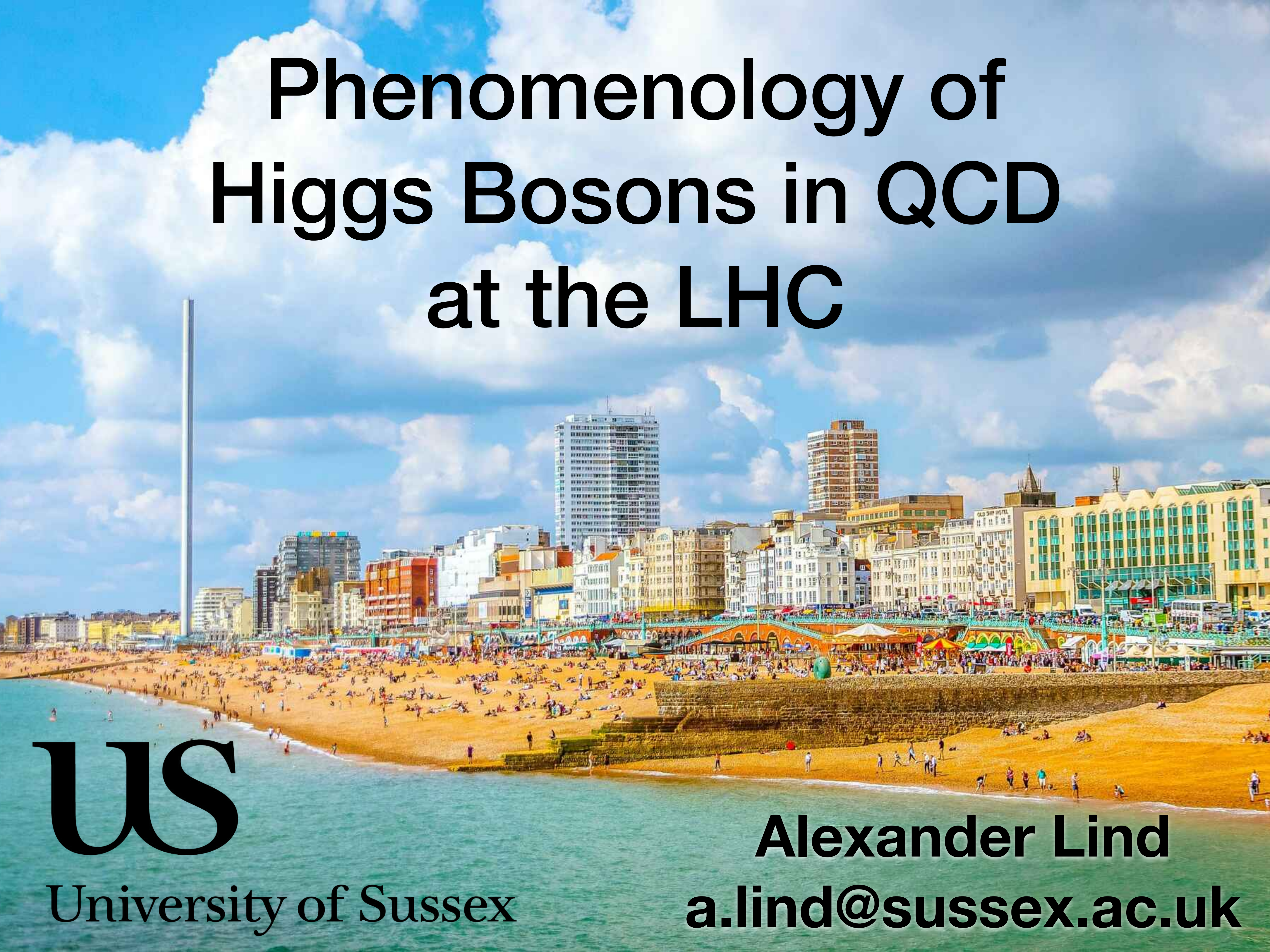
Phenomenology of Higgs Bosons in QCD at the LHC



University of Sussex

Alexander Lind
a.lind@sussex.ac.uk

Who am I?

- Did my Bachelor's and Master's in this group with Jørgen on diffraction (soft QCD) with Pythia 8 and ALFA/ATLAS

- Just handed in my PhD at University of Sussex

I am interested in
collider phenomenology
and the use and
development of
Monte Carlo event
generators

What's the landscape?

for collider physics

Since 2012:
"The Higgs has been found…
now what's next??"

No signs of
new physics
beyond the
Standard Model

Collider physics
is going into
a precision era

Precision

Large datasets:

LHC Run 2: $139\ \mathrm{fb}^{-1}$

LHC Run 3: $300\ \mathrm{fb}^{-1}$

HL-LHC: $3000\ \mathrm{fb}^{-1}$

Lepton colliders:

FCC-ee

Large reduction in experimental uncertainties:

Electron/muon uncertainties: permille level

JES: sub-percent level

B-tagging uncertainty: sub-percent level

And cool Machine Learning now

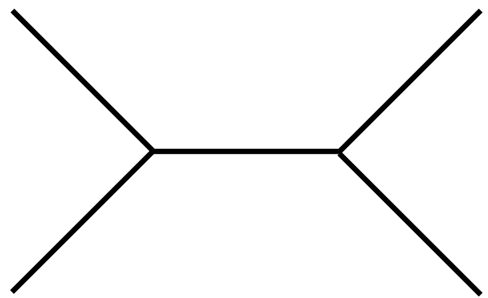
→ **Challenge for Theory/MC community:**

Need for ever increasing precision

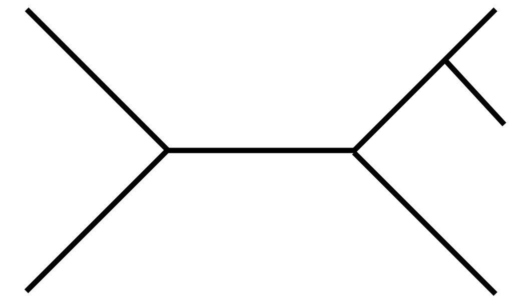
Next-To-Leading Order (NLO)

Theoretical precision: Higher orders in the hard scattering matrix element

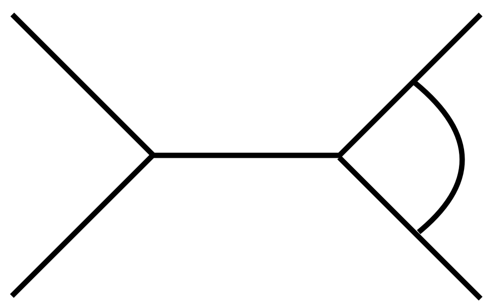
Tree level (Born / LO):



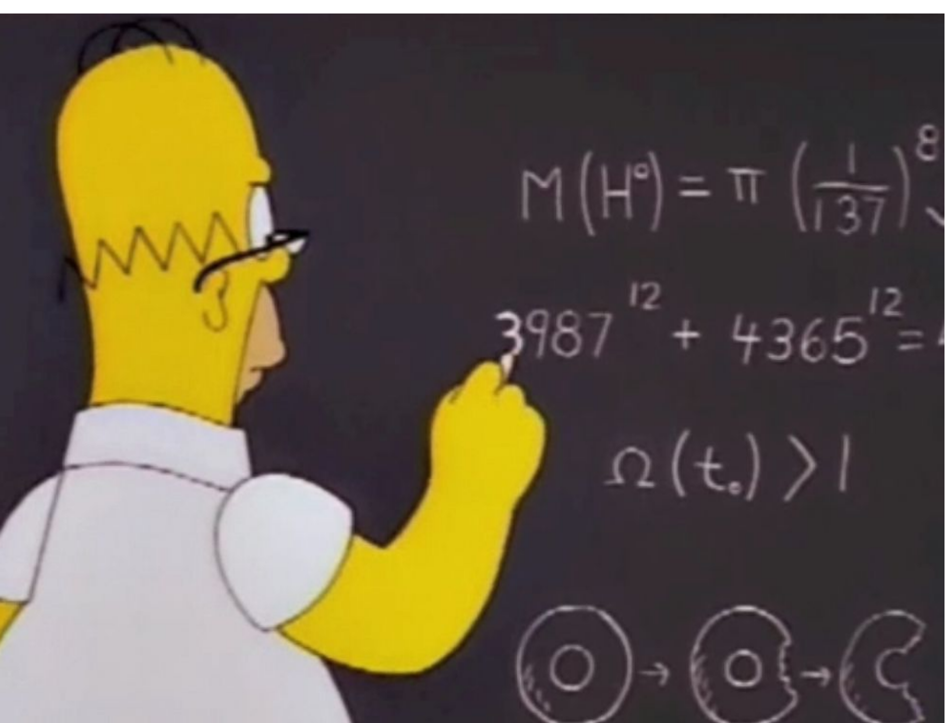
Real emission:



One-loop (Virtual):



$$\sigma_{\rm NLO} = \sigma_{\rm B} + \sigma_{\rm R} + \sigma_{\rm V}$$



NLO necessary for most processes
in particular Higgs production

$$\sigma_{\rm LO}(pp \to H + X) = 14.541(7)\ {\rm pb}\,,$$

$$\sigma_{\rm NLO}(pp \to H + X) = 35.11(2)\ {\rm pb}\,,$$

Even NNLO can give sizable corrections
but 2-loop is highly non-trivial

Divergences

$$\sigma_{\mathrm{NLO}} = \sigma_{\mathrm{B}} + \sigma_{\mathrm{R}} + \sigma_{\mathrm{V}}$$

Infrared
(soft/collinear) divergences

Cancellation (BN / KLN theorems)
Subtraction of dipoles (Catani-Seymour)

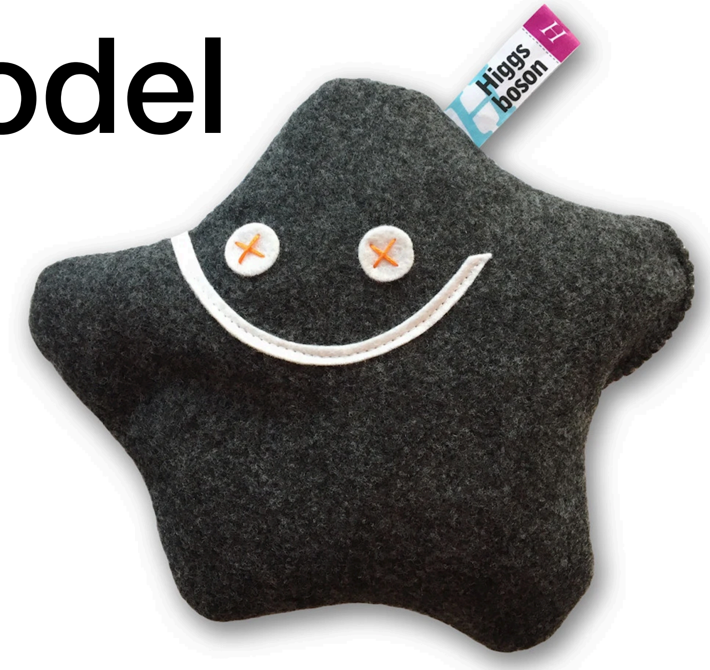
Finite
in infrared (IR) safe observables

UV divergences

Dim. reg.
Renormalisation

Finite

The 1-Higgs-Singlet model



Add a real singlet scalar field

Potential after EW symmetry breaking:

$$V = \frac{\lambda}{4}H^4 + \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \frac{\lambda_2}{2}H^2 s^2 + \lambda_2 v H s^2 + \mu_1 s^3 + \frac{\mu_2}{2}H^2 s + \mu_2 v H s$$

Mixing:

$$h_1 = H\cos\theta - s\sin\theta$$
$$h_2 = H\sin\theta + s\cos\theta$$

Free parameters: M_{h_2}, θ

$$M_{h_1} = 125 \text{ GeV} \qquad \mu_1 = \lambda_1 = \lambda_2 = 0$$

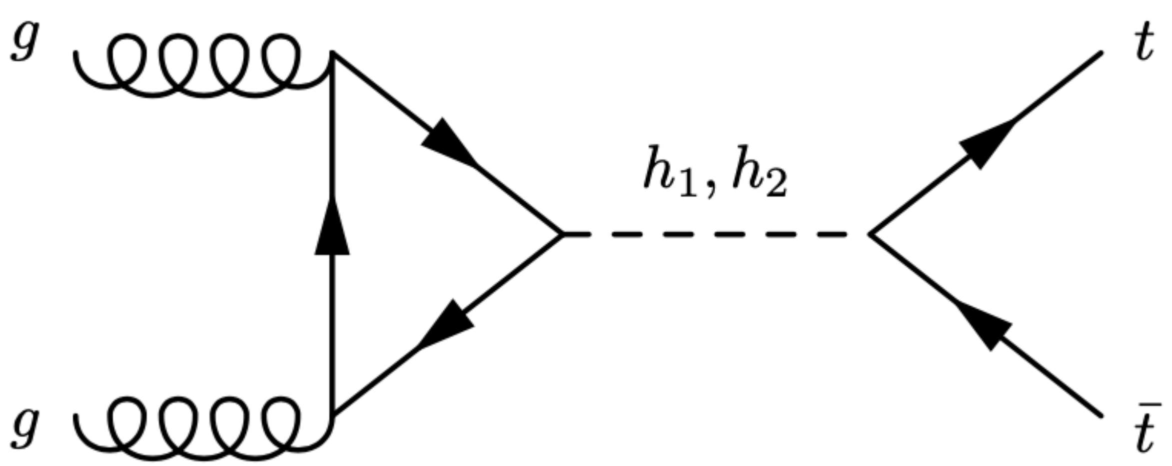
8 benchmark points:

M_{h_2} [GeV]	700	1000	1500	3000
θ_1	$\pi/15$ ≈ 0.21	$\pi/15$ ≈ 0.21	$\pi/22$ ≈ 0.14	$\pi/45$ ≈ 0.07
θ_2	$\pi/8$ ≈ 0.39	$\pi/8$ ≈ 0.39	$\pi/12$ ≈ 0.26	$\pi/24$ ≈ 0.13

