# Discussion group report
# Multi-leg NLO

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# Contributions

Convenor: G. Passarino

| | |
|---|---|
| A. Denner | Scalar one-loop 4-point functions with complex masses |
| J. Fleischer | NLO tensor reduction, where we are |
| C. Papadopoulos | Automatic calculations, HELAC NLO status report |
| L. Dixon | Interference between Higgs signal and background |

A. Denner

# Complex mass scheme

# Motivation

- Almost all interesting elementary particles are unstable
- description of resonance requires resummation of propagator corrections
- mixing of perturbative order violates gauge invariance in general
  formally of higher orders but can be drastically enhanced
- many finite-width schemes have been proposed
  all have some drawbacks
- practical and consistent scheme: complex-mass scheme

# The complex-mass scheme

Denner, Dittmaier, Roth, Wackeroth '99, Denner, Dittmaier, Roth, Wieders '05

Basic idea: (renormalized mass)$^2$ = location of propagator pole in complex $p^2$ plane

$\hookrightarrow$ consistent use of complex masses everywhere !

replace $M_\mathrm{W}^2 \to \mu_\mathrm{W}^2 = M_\mathrm{W}^2 - \mathrm{i} M_\mathrm{W}\Gamma_\mathrm{W}, \qquad M_\mathrm{Z}^2 \to \mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i} M_\mathrm{Z}\Gamma_\mathrm{Z}$

and define (complex) weak mixing angle via $\cos^2\theta_\mathrm{w} \equiv c_\mathrm{w}^2 = 1 - s_\mathrm{w}^2 = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

$\hookrightarrow$ complex mass renormalization: $\underbrace{M_{\mathrm{W},0}^2}_{\text{bare mass}} = \mu_\mathrm{W}^2 + \underbrace{\delta\mu_\mathrm{W}^2}_{\text{ren. constant}}, \quad \ldots$

