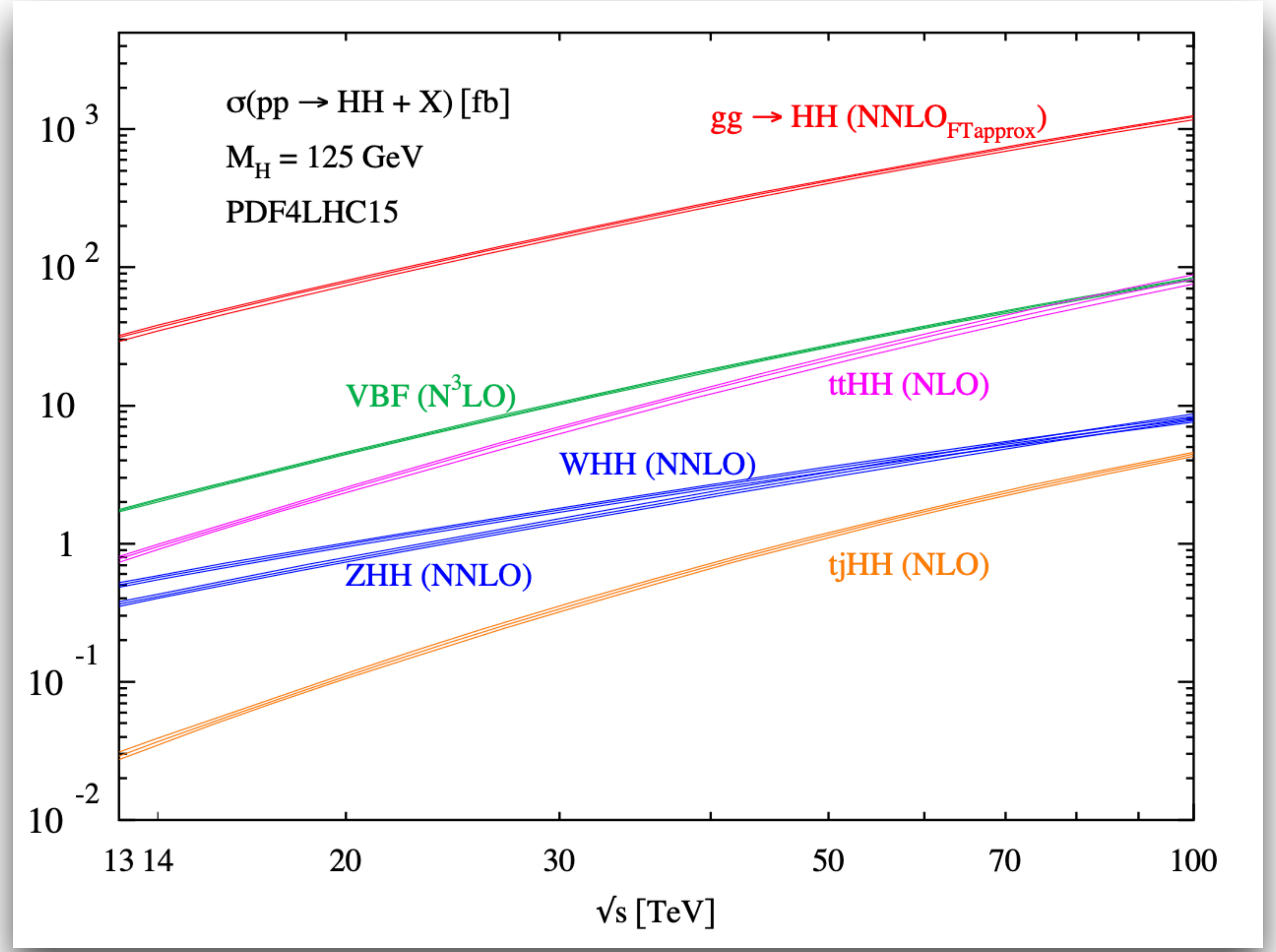
(a) trilinear coupling : via Higgs pair production

(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential	} ⇒	establish the scalar sector of the Higgs mechanism experimentally

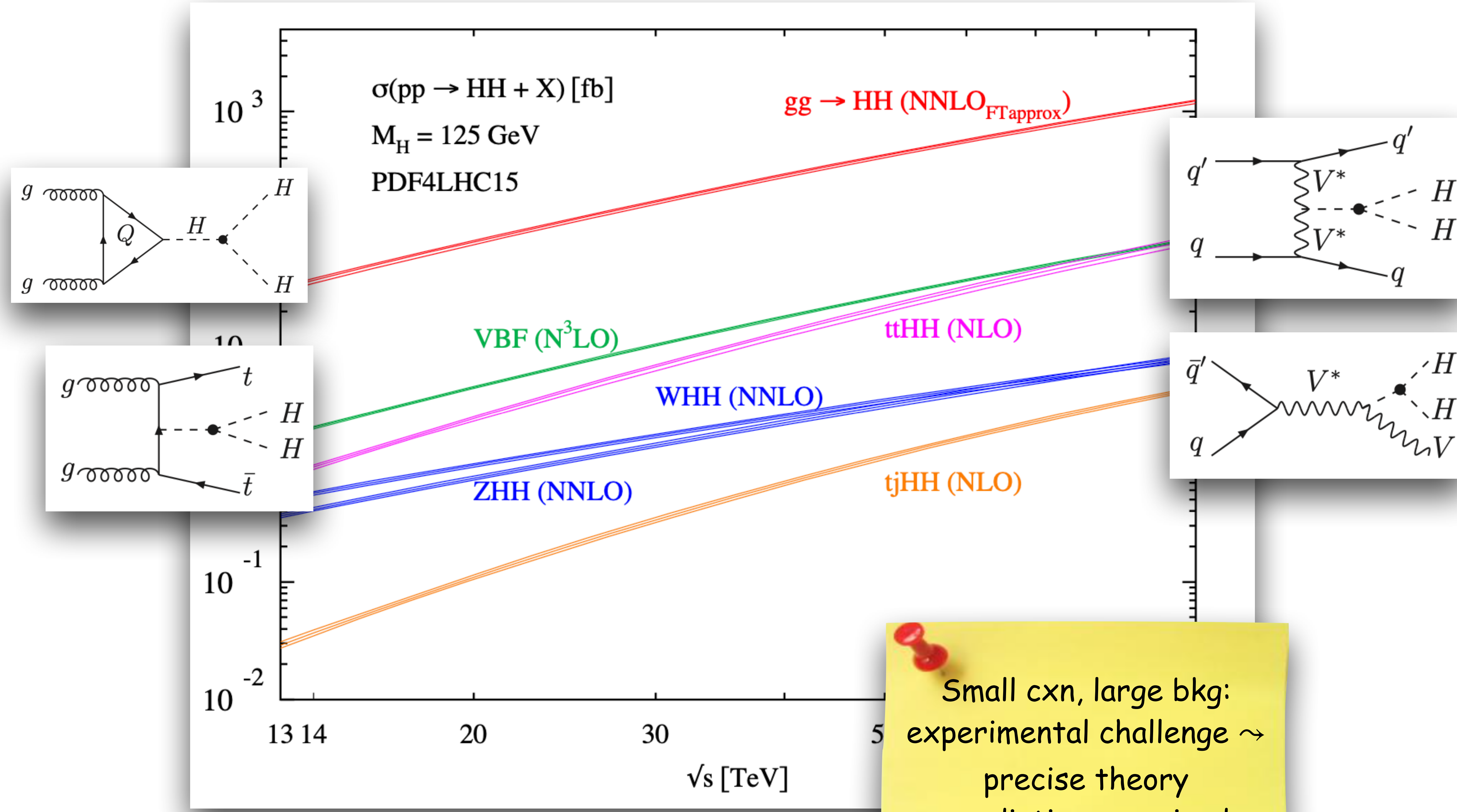
Double Higgs Production Processes

[HH, White paper]



Double Higgs Production Processes

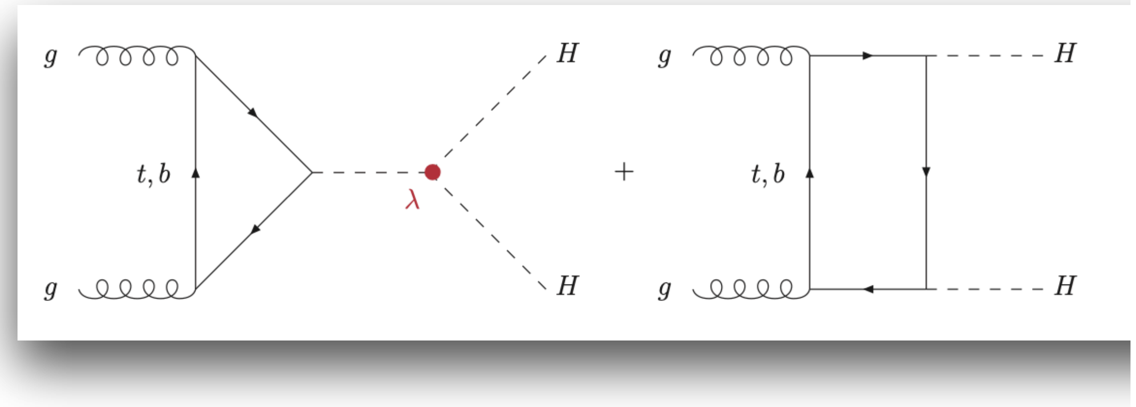
[HH, White paper]



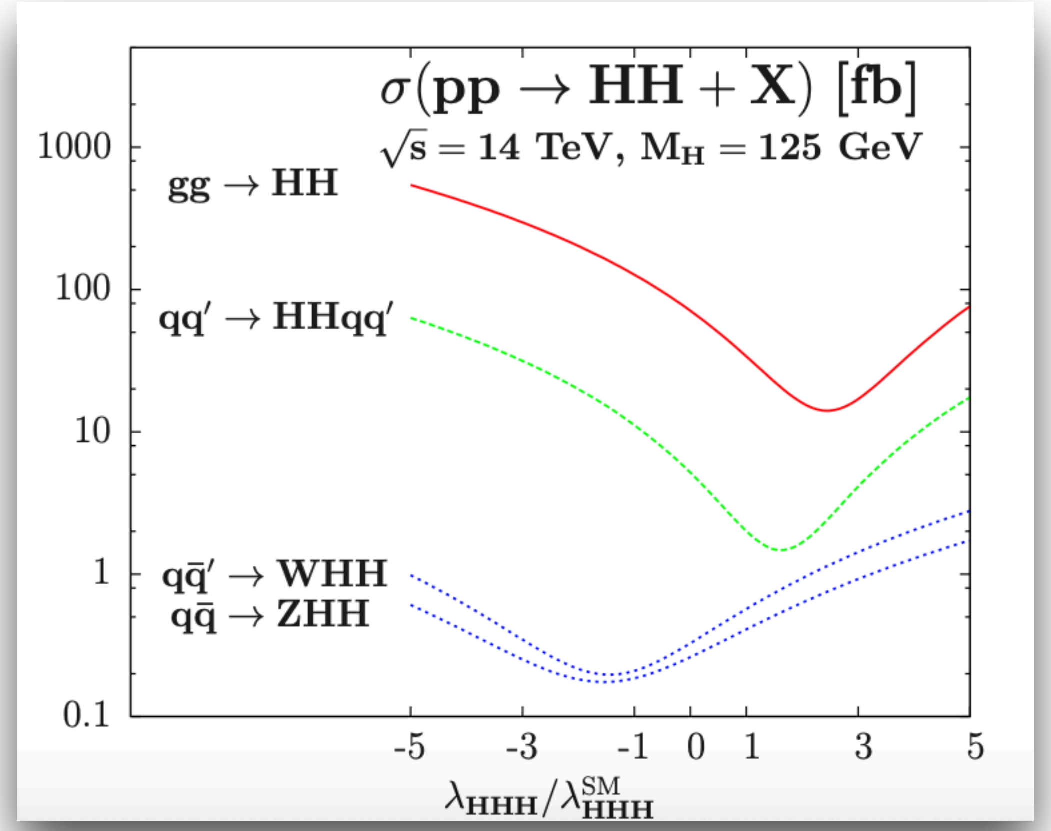
Small cxn, large bkg: experimental challenge ⇝ precise theory predictions required

Higgs Pair Production through Gluon Fusion

✦ Loop mediated at leading order - SM: third generation dominant



✦ Threshold region sensitive to λ; large M_{HH}: sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]



