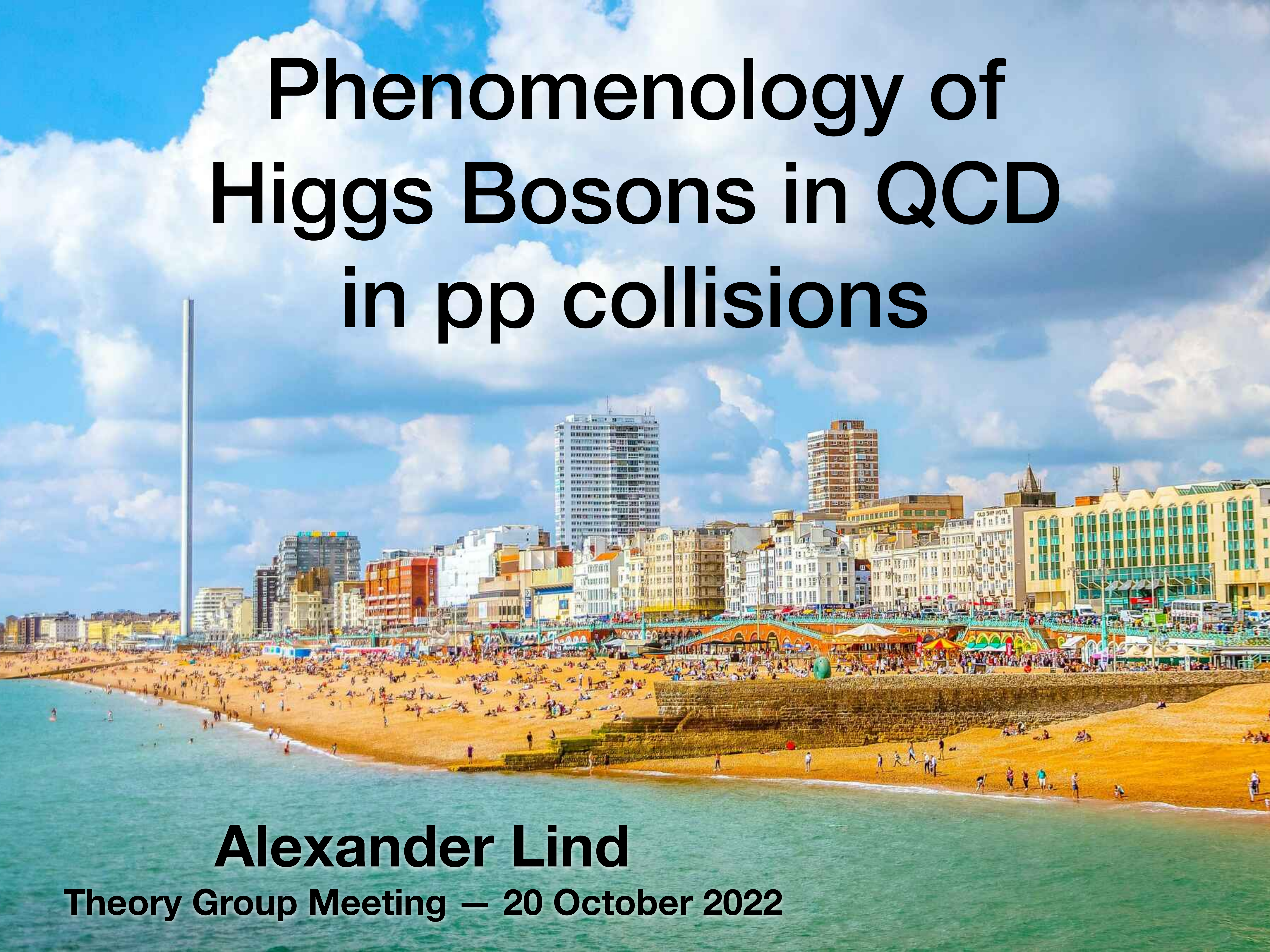


Phenomenology of Higgs Bosons in QCD in pp collisions

Alexander Lind

Theory Group Meeting — 20 October 2022

A first project…

Higgs interference effects in top pair production at NLO QCD

with Andrea Banfi, Jonas Lindert, Nikolas Kauer, and Ryan Wood

What's the landscape?

for BSM 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: $139\ \text{fb}^{-1}$

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

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

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

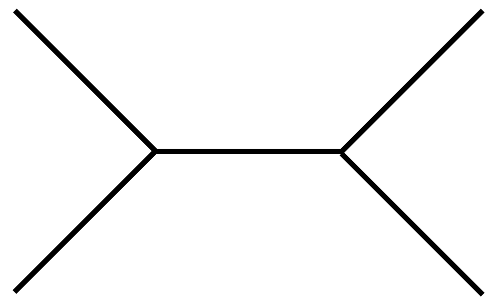
→ **Challenge for Theory/MC community:**

Need for ever increasing precision

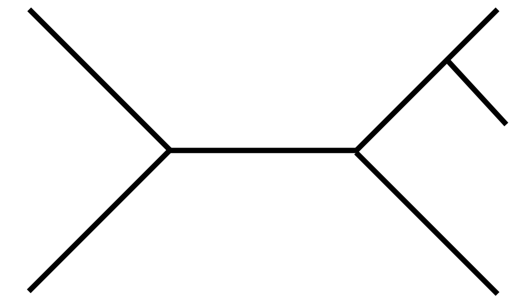
Next-To-Leading Order (NLO)

Theoretical precision: Higher orders in the hard scattering matrix element

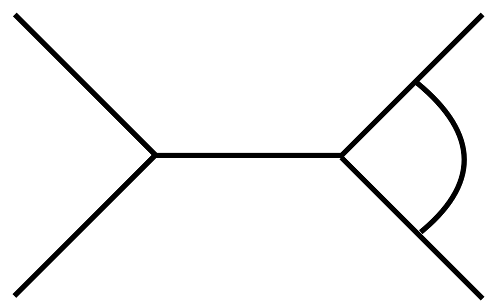
Tree level (Born / LO):



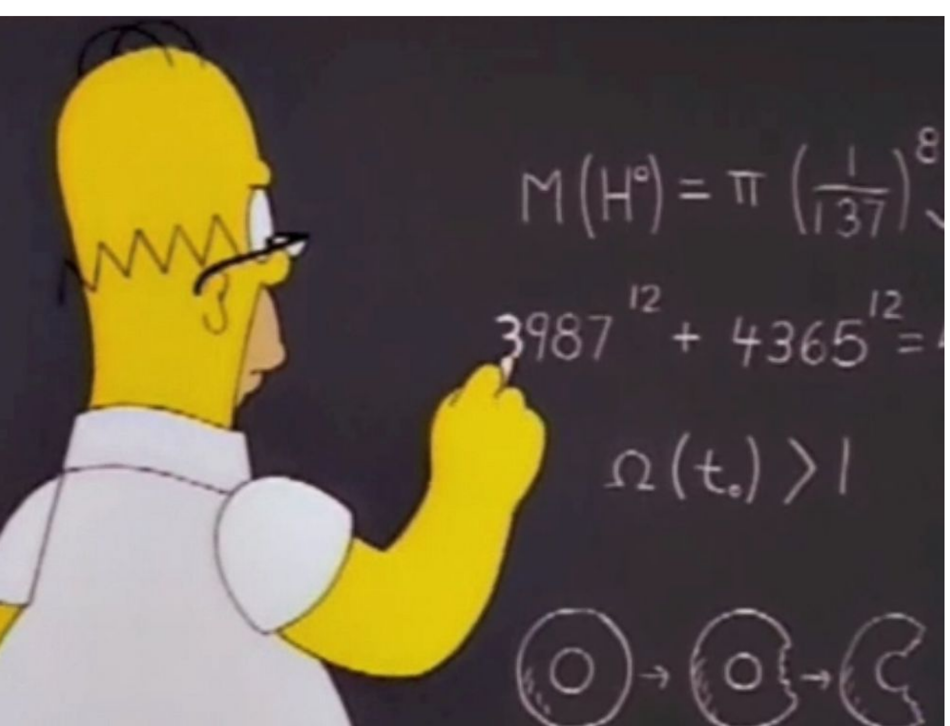
Real emission:



One-loop (Virtual):



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



NLO necessary for most processes
in particular Higgs production

$$\sigma_{\mathrm{LO}}(pp \to H + X) = 14.541(7)\ \mathrm{pb}\,,$$
$$\sigma_{\mathrm{NLO}}(pp \to H + X) = 35.11(2)\ \mathrm{pb}\,,$$

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)

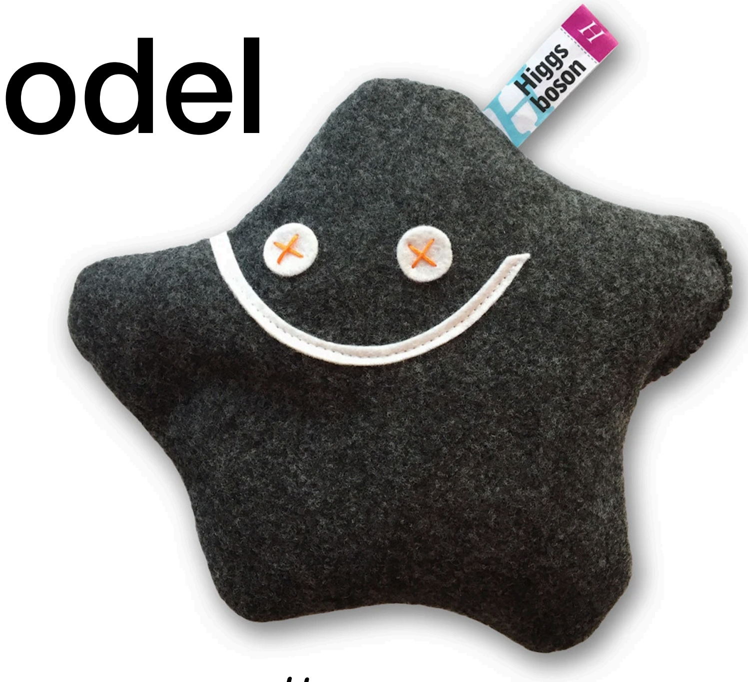
Finite
in infrared (IR) safe observables

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

$$M_{h_1} = 125\ \mathrm{GeV}$$

$$\mu_1 = \lambda_1 = \lambda_2 = 0$$

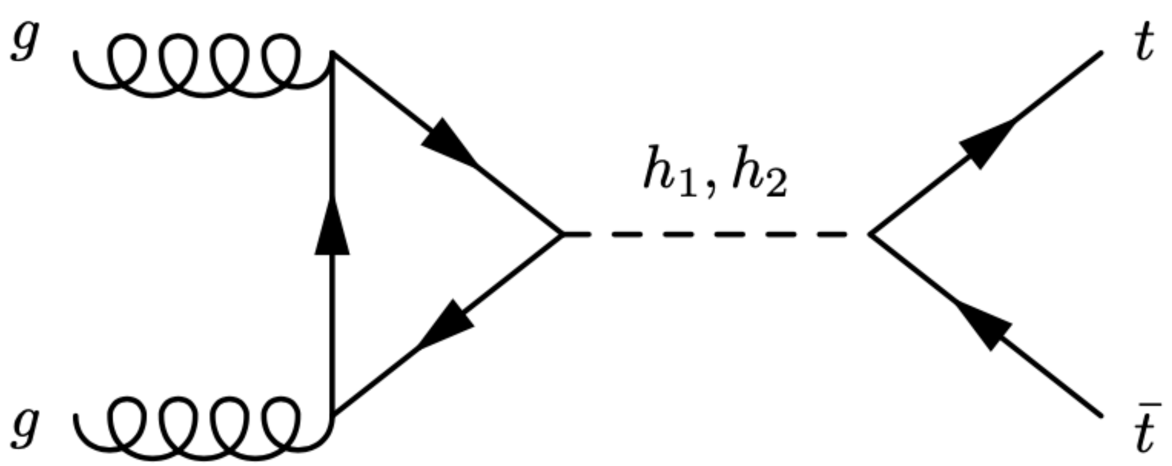
8 benchmark points:

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

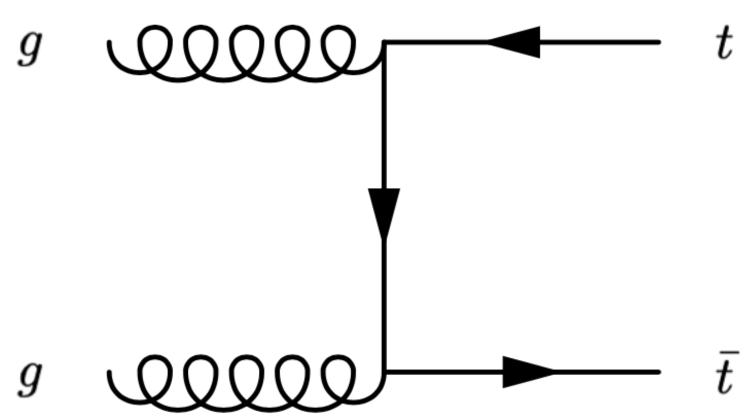
Process of Interest

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

Higgs signal

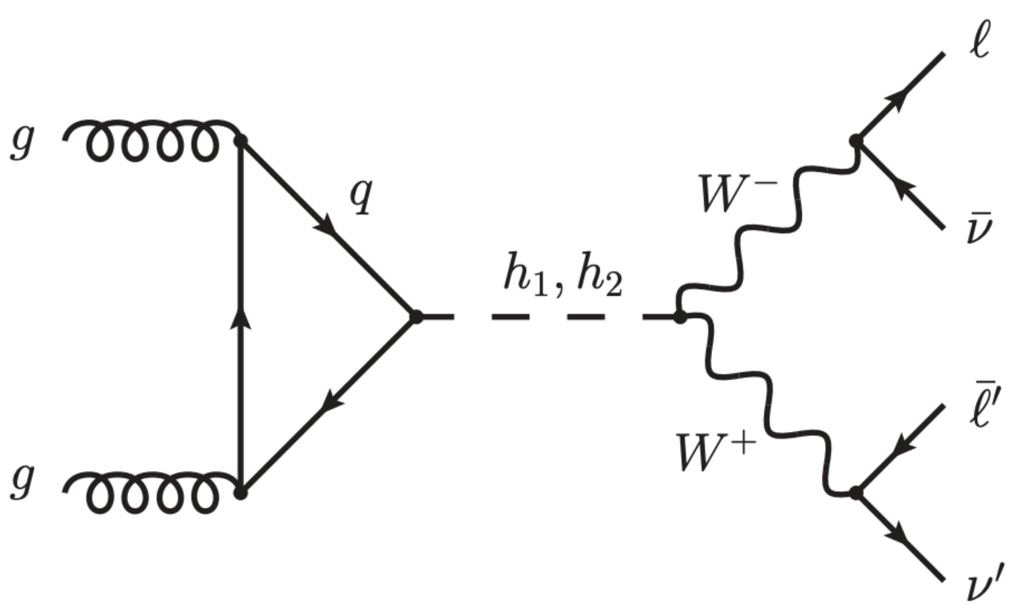


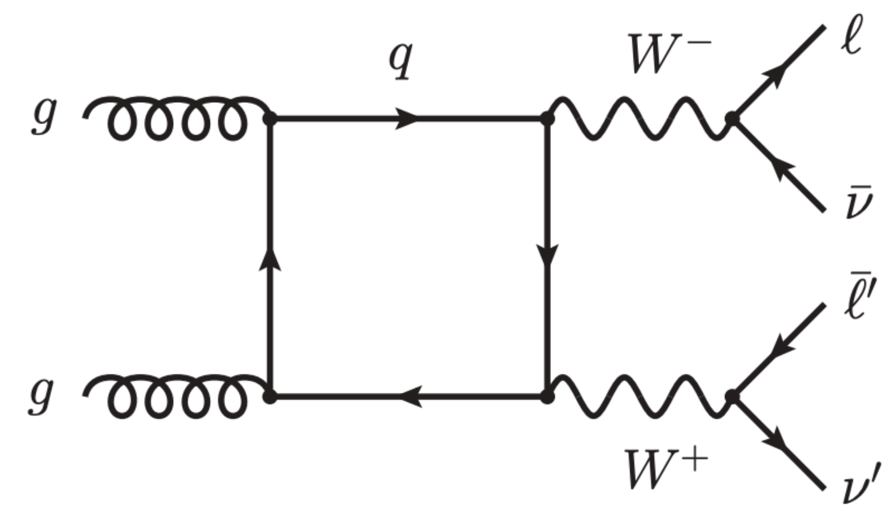
QCD background

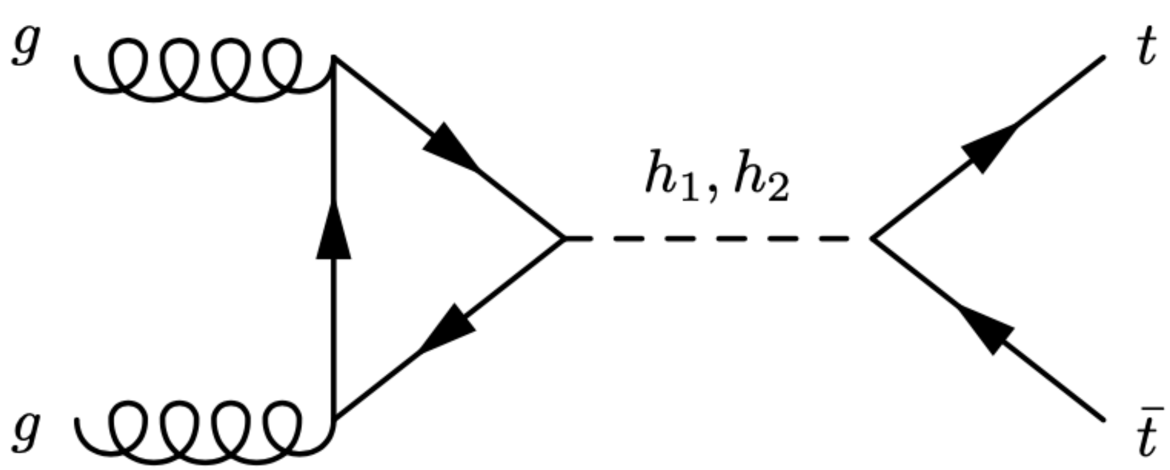


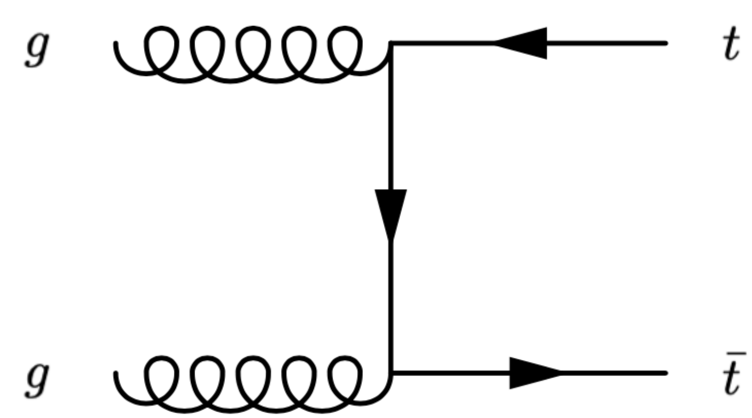
Alternative to “Bump Hunting”?

Invariant mass spectrum



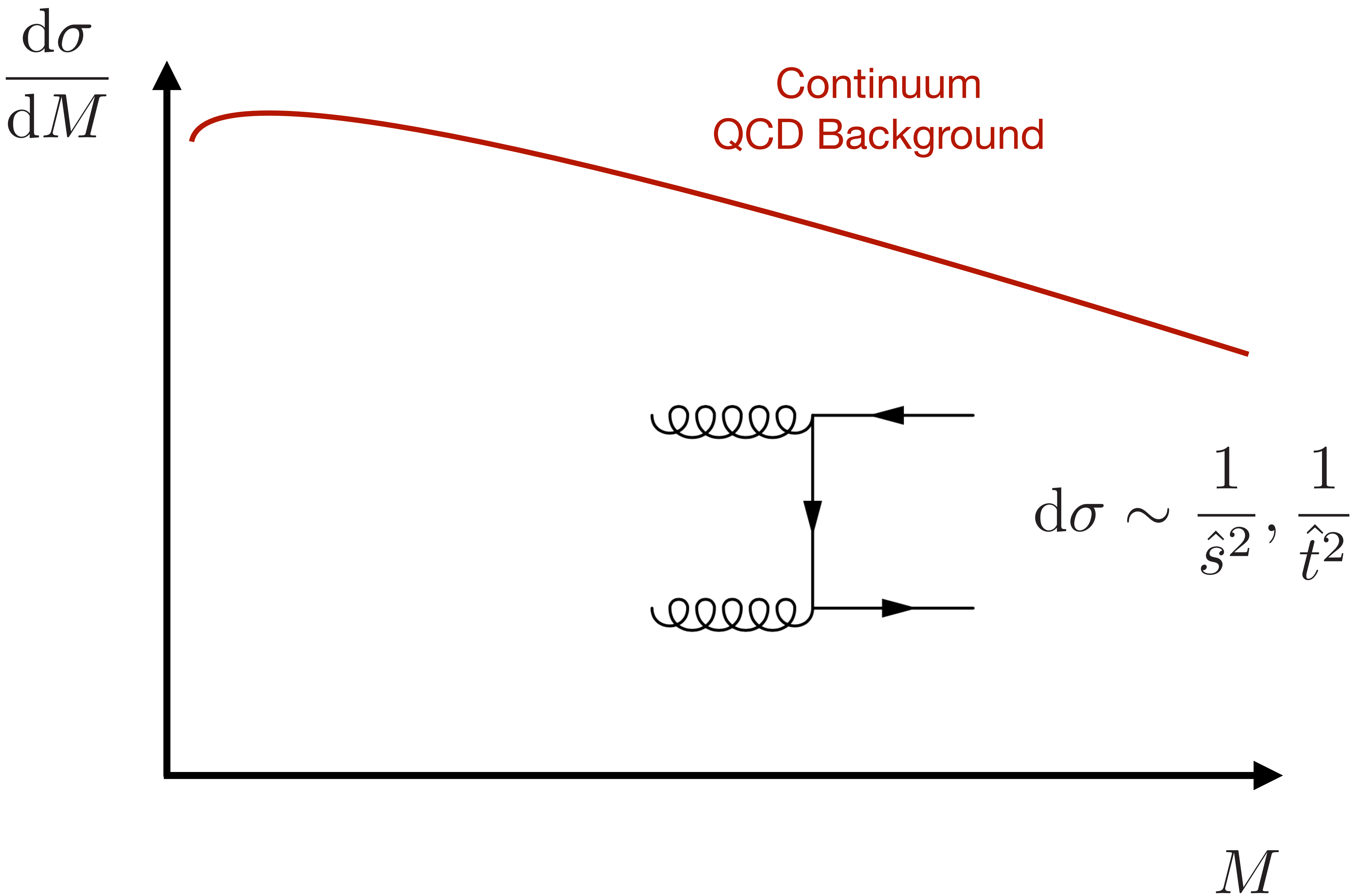




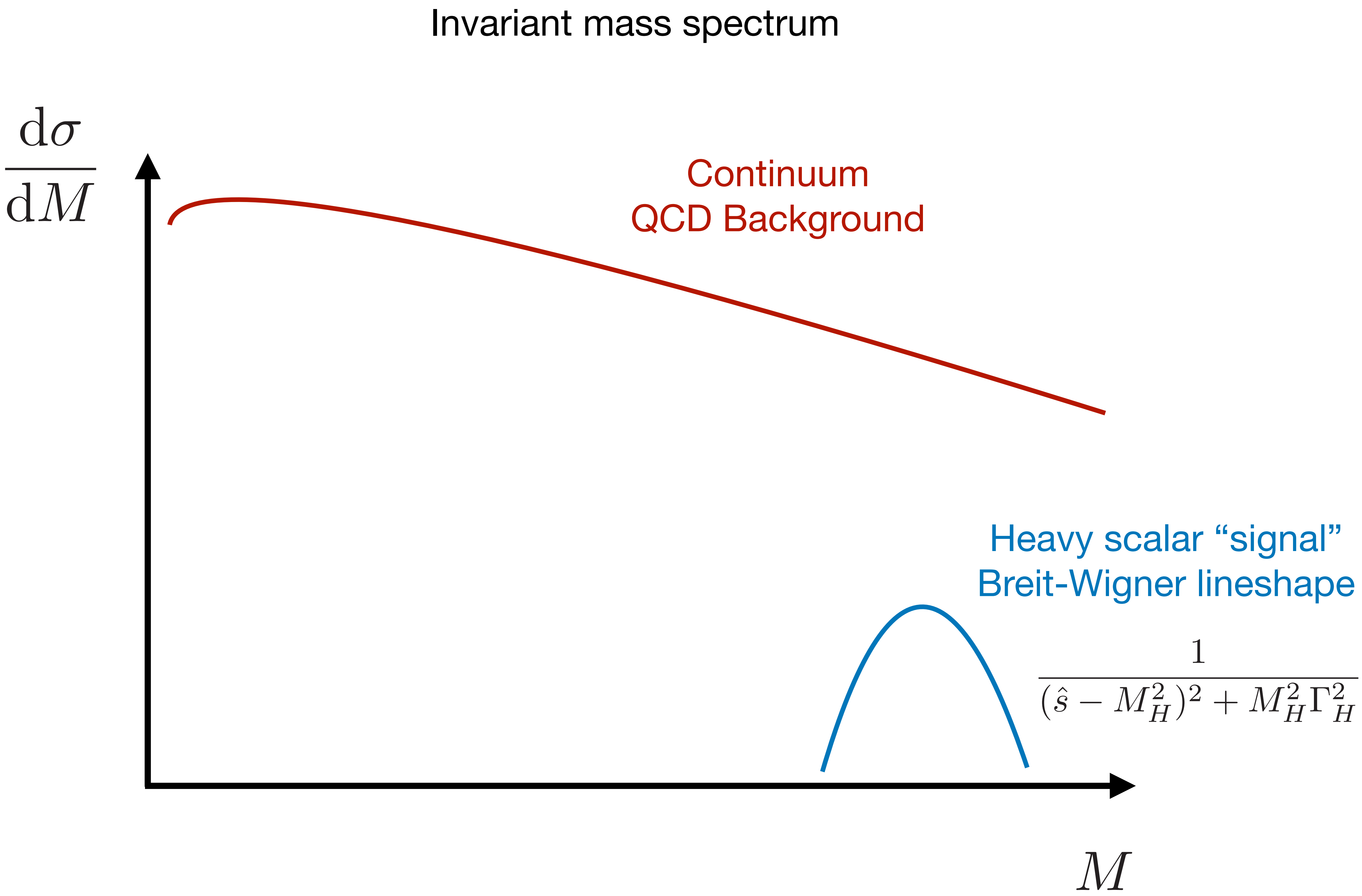


Alternative to “Bump Hunting”?

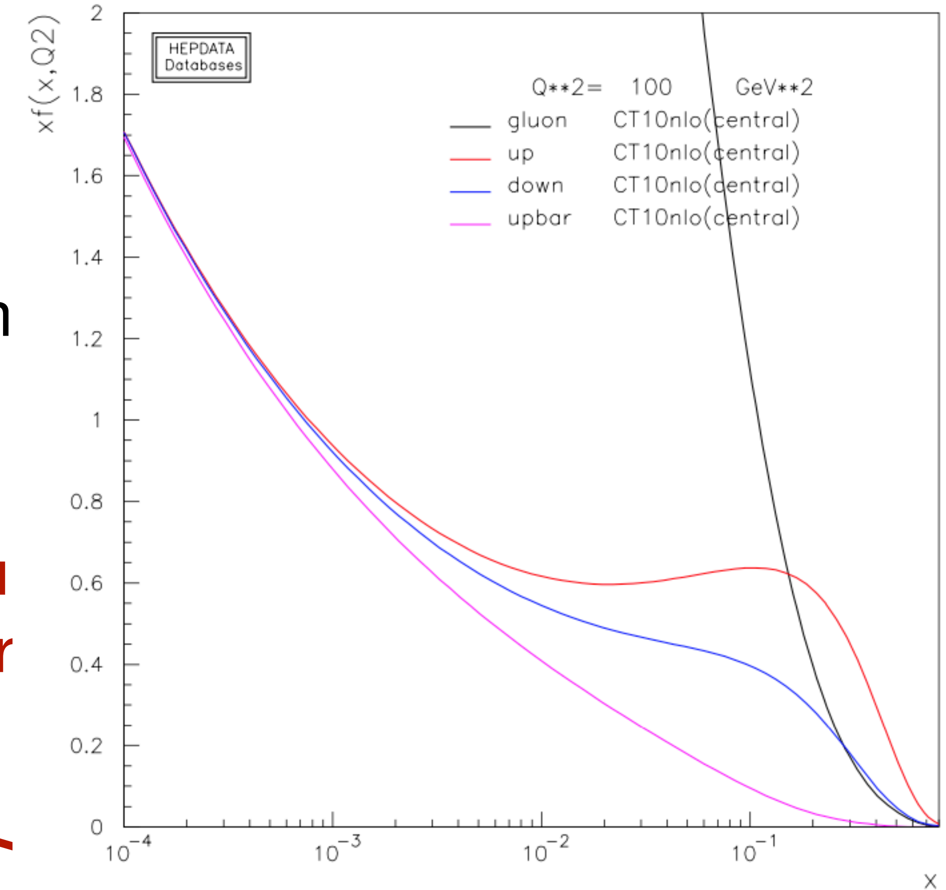
Invariant mass spectrum



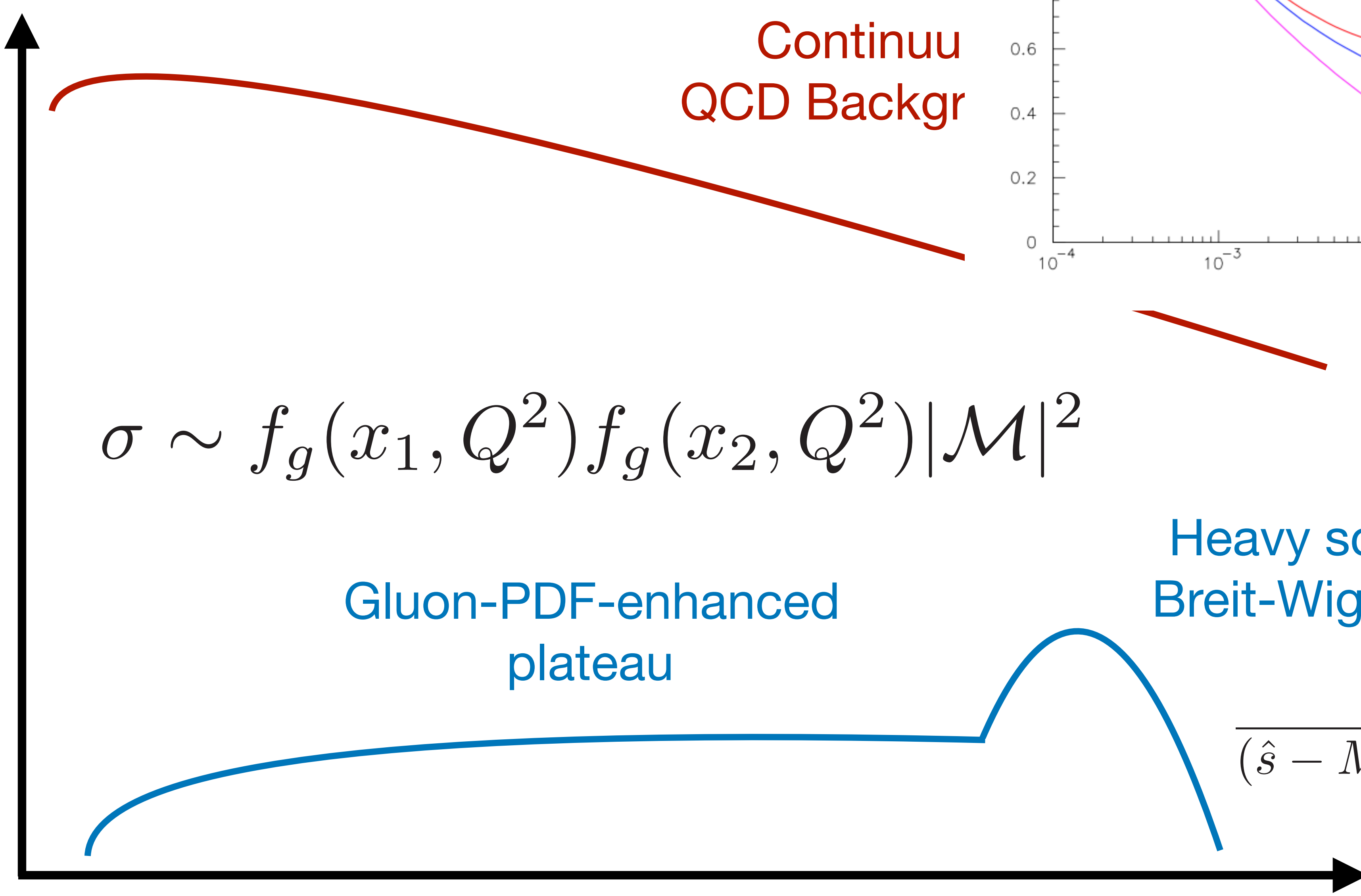
Alternative to “Bump Hunting”?