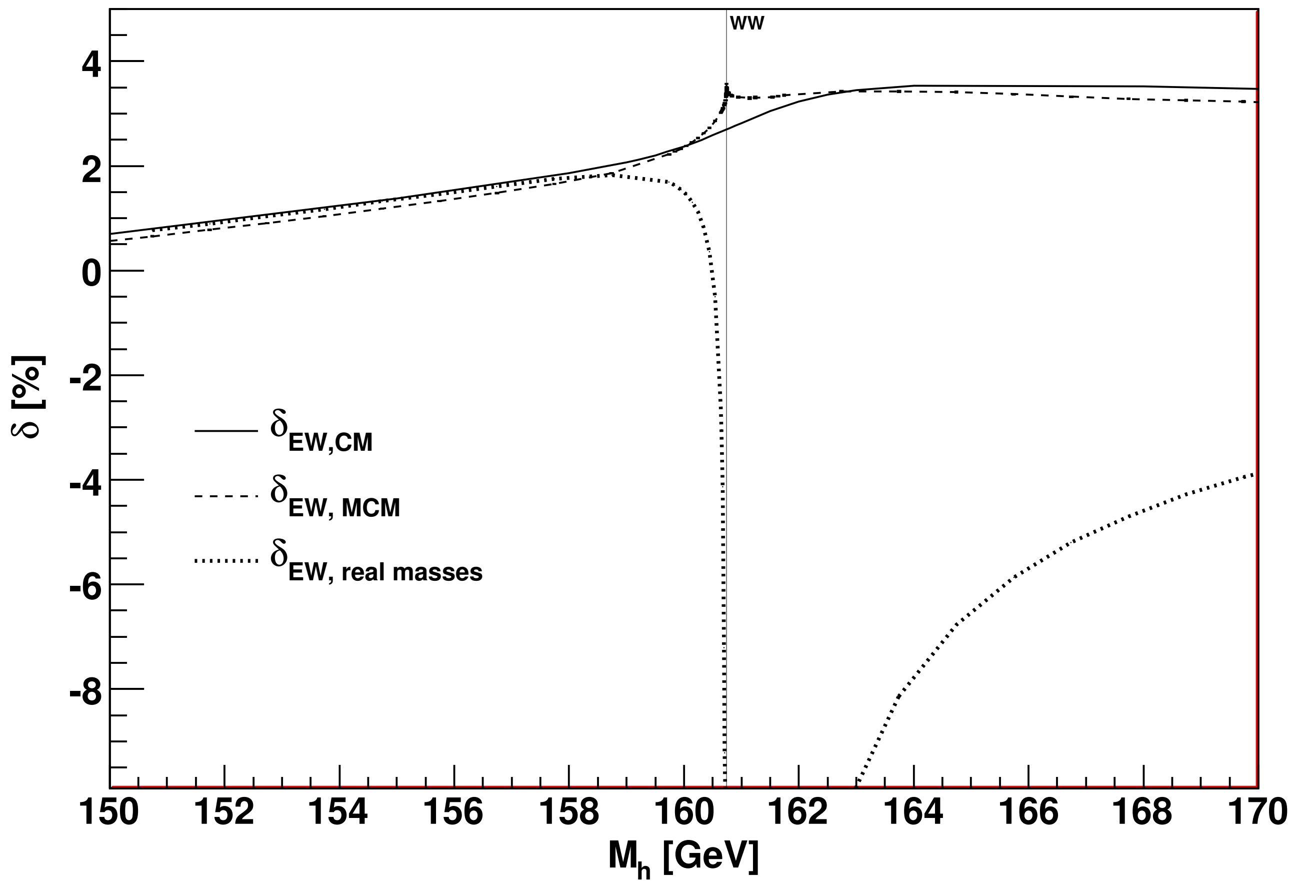
virtues

- gauge invariance (Ward identities), gauge-parameter independence hold exactly
- perturbative calculations as usual (with complex masses and counterterms)
- no double counting (bare Lagrangian unchanged !)

drawbacks

- spurious terms of $\mathcal{O}(\Gamma/M)$, of higher order [$\mathcal{O}(\alpha^2)$ in $\mathcal{O}(\alpha)$ calculation]
- loop integrals with complex masses, now available!

# Example: electroweak two-loop corrections to $H \to \gamma\gamma$




Actis, Passarino, Sturm, Uccirati ’08

CM = complex-mass scheme

MCM = “minimal” complex-mass scheme

$\Rightarrow$ consistent use of complex masses mandatory!

# Scalar one-loop integrals for complex masses

All NLO amplitudes reducible to scalar 1-, 2-, 3-, and 4-point integrals

- regular 1-, 2-, 3-point integrals 't Hooft, Veltman '79:
- regular 4-point integral
  - Dao, Le '09: result in terms of 108 dilogarithms following 't Hooft, Veltman '79
  - Denner, Dittmaier '10: result in terms of 72 dilogarithms based on improved approach of 't Hooft, Veltman '79
  - Denner, Dittmaier '10: result in terms of 32 dilogarithms generalizing approach of Denner, Nierste, Scharf '91
- soft and/or collinear singular 4-point integrals in dimensional, mass and mixed regularizations Denner, Dittmaier '10

J. Fleischer

# NLO tensor reduction

# Motivation

- Conventional techniques for NLO calculations rely on reduction of tensor integrals
- simple Passarino–Veltman reduction breaks down when Gram determinants become small or zero
- improved methods are required to circumvent this problem
- various methods are available in the literature
- publically available packages are not complete

goal: provide opensource package for reduction of tensor integrals

# Method of Fleischer/Riemann

Fleischer/Riemann arXiv:1009.4436 [hep-ph]