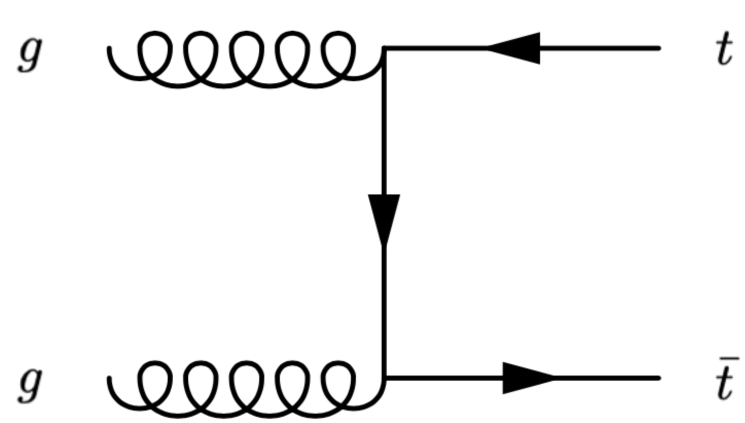
Process of Interest

$$pp\ (\rightarrow \{h_1, h_2\}) \rightarrow t\bar{t} + X$$ at NLO

Higgs signal

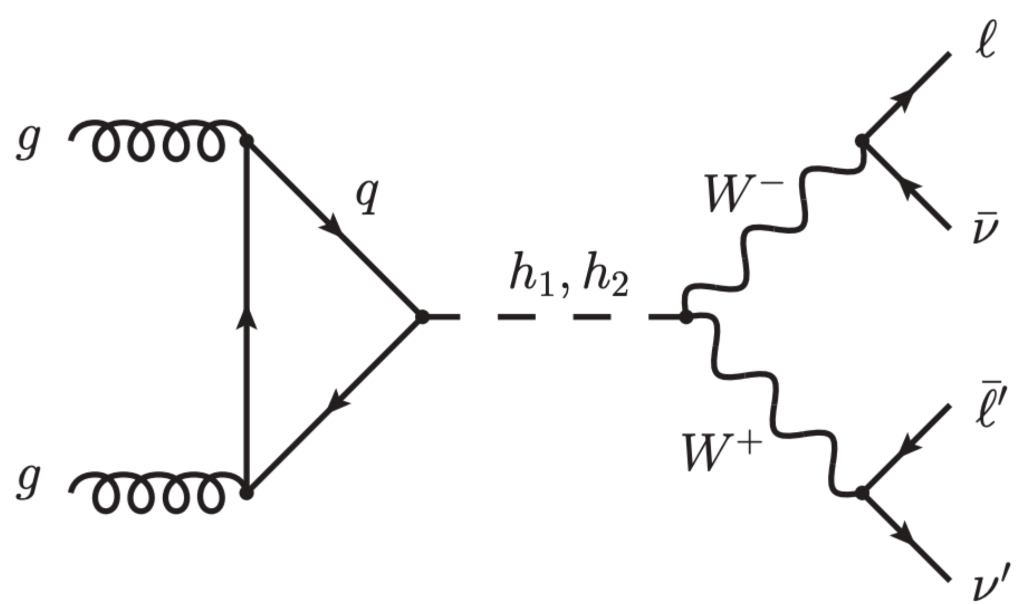


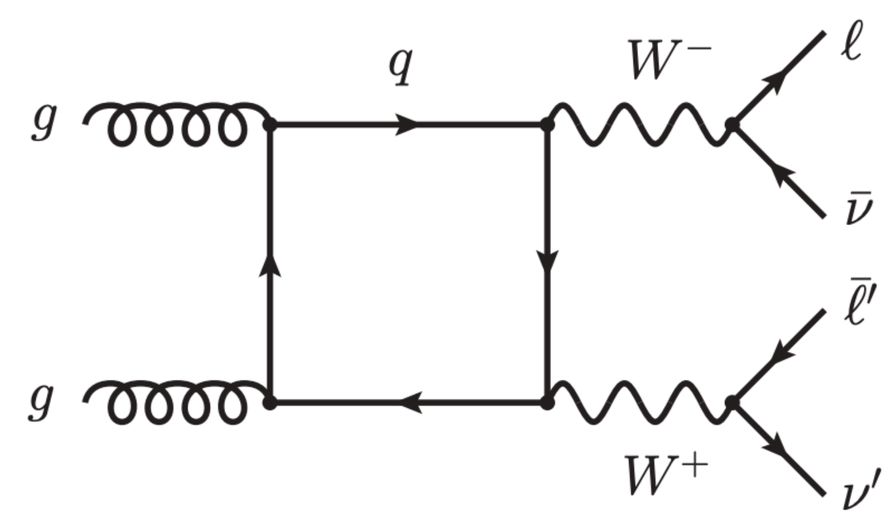
QCD background

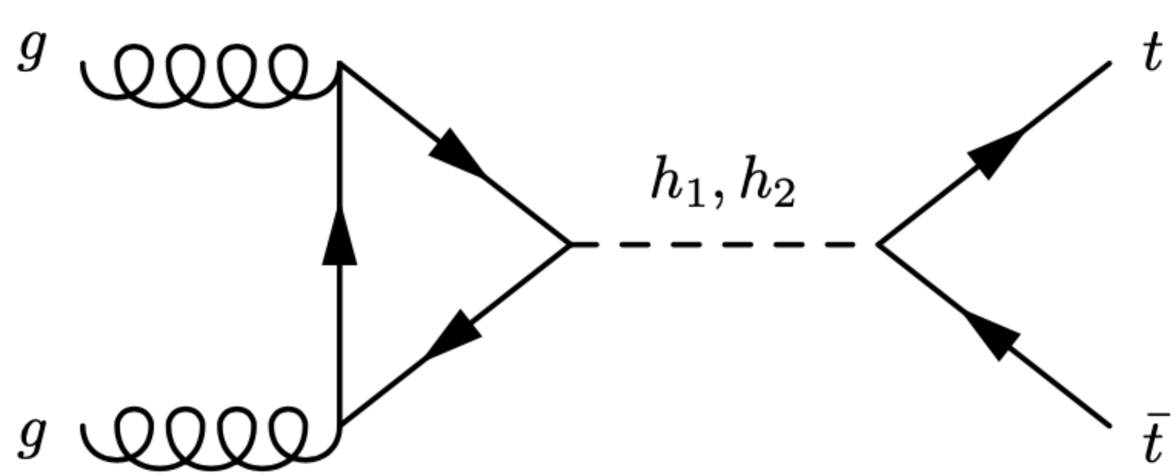


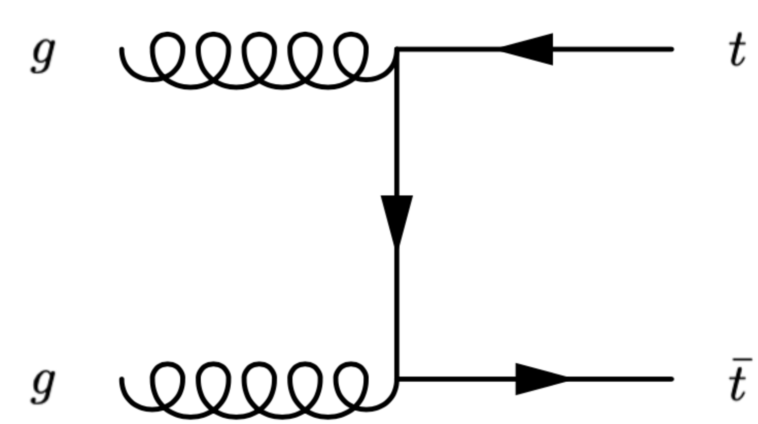
Alternative to “Bump Hunting”?

Invariant mass spectrum



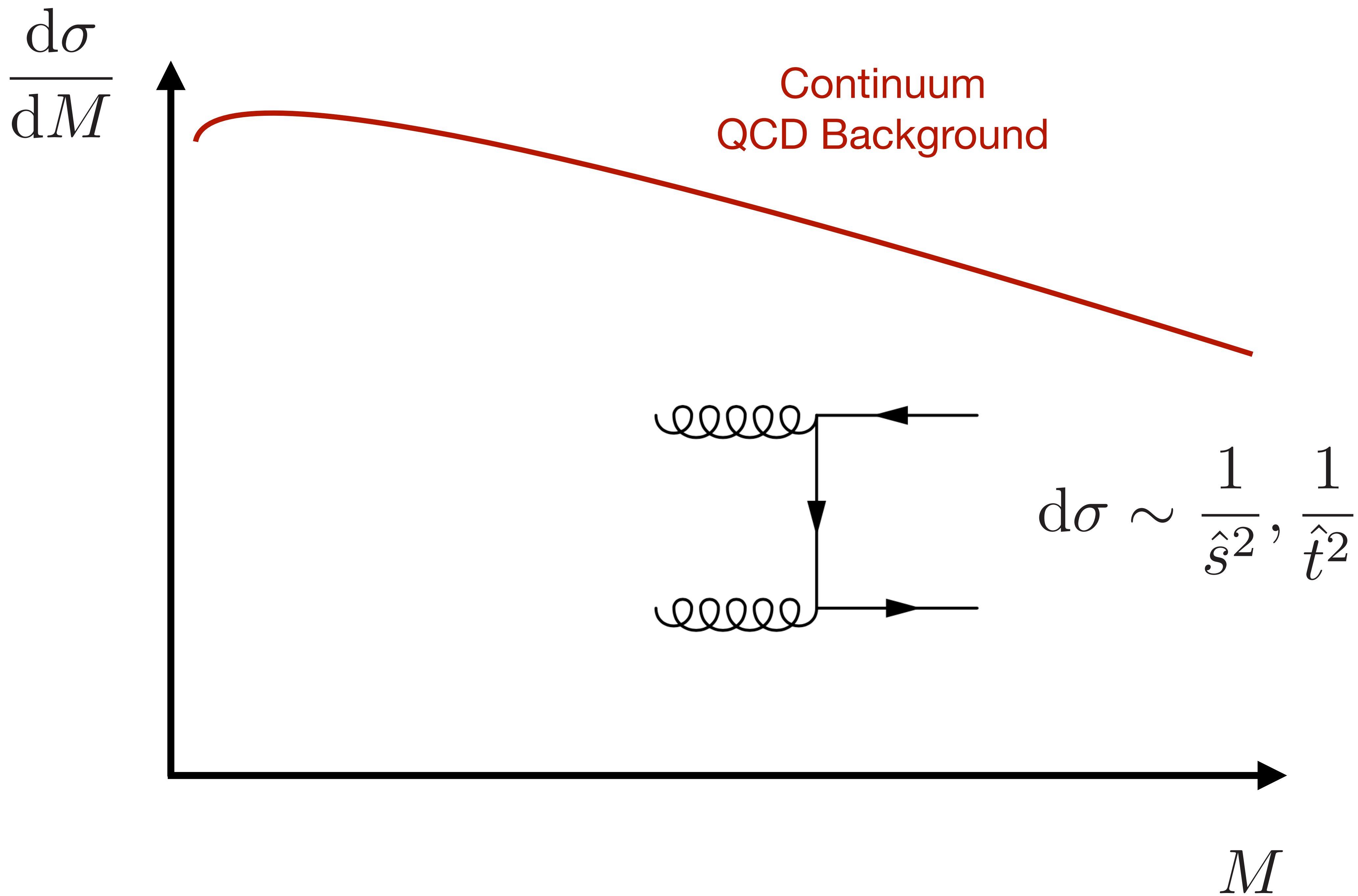






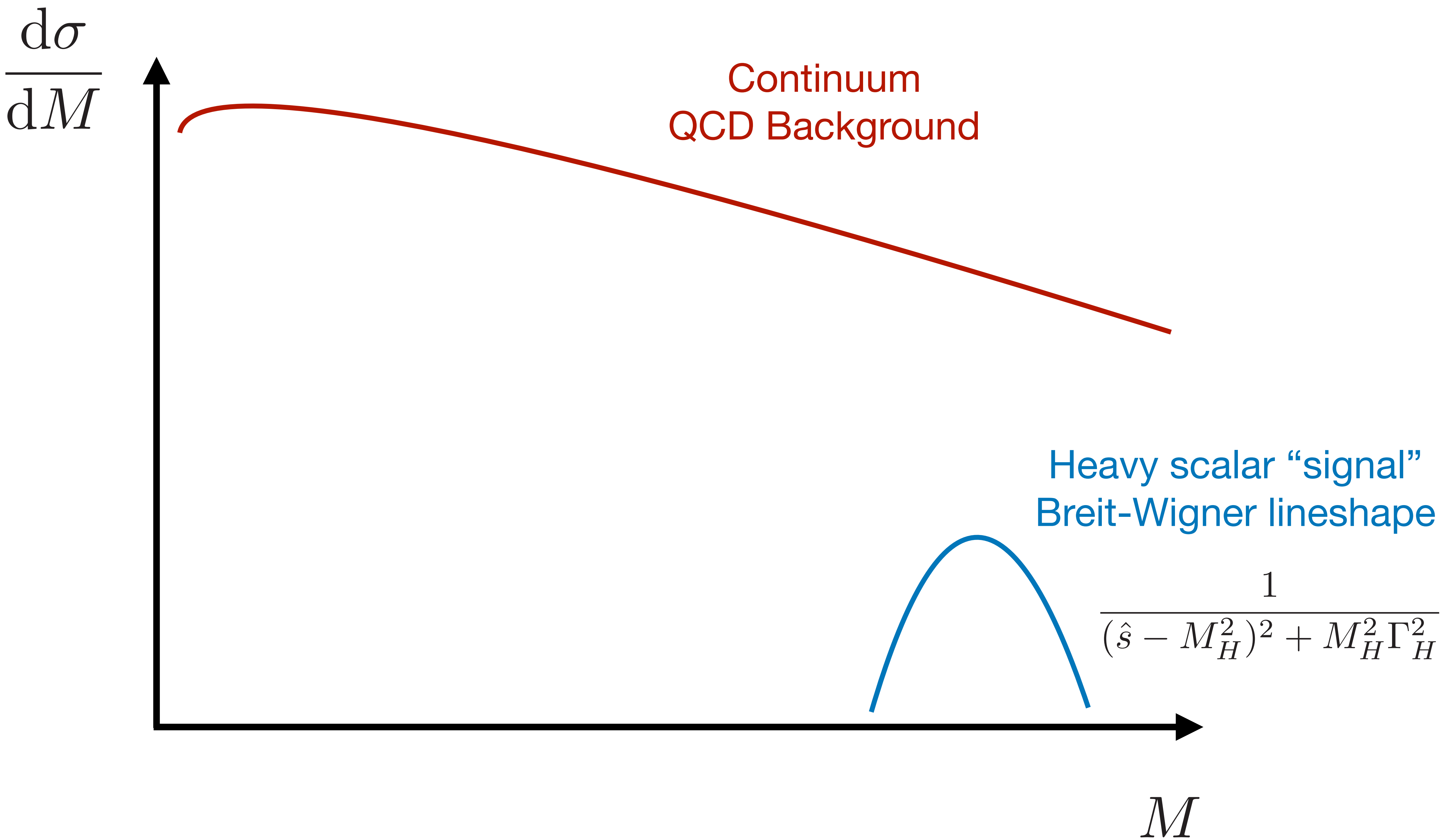
Alternative to “Bump Hunting”?