Alternative to “Bump



Invariant mass spectrum



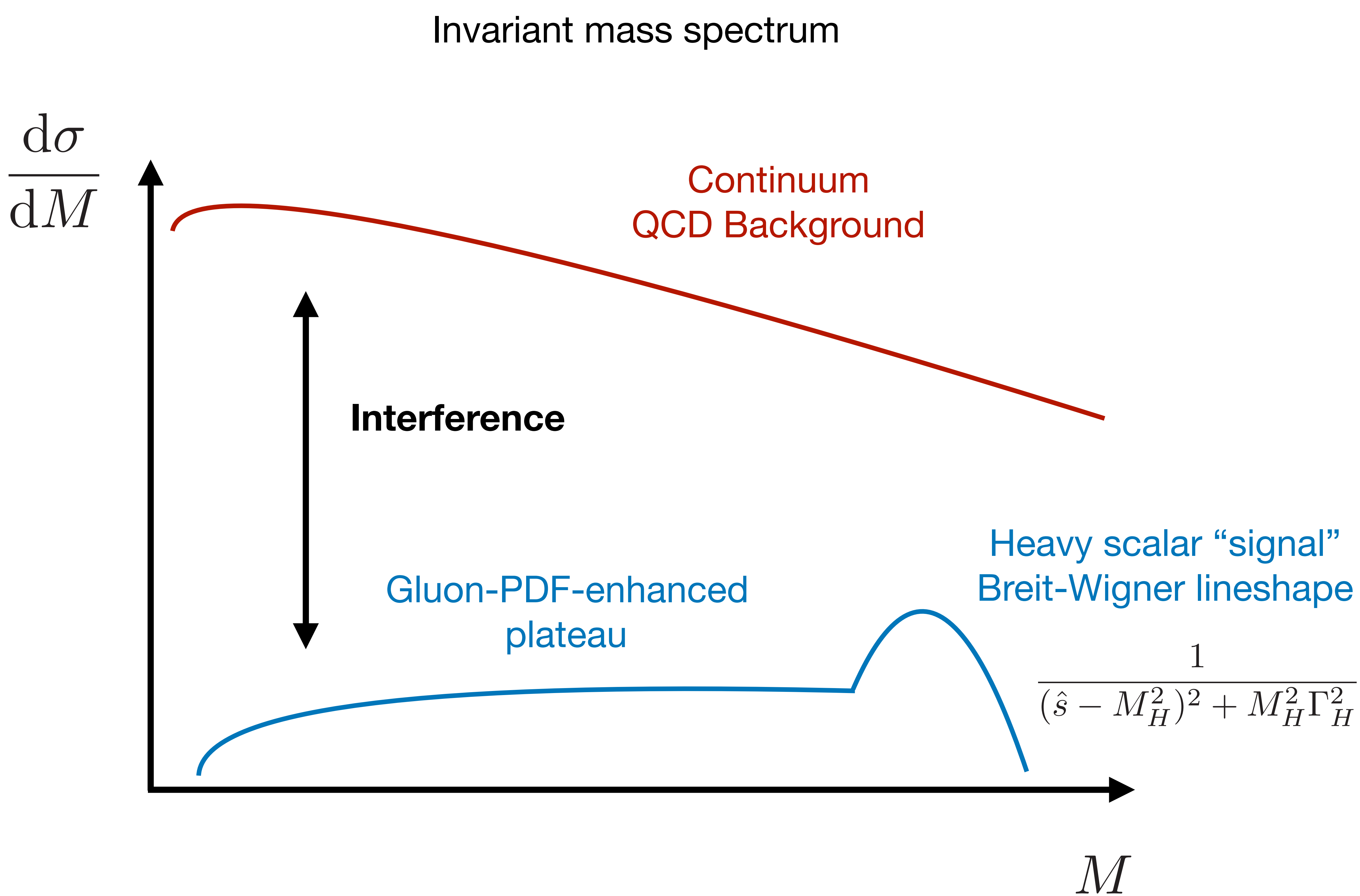
$$\frac{\mathrm{d}\sigma}{\mathrm{d}M}$$

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

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

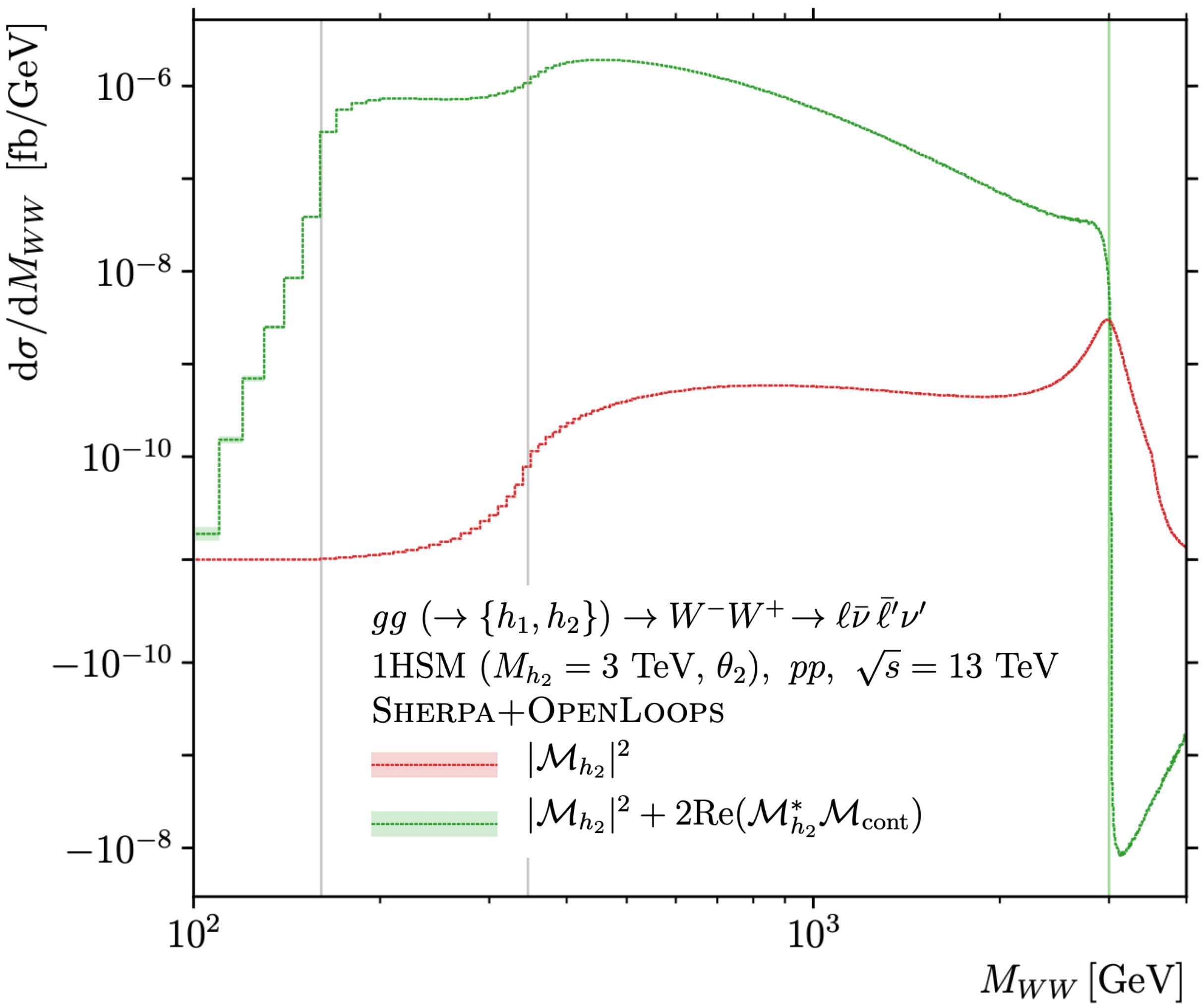
$$M$$

Alternative to “Bump Hunting”?

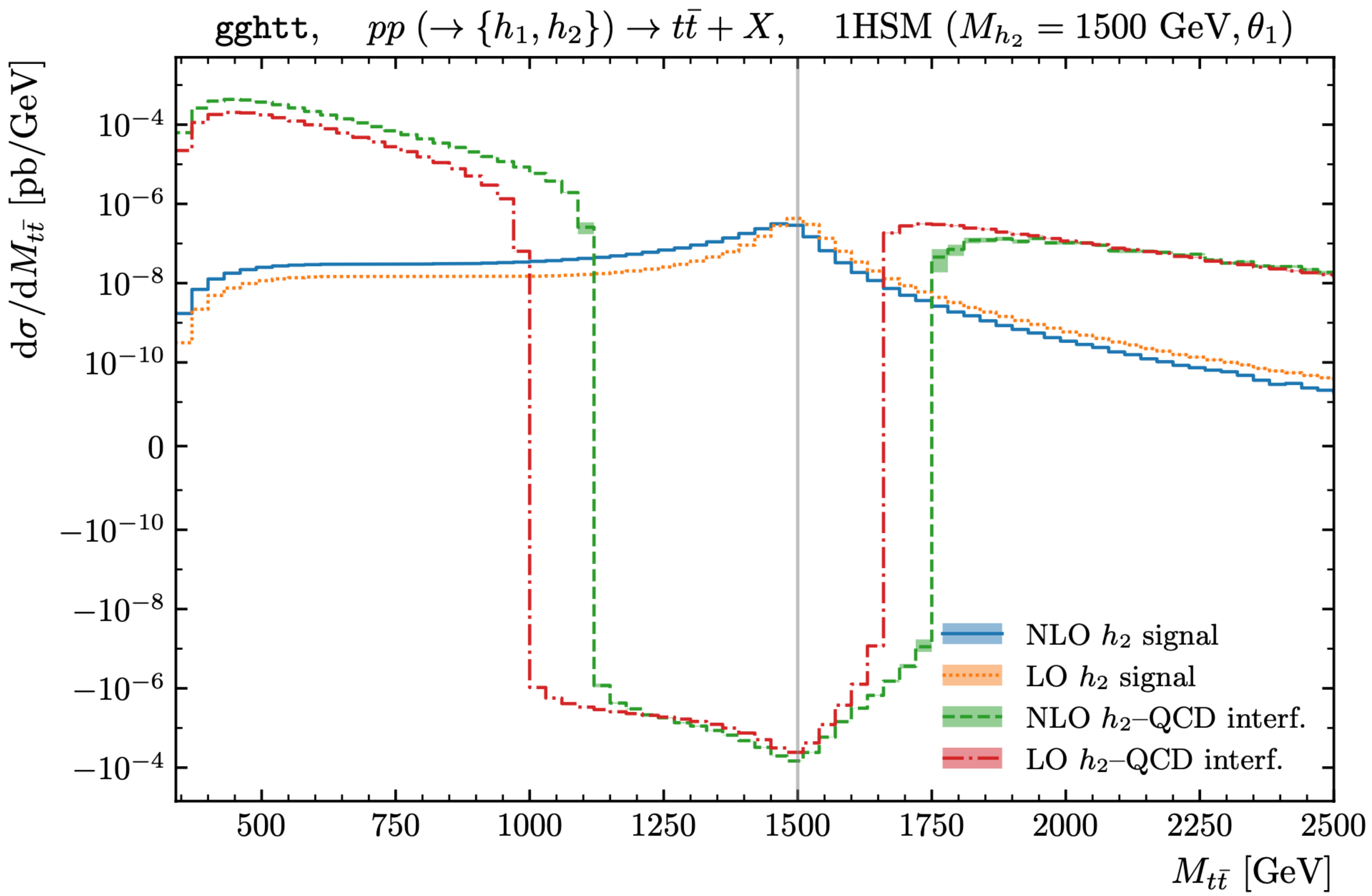


Alternative to “Bump Hunting”?

Invariant mass spectrum



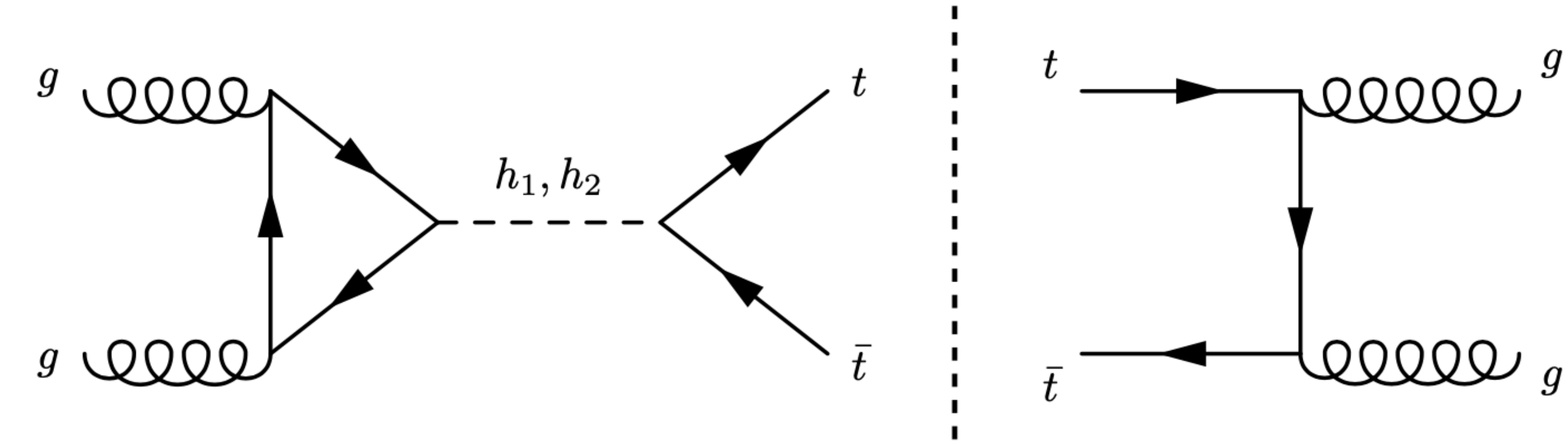
$$\mathrm{d}\sigma \sim \frac{1}{\hat{s}^2}$$