- Tensors are expressed by scalar integrals in higher dimensions following Davydychev '91
- notations for determinants according to Melrose '65
- use recurrence relations for higher-dimensional scalar integrals Tarasov '96, Fleischer '99
- reduce rank $r$ pentagons to rank $r-1$ pentagons and boxes without inverse Gram determinants
- for small Gram determinants: expansion in Gram determinant improve convergence with Padé approximants

remark AD: used methods are similar to those of other groups

Binoth et al, Denner/Dittmaier, R.K. Ellis et al

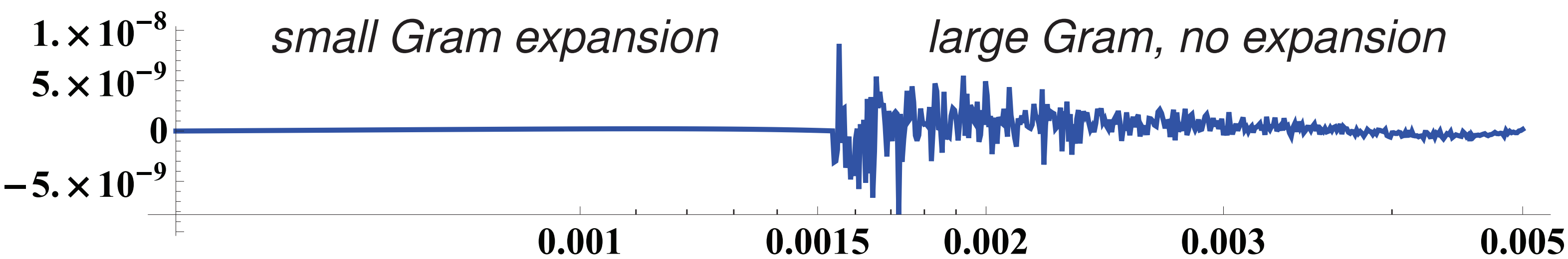
differences in details

## PJFry — numerical package

Numerical implementation of described algorithms:
C++ package **PJFry** by V. Yundin [in preparation]

- Reduction of **5-point** 1-loop tensor integrals up to **rank 5**
- No limitations on internal/external masses combinations
- Small Gram determinants treatment by expansion
- Interfaces for C, C++, FORTRAN and MATHEMATICA