Invariant mass spectrum



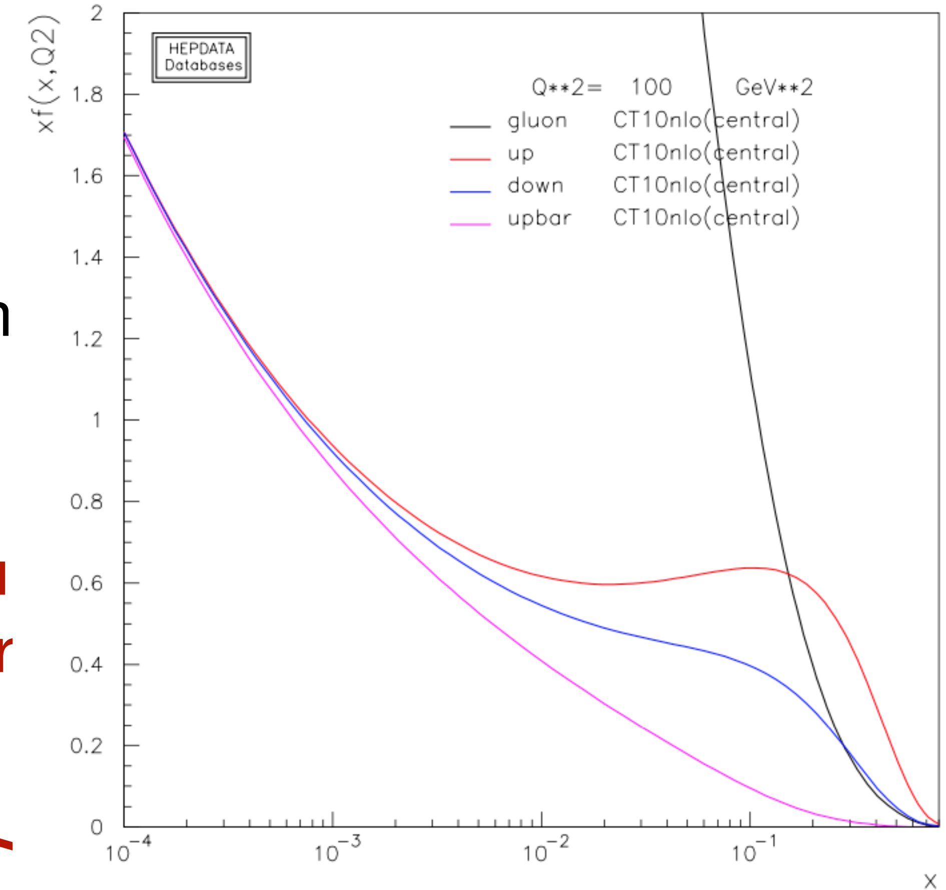
Alternative to "Bump Hunting"?

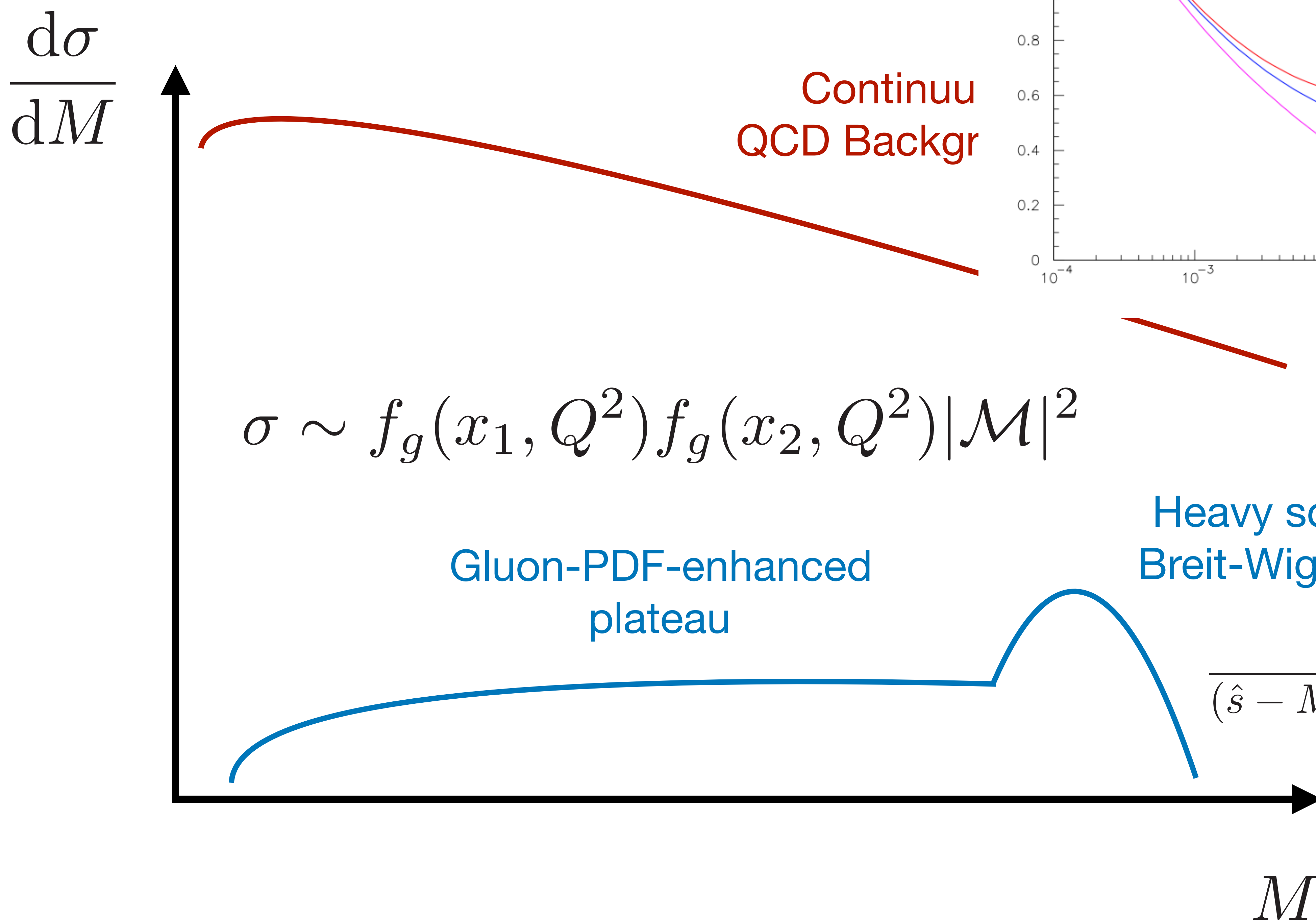
Invariant mass spectrum



Alternative to “Bump

Invariant mass spectrum

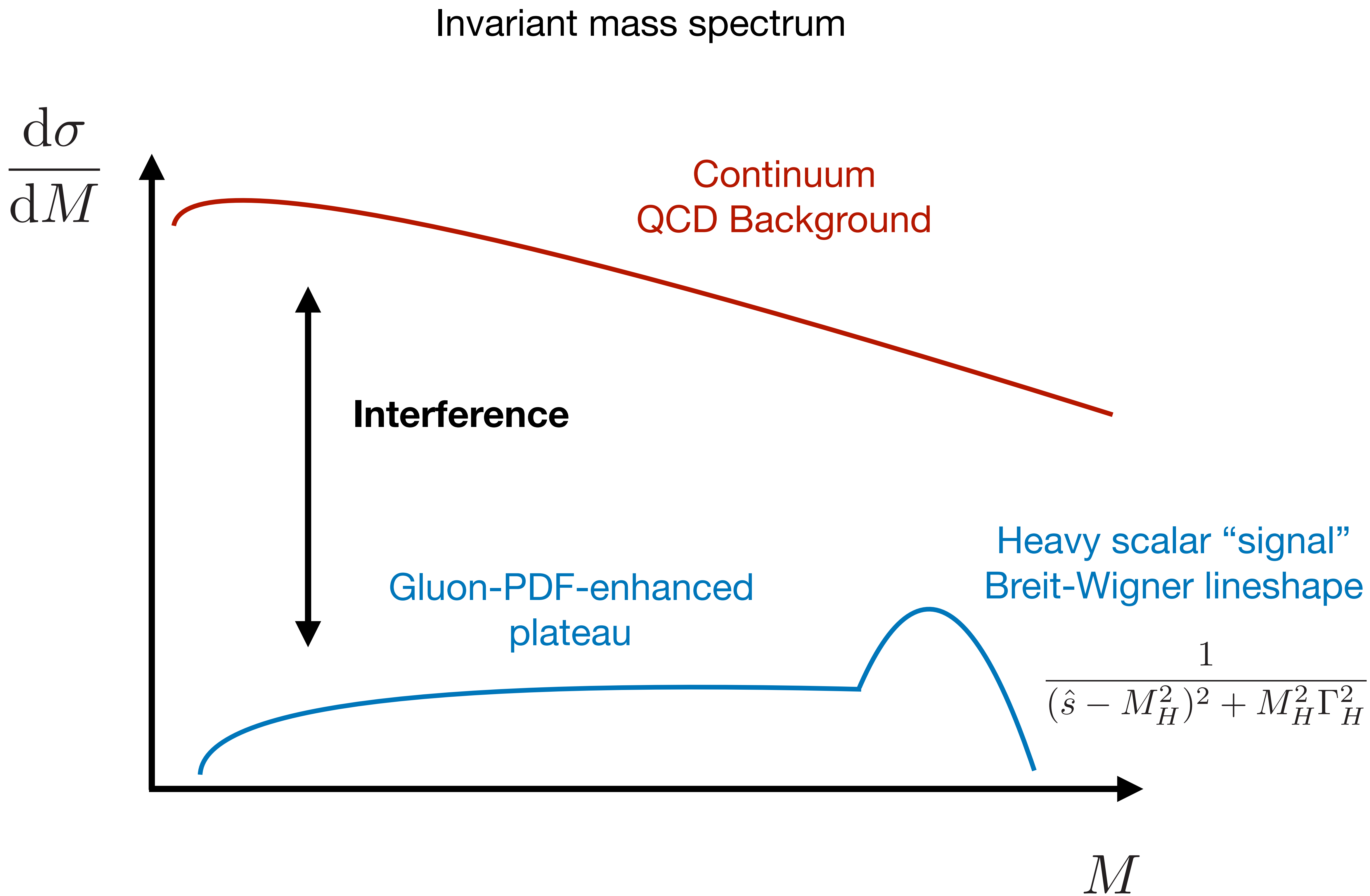




$$\sigma \sim f_g(x_1, Q^2) f_g(x_2, Q^2) |\mathcal{M}|^2$$

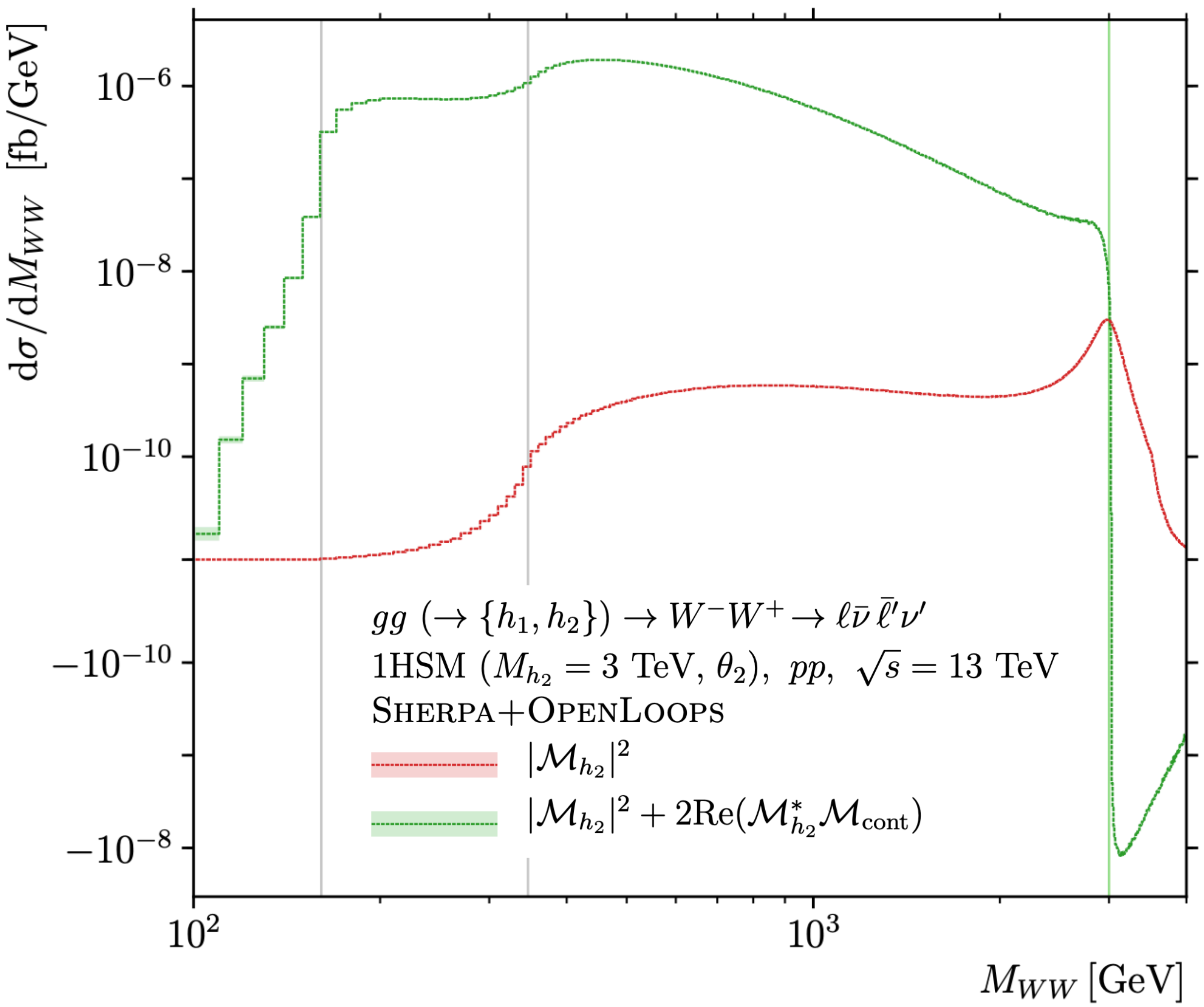
$$\frac{1}{(\hat{s} - M_H^2)^2 + M_H^2 \Gamma_H^2}$$

Alternative to “Bump Hunting”?