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

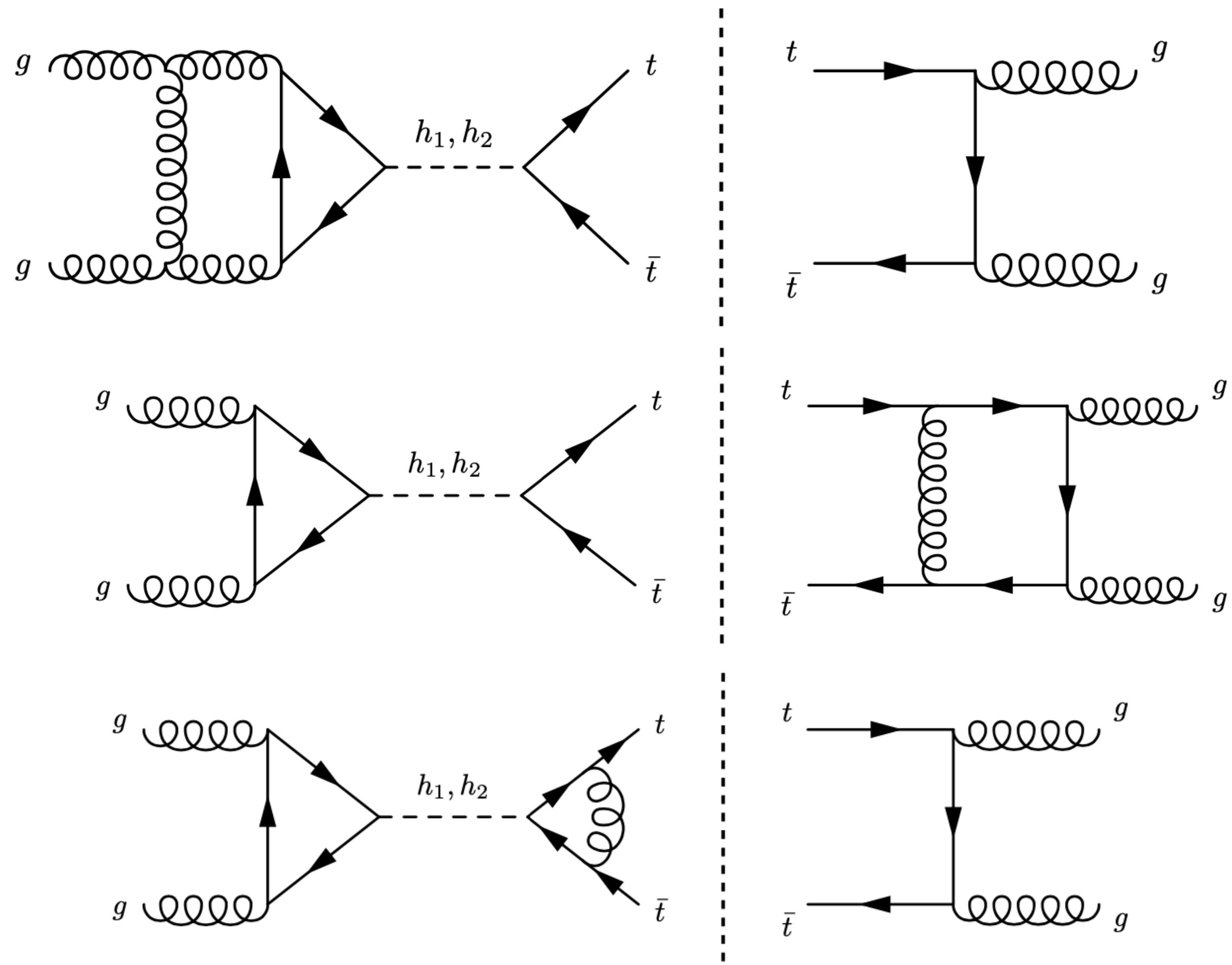
NLO QCD Corrections to Interference

LO



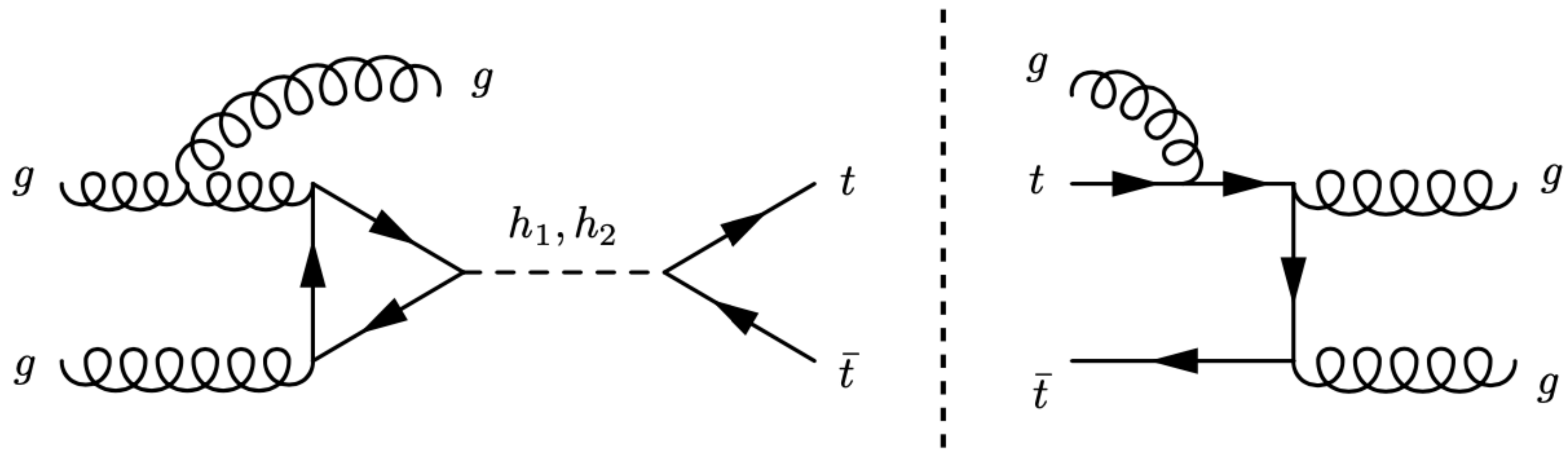
NLO

Virtual Contributions

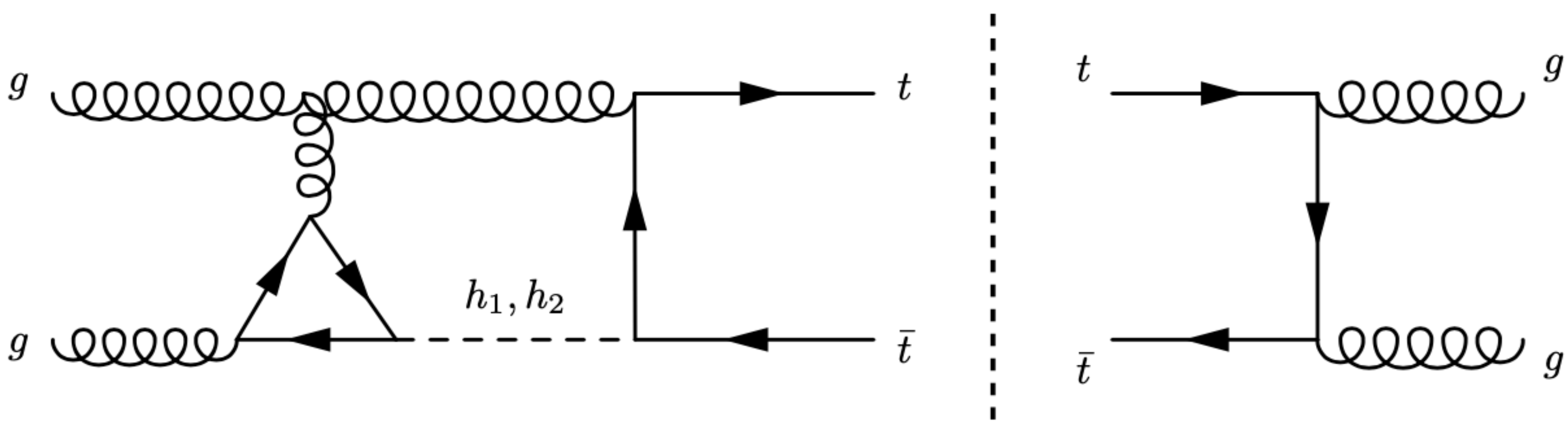


Non-Factorisable Corrections

IR divergent non-factorisable **real** contribution

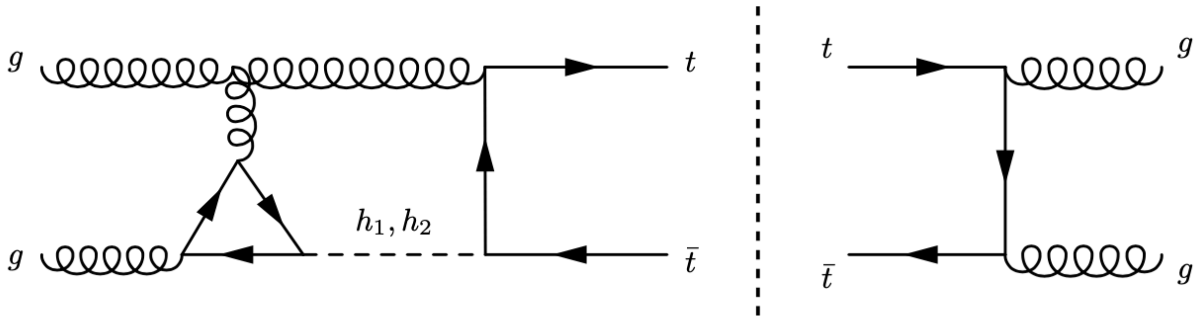


IR divergent non-factorisable **virtual** contribution

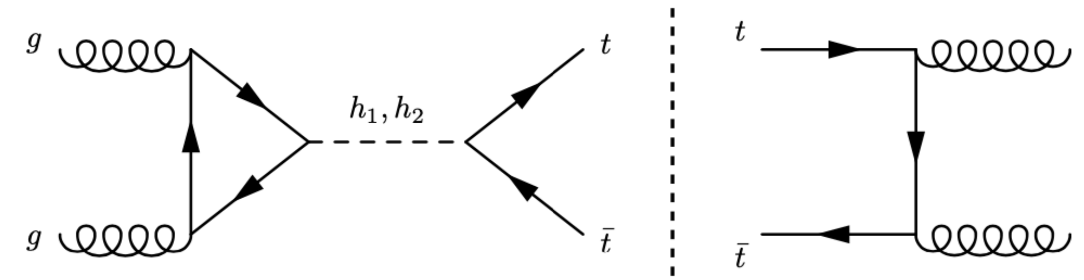


Non-Factorisable Corrections

However, in the soft limit:

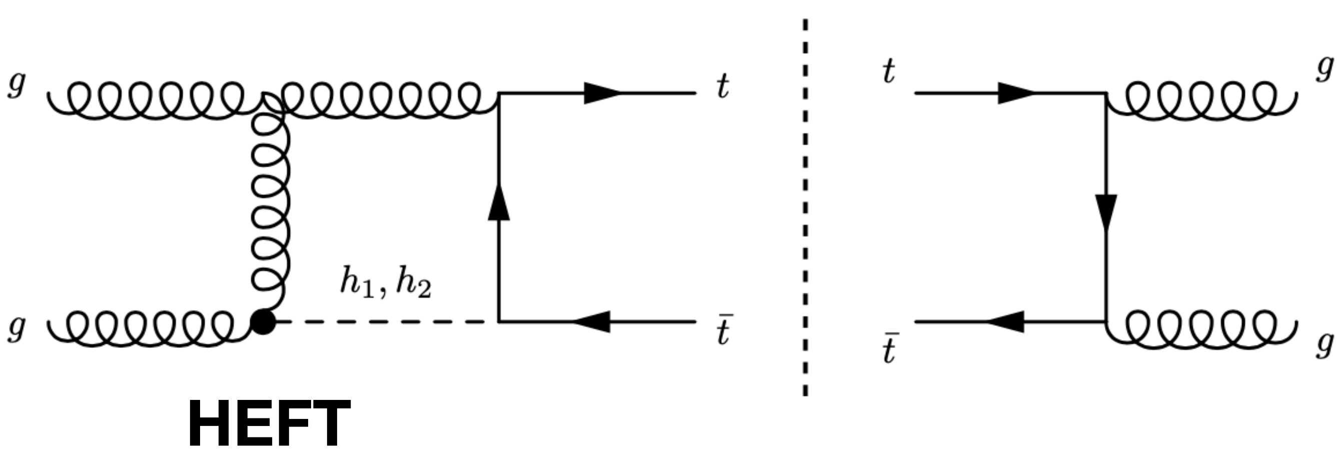


$= C \times$

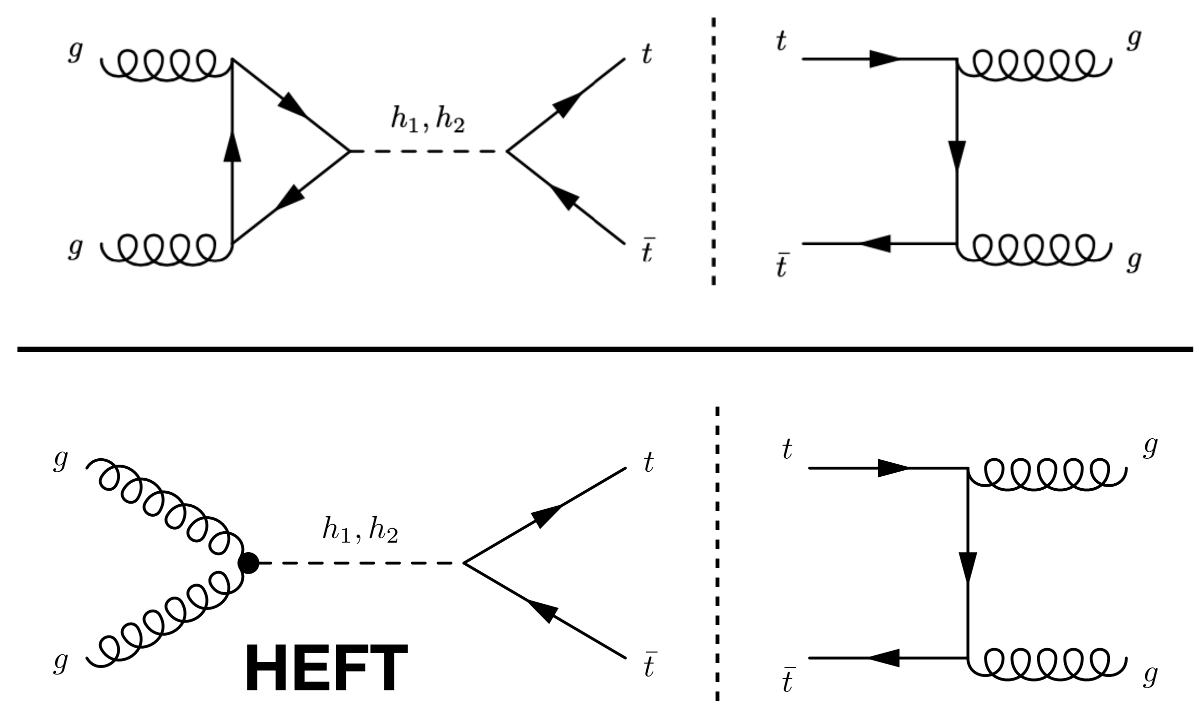


Singular term

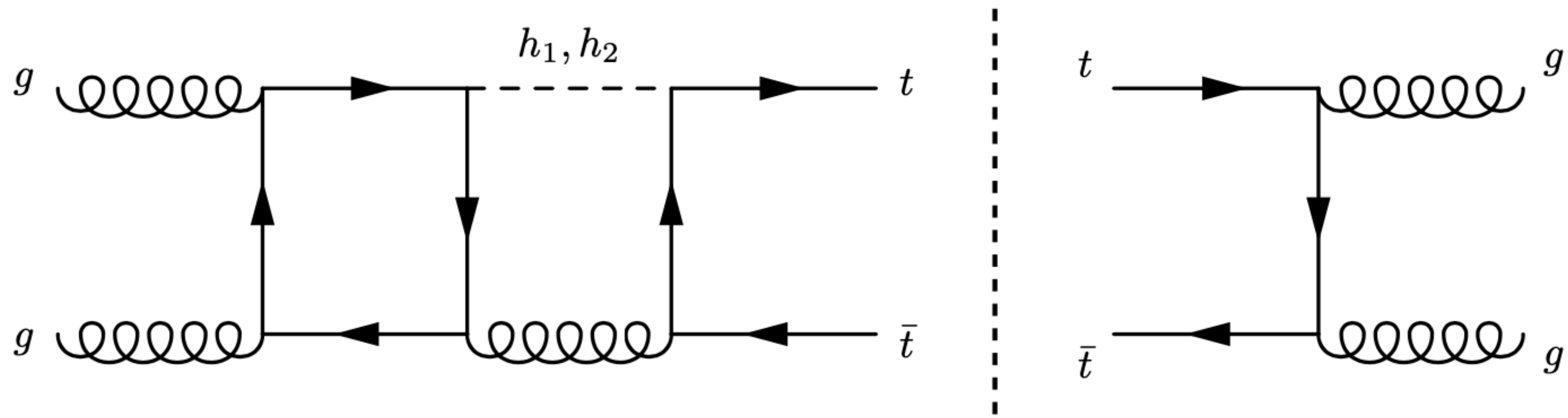
Reweighting:

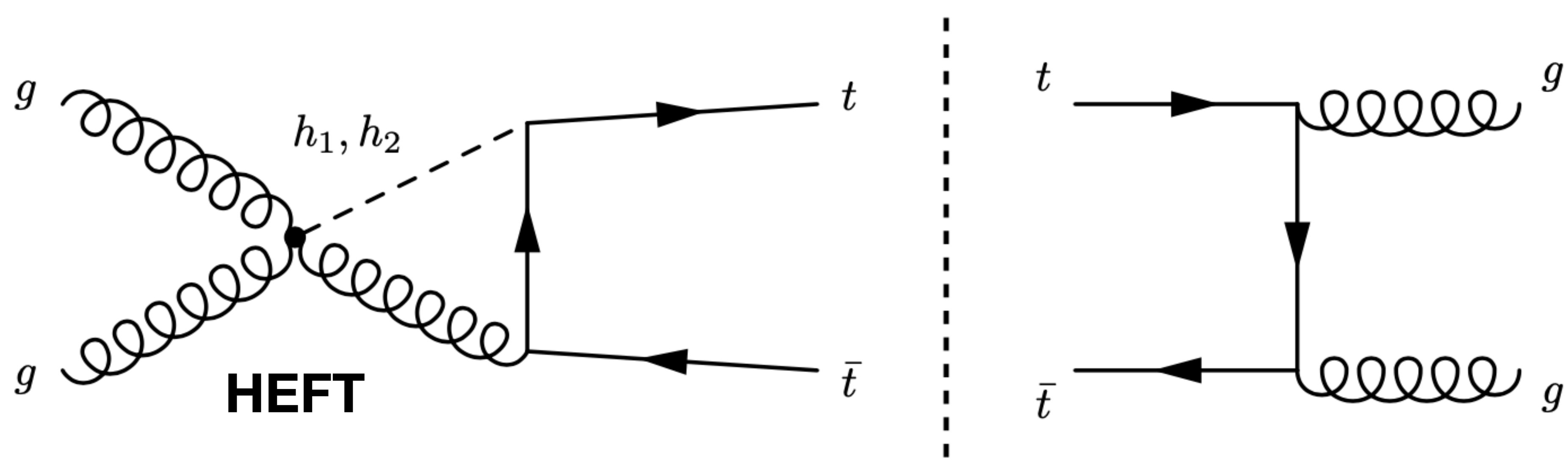


$\times$



Non-Factorisable Corrections





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

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

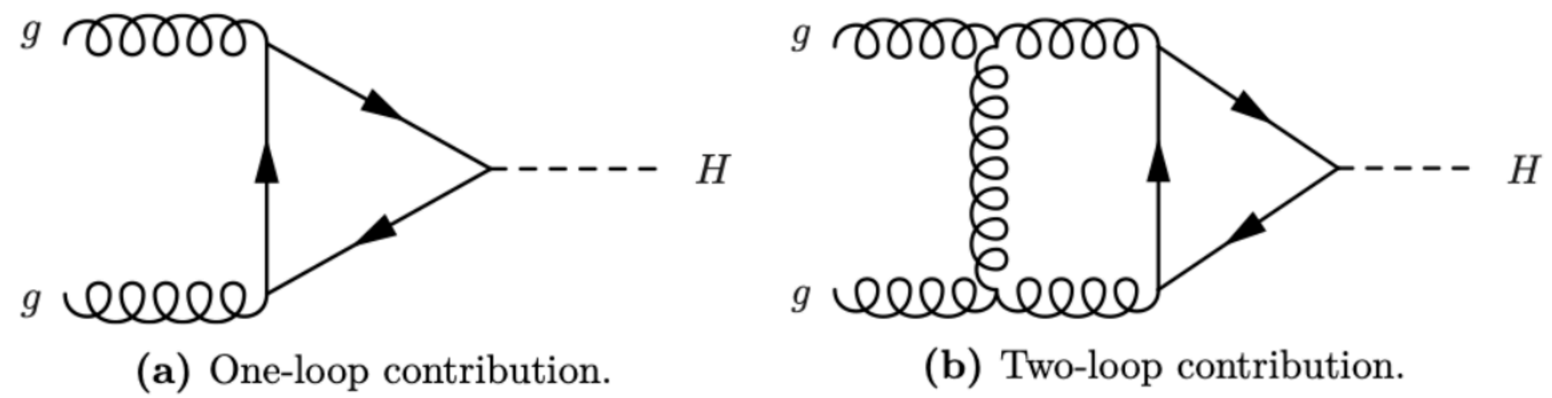
Modified OpenLoops with:

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

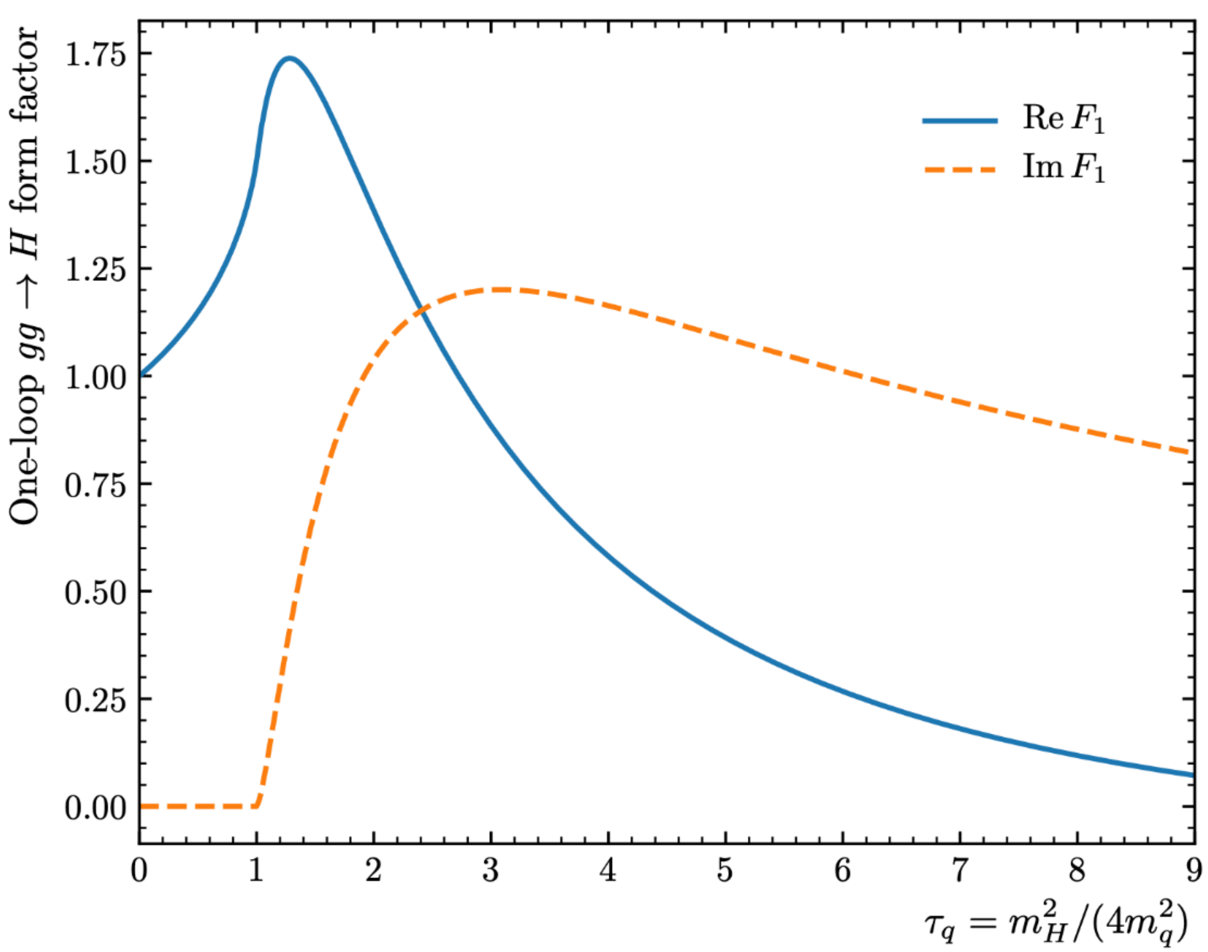
Form Factors

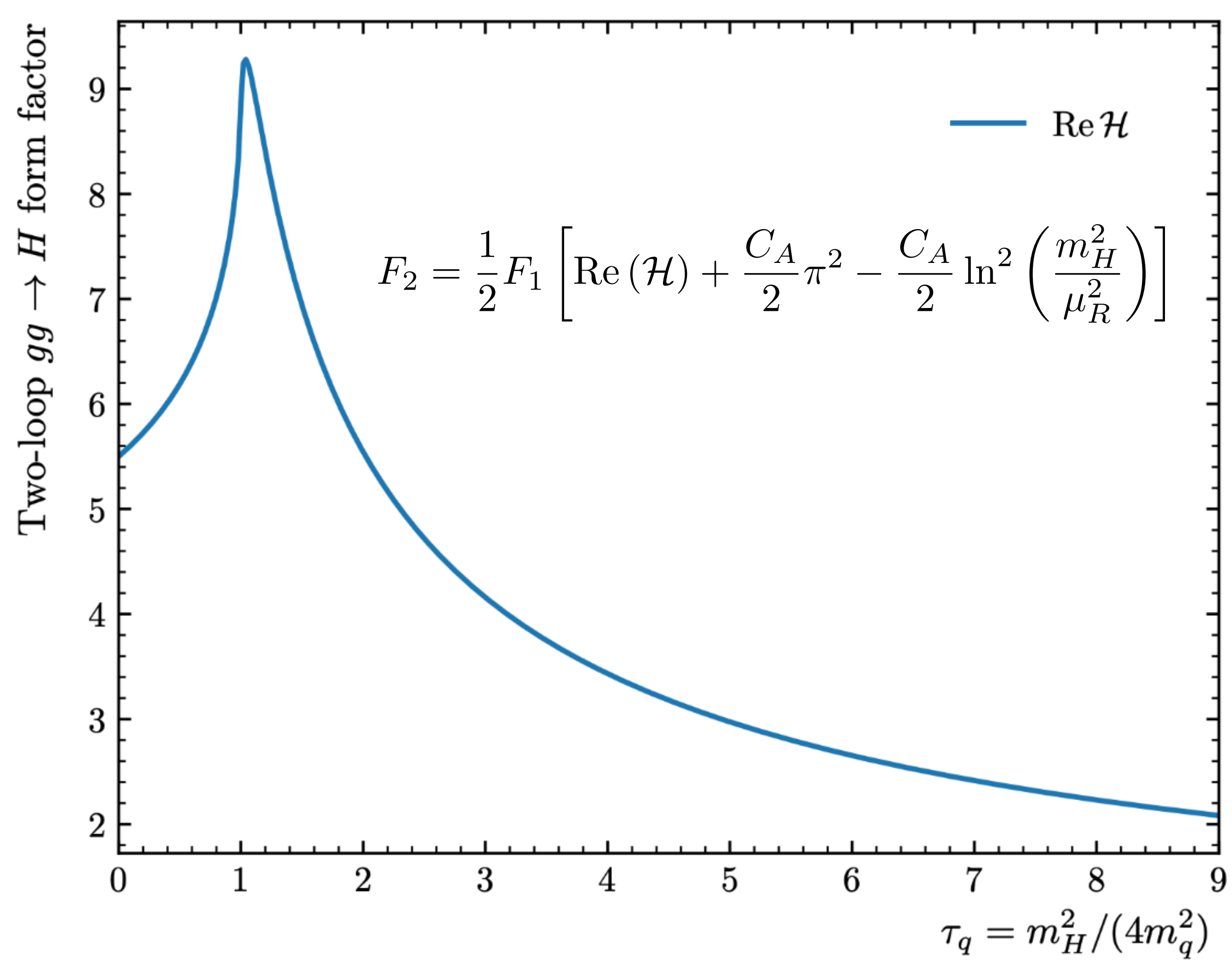
Gluon-fusion Higgs production:

$$gg \to H$$



$$\mathcal{M} = \frac{\alpha_s}{3\pi v} F \delta^{ab} \left(q_1 q_2 g^{\mu\nu} - q_1^\nu q_2^\mu \right) \qquad F = F_1 + \frac{\alpha_s}{\pi} F_2 + \mathcal{O}(\alpha_s^2)$$

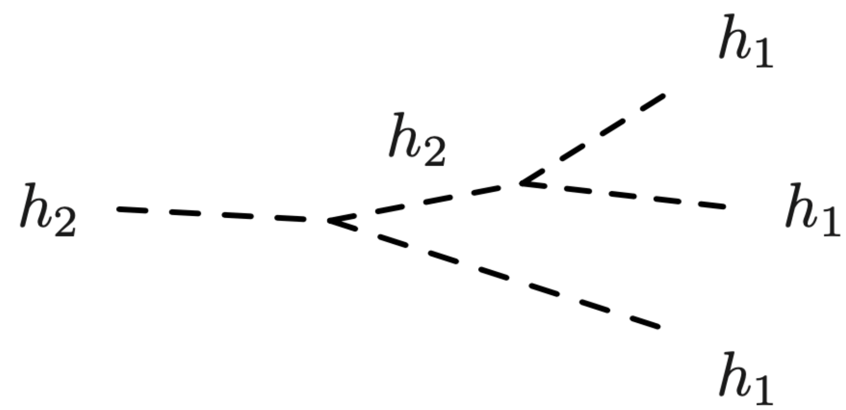




Heavy Higgs Propagator

For one benchmark point:

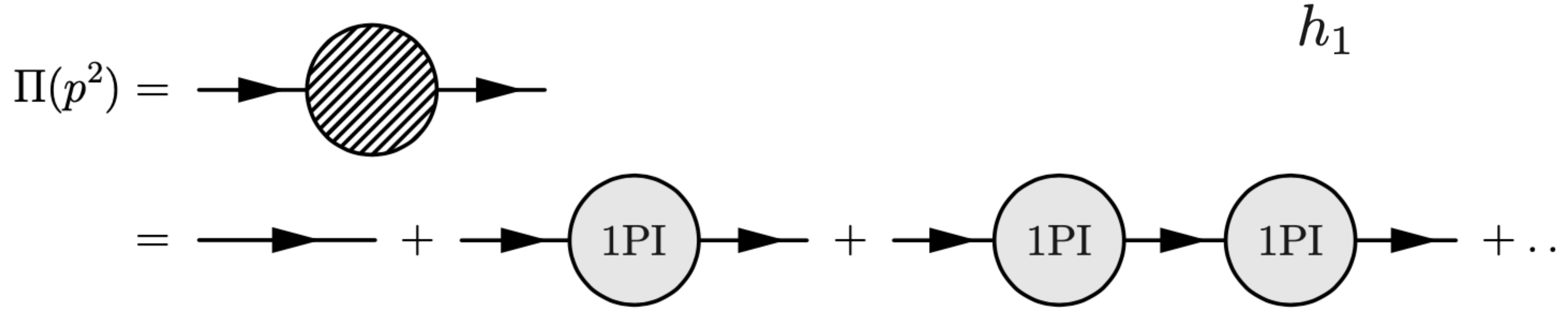
$$\Gamma_{h_2}/M_{h_2} \sim 0.18$$



Cascaded decays:

$$h_2 \to 3 \times h_1$$

Circular dependence on decay width



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

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

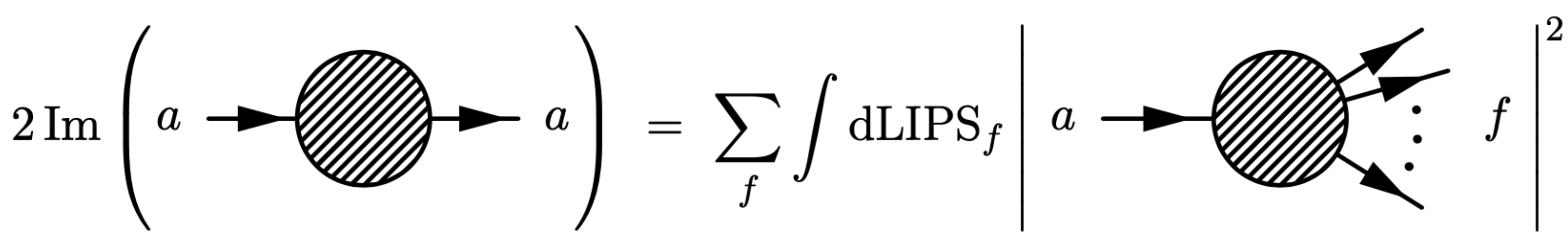
Exact scalar propagator:

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

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

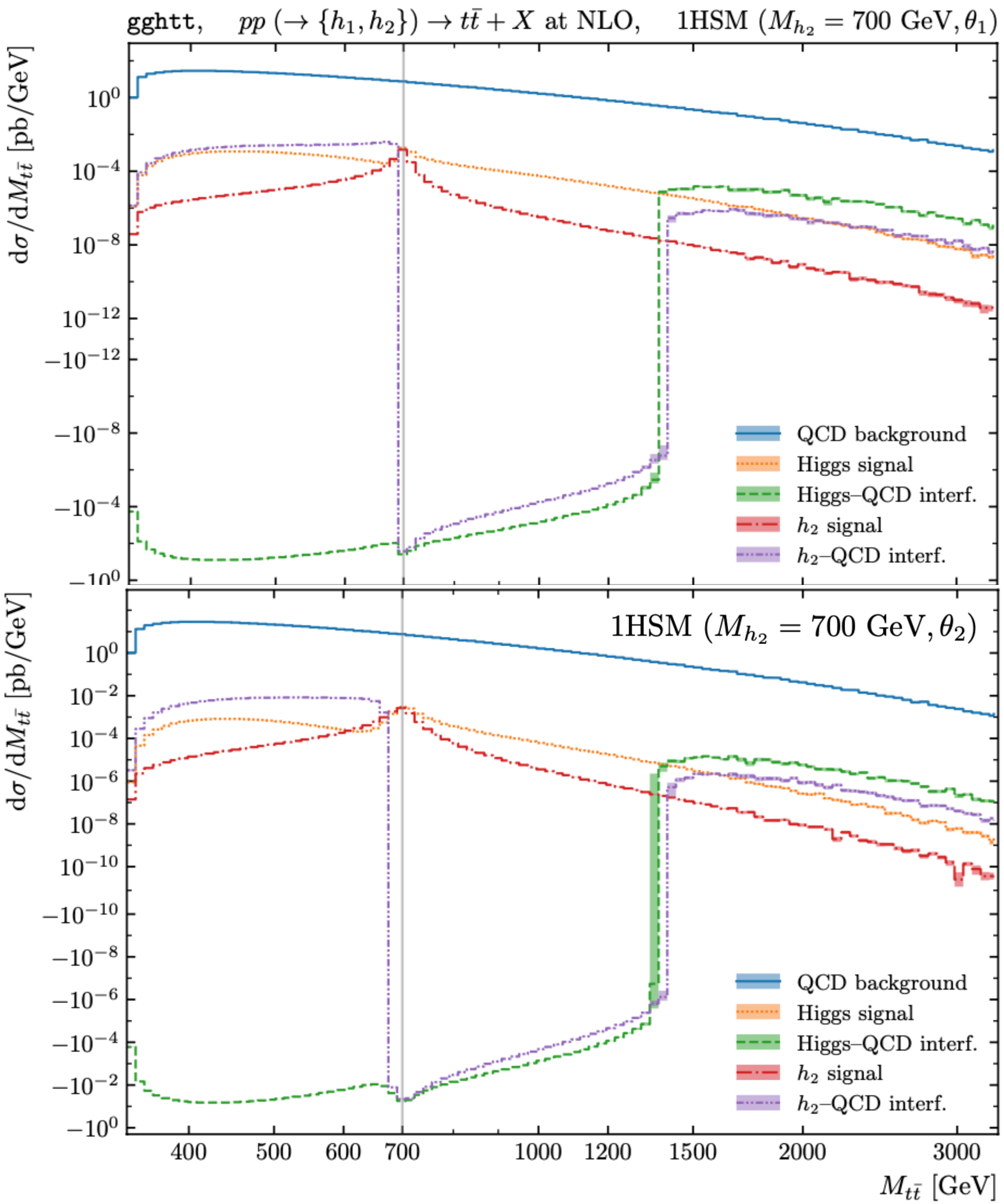
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the SM, pp, $\sqrt{s} = 13$ TeV					
Higgs signal		QCD background		Interference	
σ_{NLO} [pb]	K	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
0.030971(3)	1.6512(2)	675.23(4)	1.5965(1)	−1.5865(2)	2.1807(2)

1HSM

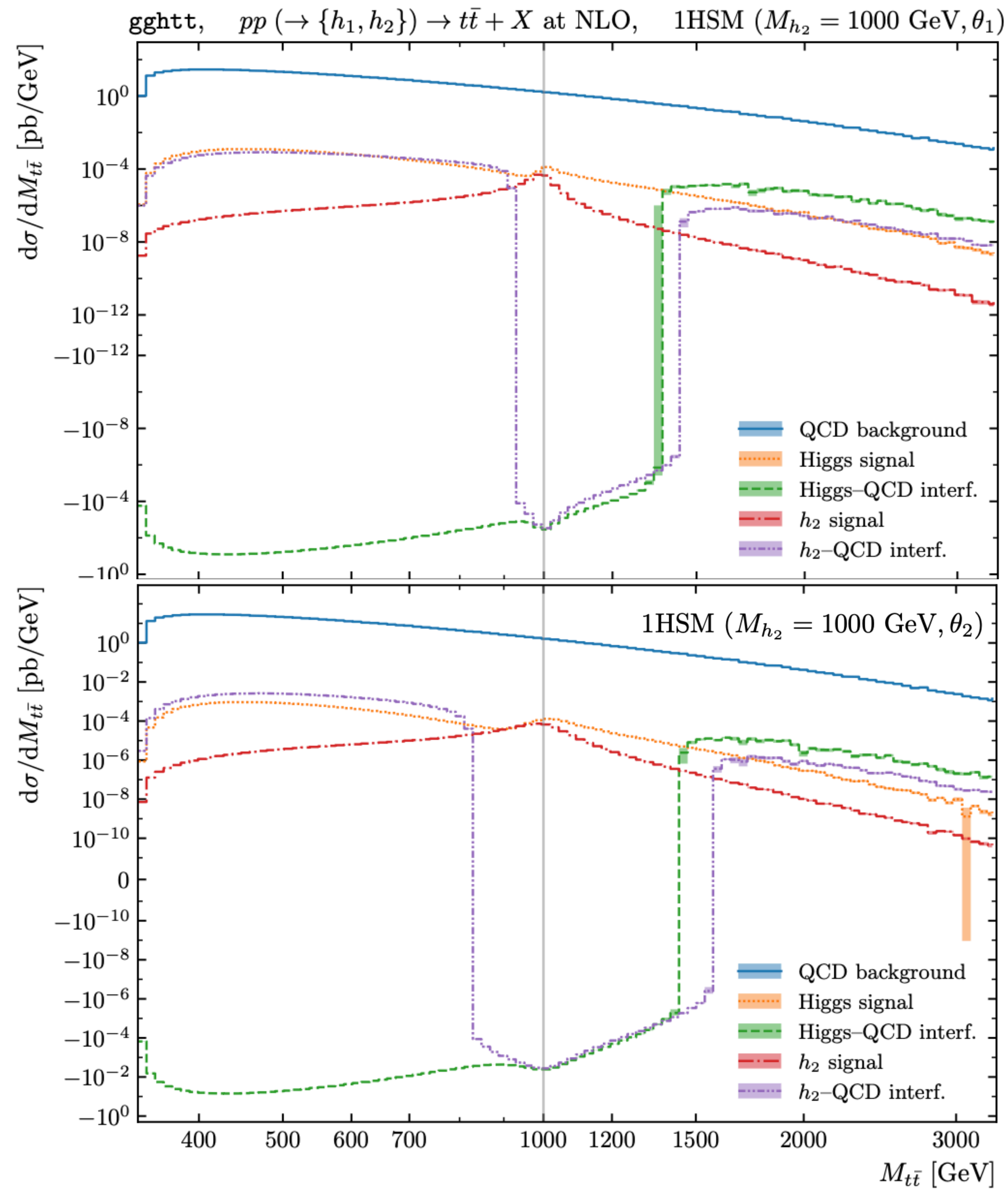
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM, pp, $\sqrt{s} = 13$ TeV					
		Higgs signal		Higgs–QCD interference	
	M_{h_2} [GeV]	σ_{NLO} [pb]	K	σ_{NLO} [pb]	K
θ_1	700	0.029108(2)	1.6234(2)	−1.5169(2)	2.1743(3)
	1000	0.027334(2)	1.6459(2)	−1.49132(9)	2.1579(2)
	1500	0.029932(3)	1.6745(2)	−1.5601(2)	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