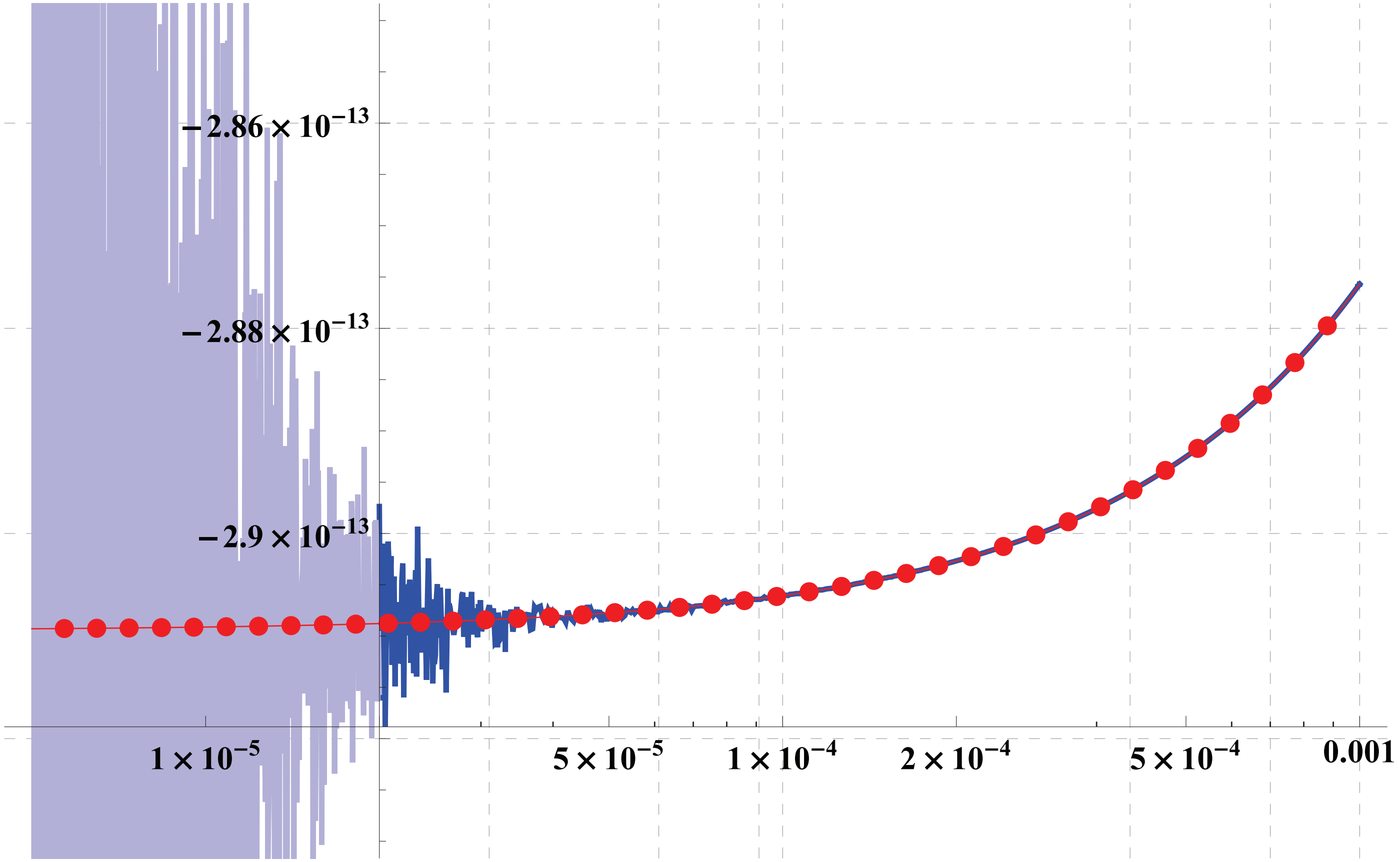
**Example:**
Relative accuracy of $E_{3333}$ coef. around small Gram4 region



## PJFry — small Gram region example

**Example:** $E_{3333}$ coefficient in small Gram region $(x = 0)$

Comparison of Regular and Expansion formulae:




$x{=}0$: $E_{3333}(0, 0, -6\times10^4, 0, 0, 10^4, -3.5\times10^4, 2\times10^4, -4\times10^4, 1.5\times10^4, 0, 6550, 0, 0, 8315)$

C. Papadopoulos

# HELAC-NLO

# HELAC-NLO

Authors: Bevilacqua, Czakon, Garzelli, van Hameren, Malamos, Papadopoulos, Pittau, Worek

General, automatized NLO calculator

ingredients:

- Dyson-Schwinger recursive equations
- Feynman rules in colour-flow representation
- OPP method for virtual corrections (`CutTools`)
- Rational terms (R2) via “counterterms”
- `OneLOop` library for scalar one-loop integrals in dimensional regularization
- HELAC-Dipoles: automatic production of Catani-Seymour dipoles
  - for arbitrary QCD and EW processes
  - massive and massless external states
  - restrictions on phase space (via $\alpha$ parameter)

# HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order. Information included: LH + color assignment, helicity. Optimization!

Calculate using `HELAC-1L` virtual part for each $w = 1$ event. Produce a new LH file including virtual corrections. Includes UV renormlization

The final LH file can now be used to produce any kinematical distribution !