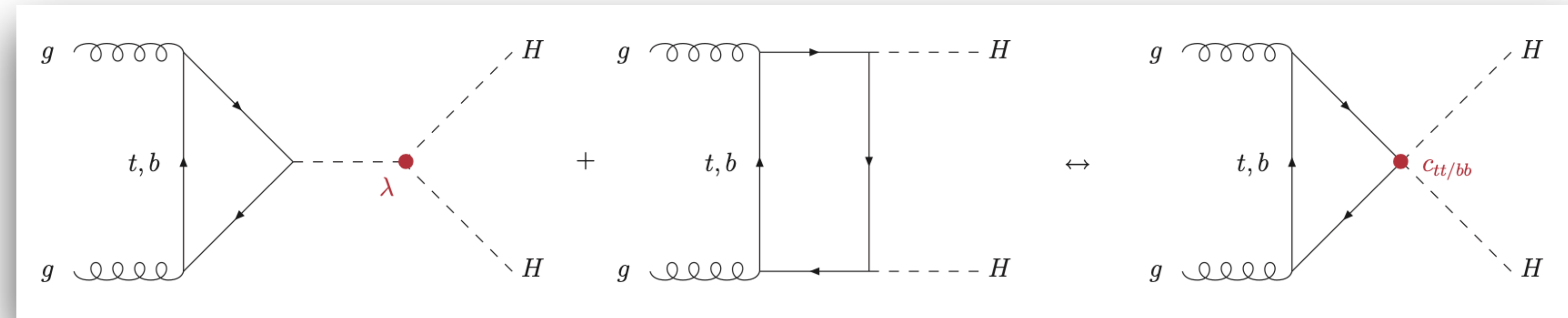
[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

decreasing with M_{HH}

Higgs Pair Production through Gluon Fusion

✦ Loop mediated at leading order - SM: third generation dominant



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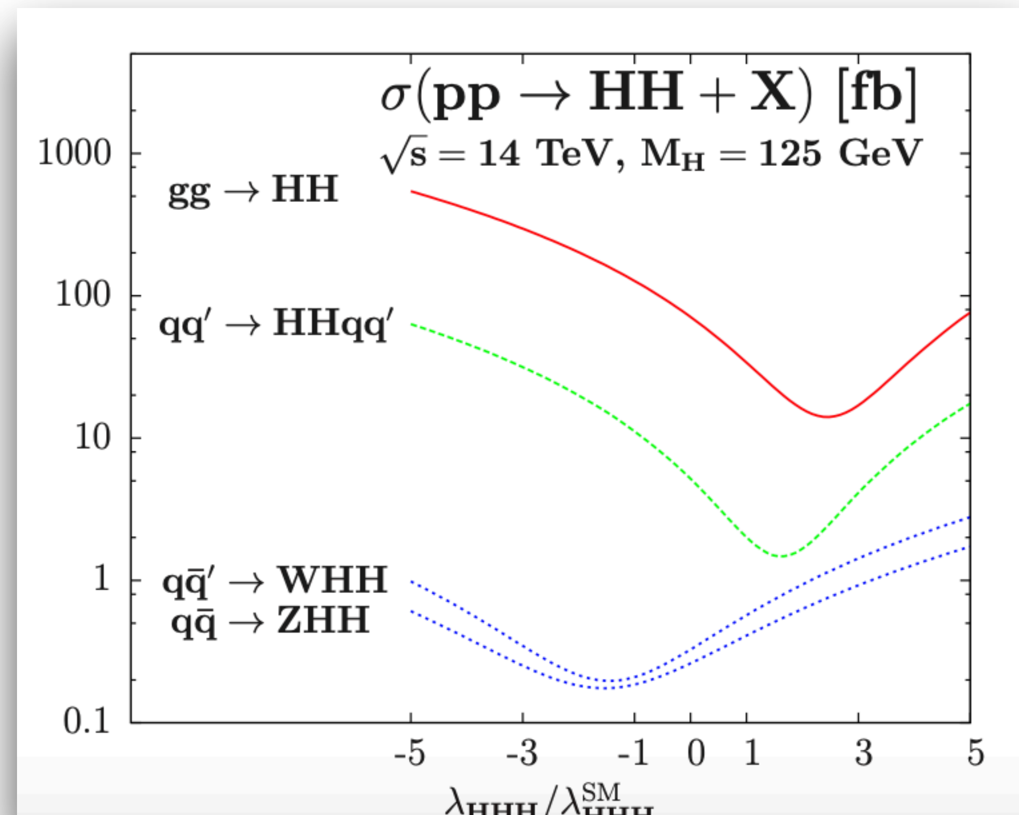

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$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

decreasing with M_{HH}

NLO Predictions for HH

Status of Higher-Order Corrections

- 2-loop QCD corrections: $\lesssim$ 70% [HTL, $\mu=M_{HH}/2$] [Dawson,Dittmaier,Spira]
- 2-loop QCD corrections: $\sigma = \sigma_0 + \sigma_1/m_t^2 + \ldots + \sigma_4/m_t^8$
  [refinement: full LO at differential level] [Grigo,Hoff,Melnikov,Steinhauser]
- Mass effects @ NLO in real corrections: ~ - 10%
  [Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro]
- NNLO QCD corrections: ~ 20% [HTL] [de Florian,Mazzitelli; Grigo,Melnikov,Steinhauser]
- N^3LO QCD corrections: ~ 5% [HTL] [Chen,Li,Shao,Wang]
- NNLO Monte Carlo: inclusion of full top-mass effects @ NLO [partly at NNLO]
  [Grazzini,Heinrich,Jones,Kallweit,Kerner,Lindert,Mazzitelli]
- NLO: matching to parton showers [Heinrich,Jones,Kerner,Luisoni,Vryonidou]
- New expansion/extrapolation methods:
  (i) $1/m_t^2$ expansion + conformal mapping + Padé approximants [Gröber,Maier,Rauh]
  (ii) p_T^2 expansion [Bonciani,Degassi,Giardino,Gröber]
- NLO: small mass expansion [$Q^2 \gg m_t^2$] [Davies,Mishima,Steinhauser,Wellmann]
- Combination of full NLO and small mass expansion
  [Davies,Heinrich,Jones,Kerner,Mishima, Steinhauser,Wellmann]

Full NLO Calculation

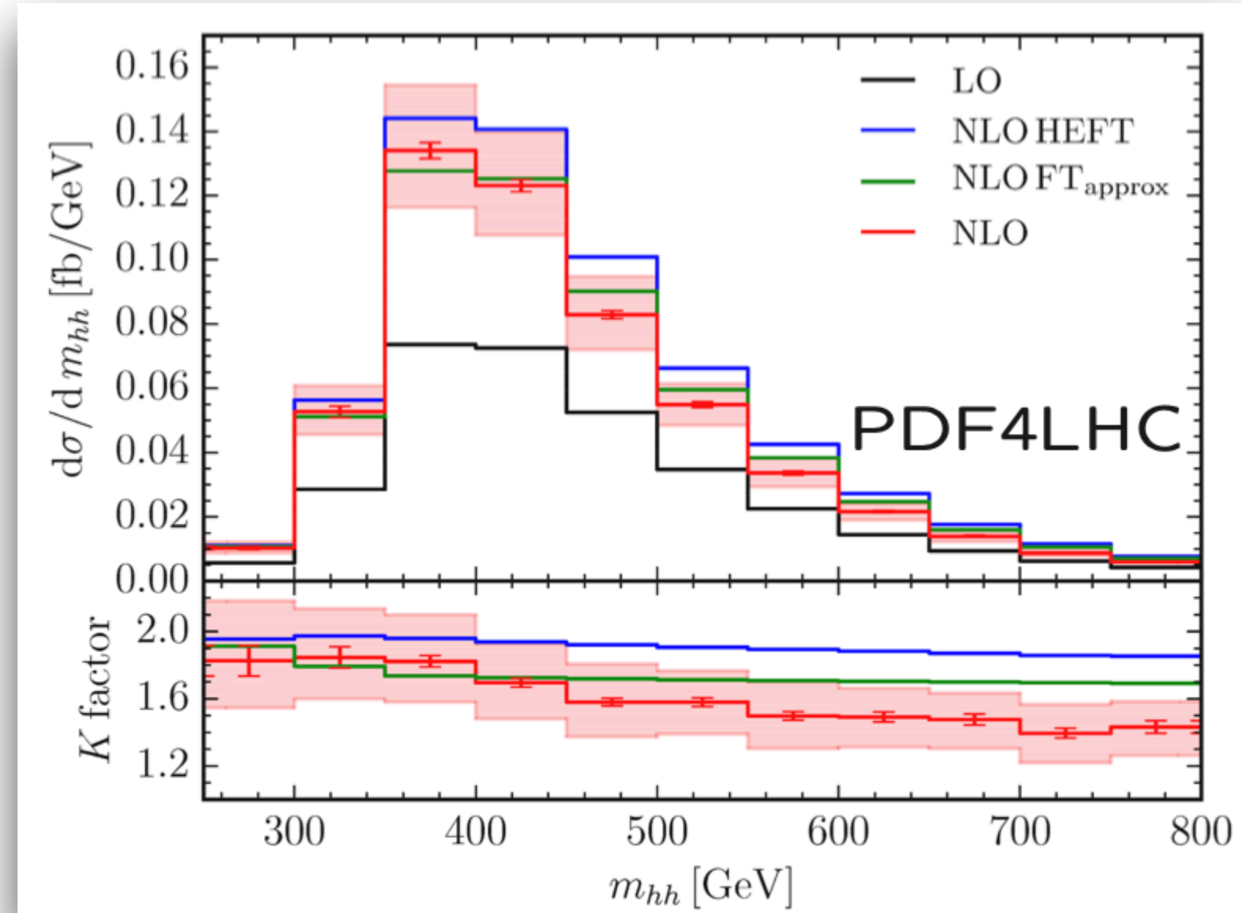
✦ Remark: Top only, numerical integration, two independent groups with different approaches

Borowka et al.	Baglio et al.
Tensor reduction	No tensor reduction
Sector decomposition	IR, end-point subtraction
Contour deformation	IBP, Richardson extrapolation
m_t = 173 GeV	m_t = 172.5 GeV

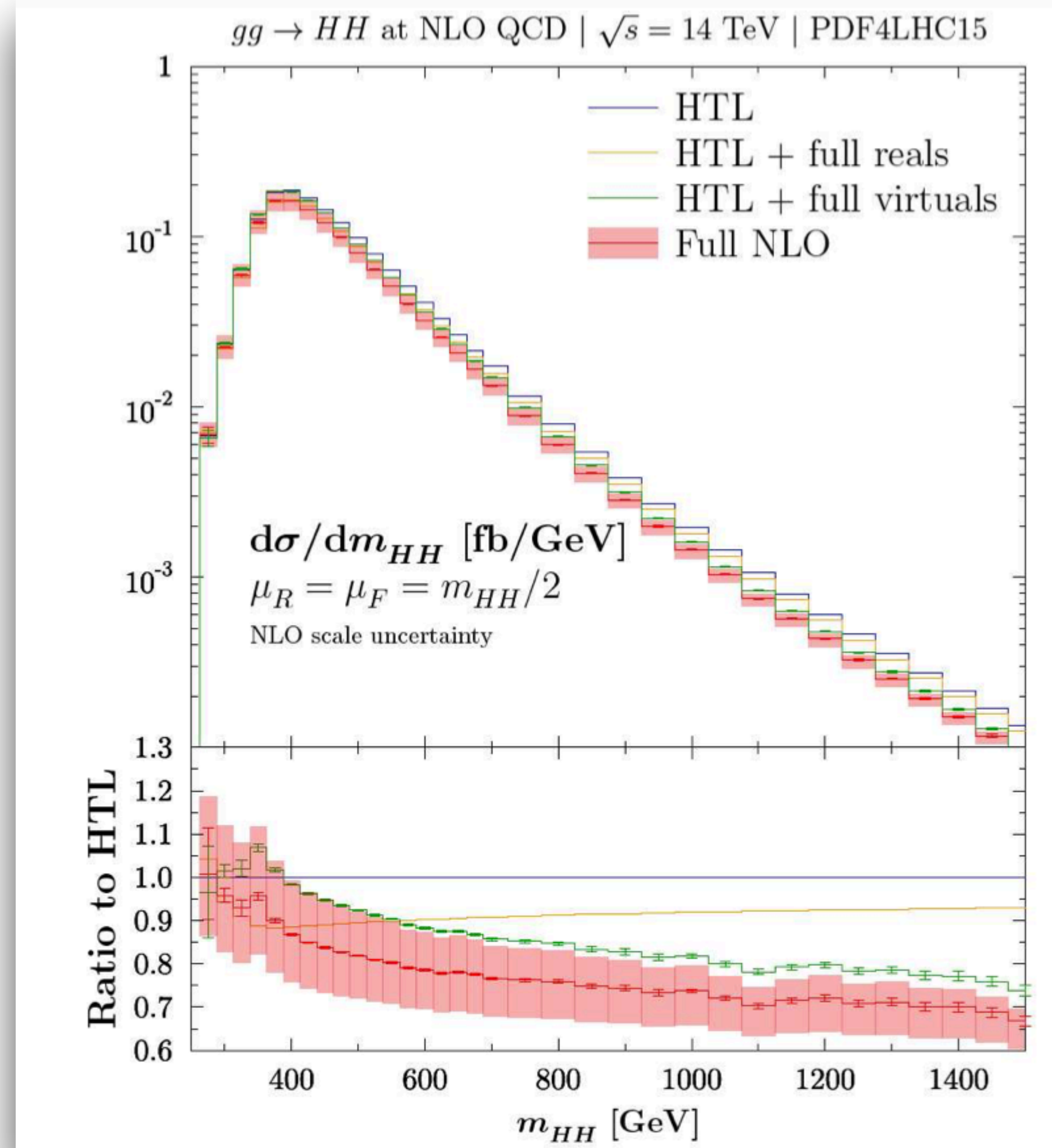
[Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke]
[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher]

Full NLO Calculation

[Borowka,Greiner,Heinrich,Jones,Kerner, Schlenk,Schubert,Zirke]



[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher]



$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

$\Rightarrow$ -15% mass effects on top of LO

Uncertainties due to m_t

- Use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ → uncertainty = envelope:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \text{GeV}} = 0.02978(7)^{+6\%}_{-34\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\ \text{GeV}} = 0.1609(4)^{+0\%}_{-13\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\ \text{GeV}} = 0.03204(9)^{+0\%}_{-30\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \text{GeV}} = 0.000435(4)^{+0\%}_{-35\%}\ \text{fb/GeV}$$

- Bin-by-bin interpolation:

$$\sigma(gg \to HH) = 32.81^{+4\%}_{-18\%}\ \text{fb}$$

Why a Dynamical Scale?