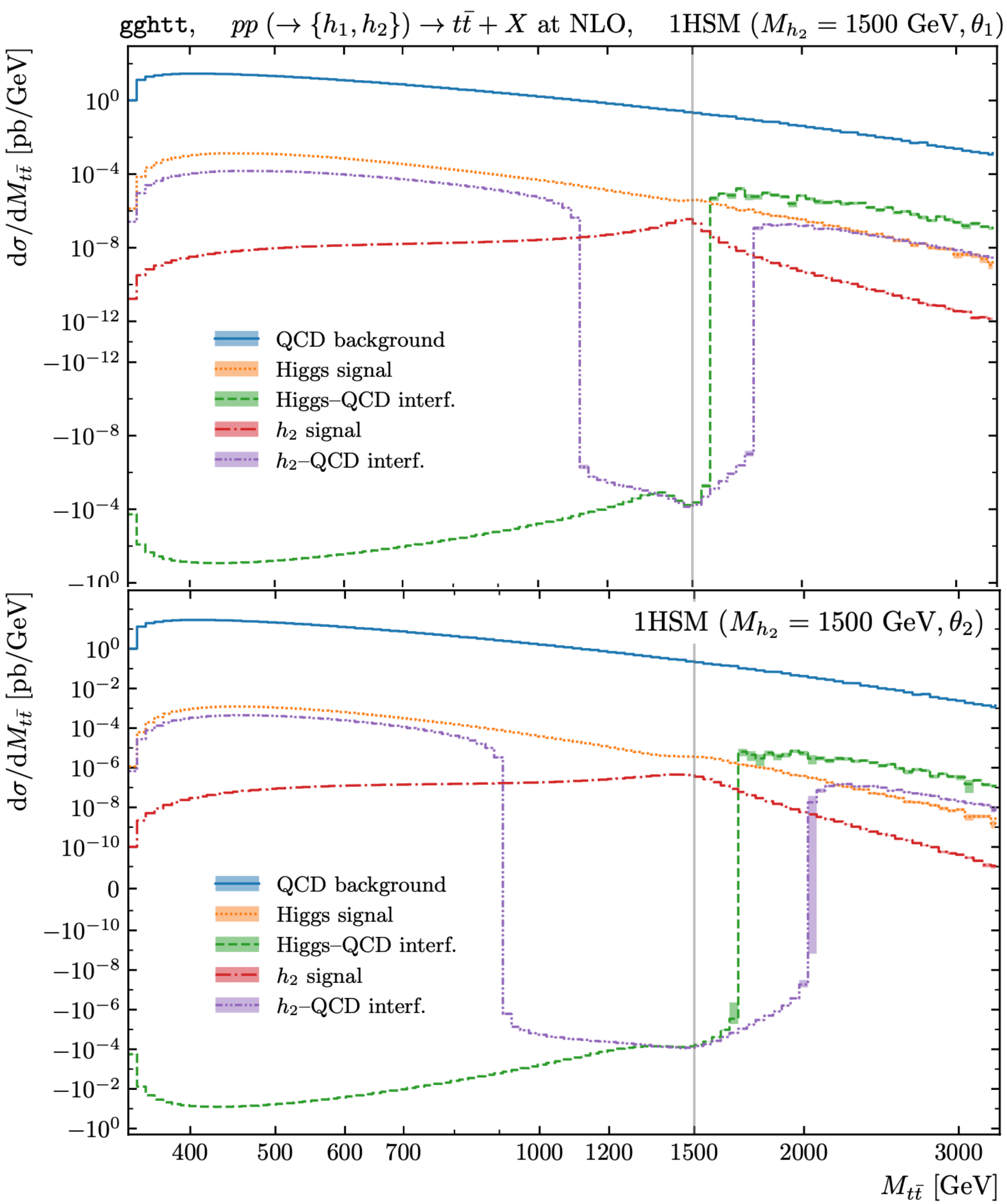


1 TeV

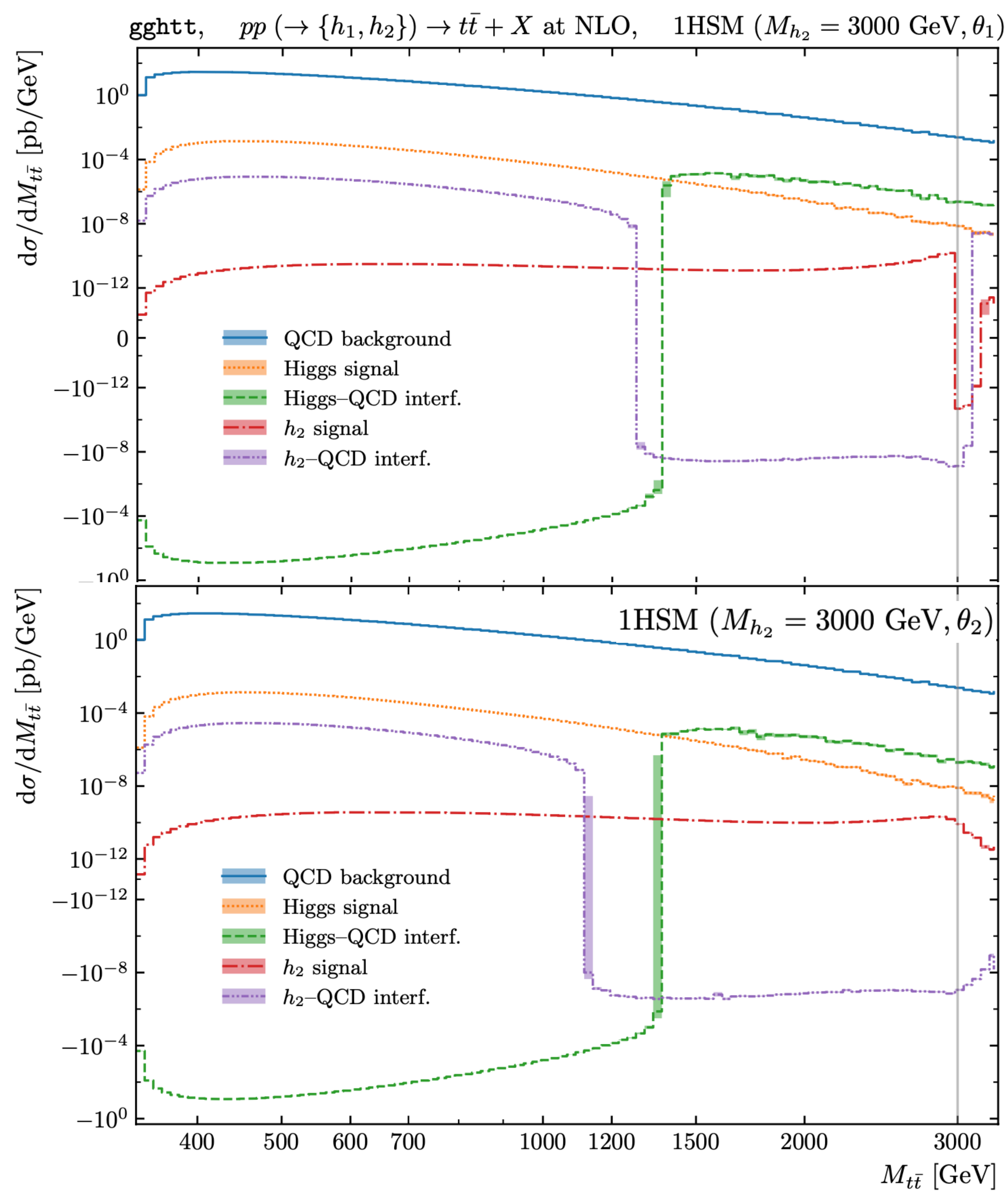


Results

1.5 TeV



3 TeV



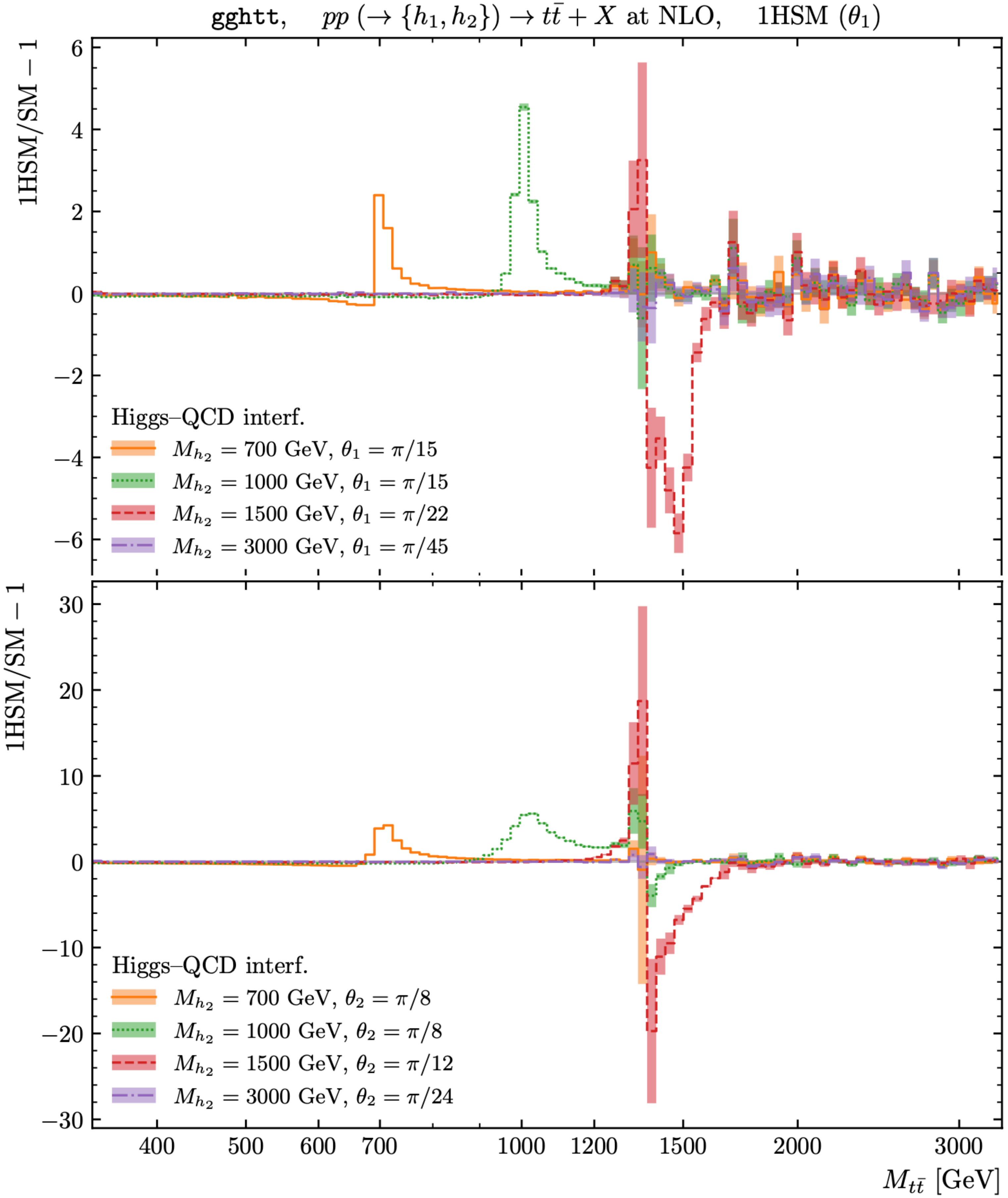
Results

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	Run 3	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	–	–	–

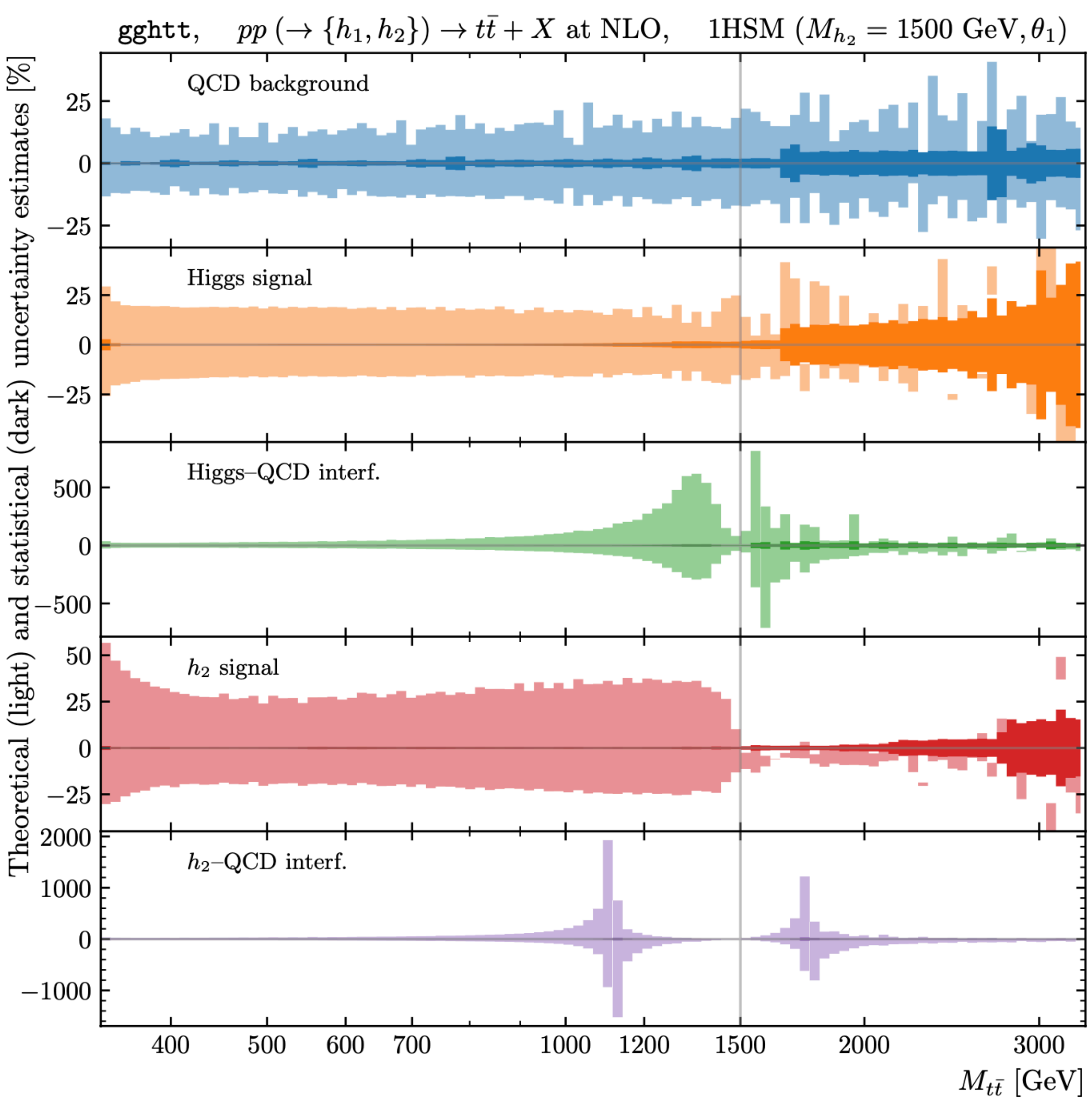


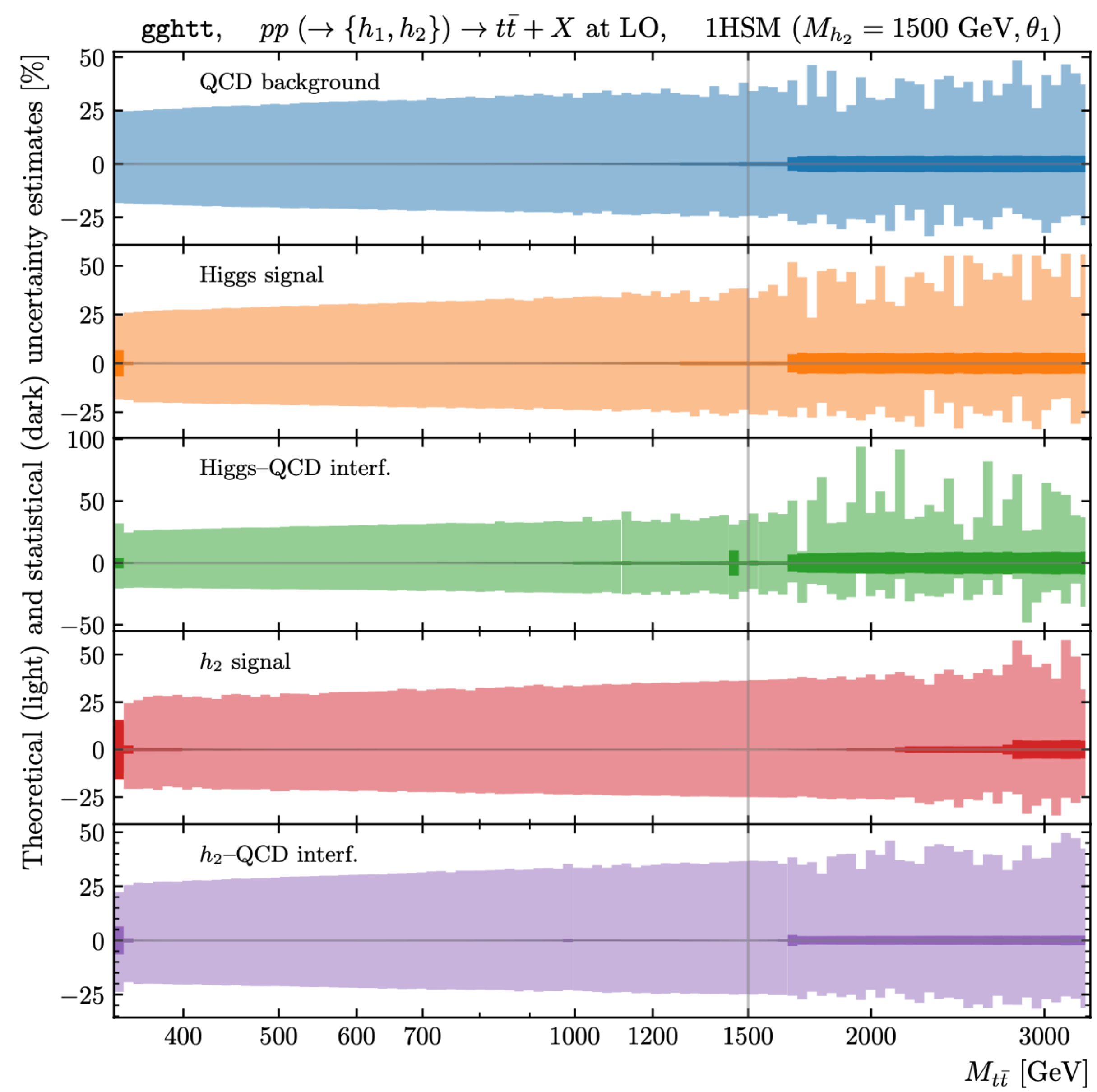
Scale Uncertainties

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

QCD bg: 12%

h2-QCD: 27—42%

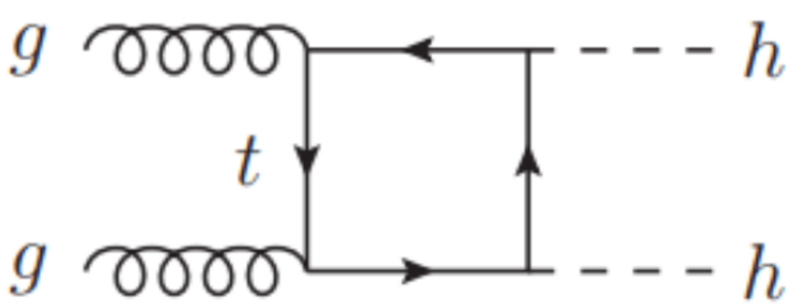


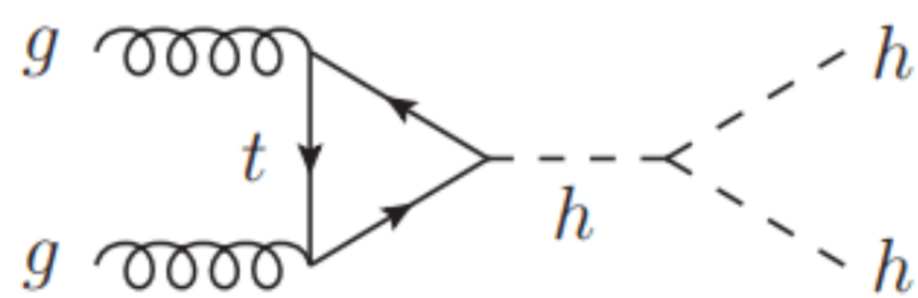


Generalisation

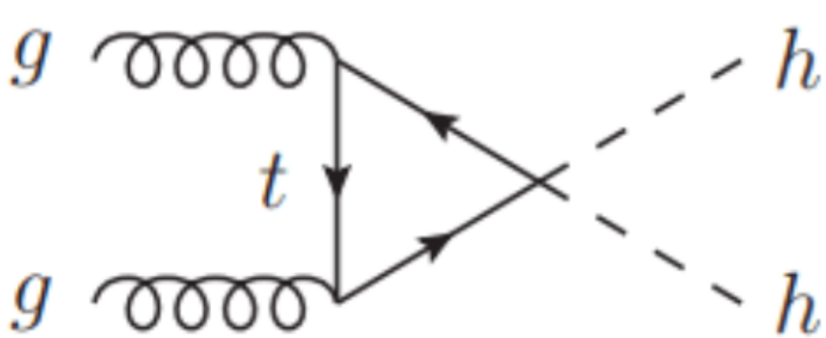
The code be generalised to work for any loop-induced process