# *HELAC-NLO in a Nutshell*

- **HELAC-PHEGAS**
  - Event generator for all parton level processes @ LO
- **HELAC-1LOOP**
  - Evaluation of virtual one-loop amplitudes, based on **HELAC**
- **CUTTOOLS**
  - Reduction of tensor integrals and determination of coefficients via OPP reduction method
- **ONELOOP**
  - Evaluation of scalar integrals (divergent and finite scalar integrals)
- **HELAC-DIPOLES**
  - Catani-Seymour dipole subtraction for massless and massive cases
  - Phase space integration of subtracted real radiation and integrated dipoles
  - Arbitrary polarizations & phase space restriction on dipoles contribution

**http://helac-phegas.web.cern.ch/helac-phegas/**

11

# HELAC-NLO

HELAC-NLO has been applied to

- $\mathrm{pp} \to VVV$
- $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$
- $\mathrm{pp} \to \mathrm{t\bar{t}jj}$

goal: provide NLO calculator for $2 \to n$ processes with $n = 6, 7$ particles attached to the loop

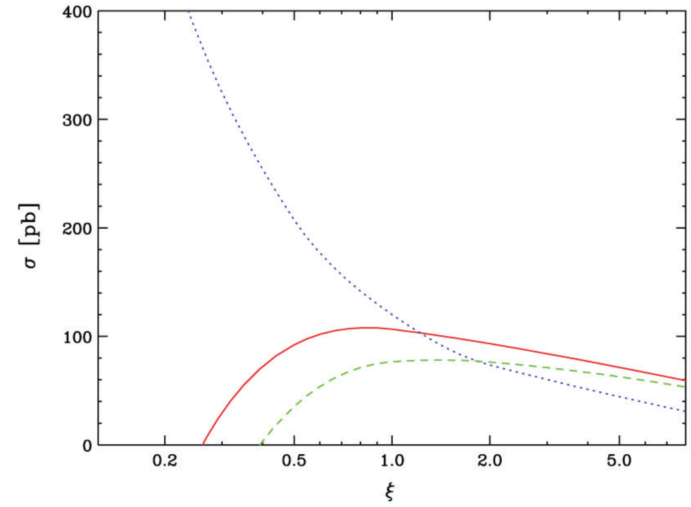
complete software package for NLO-QCD at LHC including virtual and real corrections

# Pp -> ttjj @ LHC

- Scale dependence & integrated cross sections

*Bevilacqua, Czakon, Papadopoulos, Worek '10*

| Process | $\sigma^{\rm LO}$ [pb] | Contribution |
|---|---|---|
| $pp \to t\bar{t}jj$ | 120.17(8) | 100% |
| $qg \to t\bar{t}qg$ | 56.59(5) | 47.1% |
| $gg \to t\bar{t}gg$ | 52.70(6) | 43.8% |
| $qq' \to t\bar{t}qq'$, $q\bar{q} \to t\bar{t}q'\bar{q}'$ | 7.475(8) | 6.2% |
| $gg \to t\bar{t}q\bar{q}$ | 1.981(3) | 1.6% |
| $q\bar{q} \to t\bar{t}gg$ | 1.429(1) | 1.2% |




$$\sigma_{\rm LO} = (120.17 \pm 0.08)\ {\rm pb}$$

$$\sigma_{\rm NLO} = (106.94 \pm 0.17)\ {\rm pb}$$

$$\sigma_{\rm NLO}^{\rm veto} = (76.58 \pm 0.17)\ {\rm pb}$$

Scale dependence reduced:
**72% @ LO** down to **13% @ NLO**
**54% @ NLO** with **jet veto** of 50 GeV

K factor of **K = 0.89** (**K = 0.64**)
Negative shift of **11%** (**36%**)