- Large momentum expansion ($\hat{s} = Q^2 \gg m_t^2$), two form factors:

[Davies,Mishima,Steinhauser,Wellmann]

pole mass m_t:

$$\Delta F_{1,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\overline{\mathrm{MS}}$ mass $\overline{m}_t(\mu_t)$:

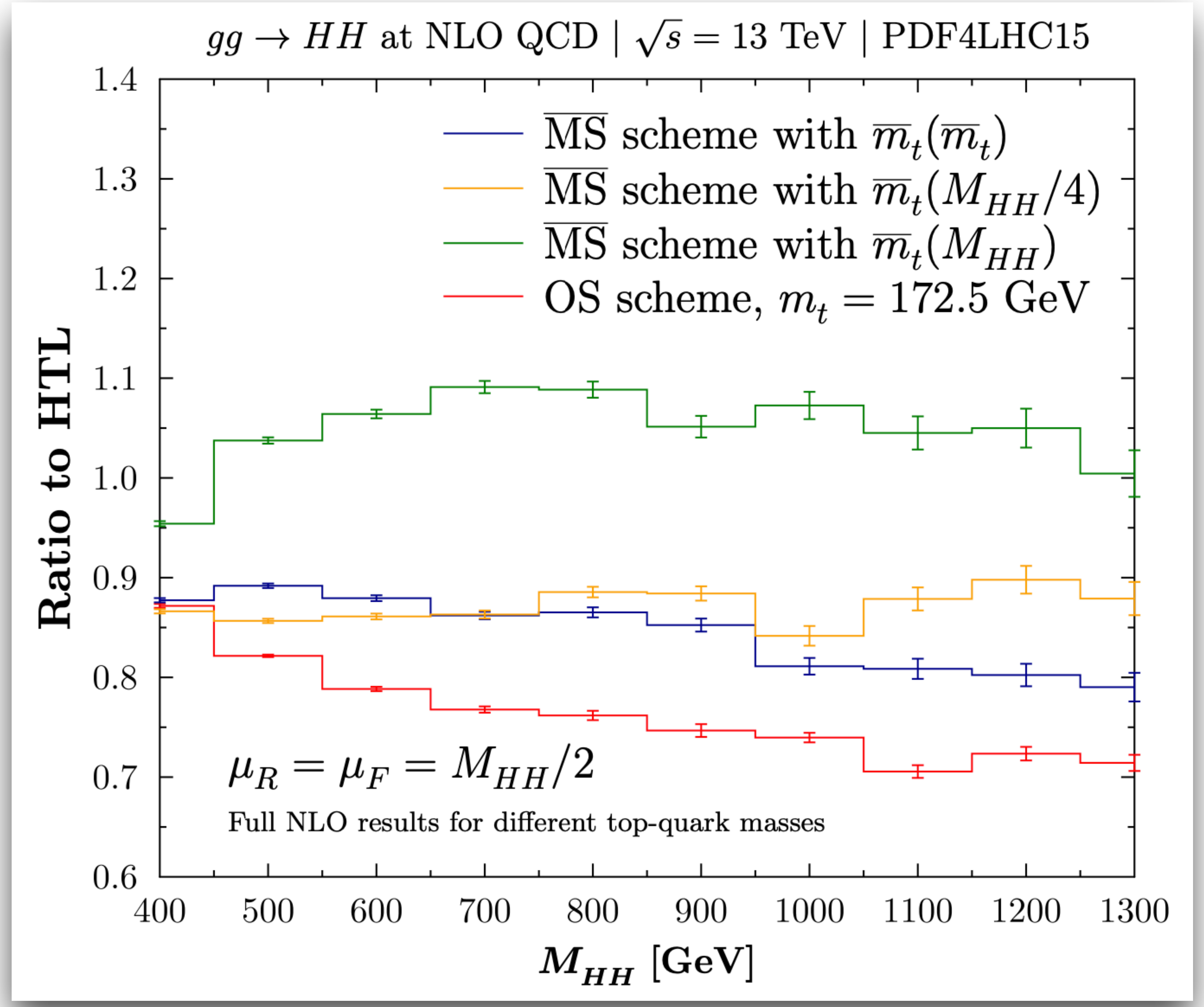
$$\Delta F_{1,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

- $\Rightarrow$ scale $\mu_t \sim Q$ preferred at large Q

Scale Choice

[Baglio,Campanario,Glaus,MM,Ronca,Spira]



Uncertainties at NLO

✦ Renormalization and factorization scale uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 27.73(7)^{+13.8\%}_{-12.8\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 32.81(7)^{+13.5\%}_{-12.5\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 127.0(2)^{+11.7\%}_{-10.7\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1140(2)^{+10.7\%}_{-10.0\%} \text{ fb}
\end{aligned}$$

✦ m_t scale/scheme uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 27.73(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 32.81(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 127.8(2)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1140(2)^{+3\%}_{-18\%} \text{ fb}
\end{aligned}$$

✦ How to combine them? $\rightarrow$ envelop ~ linear sum (relative error)

Combination of the Uncertainties

- Renormalization and factorization scale uncertainties at $NNLO_{FTapprox}$:

  FT_{approx} - NNLO cxn in HTL w/ full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+2.2\%}_{-5.0\%} \text{ fb}$$
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 36.69^{+2.1\%}_{-4.9\%} \text{ fb}$$
$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 139.9^{+1.3\%}_{-3.9\%} \text{ fb}$$
$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1224^{+0.9\%}_{-3.2\%} \text{ fb}$$

- HO corrections dominated by universal soft+virtual+collinear (S+V+C) corrections

  $\Rightarrow$ ~ rescaling of relative m_t scale/scheme uncertainties

Final Uncertainties at FT_{approx}

- Final combined renormalization/factorization scale and m_t scale/scheme uncertainties at $NNLO_{FTapprox}$:

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$

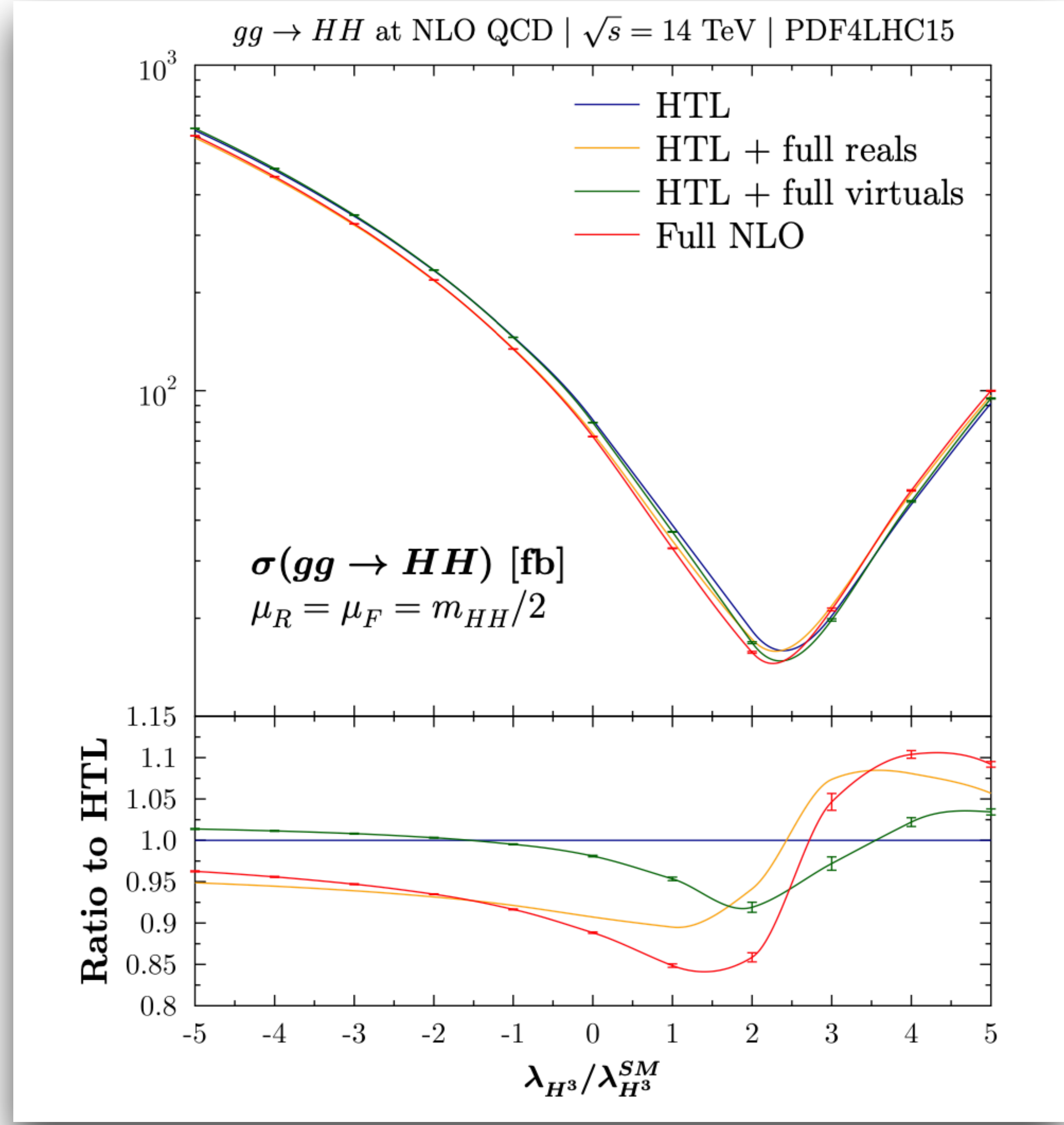
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%} \text{ fb}$$

$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%} \text{ fb}$$

$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%} \text{ fb}$$

HH Cross Section Dependence on Higgs Self-Coupling

[Baglio,Campanario,Glaus,MM,Ronca,Spira]



$gg \to HH$:

$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

Uncertainties for Different Higgs Self-Coupling Values

✦ m_t scale/scheme uncertainties at NLO:

$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%}\ \text{fb}$$
$$\kappa_\lambda = -5: \quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}\ \text{fb}$$
$$\kappa_\lambda = -1: \quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}\ \text{fb}$$
$$\kappa_\lambda = 0: \quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}\ \text{fb}$$
$$\kappa_\lambda = 1: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\ \text{fb}$$
$$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.2(1)^{+1\%}_{-23\%}\ \text{fb}$$
$$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 12.7(1)^{+4\%}_{-22\%}\ \text{fb}$$
$$\kappa_\lambda = 3: \quad \sigma_{tot} = 17.6(1)^{+9\%}_{-15\%}\ \text{fb}$$
$$\kappa_\lambda = 5: \quad \sigma_{tot} = 83.2(3)^{+13\%}_{-4\%}\ \text{fb}$$
$$\kappa_\lambda = 10: \quad \sigma_{tot} = 579(1)^{+12\%}_{-4\%}\ \text{fb}$$

Uncertainties for Different Higgs Self-Coupling Values

✦ Renormalization/factorization scale uncertainties at $\text{NNLO}_{\text{FTapprox}}$:

$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+3.0\%}_{-7.7\%}\ \text{fb}$$
$$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+2.7\%}_{-7.5\%}\ \text{fb}$$
$$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+2.5\%}_{-6.7\%}\ \text{fb}$$
$$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+2.4\%}_{-6.1\%}\ \text{fb}$$
$$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+2.2\%}_{-5.0\%}\ \text{fb}$$
$$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+2.1\%}_{-4.9\%}\ \text{fb}$$
$$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+2.3\%}_{-5.1\%}\ \text{fb}$$
$$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+2.7\%}_{-7.3\%}\ \text{fb}$$
$$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+4.9\%}_{-8.8\%}\ \text{fb}$$
$$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+4.2\%}_{-8.5\%}\ \text{fb}$$

Uncertainties for Different Higgs Self-Coupling Values

✦ Final combined uncertainties at $\mathrm{NNLO}_{\mathrm{FTapprox}}$:

$$\kappa_\lambda = -10 : \quad \sigma_{tot} = 1680^{+13\%}_{-14\%} \text{ fb}$$
$$\kappa_\lambda = -5 : \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%} \text{ fb}$$
$$\kappa_\lambda = -1 : \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%} \text{ fb}$$
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$$\kappa_\lambda = 5 : \quad \sigma_{tot} = 94.82^{+18\%}_{-13\%} \text{ fb}$$
$$\kappa_\lambda = 10 : \quad \sigma_{tot} = 672.2^{+16\%}_{-13\%} \text{ fb}$$