Double Higgs production

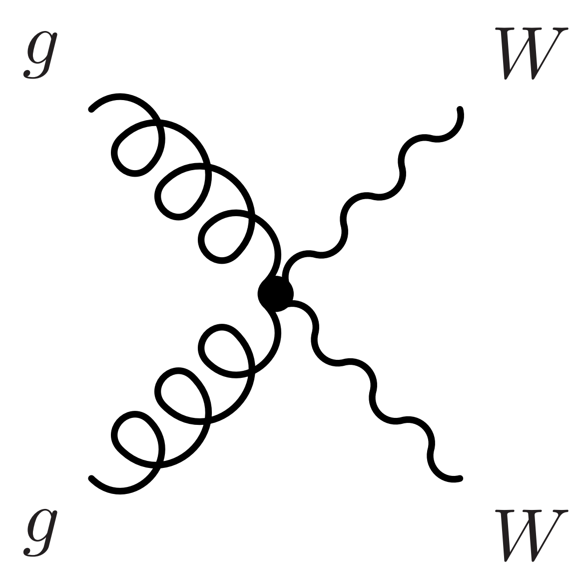




Effective field theories



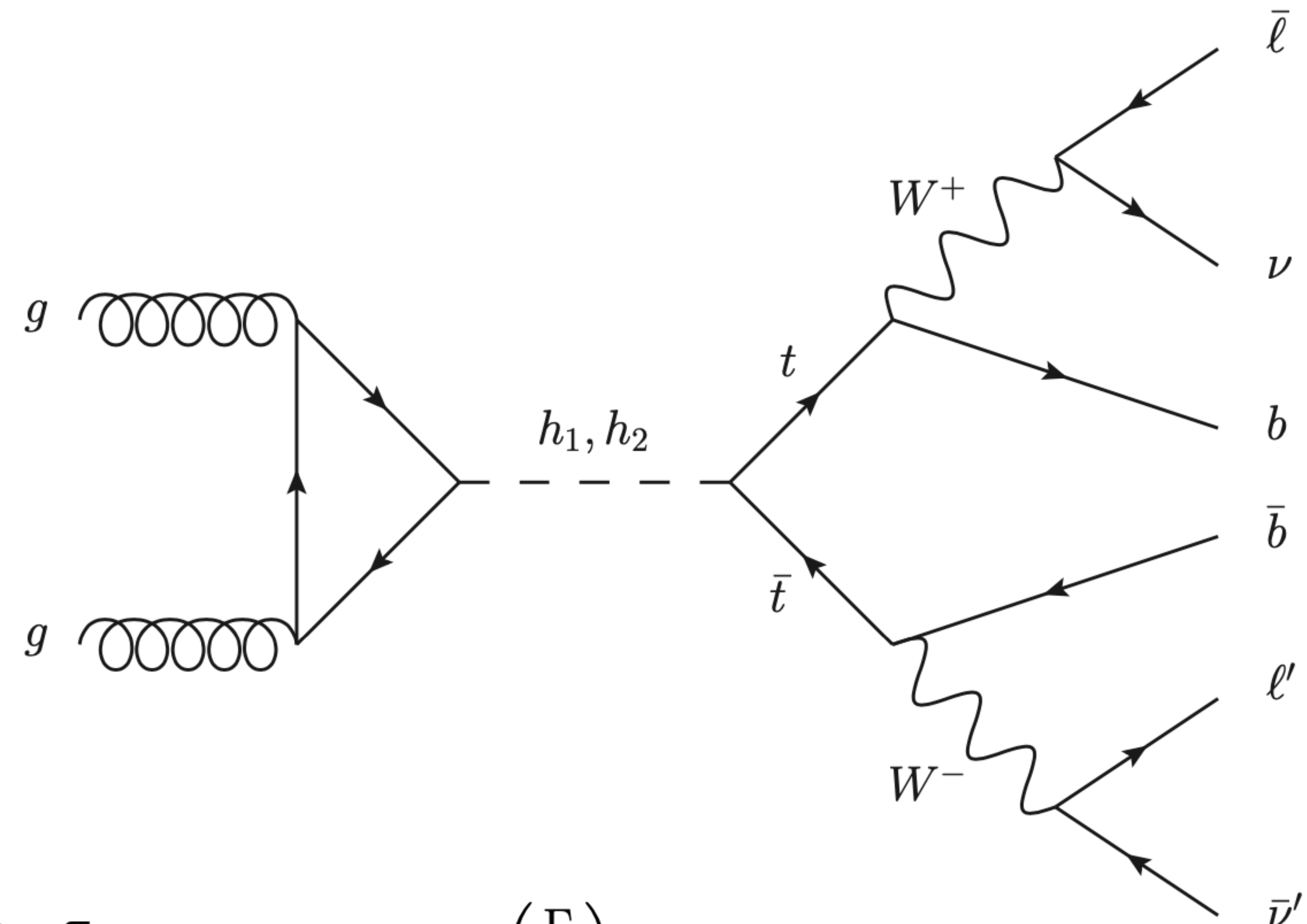
dim-6



dim-8

Top Decays

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

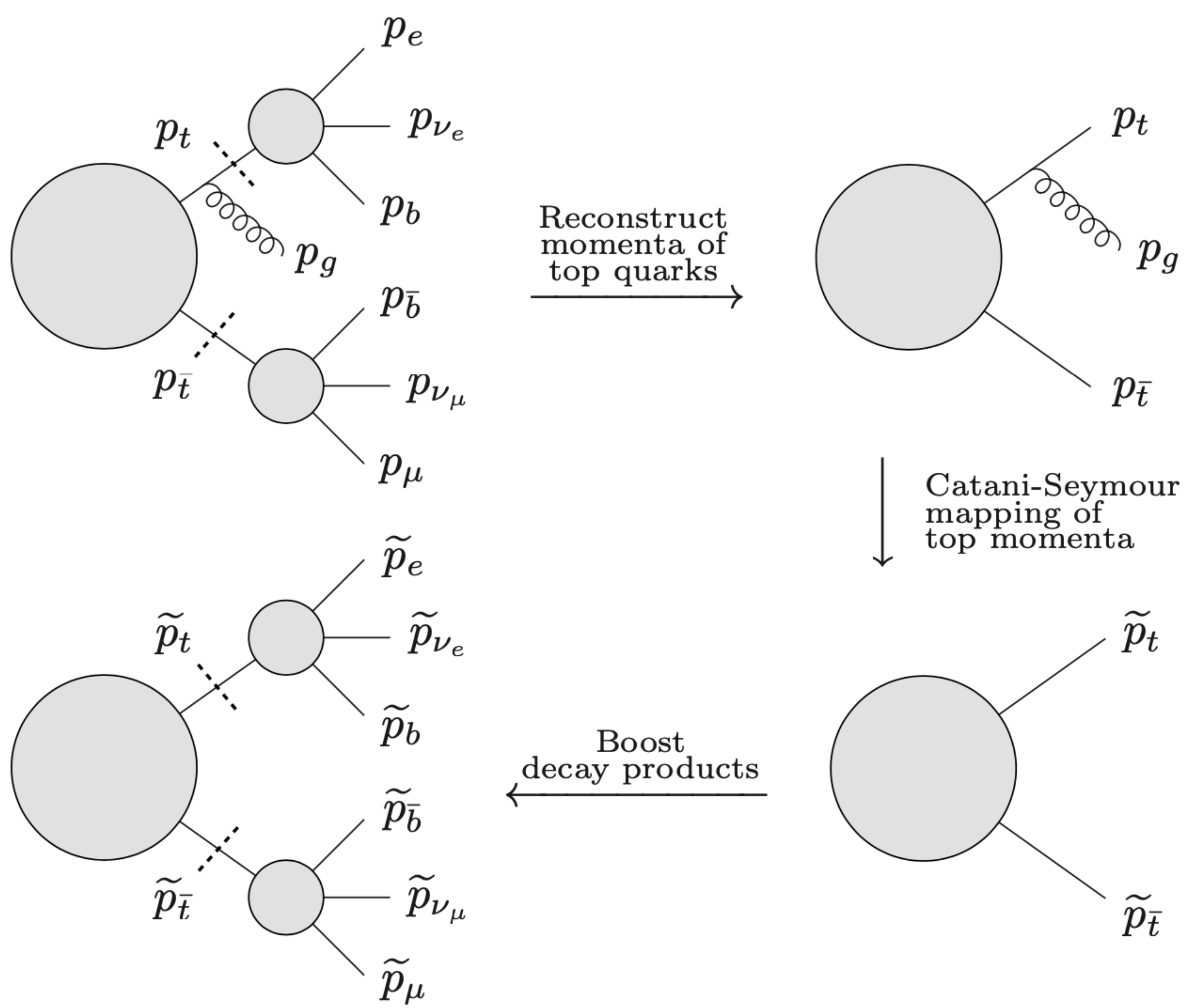


NWA:

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

Top Decays

Dipole subtraction for intermediate emitters



Summary

- We studied the interference of a heavy Higgs with the continuum QCD background at NLO QCD
- This is loop-induced x tree-level at LO and has a complicated structure at NLO
- This required a specially built Monte Carlo — which can now be used for other loop-induced processes

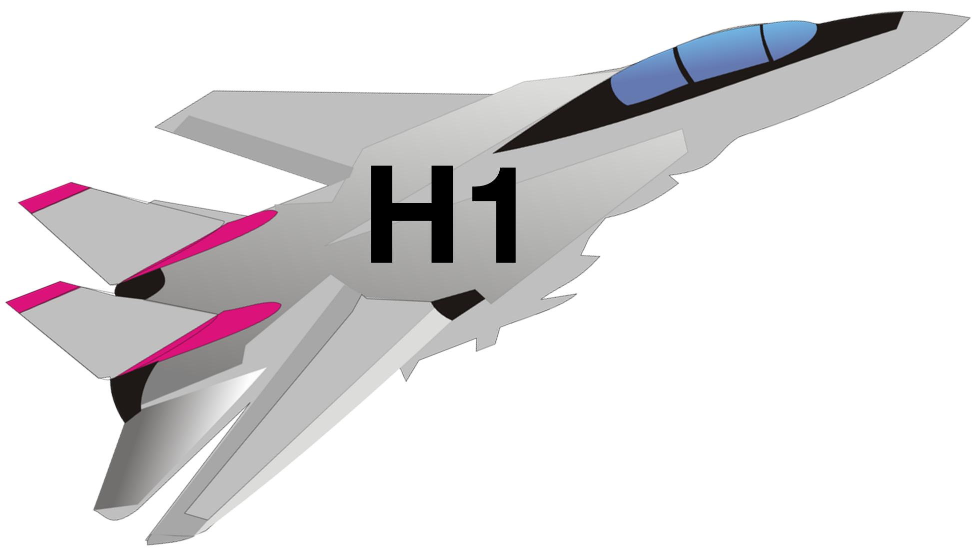
A second project…

H1JET

arXiv:2011.04694 [hep-ph]

with Andrea Banfi

h1jet.hepforge.org

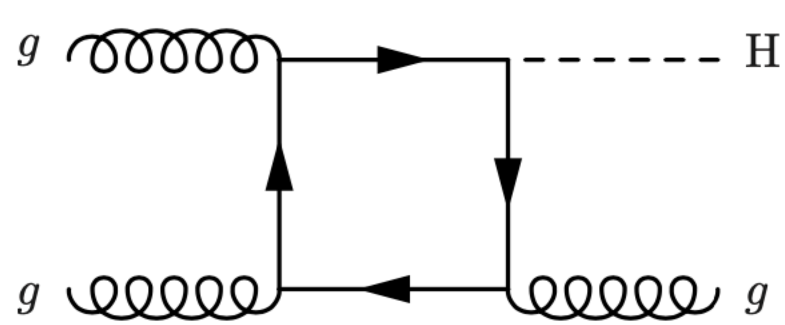


Motivation

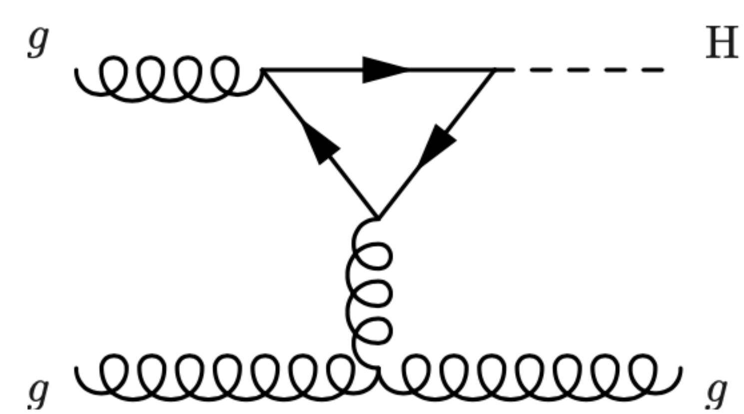
A fast and easy-to-use tool to compute transverse momentum distributions

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

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



(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

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

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

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

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

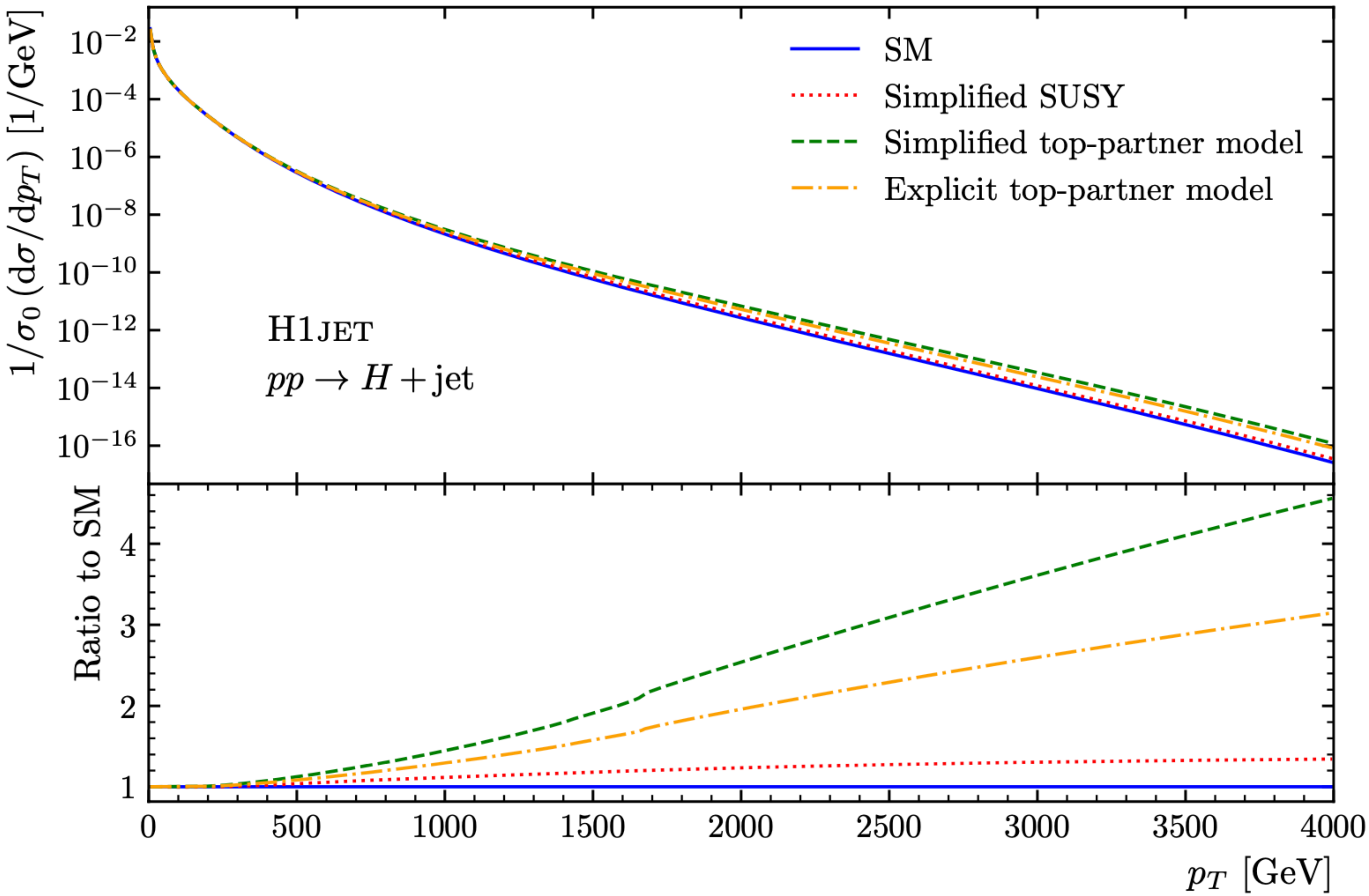
$$\hat{t} = -p_T e^{-\eta} \sqrt{\hat{s}}$$

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

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!