23

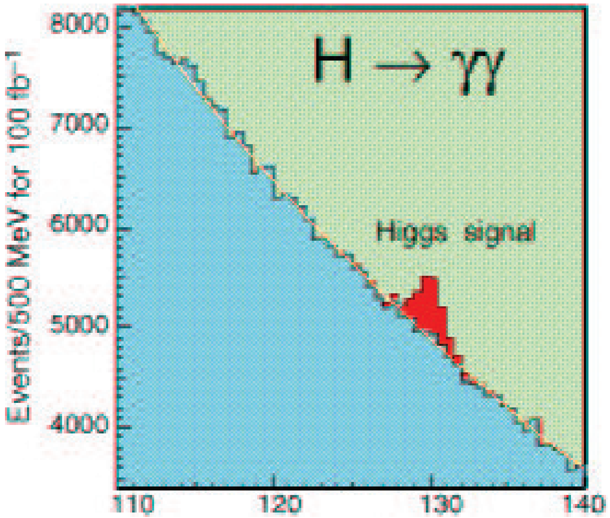
PAUL SCHERRER INSTITUT

L. Dixon

# Higgs signal-background interference

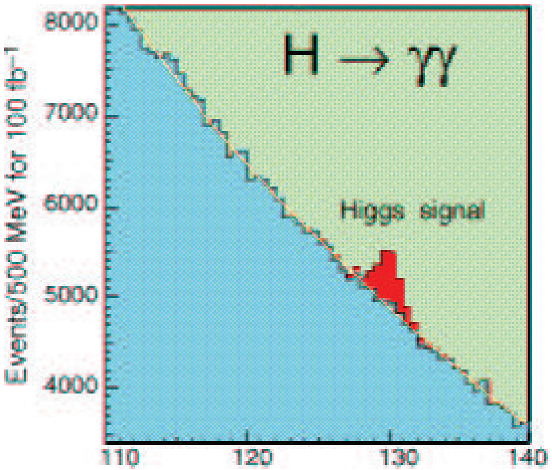
# Motivation

- For $M_{\mathrm{H}} < 140\,\mathrm{GeV}$ best decay mode is $\mathrm{H} \to \gamma\gamma$
- QCD background is huge
  – can it contaminate the signal through interference?




- how big is resonance-continuum interference for $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$?
  Dixon, Siu
- general issue when extracting couplings from experimental signal for various production/decay channels.

# Back-of-envelope calculation




- $S/B \approx 1/20$ CMS
- But expt'l resolution $\approx 1$ GeV $\approx 1000 \times \Gamma_H$
- Also, only $1/3$ or so of $B$ is from $gg \to \gamma\gamma$
- So intrinsic $S/B \approx 1/20 \times 1000 \times 3 \approx 150$
- Interference effect is $\approx 2\sqrt{B/S} \approx 15\%$