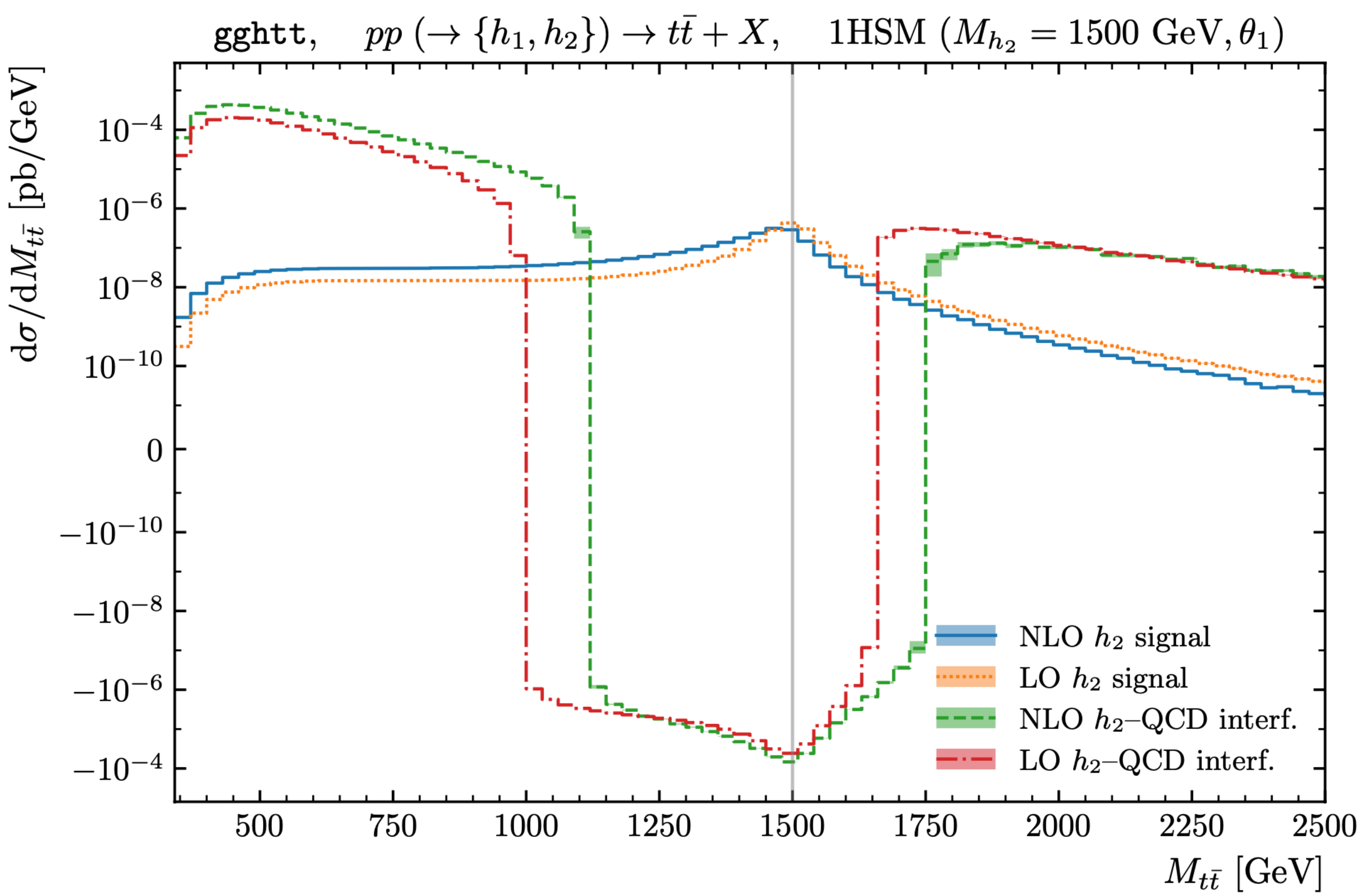


Alternative to "Bump Hunting"?

Invariant mass spectrum



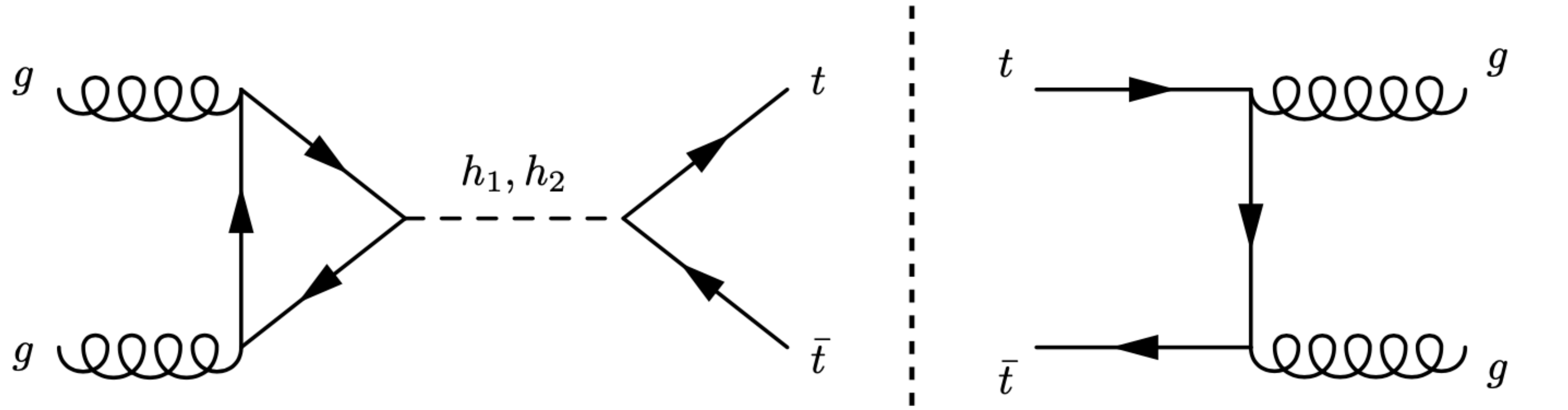
$$\mathrm{d}\sigma \sim \frac{1}{\hat{s}^2}$$



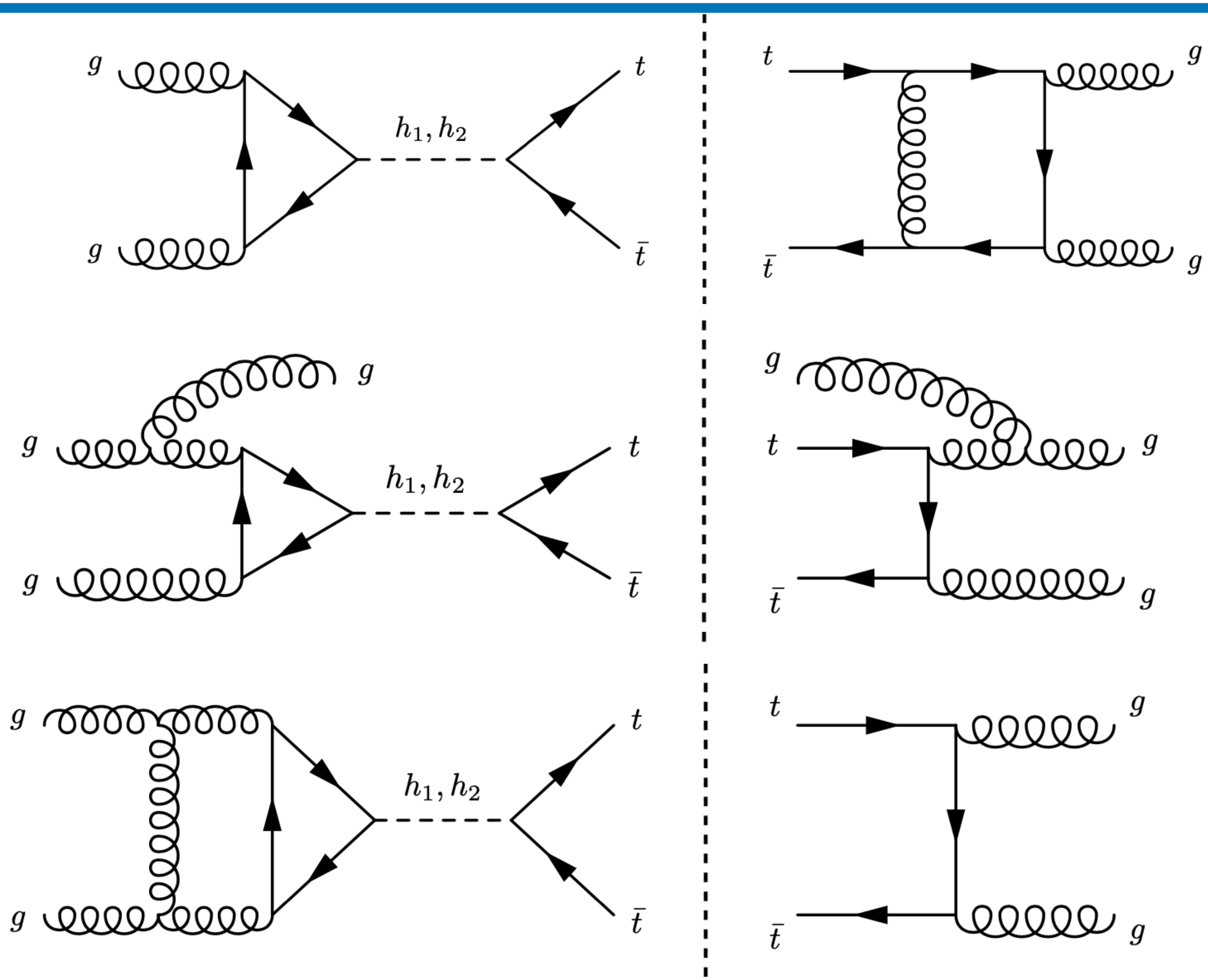
$$\mathrm{d}\sigma \sim \frac{1}{(\hat{s} - M_H^2)^2} \sim \frac{1}{M_H^4}$$

NLO QCD Corrections to Interference

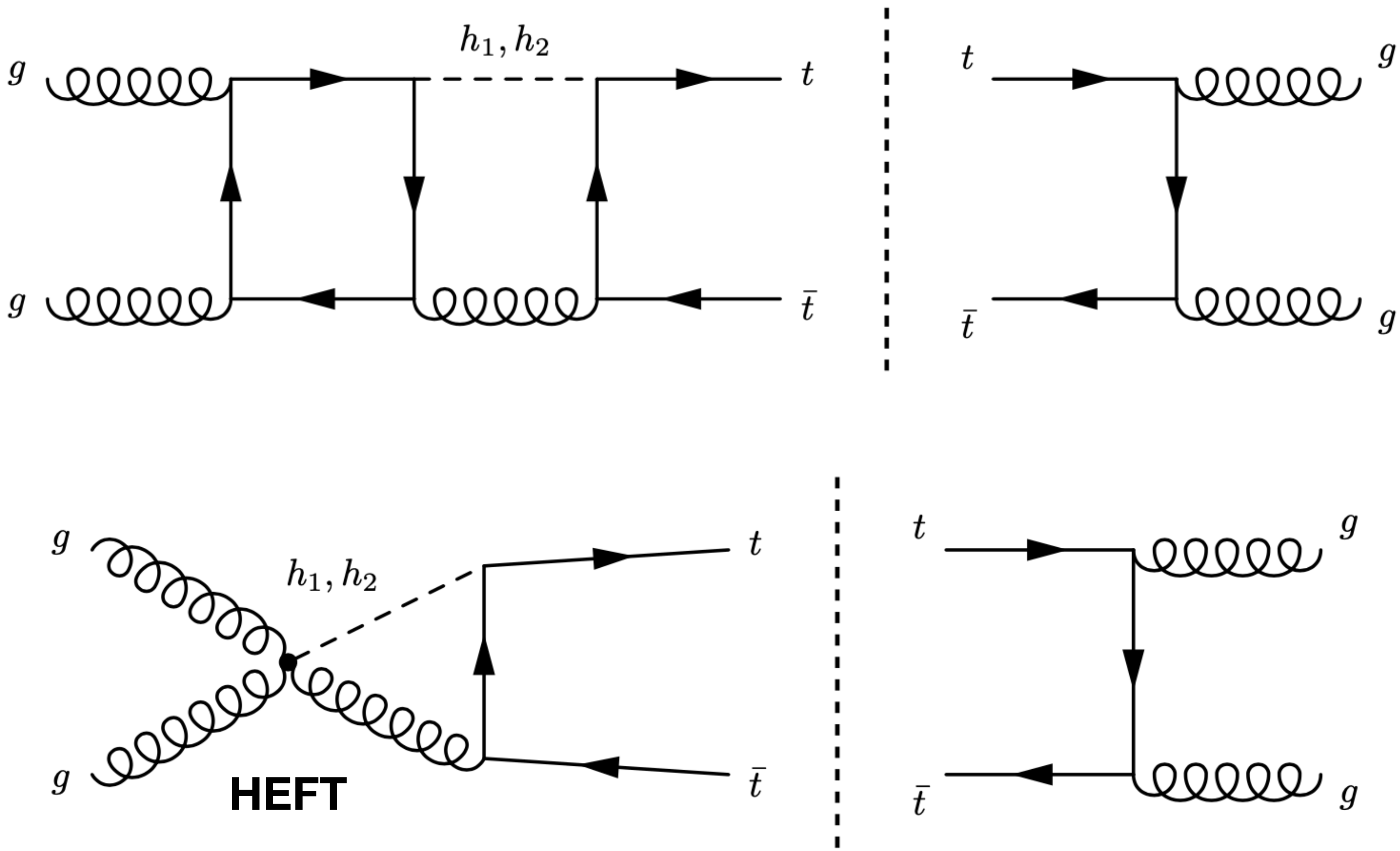
LO



NLO



Non-Factorisable Corrections



Expansion in: $$\frac{\Gamma_H}{M_H}$$

HELAC+OpenLoops

HELAC: Dipole subtraction

OpenLoops: Tree and loop amplitudes

Kaleu: Phase space generation

LHAPDF: PDF sets

Needed to develop a new NLO Monte Carlo event generator

But no need to reinvent the wheel

Written in "Olde" Fortran

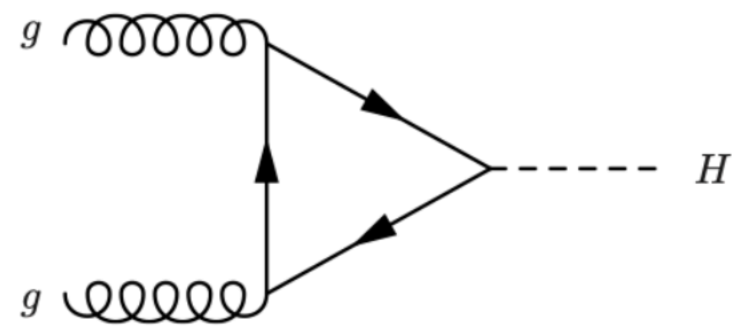
Modified OpenLoops with:

- Interface to get colour correlated helicity amplitudes
- Form factor interface (next slide)
- BSM extensions