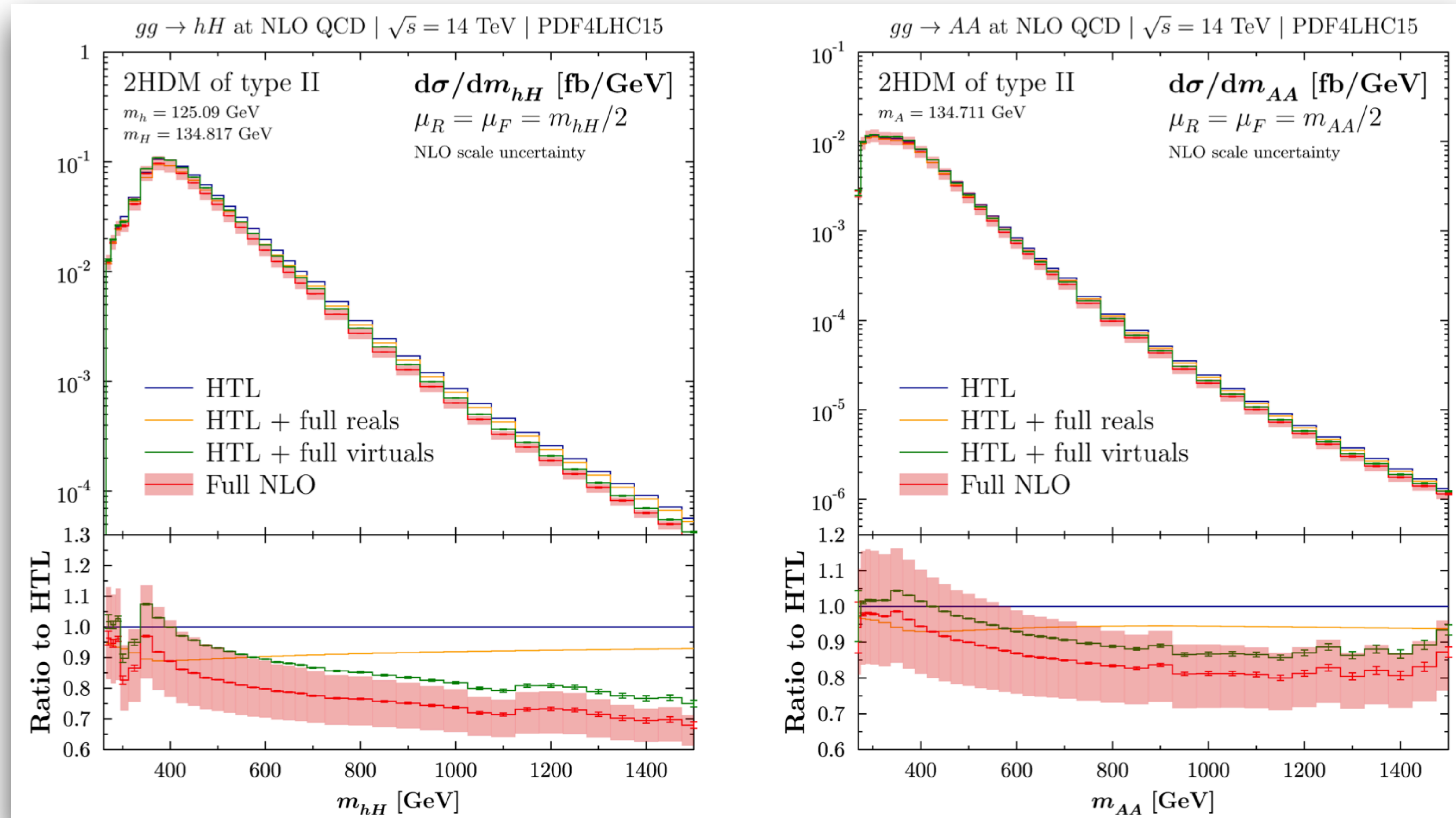
Preliminary Results for NLO 2HDM Higgs Pair Production

✦ Scenario 2HDM Type 1:

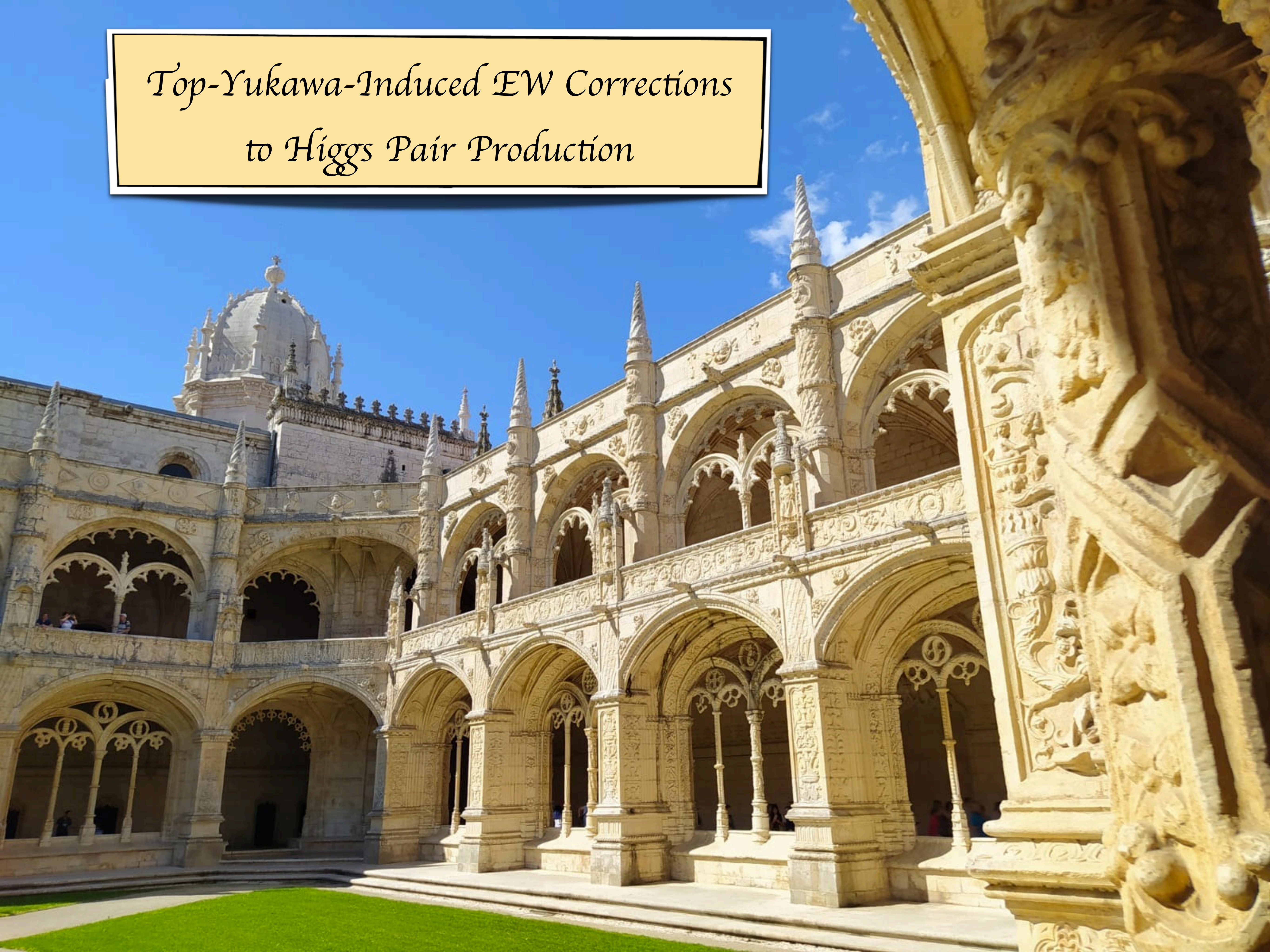
M_h=125.09 GeV, M_H=134.82 GeV, M_A=134.71 GeV, tgβ=3.234, cos(β-α)= -0.1822

PRELIMINARY

[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher]

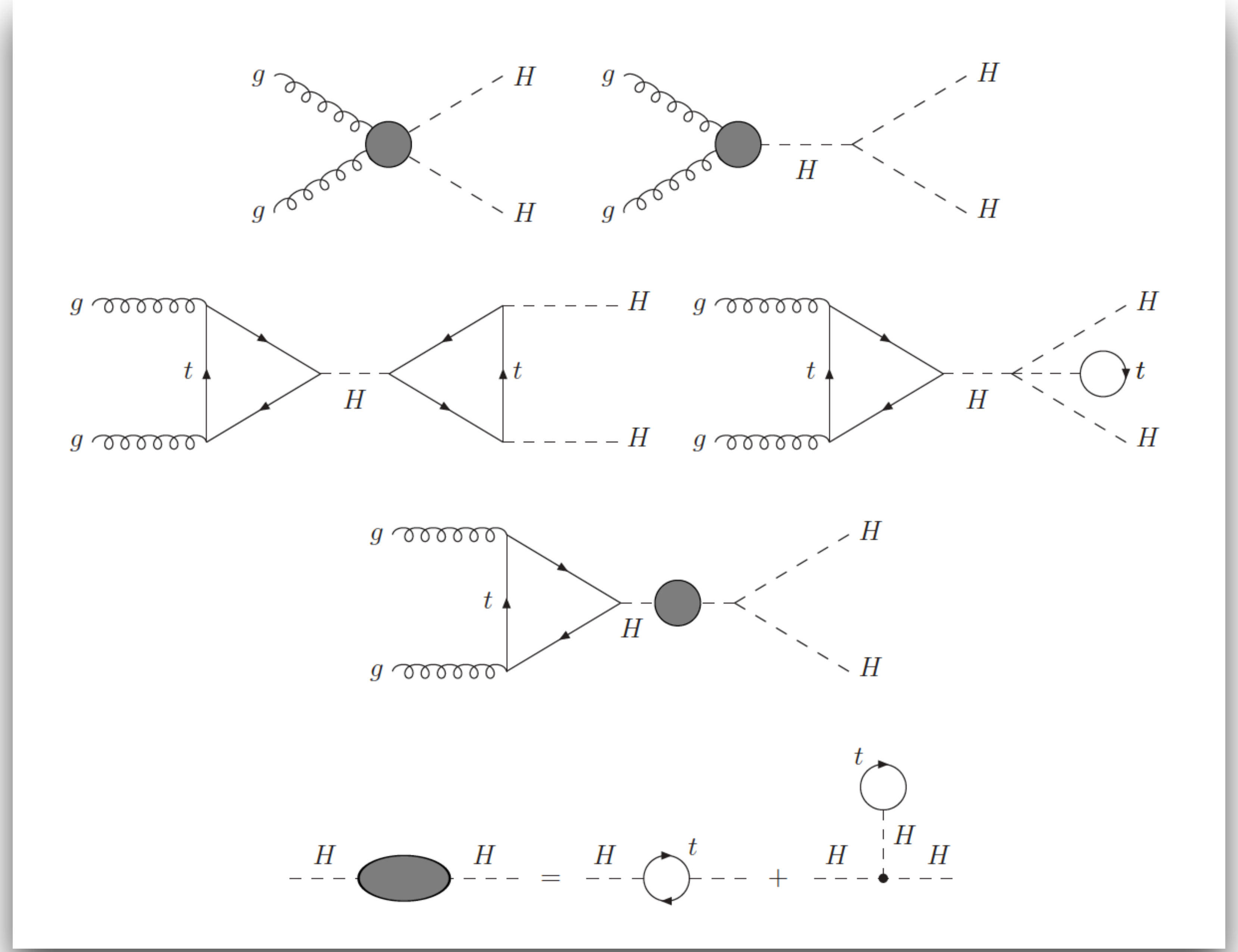


Top-Yukawa-Induced EW Corrections to Higgs Pair Production



Top-Yukawa-Induced Corrections to Higgs Pair Production

- Part of the electroweak corrections to Higgs pair production
- Full top-mass dependence in the triple Higgs vertex and self-energy corrections
  HTL in radiative corrections to the effective ggH and ggHH vertices



- Effective ggH and ggHH vertices:

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \left\{ (1+\delta_1)\frac{H}{v} + (1+\eta_1)\frac{H^2}{2v^2} + \mathcal{O}(H^3) \right\}$$

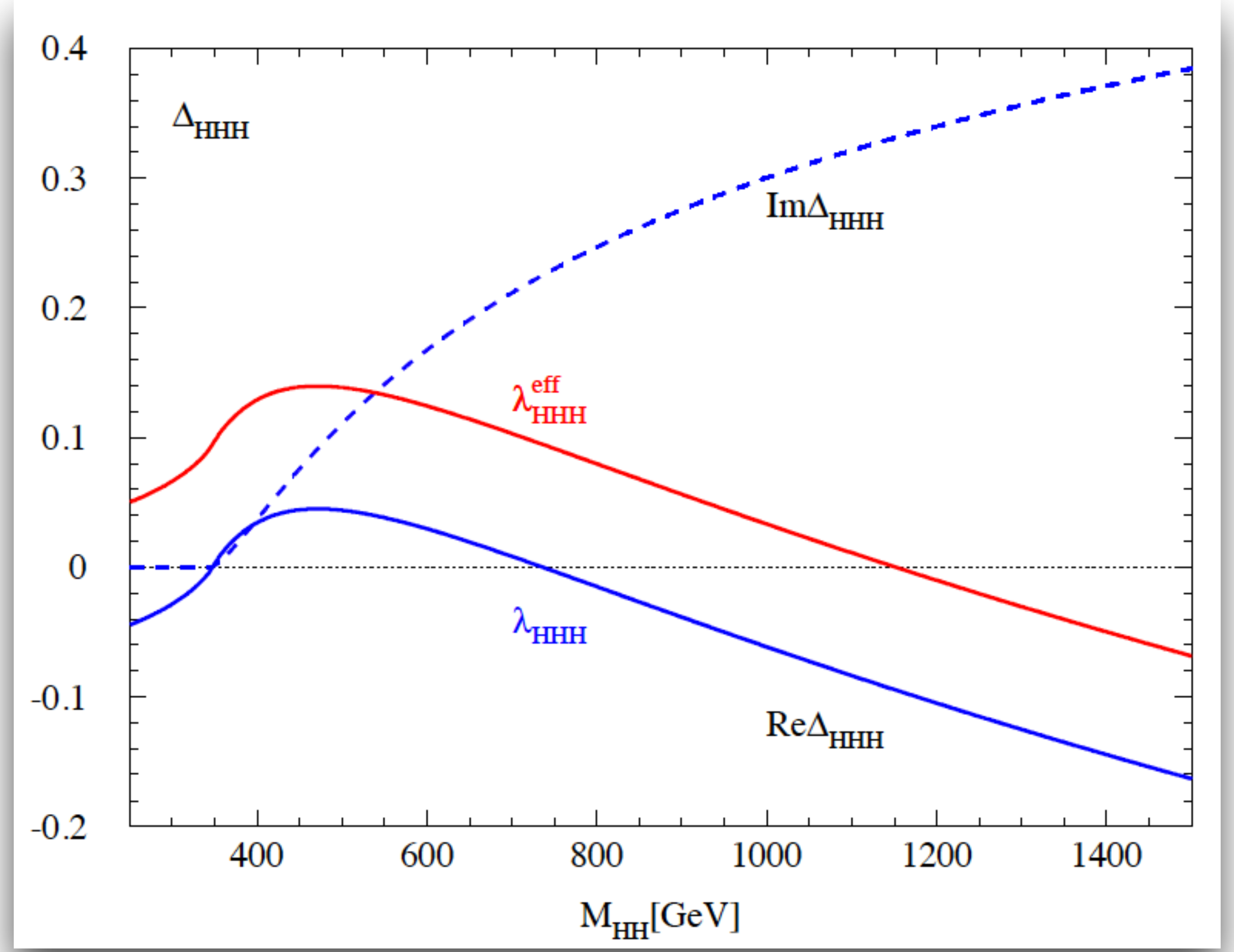
$$\delta_1 = \frac{x_t}{2} + \mathcal{O}(x_t^2) \qquad \eta_1 = 4x_t + \mathcal{O}(x_t^2) \qquad x_t = \frac{m_t^2}{(4\pi)^2 v^2}$$