# In search of a phase

- Total $gg \to \gamma\gamma$ amplitude

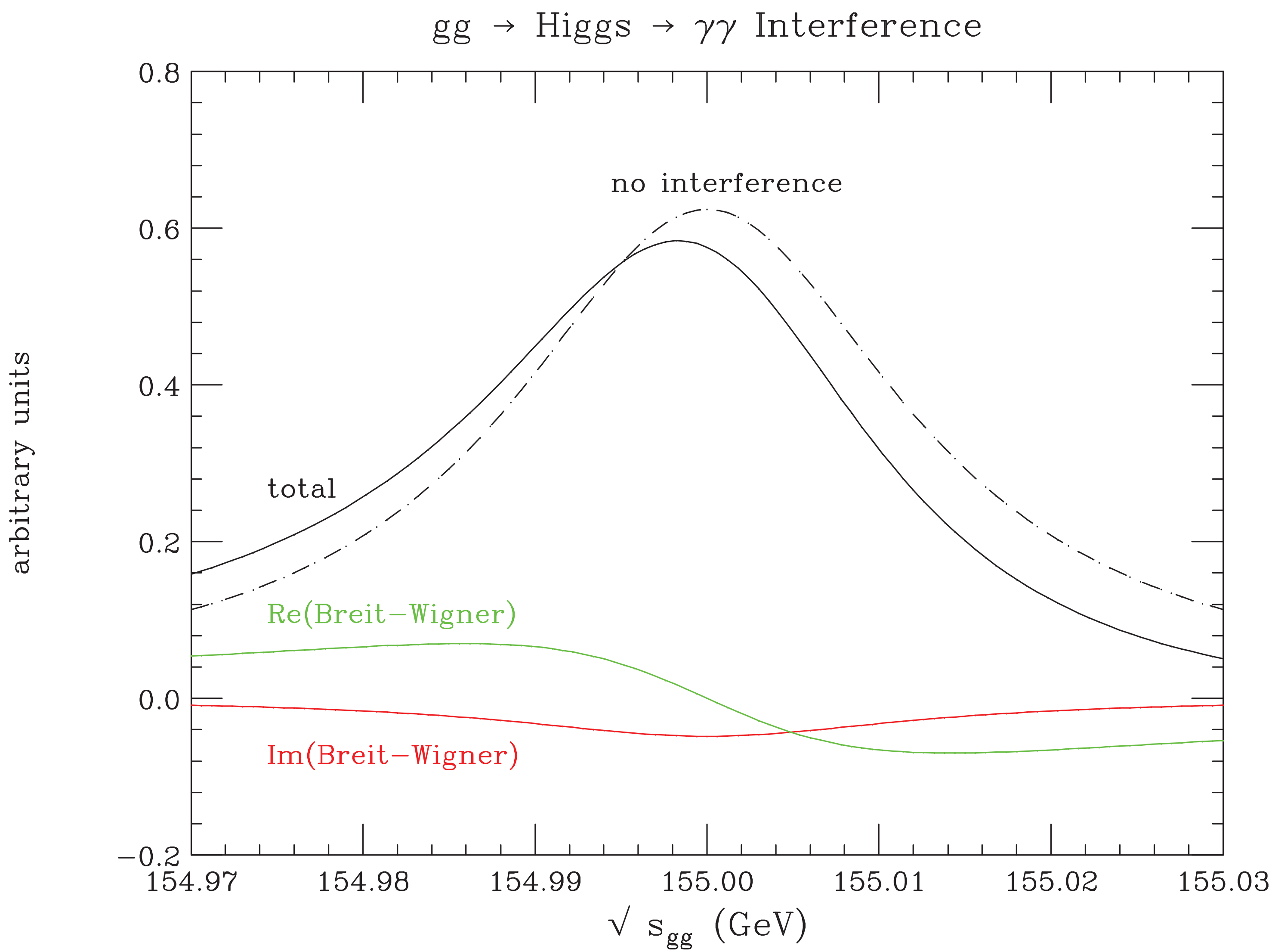
$$\mathcal{A}_{gg\to\gamma\gamma} = \frac{-\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}}{\hat{s} - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\text{cont}}$$