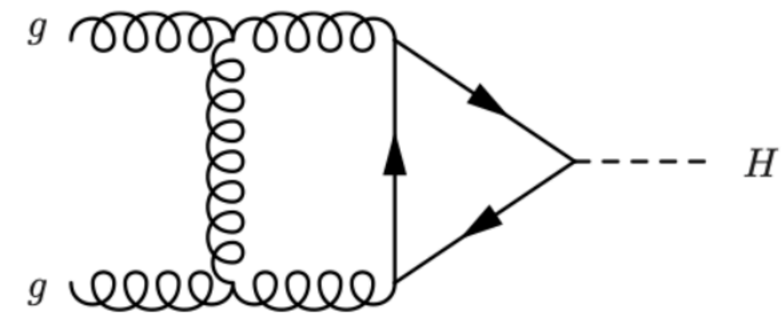
Form Factors

Gluon-fusion Higgs production:

$$gg \to H$$



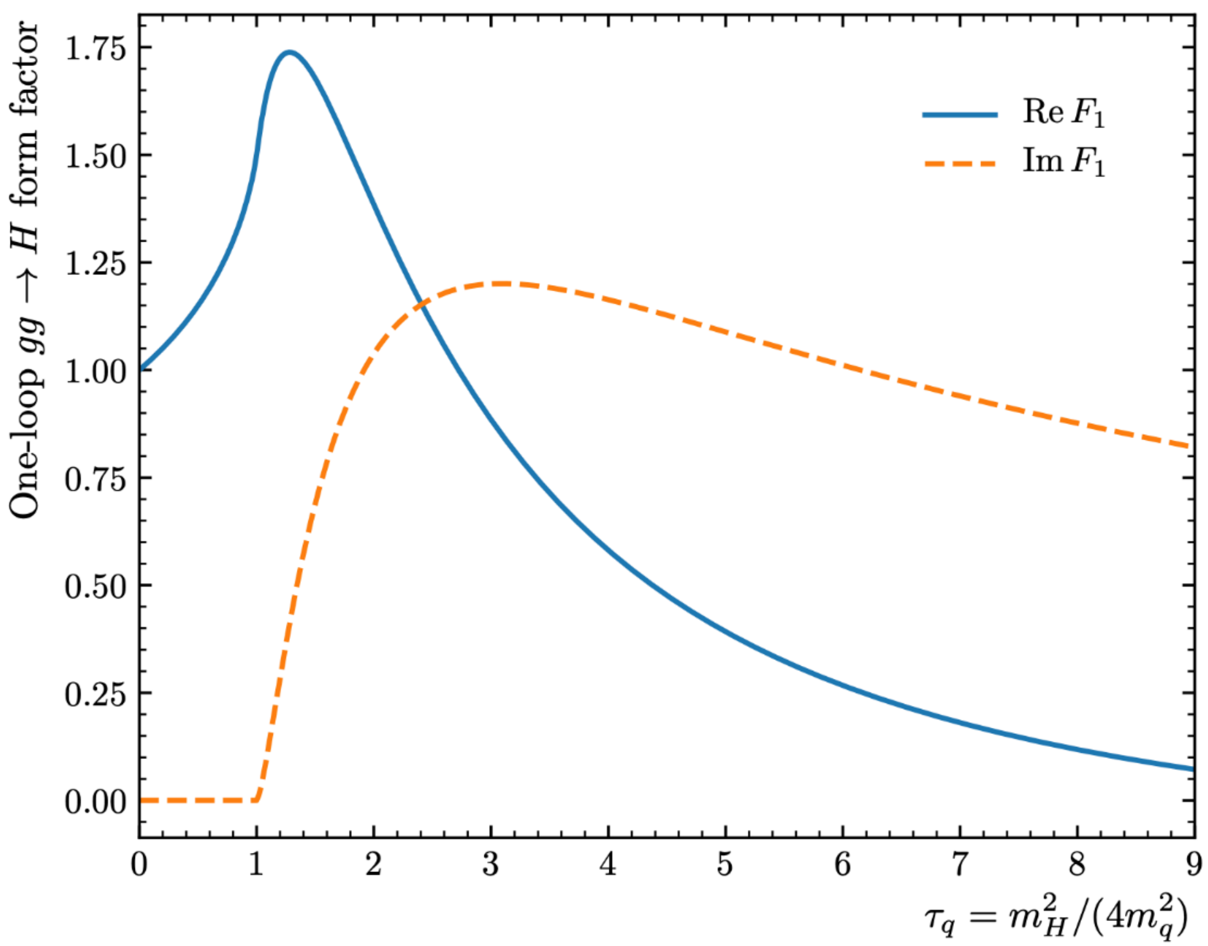
(a) One-loop contribution.

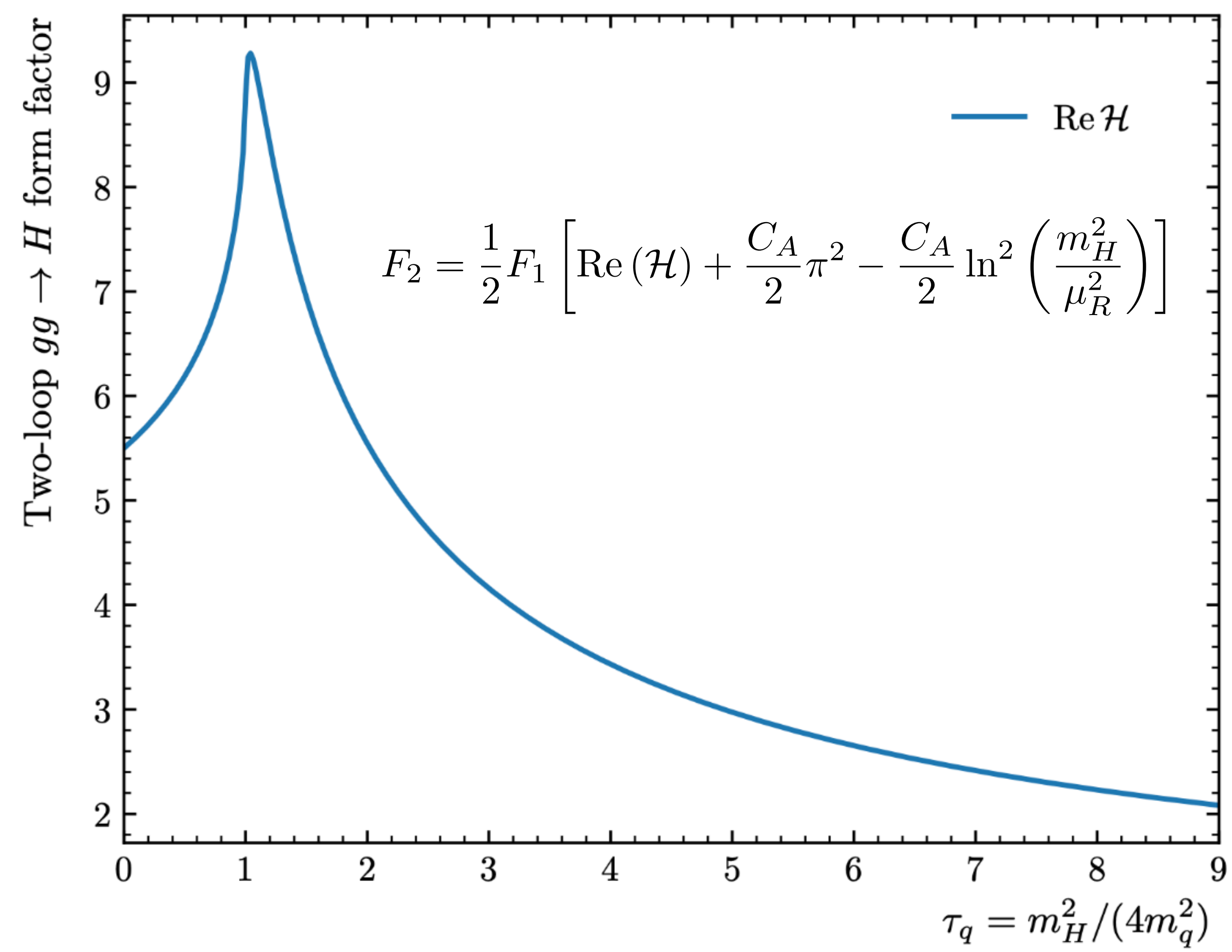


(b) Two-loop contribution.

$$\mathcal{M} = \frac{\alpha_s}{3\pi v} F \delta^{ab} \left(q_1 q_2 g^{\mu\nu} - q_1^{\nu} q_2^{\mu} \right)$$

$$F = F_1 + \frac{\alpha_s}{\pi} F_2 + \mathcal{O}(\alpha_s^2)$$

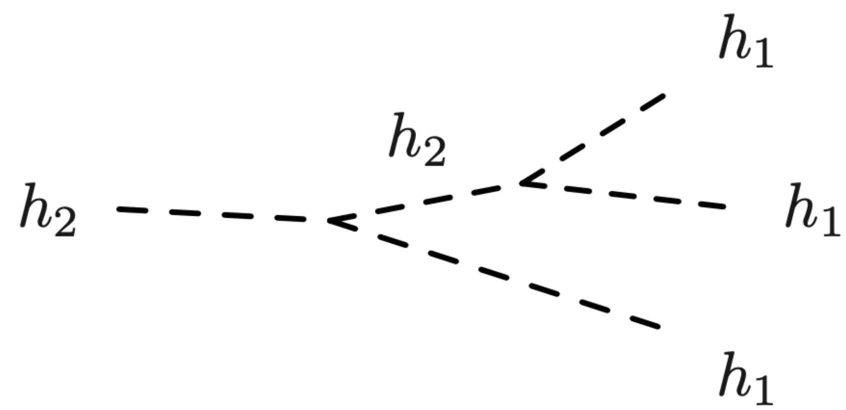




Heavy Higgs Propagator

For one benchmark point:

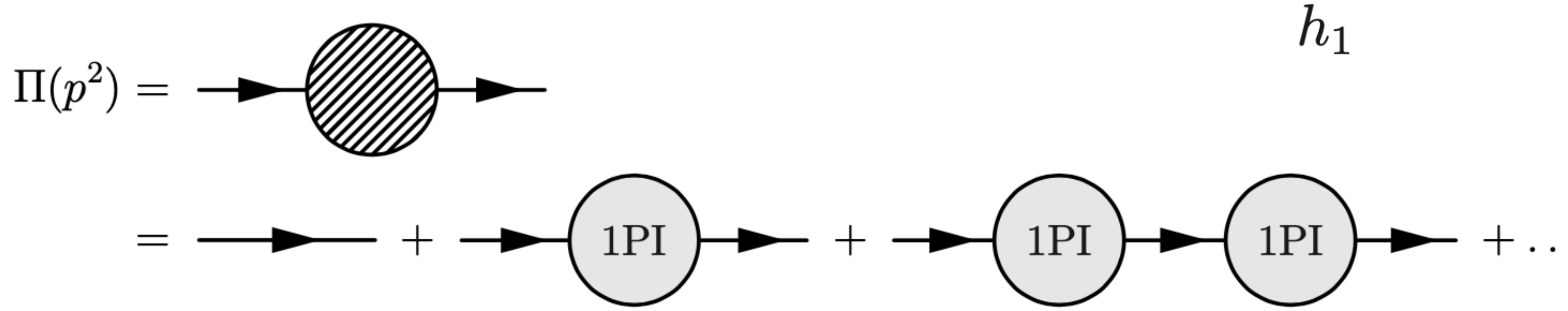
$$\Gamma_{h_2}/M_{h_2} \sim 0.18$$



Cascaded decays:

$$h_2 \to 3 \times h_1$$

Circular dependence on decay width



$$= \frac{i}{p^2 - m_0^2} + \frac{i}{p^2 - m_0^2}\left[-i\Sigma(p^2)\right]\frac{i}{p^2 - m_0^2} + \ldots$$

$$= \frac{i}{p^2 - m_0^2 - \Sigma(p^2)} .$$

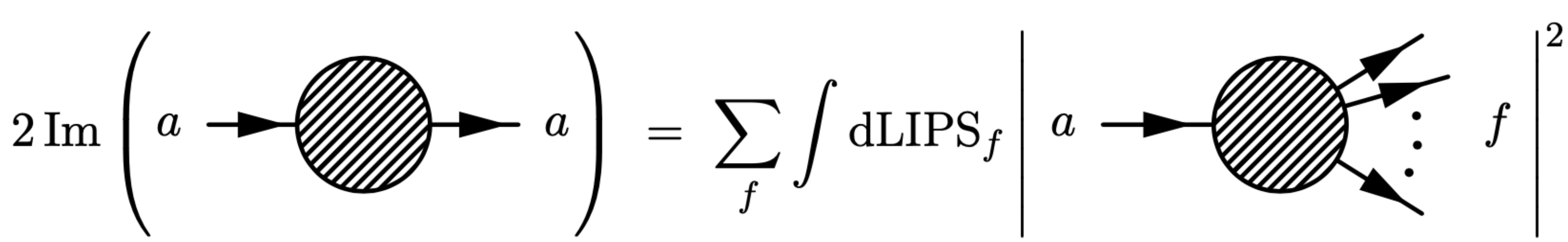
Exact scalar propagator:

$$\Pi(p^2) = \frac{i}{p^2 - m_0^2 - \Sigma(p^2)}$$

Optical Theorem
On-shell approx.