- Effective Higgs self-couplings: from effective Higgs potential

$$\lambda^{eff}_{HHH} = 3\frac{M_H^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \approx 0.91 \times 3\frac{M_H^2}{v}$$

Relative Top-Yukawa-Induced EW Correction Factor Δ_{HHH}

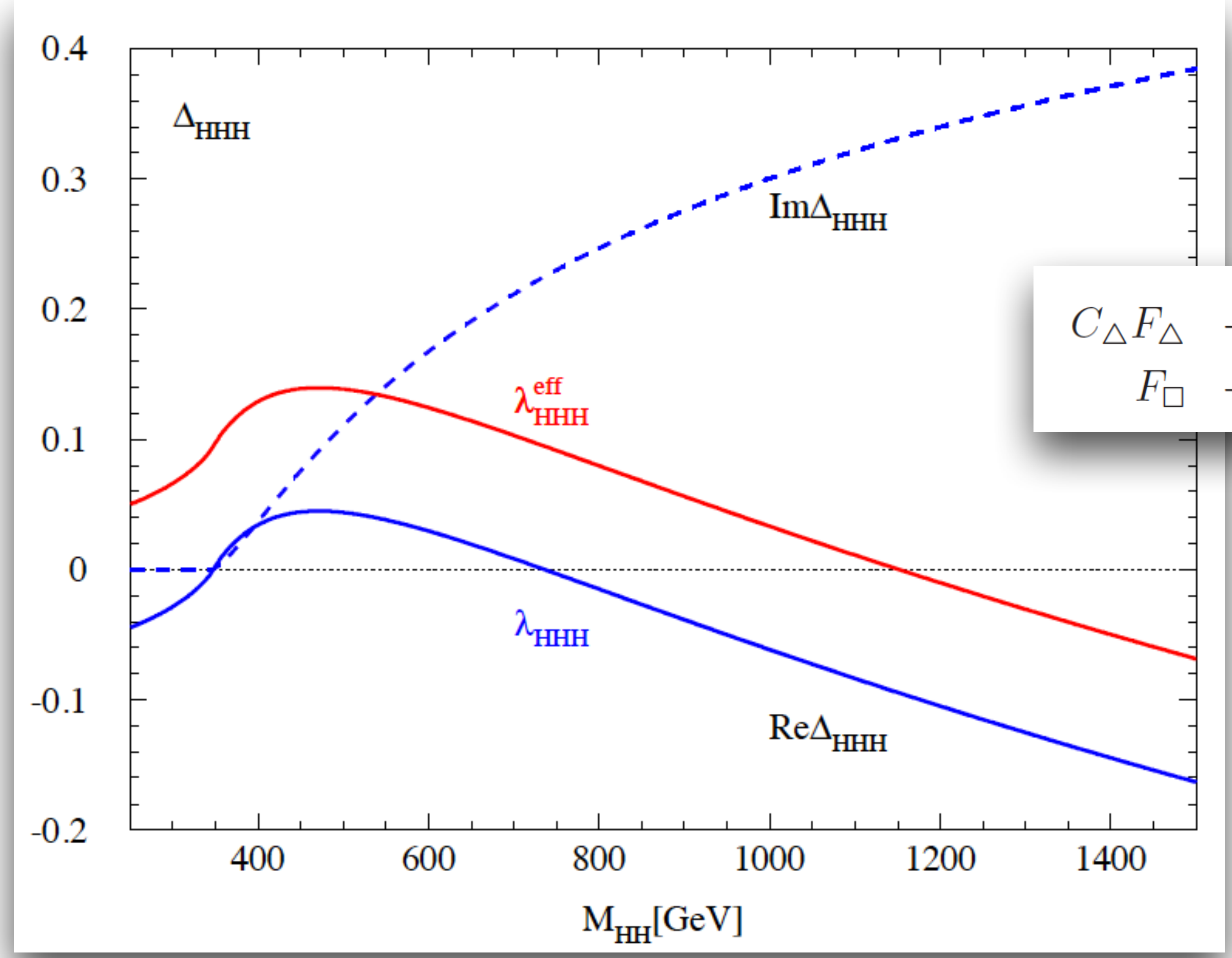
[MM,Schlenk,Spira,'22]



Effective trilinear coupling does not capture the bulk of the EW corrections

Relative Top-Yukawa-Induced EW Correction Factor Δ_{HHH}

[MM,Schlenk,Spira,'22]

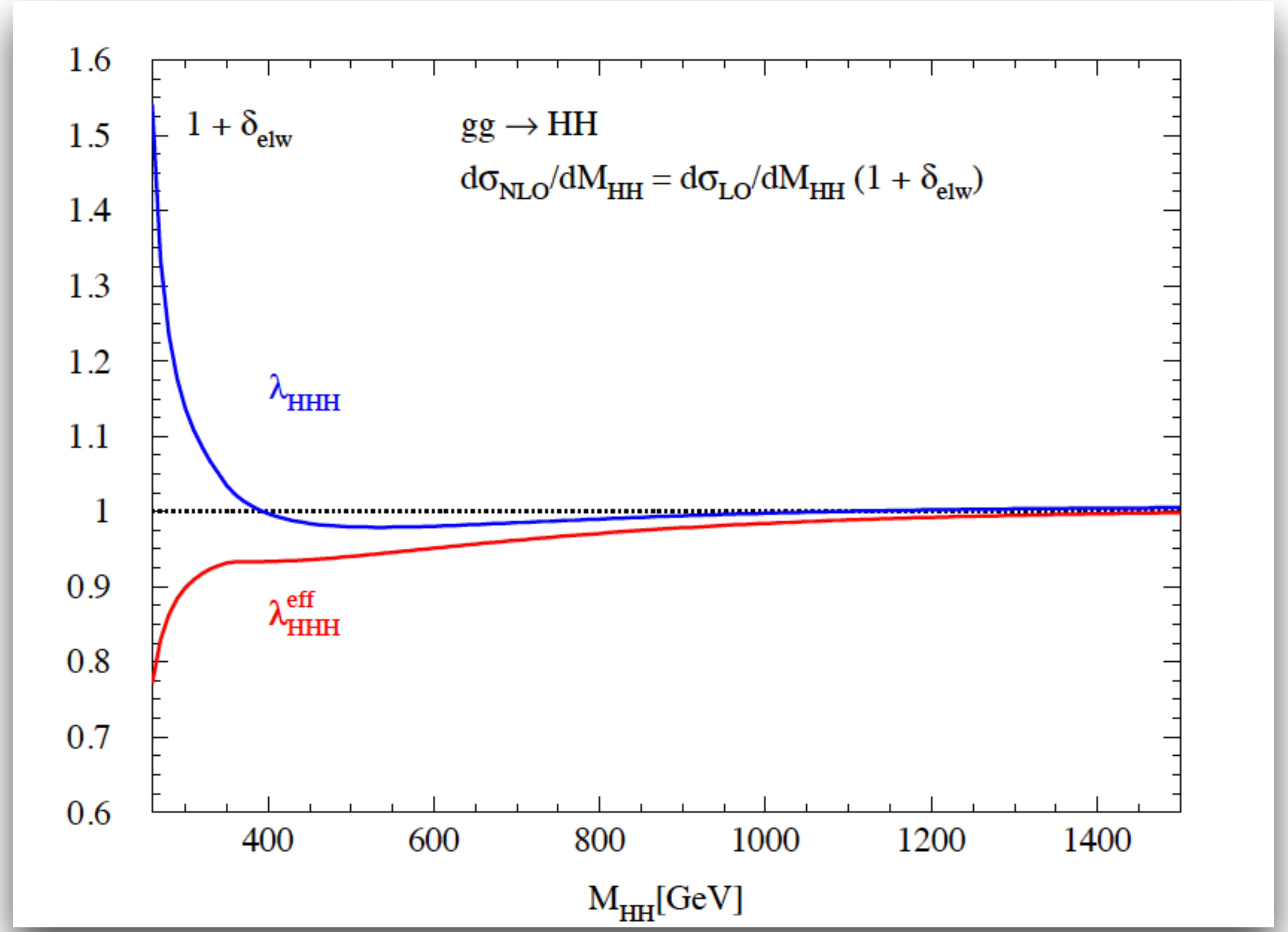


$$C_\triangle F_\triangle \to C_\triangle F_\triangle (1 + \Delta_\triangle)$$
$$F_\Box \to F_\Box (1 + \Delta_\Box)\,,$$

Effective trilinear coupling does not capture the bulk of the EW corrections

Relative Top-Yukawa-Induced EW Correction to differential HH prod

[MM,Schlenk,Spira,'22]



- Large enhancement near threshold because of vanishing LO matrix element
- Suppression is lifted by mismatch of EW corrections to triangle and box diagrams

Effect of Top-Yukawa-Induced EW Corrections on Total Cxn

✦ Effect of top-Yukawa-induced EW correction on total integrated hadronic cross section:

$$\begin{aligned} \sigma &= K_{elw} \times \sigma_{LO} \\ K_{elw} &\approx 1.002 \qquad (\lambda_{HHH}) \\ K_{elw}^{eff} &\approx 0.938 \qquad (\lambda_{HHH}^{eff}) \end{aligned}$$

- Corrections induce an effect of about 0.2%
- Bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling (leads to an artificial increase of the relative EW corrections)

HH and Baroygenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

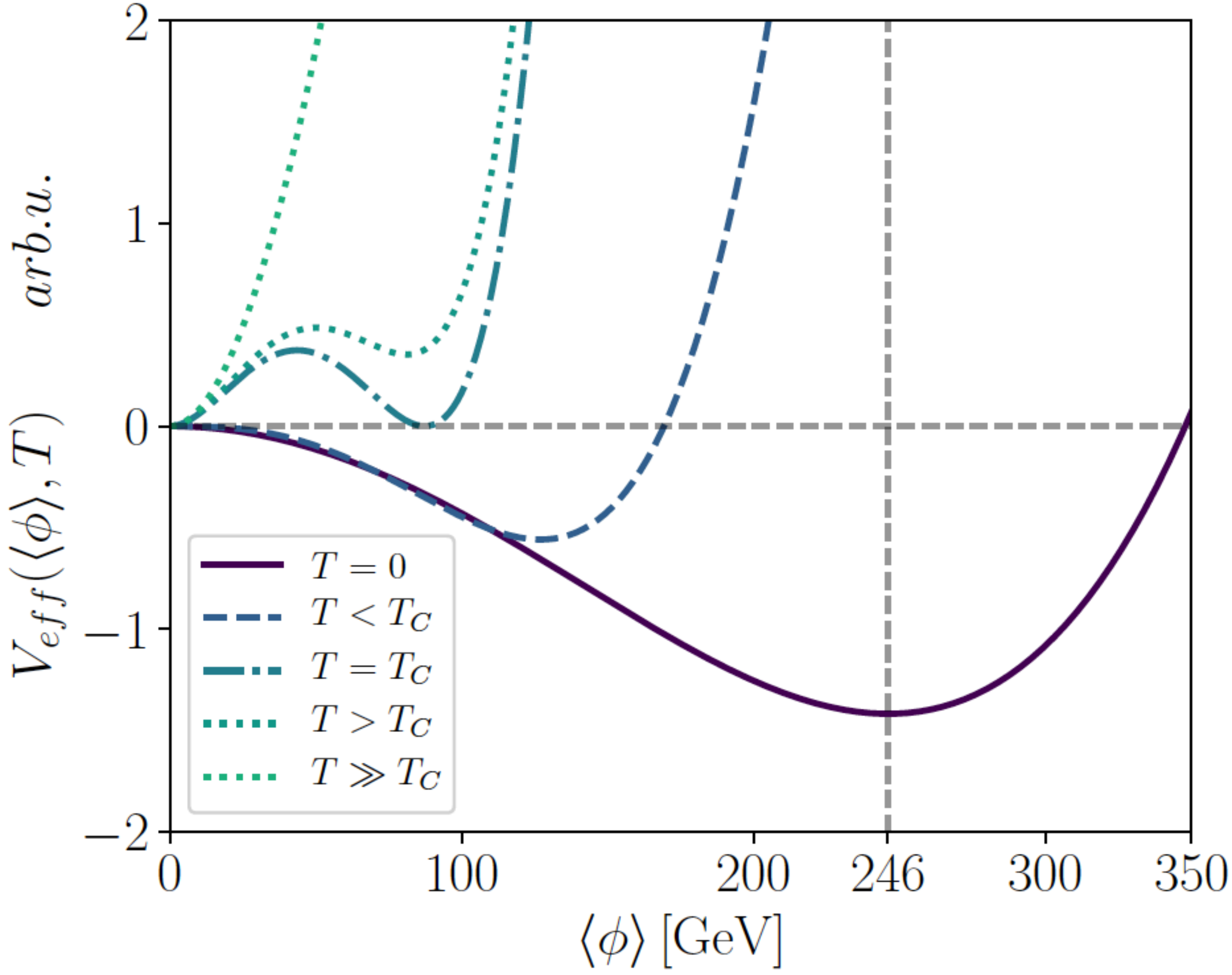
$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  * (i) B number violaton (sphaleron processes)
  * (ii) C and CP violation
  * (iii) Departure from thermal equilibrium