- Interference term has 2 pieces

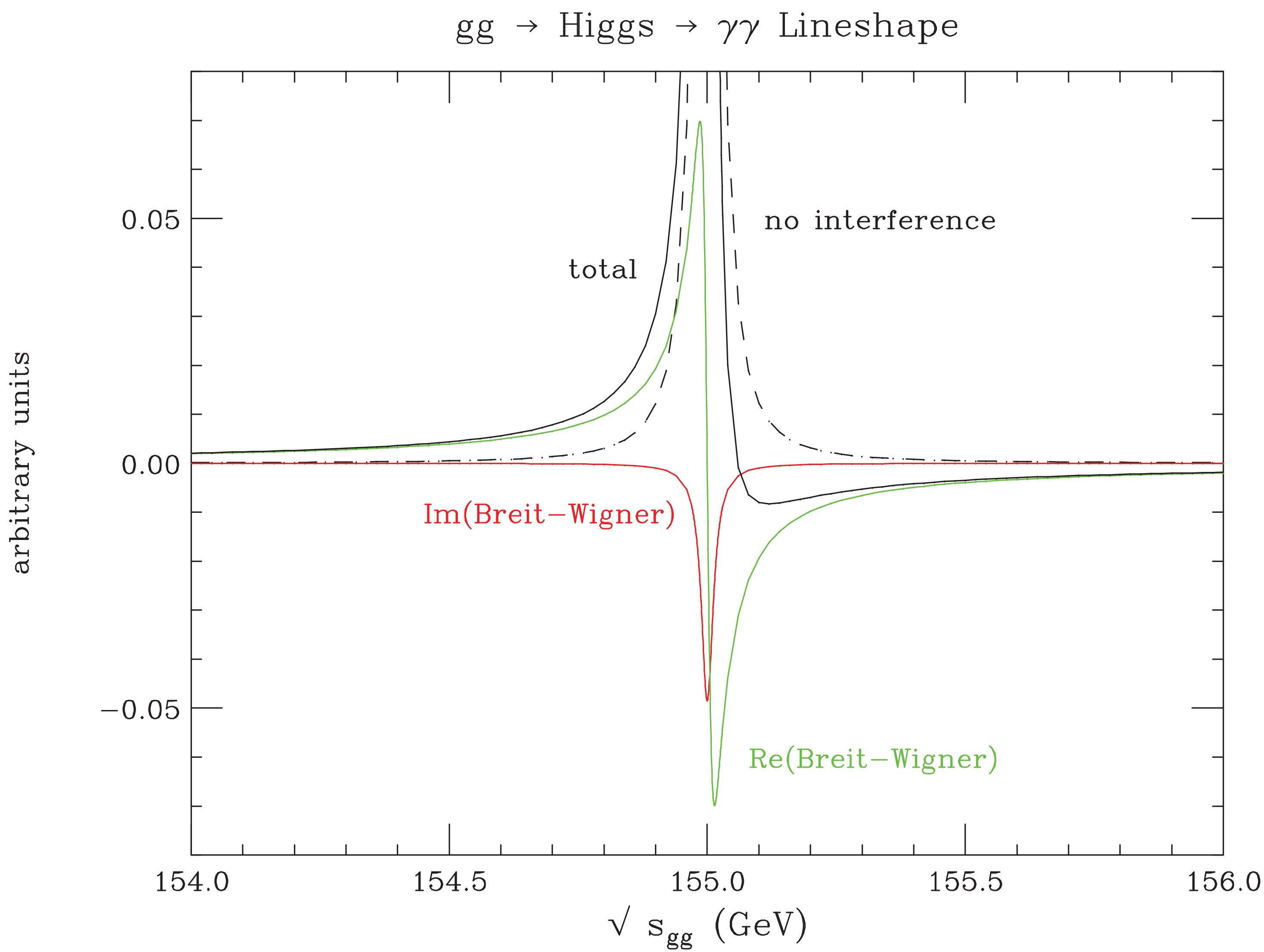
$$\begin{aligned} \delta\hat{\sigma}_{gg\to H\to\gamma\gamma} &= -2(\hat{s} - m_H^2)\frac{\text{Re}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\text{cont}}\right)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \\ &\quad - 2 m_H \Gamma_H \frac{\text{Im}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\text{cont}}\right)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \end{aligned}$$

- "Re" term vanishes upon integration over $\hat{s}$, provided that $\mathcal{A}_{gg\to H}$, $\mathcal{A}_{H\to\gamma\gamma}$, $\mathcal{A}_{\text{cont}}$ do not vary too quickly. Dicus, Willenbrock
- "Im" term needs relative phase, resonance *vs.* continuum.

# Close-up of Higgs resonance



# Not-so-close-up of Higgs resonance



# Conclusions

- Interference of $gg \to H \to \gamma\gamma$ signal with continuum background at LHC relies on an interplay between phases in QCD and electroweak amplitudes.
- In the SM, 2-loop QCD phases are more important.
- Effect is destructive in the SM, though $-(2-6)\%$ is below presently anticipated th. & expt. uncertainties.
- Effect can get larger in MSSM, for example, in regions where the $\gamma\gamma$ signal is still visible.
- Further study of effects in MSSM, other Higgs models, and in selected other channels in the (MS)SM is warranted.