Breit-Wigner approximation:

$$\Pi(p^2) \sim \frac{i}{p^2 - m^2 + im\Gamma}$$



$$\mathrm{Im}\,\Sigma(p^2 = m^2) = -m\Gamma$$

Results

Integrated cross-sections

SM

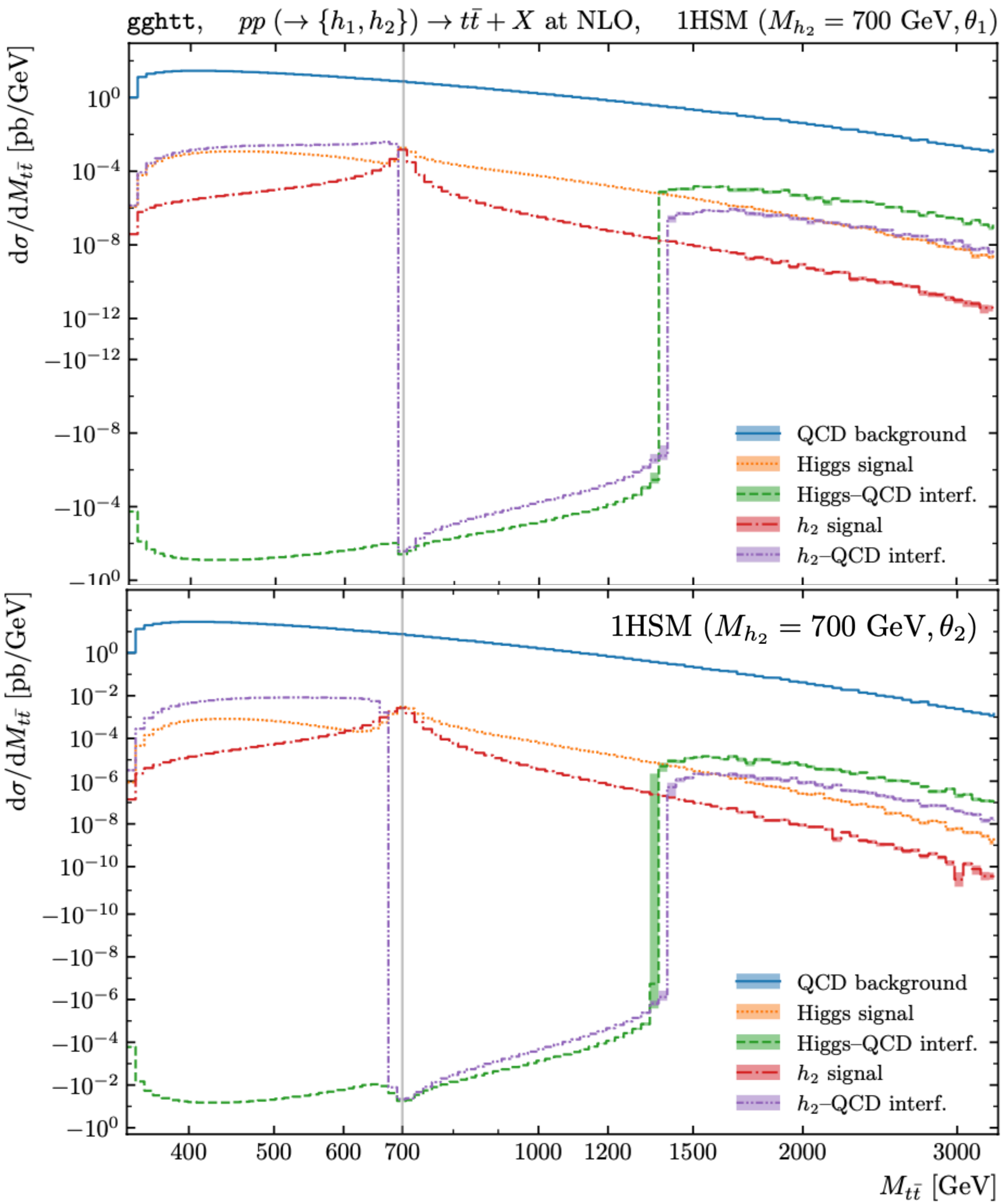
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the SM, pp, $\sqrt{s} = 13$ TeV					
Higgs signal		QCD background		Interference	
σ_{NLO} [pb]	K	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
0.030971(3)	1.6512(2)	675.23(4)	1.5965(1)	−1.5865(2)	2.1807(2)

1HSM

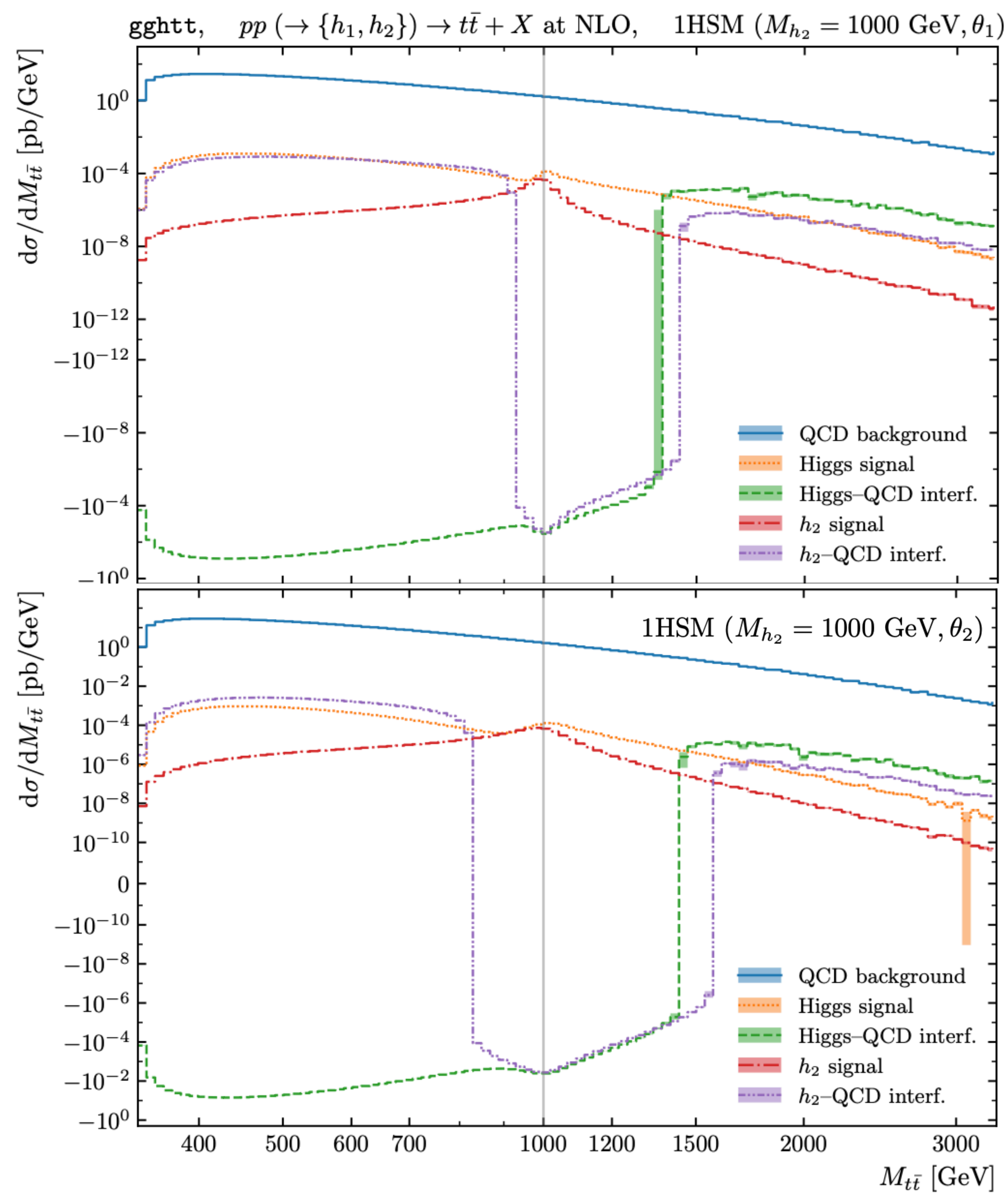
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM, pp, $\sqrt{s} = 13$ TeV					
		Higgs signal		Higgs–QCD interference	
	M_{h_2} [GeV]	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
θ_1	700	0.029108(2)	1.6234(2)	−1.5169(2)	2.1743(3)
	1000	0.027334(2)	1.6459(2)	−1.49132(9)	2.1579(2)
	1500	0.029932(3)	1.6745(2)	−1.5601(2)	2.1926(2)
	3000	0.030933(3)	1.6661(2)	−1.5724(1)	2.1719(2)
θ_2	700	0.027231(2)	1.5689(2)	−1.3487(2)	2.1383(3)
	1000	0.020114(2)	1.6442(2)	−1.30744(8)	2.1458(2)
	1500	0.026519(2)	1.6617(2)	−1.4796(2)	2.1903(2)
	3000	0.029772(2)	1.6452(2)	−1.5673(2)	2.1924(2)

Results

700 GeV

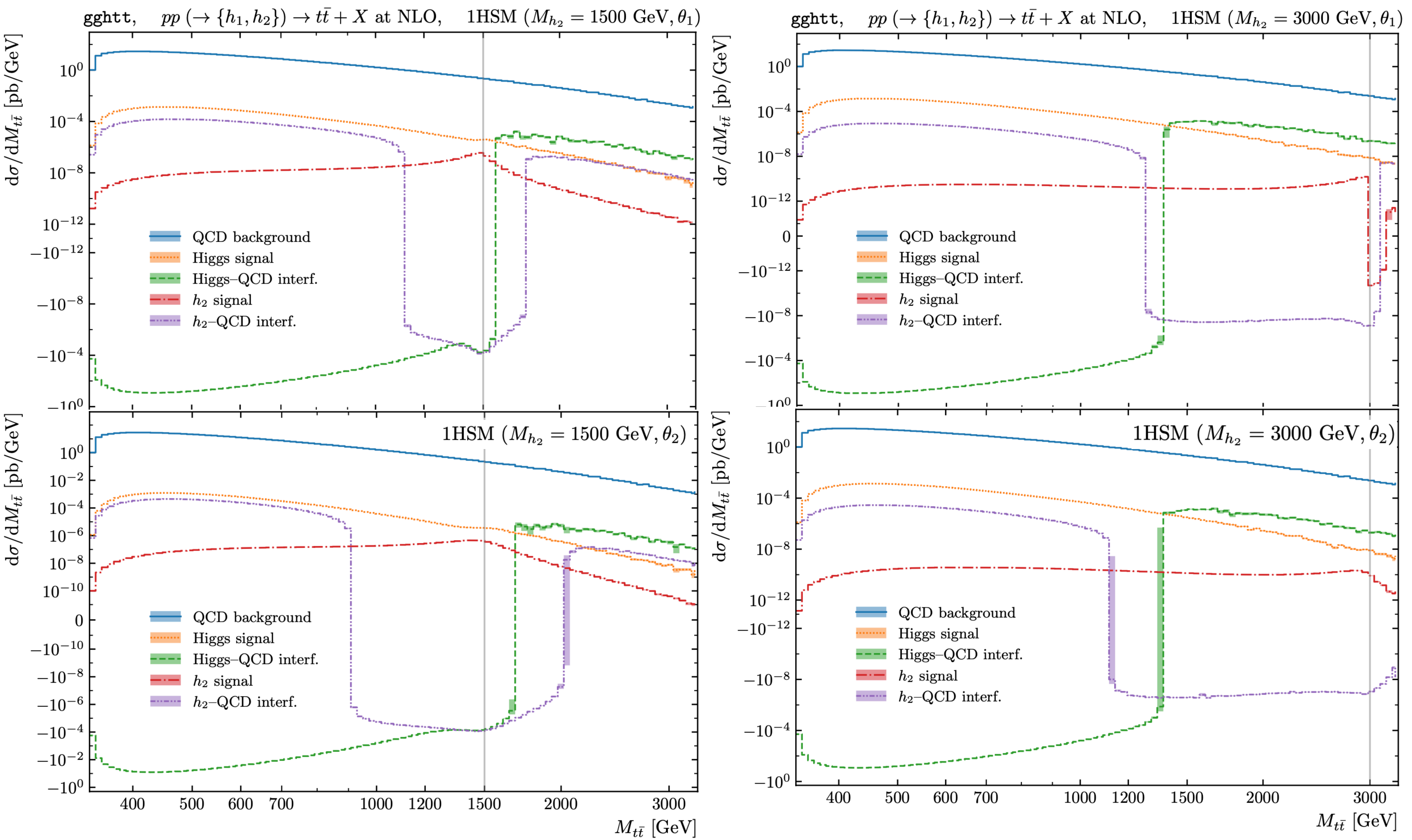


1 TeV



Results

1.5 TeV **3 TeV**



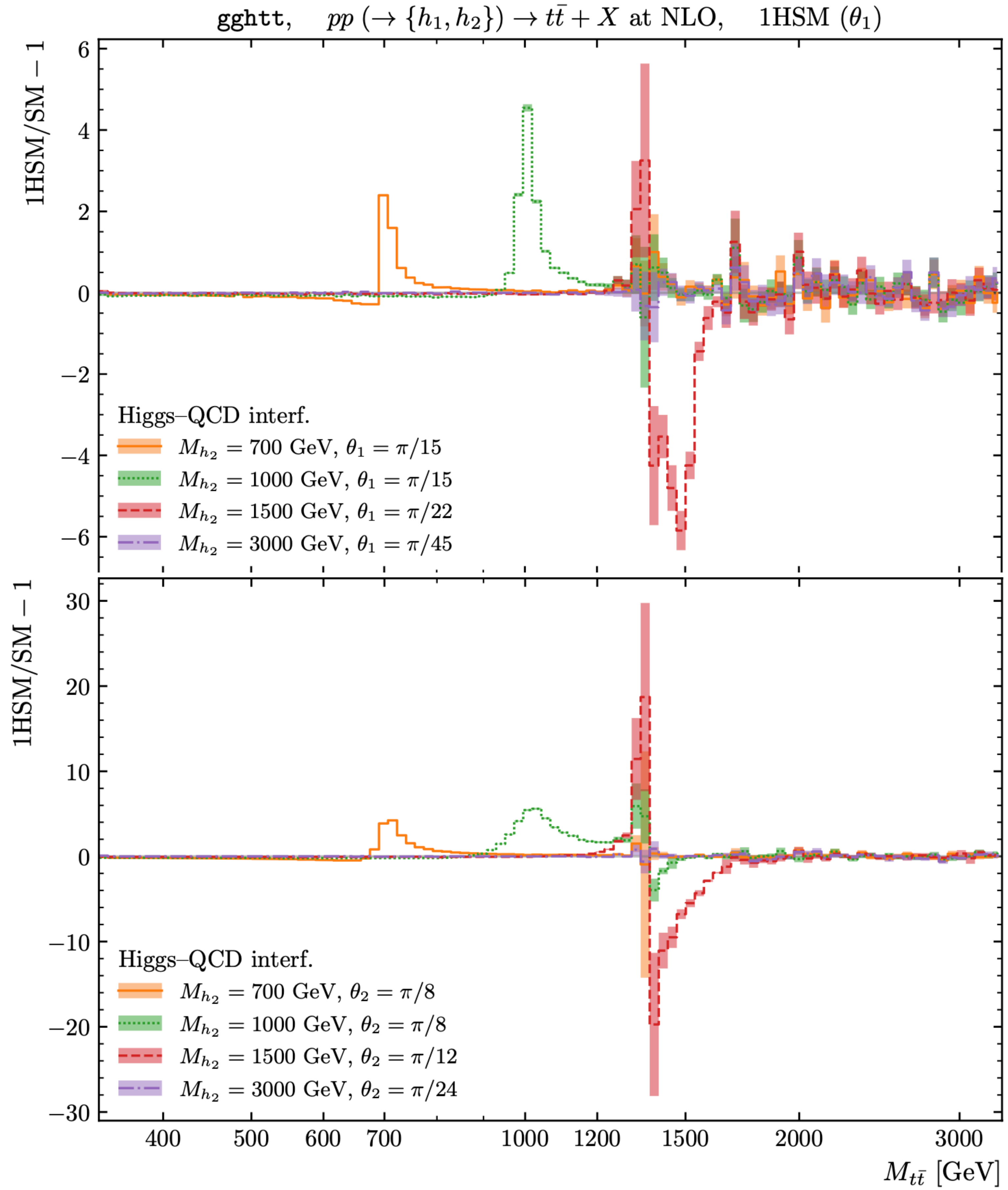
Results

Observed dip structures around heavy resonance mass when considering the 1HSM

Consider mass windows around dips

Significance $$\frac{S}{\sqrt{B}} = \sqrt{\mathcal{L}}\frac{\sigma_S}{\sqrt{\sigma_B}}$$