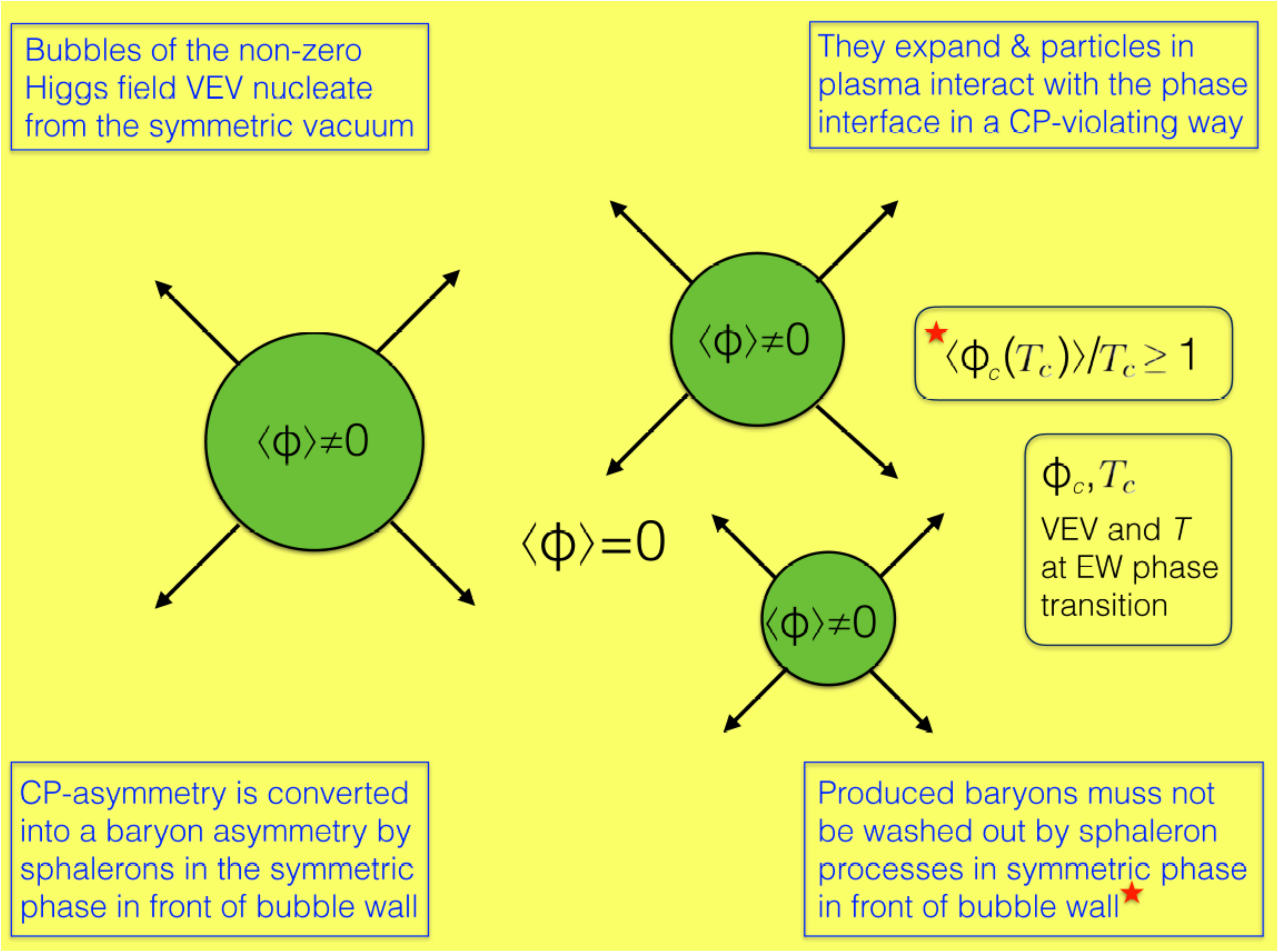
- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition


2
1
0
−1
−2
$V_{eff}(\langle\phi\rangle, T)$ arb.u.
$T = 0$
$T < T_C$
$T = T_C$
$T > T_C$
$T \gg T_C$
0
100
200
246
300
350
$\langle\phi\rangle$ [GeV]

Baryogenesis in a Nutshell



Higgs Pair Production and a 2HDM-EFT [Anisha,Biermann,Englert,MM,'22]

- 2HDM type II struggle to reach SFOEWPT (compared to type I)

[see e.g. Basler,Krause,MM,Wittbrodt,Wlotzka,'16]

- For 2HDM type II points with $\xi_c < 1$:

What extra dynamics is required to achieve SFOEWPT?

- Our model: CP-conserving 2HDM with softly broken discrete Z_2 symmetry

$$V_{\text{tree}}(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

- Extended by (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha eal,'19]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = -\sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

- Higgs pair production: a tool for fingerprinting an SFOEWPT?

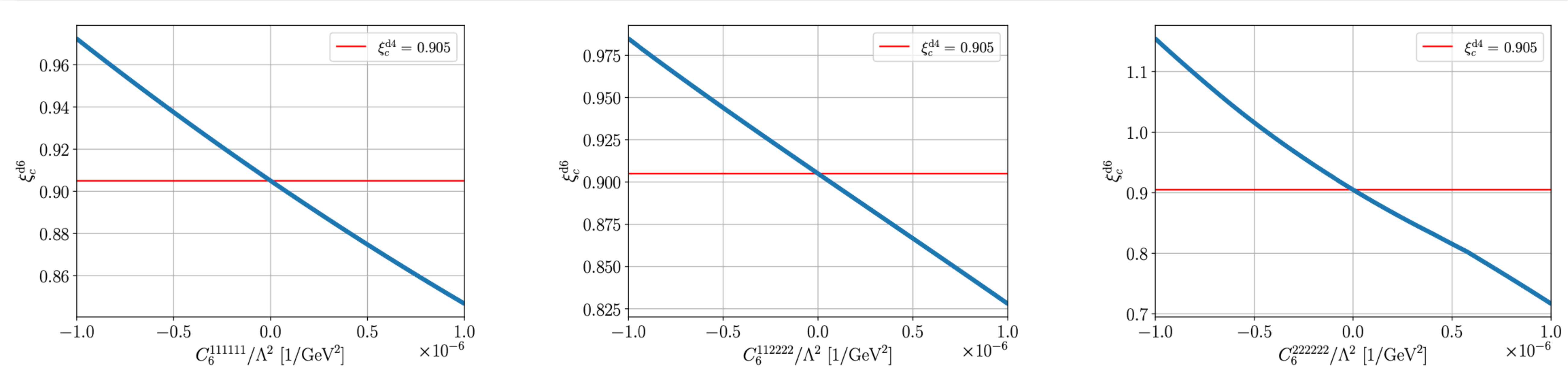
O_6^{111111}	$(\Phi_1^\dagger\Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger\Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$
O_6^{121211}	$(\Phi_1^\dagger\Phi_2)^2(\Phi_1^\dagger\Phi_1)$ + h.c.	O_6^{121222}	$(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2)$ + h.c.

- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ scalar mass spectrum same as for dim-4 @ LO
$\Rightarrow$ shift EFT effects into **Higgs self-couplings & multi-Higgs final states**

Effect of Dim-6 Operators

[Anisha,Biermann,Englert,MM,'22]



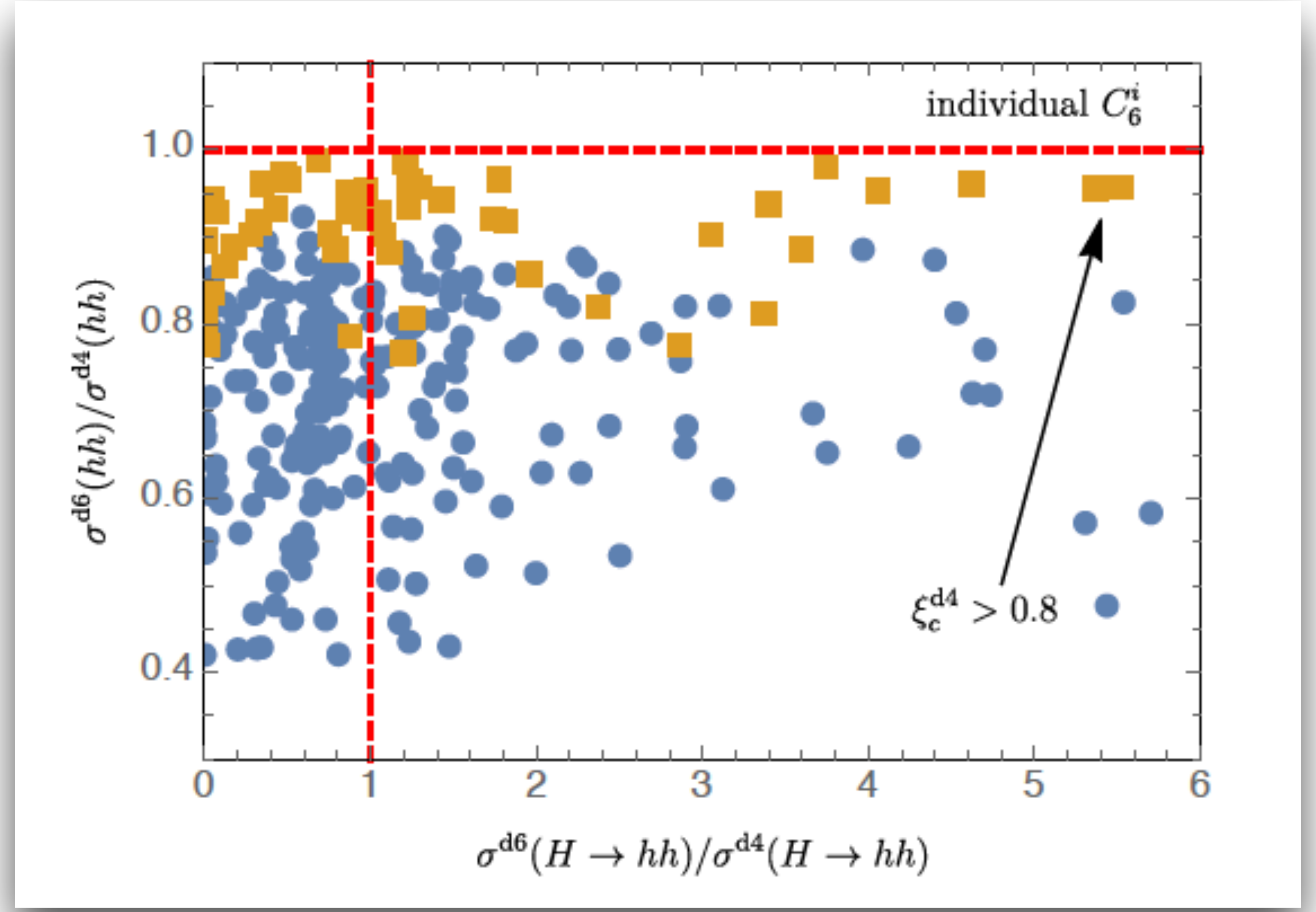
impact of individual Wilson coefficients on ξ_c^{d6} for $\xi_c^{d4} \cong 0.9$:

- linear response ~ C^i_6 -> perturbativity ok
- SFOEWPT achievable in agreement with experimental constraints

interference effects in heavy Higgs production in tt final state are width dependent -> sensitive to EFT modifications: overall effect is small after taking the Higgs data constraints into account => hh production important tool for fingerprinting SFOEWPT

Strength of EWPT and hh production

[Anisha,Biermann,Englert,MM,'22]

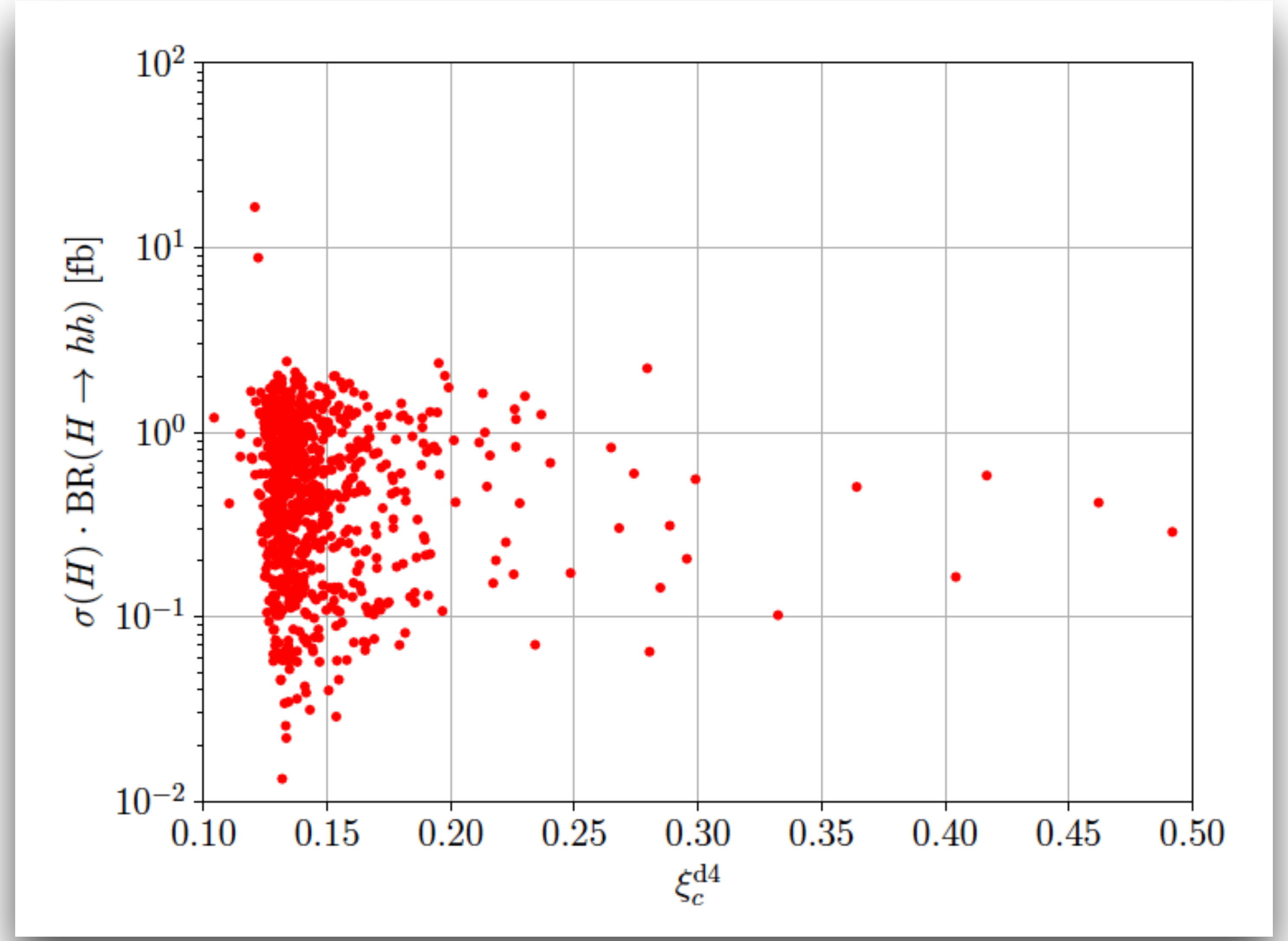


Points with $\xi_c^{d6} \cong 1$ for $\xi_c^{d4} \geqq 0.3$, orange points $\xi_c^{d4} > 0.8$