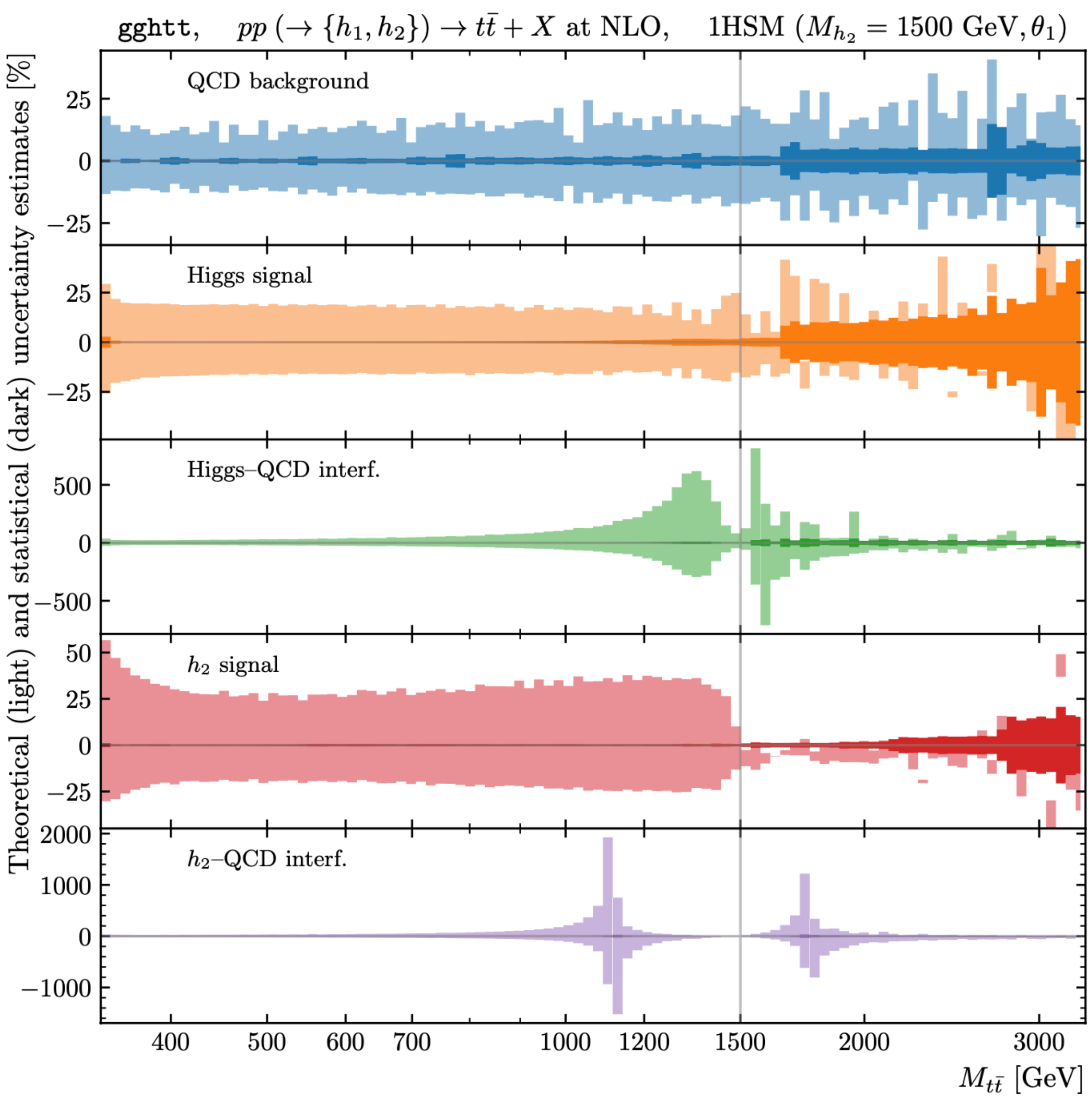
	M_{h_2} [GeV]	Invariant mass window	Excludable Run 2	Excludable Run 3	Excludable HL-LHC
θ_1	700	600–790 GeV	✓	✓	✓
	1000	900–1115 GeV	–	–	✓
	1500	1200–1600 GeV	–	–	–
	3000	2500–3340 GeV	–	–	–
θ_2	700	530–870 GeV	✓	✓	✓
	1000	830–1200 GeV	–	✓	✓
	1500	1050–1800 GeV	–	–	–
	3000	2100–3340 GeV	–	–	–



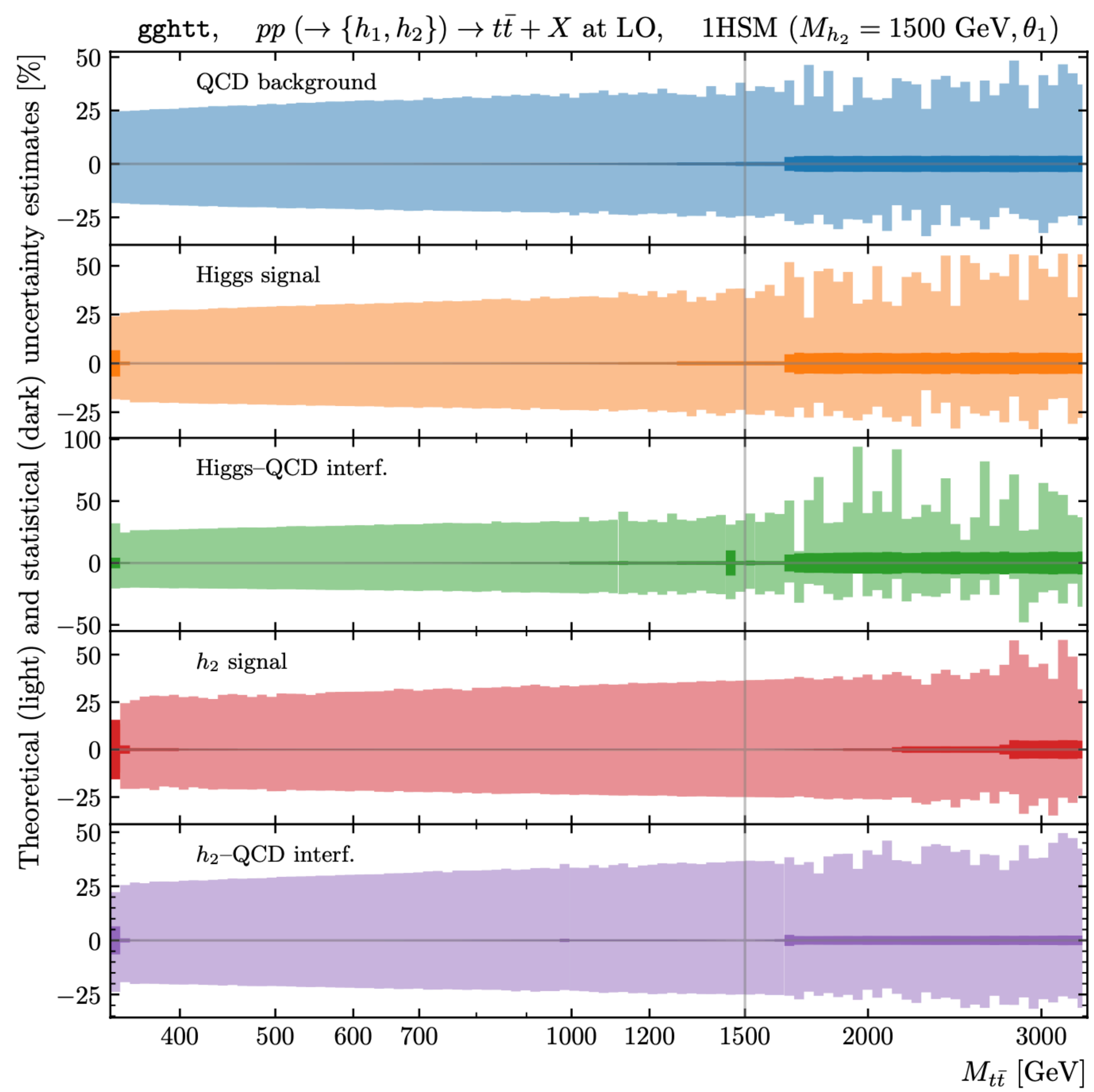
Scale Uncertainties

$$\mu_R = \mu_F = \{\mu/2, \mu, 2\mu\}, \text{ for } \mu = M_{t\bar{t}}/2$$

QCD bg: 12%



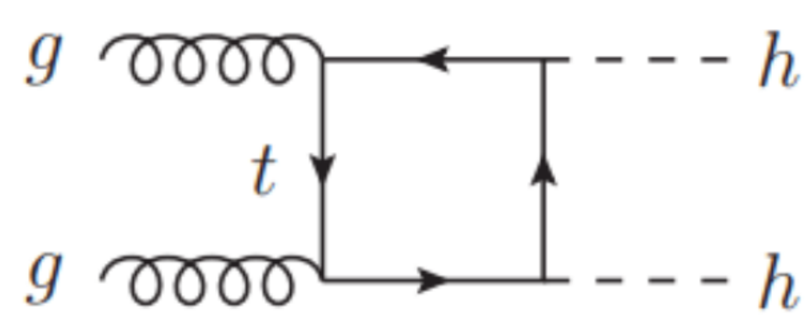
h2-QCD: 27—42%

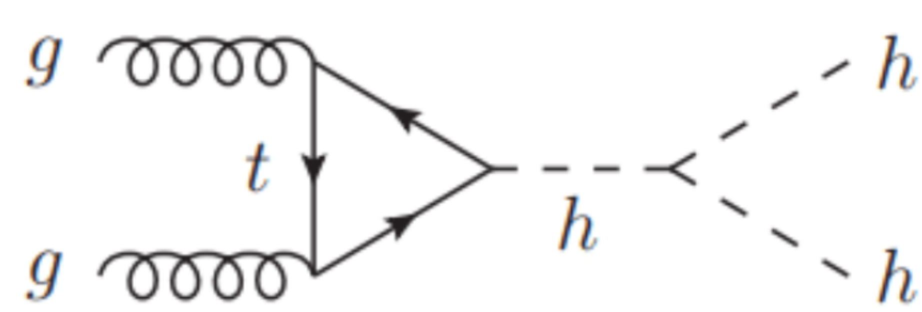


Generalisation

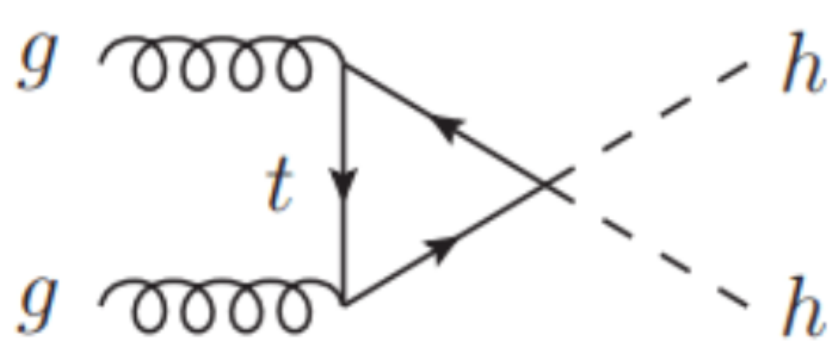
The code be generalised to work for any loop-induced process

Double Higgs production

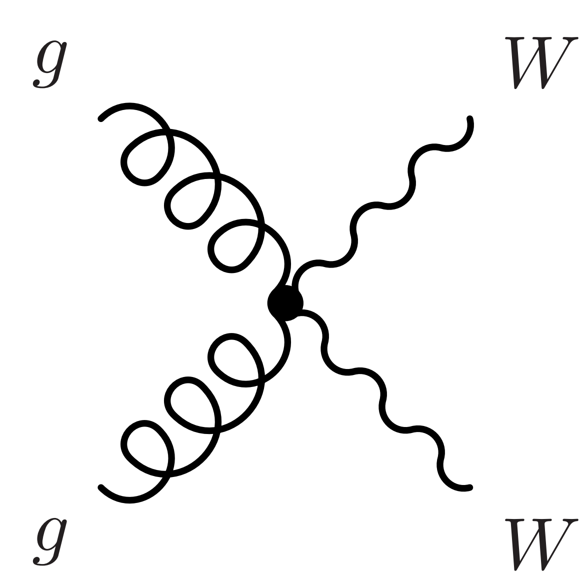




Effective field theories



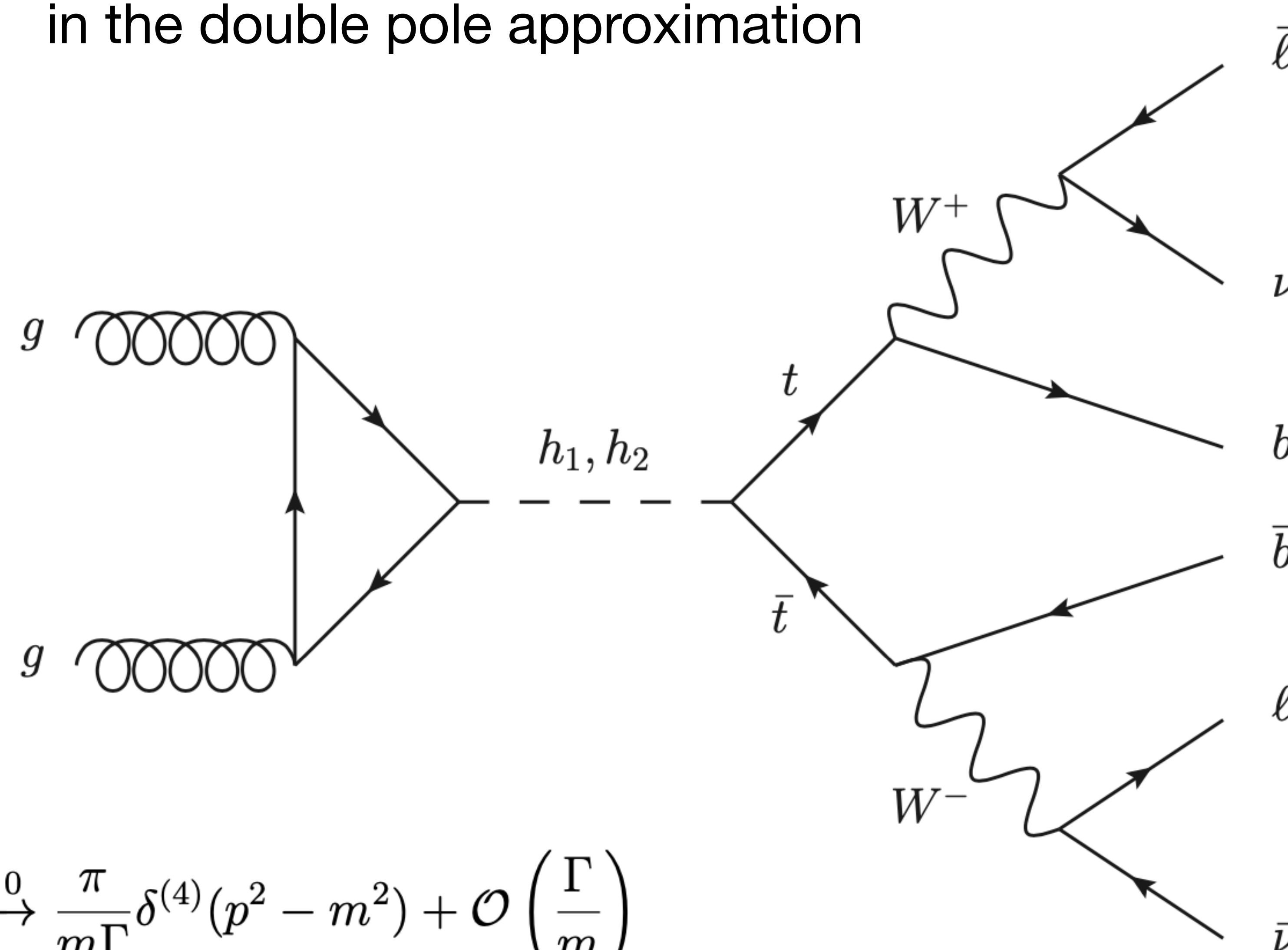
dim-6



dim-8

Top Decays

We want to consider the full 2 to 6 top decay amplitudes
with spin correlations
in the double pole approximation



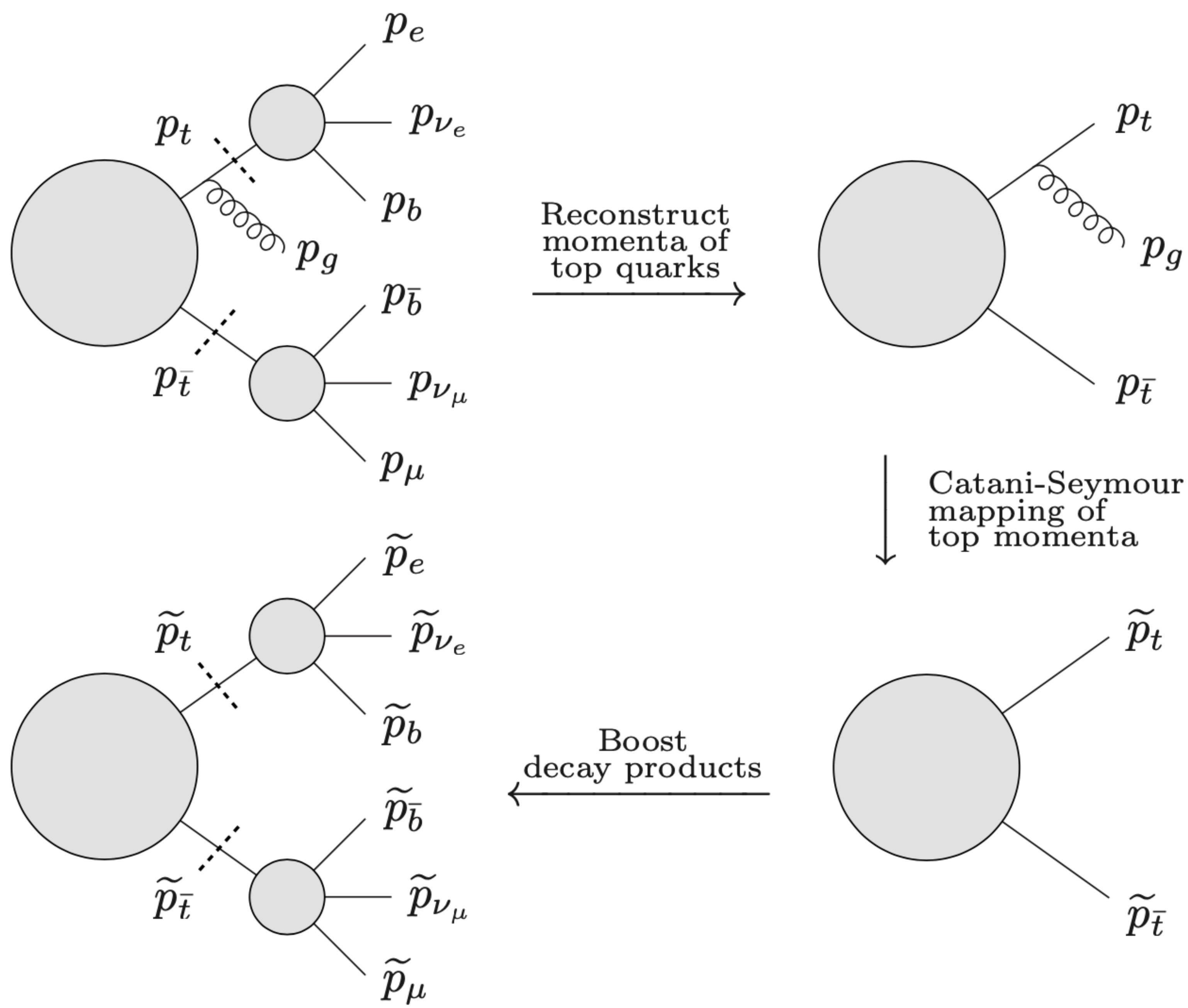
NWA:

$$\frac{1}{(p^2-m^2)^2+m^2\Gamma^2} \xrightarrow{\Gamma/m \to 0} \frac{\pi}{m\Gamma}\delta^{(4)}(p^2-m^2)+\mathcal{O}\left(\frac{\Gamma}{m}\right)$$

arXiv:2112:????? with A. Banfi, N. Kauer, J. Lindert, and R. Wood

Top Decays

Dipole subtraction for intermediate emitters



arXiv:2112:?????   with A. Banfi, N. Kauer, J. Lindert, and R. Wood

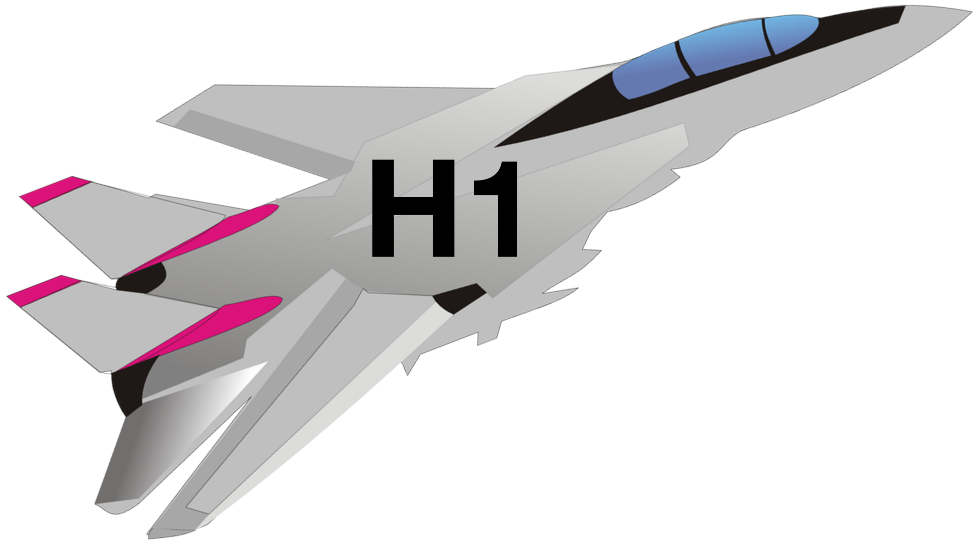
A second project…

H1JET

arXiv:2011.04694 [hep-ph]

with Andrea Banfi

h1jet.hepforge.org

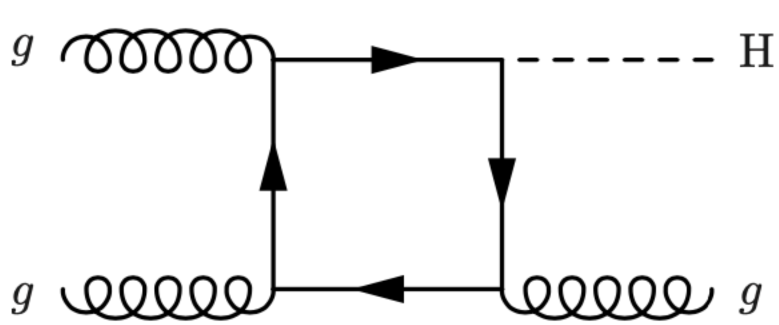


Motivation

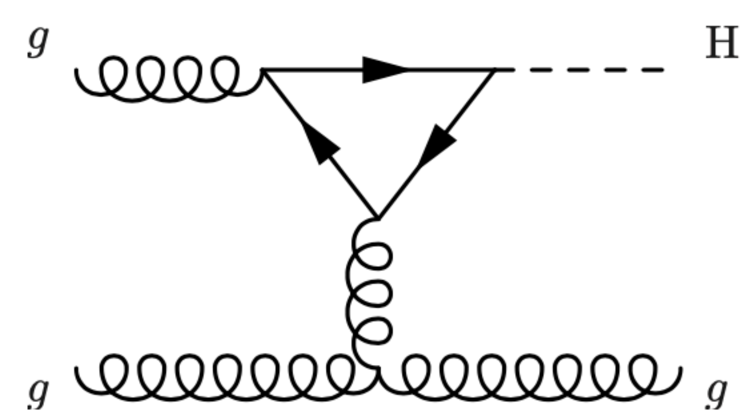
A fast and easy-to-use tool to compute transverse momentum distributions

$$\mathcal{L}_{\text{eff.}} \supset -\kappa_t \frac{m_t}{v} t\bar{t}H + \kappa_g \frac{\alpha_s}{12\pi}\frac{H}{v} G^a_{\mu\nu} G^{\mu\nu\, a}$$

$$\frac{\sigma(\kappa_t, \kappa_g)}{\sigma^{\text{SM}}} \propto (\kappa_t + \kappa_g)^2$$



(a) Box diagram.



(b) Triangle diagram.

Loops:
SM top + BSM top partner

The Method

$2 \to 1$ and $2 \to 2$ but can be extended

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \frac{p_T}{8\pi}\int_{-\eta_M}^{\eta_M} \mathrm{d}\eta \sum_{i,j}\left[\frac{M_{ij}^2\left(\hat{s},\hat{t},\hat{u}\right)}{E_X \hat{s}^{3/2}}\mathcal{L}_{ij}\left(\frac{\hat{s}}{s},\mu_F\right)\right]$$

$$\eta_M = \ln\left(x_M + \sqrt{x_M^2 - 1}\right)$$

$$x_M = \frac{s - m_X^2}{2p_T\sqrt{s}}$$

$$\hat{s} = \left(p_T\cosh\eta + \sqrt{m_X^2 + p_T^2\cosh^2\eta}\right)^2$$

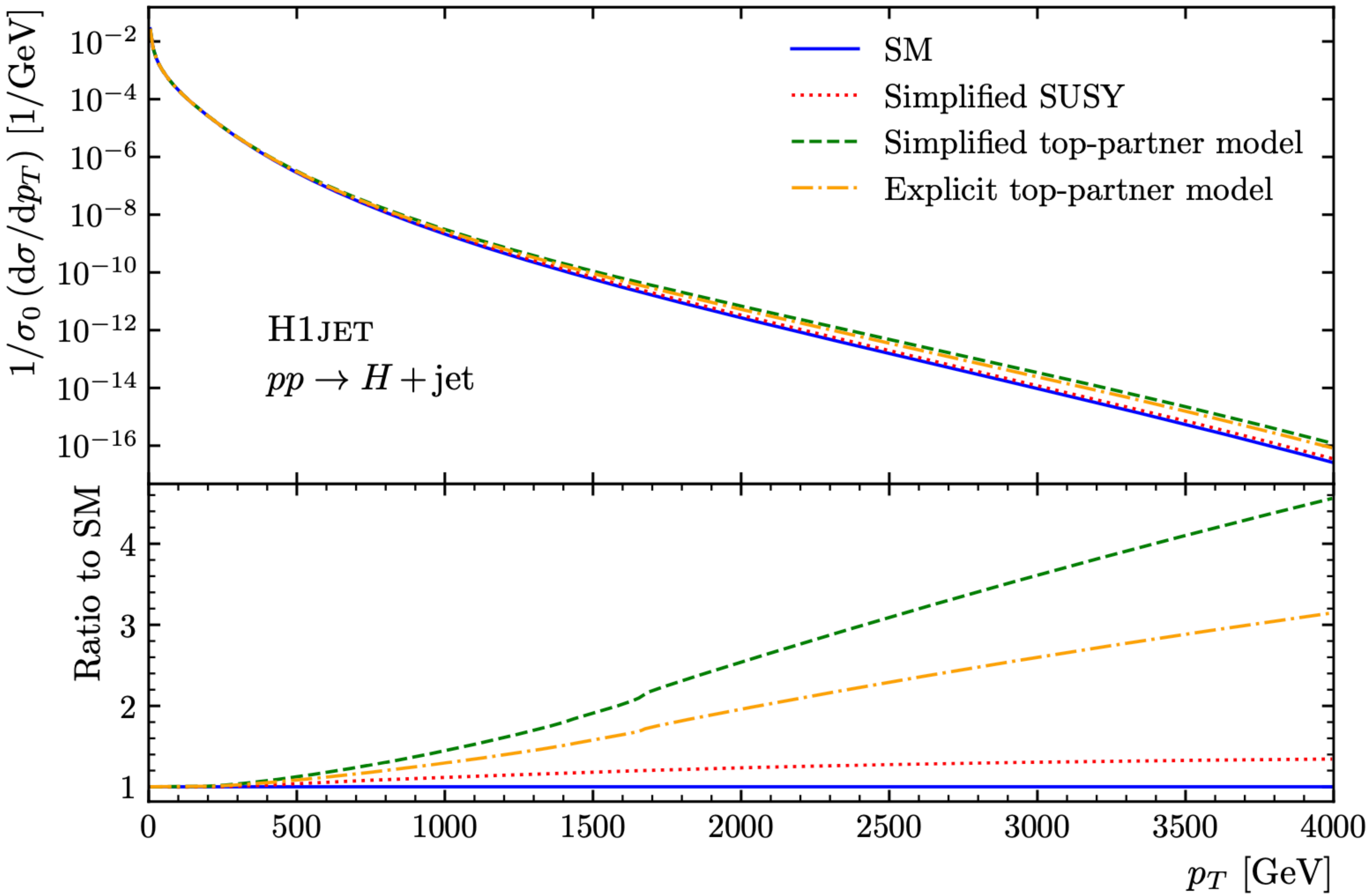
$$\hat{t} = -p_T e^{-\eta}\sqrt{\hat{s}}$$

$$\hat{u} = -p_T e^{\eta}\sqrt{\hat{s}}$$

1-dimensional integration done using adaptive Gaussian quadrature ➞ super fast

Written in Fortran 95, interfaced with CHAPLIN and HOPPET

Built-In Models



Provided user-interface allows for
a custom process given a user-provided amplitude

$$|\mathcal{M}(\hat{s}, \hat{t}, \hat{u})|^2$$

A live demonstration…

h1jet.hepforge.org/online

Thank you for listening!