- suppression of overall hh: additional potential contributions enhance λ_{hhh} by O(50%)
- analysis of the separated res. production H→hh compared to hh continuum production
  → indirect constraint on ξ_c~1

Correlation of ξ_c^{d4} and resonant $H \to hh$ Production

[Anisha,Biermann,Englert,MM,'22]

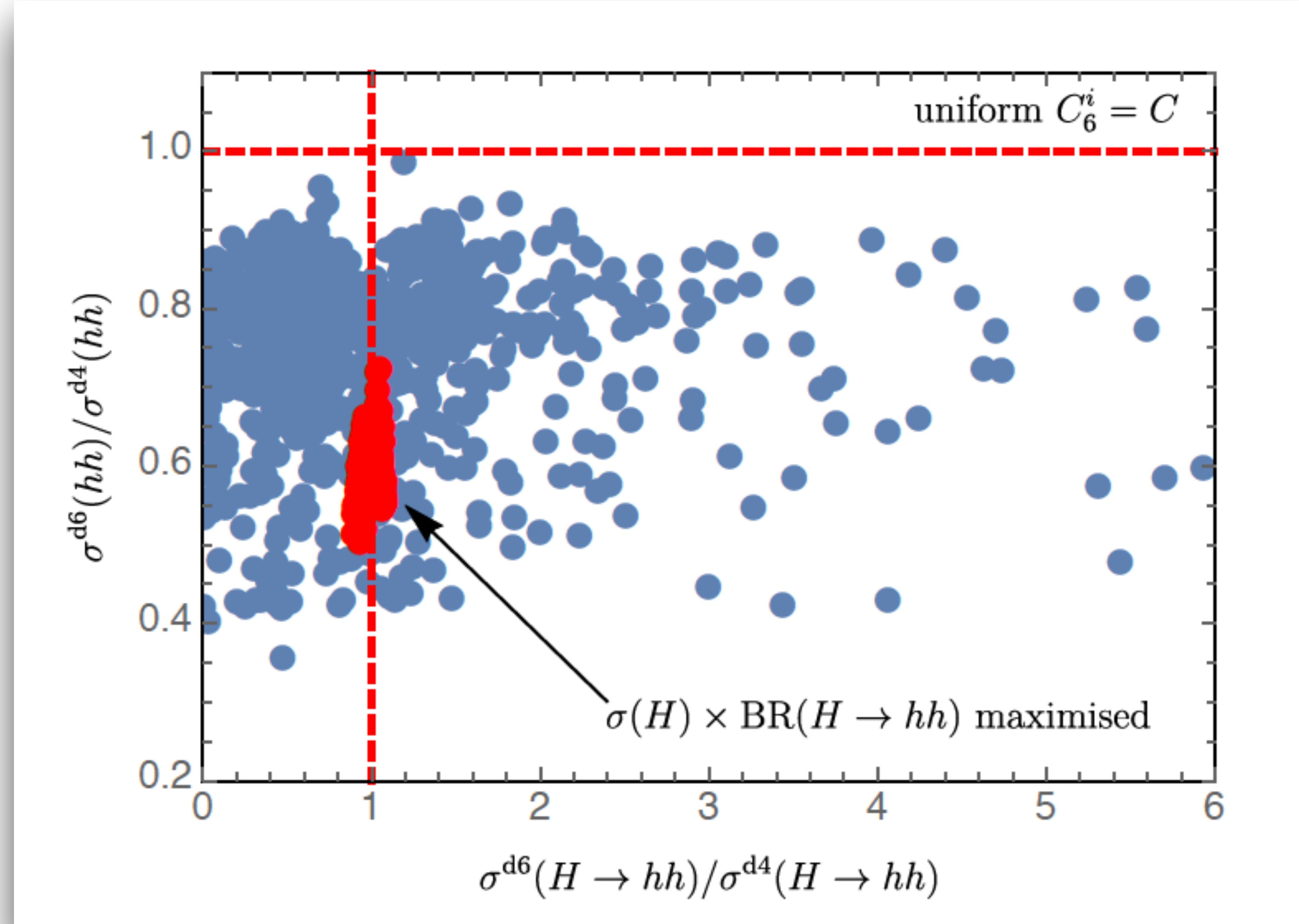


- Higgsphilic points characterized by larger distance $|1- \xi_c^{d4}|$

  ⇝ interplay of different dim-6 operators to achieve ξ_c~1 in a controlled way

Correlation of ξ_c^{d4}, continuum and resonant hh production

[Anisha,Biermann,Englert,MM,'22]



- Resonant H→hh production enhancement factor of 2.5 possible for cxn in fb range
- Higgs-philic points: resonance contribution modified by ~5-10%, continuum production modified by ~50%

Conclusions

- Precision prediction for Higgs pair production -> required for accurate extraction of Higgs self-coupling
  - NLO QCD corrections: mass effects 15% on top of LO; more for distributions
  - Uncertainty estimate: renormalization and factorization scale uncertainty, top mass scale and scheme uncertainty

- Top Yukawa-induced EW corrections to Higgs pair production:
  - effect of about 0.2%
  - bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling

- 2HDM plus dim-6 operators (-> additional dynamics)
  - get an SFOEWPT in type II more easily
  - Higgsphilic scenario: dim-6 ops necessary for SFOEWPT => reduction of gg-> hh and modification of gg->H->hh; can be probed by LHC to some extent

Thank you for your attention!

LO Cross Section

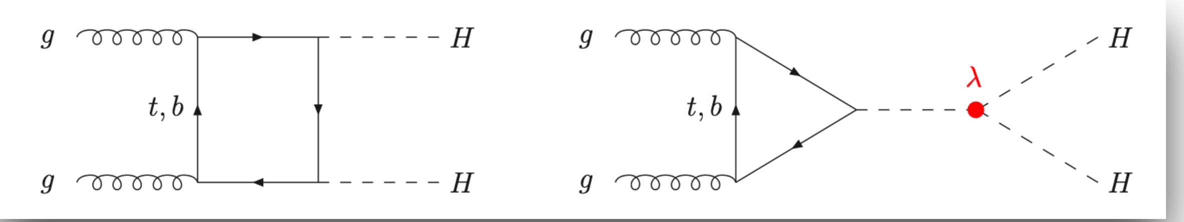
✦ The LO cross section: 2 form factors

$$\mathcal{M}(g^a g^b \to HH) = -i \frac{G_F \alpha_s(\mu_R) Q^2}{2\sqrt{2}\pi} \mathcal{A}^{\mu\nu} \epsilon_{1\mu} \epsilon_{2\nu} \delta_{ab}$$

with $\mathcal{A}^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu}$,

$$F_1 = C_\triangle F_\triangle + F_\Box \, , \qquad F_2 = G_\Box$$

$$C_\triangle = \frac{\lambda_{H^3} v}{Q^2 - M_H^2 + i M_H \Gamma_H}$$



Heavy top limit:

$$F_\triangle \to \frac{2}{3}, \qquad F_\Box \to -\frac{2}{3}, \qquad G_\Box \to 0$$

Hadronic cross section

$$\sigma_{LO} = \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{LO}(Q^2 = \tau s)$$

Partonic cross section

$$\hat{\sigma}_{LO} = \frac{G_F^2 \alpha_s^2(\mu_R)}{512(2\pi)^3} \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[|F_1|^2 + |F_2|^2 \right]$$

$$\hat{t}_\pm = -\frac{1}{2}\left[Q^2 - 2M_H^2 \mp Q^2 \sqrt{1 - 4\frac{M_H^2}{Q^2}} \right]$$

Gluon luminosity

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x, \mu_F) g\left(\frac{\tau}{x}, \mu_F\right)$$

NLO Cross Section

- The NLO cross section:

$$\sigma_{\text{NLO}}(pp \to HH + X) = \sigma_{\text{LO}} + \Delta\sigma_{\text{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

C and d_{ij} depend on Q^2

$$\sigma_{\text{LO}} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\text{LO}}(Q^2 = \tau s)$$

$$\Delta\sigma_{\text{virt}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) \; C$$

$$\Delta\sigma_{gg} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -z P_{gg}(z) \log \frac{\mu_F^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}$$

$$\Delta\sigma_{gq} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{\mu_F^2}{\tau s (1-z)^2} + d_{gq}(z) \right\}$$

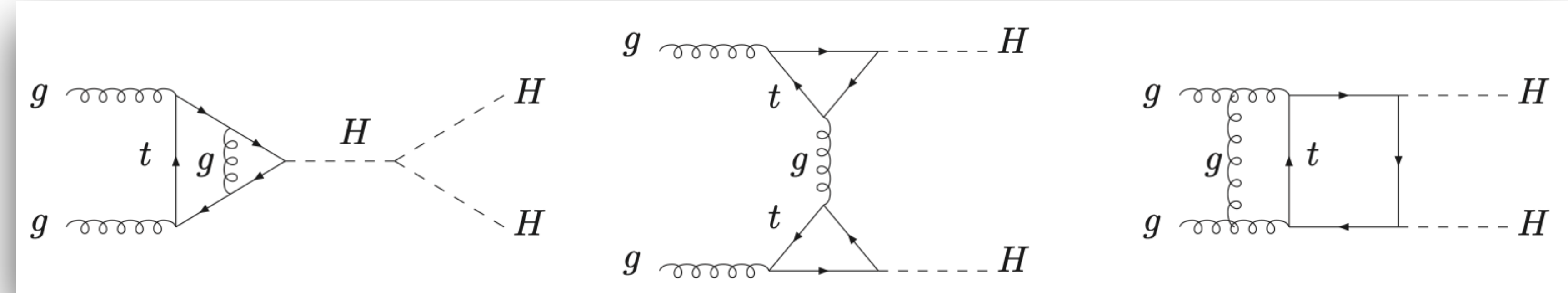
$$\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \; d_{q\bar{q}}(z)$$

- HTL:

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \quad d_{gg} \to -\frac{11}{2}(1-z)^3, \quad d_{gq} \to \frac{2}{3} z^2 - (1-z)^2, \quad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

Virtual Corrections

- Contributing diagrams: 47 generic box diagrams, 8 triangle diagrams (← single Higgs), 1 PR (← H→Zγ)



- Full diagram w/o tensor reduction → 6-dim. Feynman integral (for 2 form factors)

- UV singularities: → endpoint subtractions

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx\, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- IR singularities: IR subtraction (based on structure of integr. and rel. to HTL)

- Thresholds: $Q^2 \geq 0, 4m_t^2$ → IBP → reduction of power of denominator

$$[m_t^2 \to m_t^2(1-ih)]$$

$$\int_0^1 dx\, \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

Further Calculational Details

- Renormalization: α_S: MSbar, 5 flavors, m_t: on-shell
- Phase space integration → 7-dim. integrals for $d\sigma/dQ^2$
- Subtraction of HTL → IR-finite mass effects [adding back HTL results ← HPAIR]
- Extrapolation to NWA ($h \to 0$): Richardson extrapolation

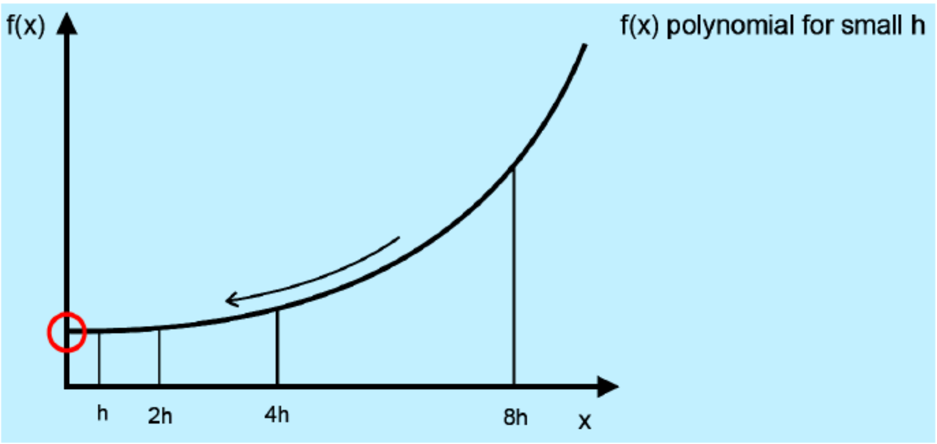
$$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$$

$$M_4 = \{8f(h) - 6f(2h) + f(4h)\}/3 = f(0) + \mathcal{O}(h^3)$$

$$M_8 = \{64f(h) - 56f(2h) + 14f(4h) - f(8h)\}/21 = f(0) + \mathcal{O}(h^4)$$

etc.

$[h \geq 0.025]$



Real Corrections

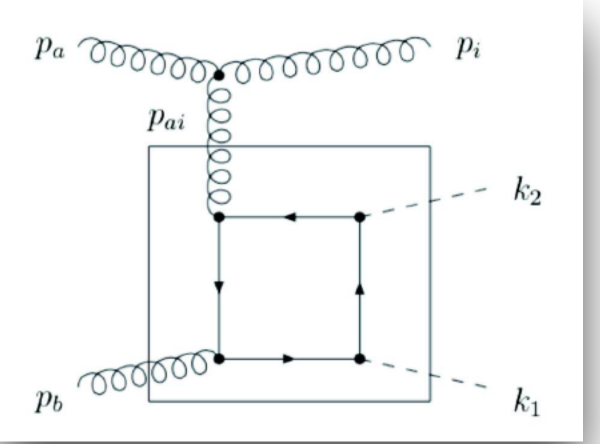
- Full matrix element: generated with FeynArts and FormCalc
- Matrix elements in HTL involving full LO sub-matrix elements subtracted
  → IR-, COLL-finite [adding back HTL results ← HPAIR]

$$\sum \overline{|\mathcal{M}_{gg}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{24\pi^2}{Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^4+t^4+u^4+Q^8}{stu} - 4\frac{\epsilon}{1-\epsilon}Q^2\right\}$$

$$\sum \overline{|\mathcal{M}_{gq}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{32\pi^2}{3Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^2+u^2}{-t} + \epsilon\frac{(s+u)^2}{t}\right\}$$

$$\sum \overline{|\mathcal{M}_{q\bar{q}}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{256\pi^2}{9Q^4}\frac{\alpha_s}{\pi}(1-\epsilon)\left\{\frac{t^2+u^2}{s} - \epsilon\frac{(t+u)^2}{s}\right\}$$

- PDFs: MSbar, 5 flavors



Results

	PDF4LHC15	MMHT2014
σ_{LO}	19.80 fb	23.75 fb
σ^{HTL}_{NLO}	38.66 fb	39.34 fb
σ_{NLO}	32.78(7) fb	33.33(7) fb

Conversion from Pole to MSbar Mass

$$F_i = F_{i,LO} + \Delta F_i = F_{i,LO} + \Delta F_{1,HTL} + \Delta F_{1,mass}$$

Pole mass: $F_{1,LO} = 4 m_t^2 / \hat{s}$

Conversion pole mass → $\overline{MS}$ mass at μ_t: $m_t \to \overline{m}_t(\mu_t)\left[1 + \frac{\alpha_s}{\pi}\left(\frac{4}{3} + \log\frac{\mu_t^2}{m_t^2}\right)\right]$

$$F_{1,LO} + \Delta F_{1,HTL}$$

$$\to \frac{4\overline{m}_t^2(\mu_t)}{\hat{s}}\left[1 + 2\cdot\frac{\alpha_s}{\pi}\cdot\frac{4}{3} + 2\frac{\alpha_s}{\pi}\log\frac{\mu_t^2}{m_t^2}\right]$$

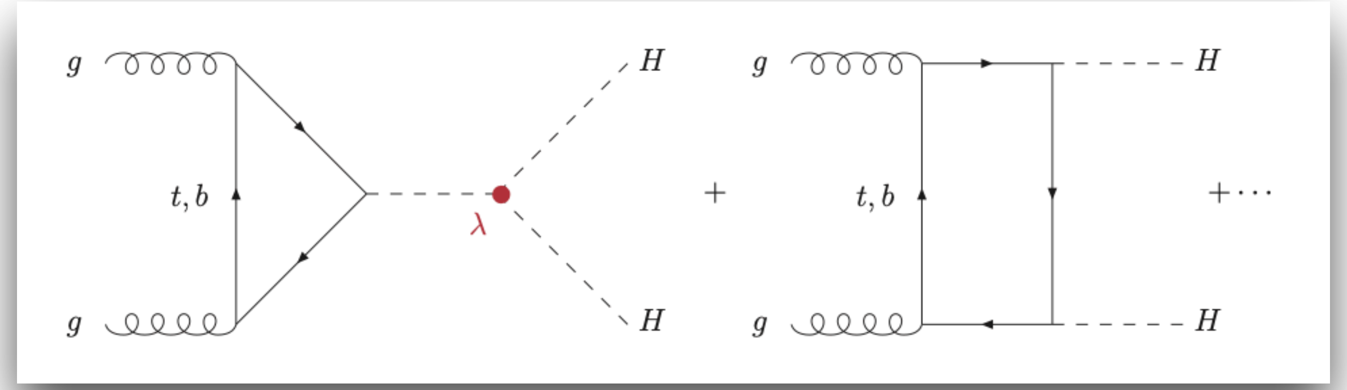
$$+ \frac{4\overline{m}_t^2(\mu_t)}{\hat{s}}\cdot 2\cdot\frac{\alpha_s}{\pi}\log\frac{m_t^2}{\hat{s}}$$

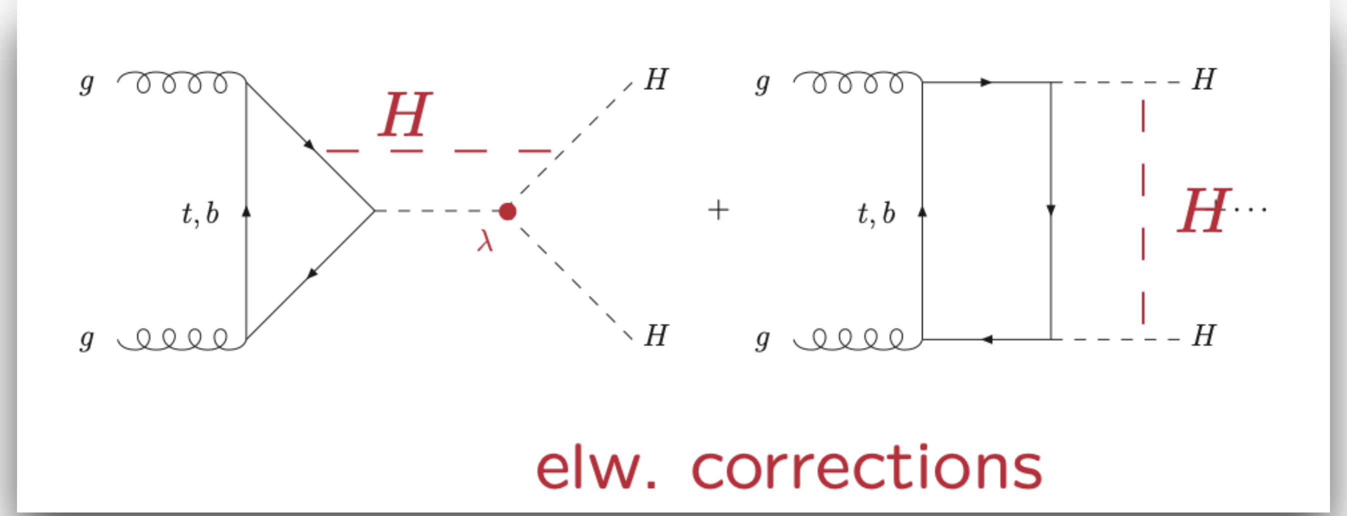
$$= \frac{4\overline{m}_t^2(\mu_t)}{\hat{s}}\left[1 + 2\frac{\alpha_s}{\pi}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right]\right]$$

Scales for y_t

✦ Different scales for y_t in triangle (Q) and box (M_H) diagrams?

→ has to hold to all orders





⇒ Same scale in all diagrams

LO Uncertainties

- Scale and scheme uncertainties at LO

$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=300\ \text{GeV}} = 0.01656^{+62\%}_{-2.4\%}\ \text{fb/GeV}$$

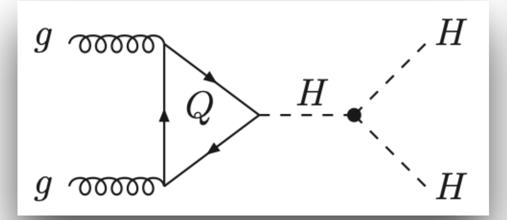
$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=400\ \text{GeV}} = 0.09391^{+0\%}_{-20\%}\ \text{fb/GeV}$$

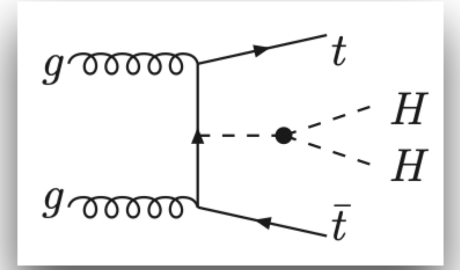
$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=600\ \text{GeV}} = 0.02132^{+0\%}_{-48\%}\ \text{fb/GeV}$$

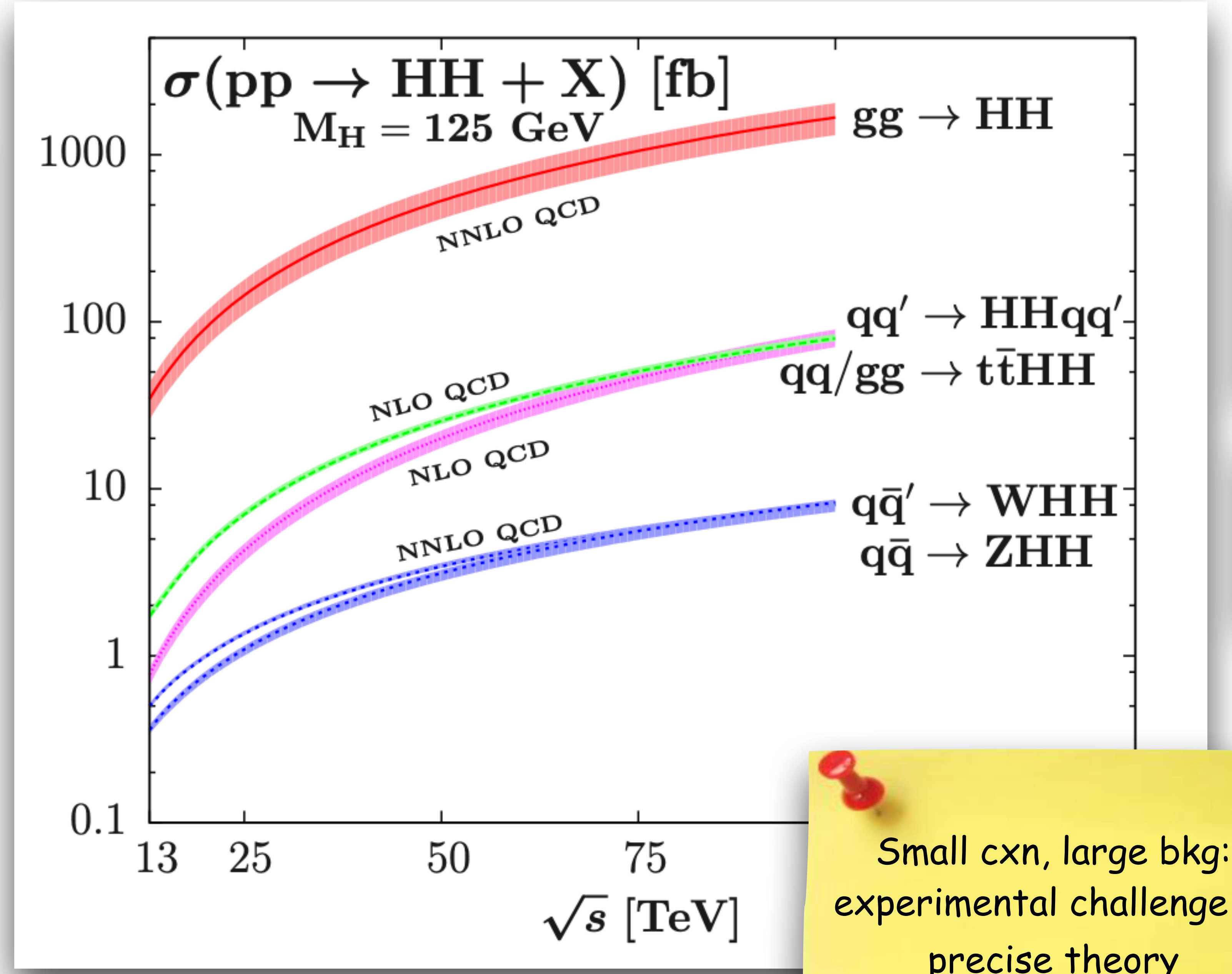
$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=1200\ \text{GeV}} = 0.0003223^{+0\%}_{-56\%}\ \text{fb/GeV}$$

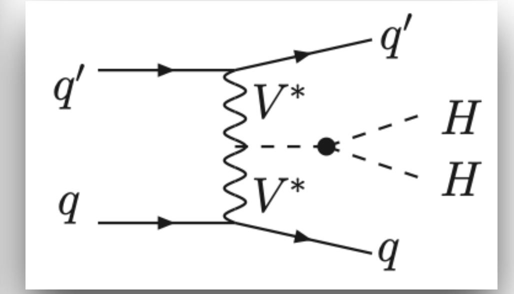
Double Higgs Production Processes

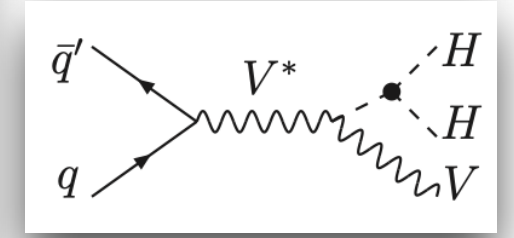
[Baglio,Djouadi,Quévillon,'15]











Small cxn, large bkg:
experimental challenge ⇝
precise theory
predictions required