Quantum collider probes of the fermionic Higgs portal

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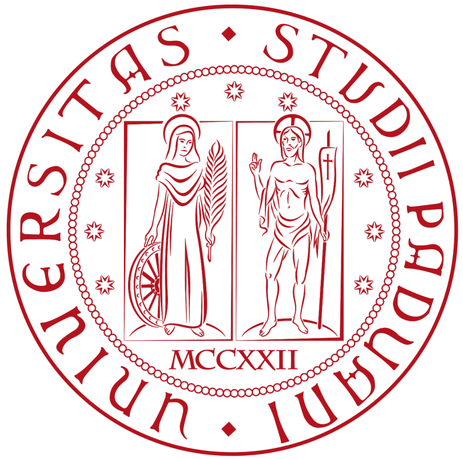
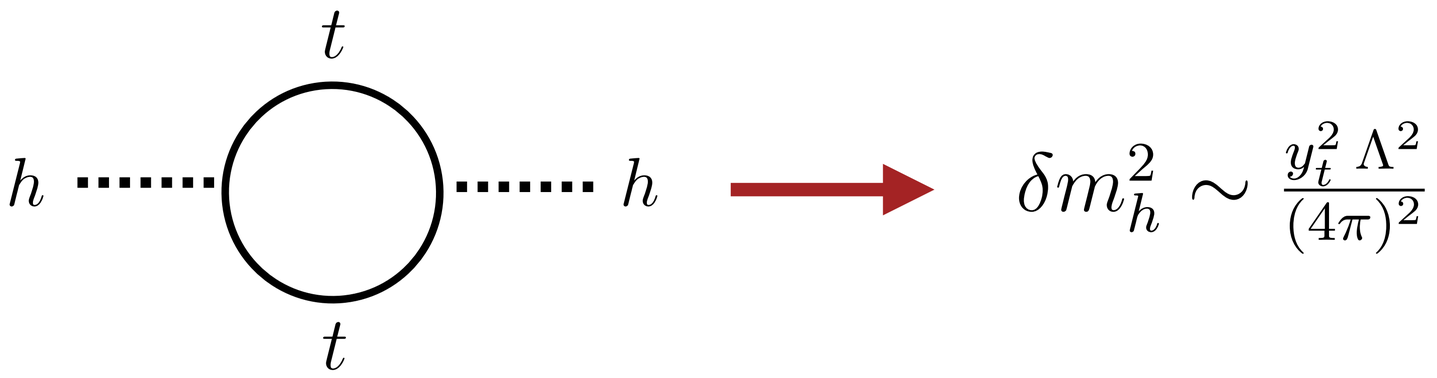
based on arXiv: 2311.03995 with U. Haisch, M. Ruhdorfer, and A. Weiler



The Hierarchy Problem of the SM



$$\delta m_h^2 \sim \frac{y_t^2\,\Lambda^2}{(4\pi)^2}$$

problem: $\frac{|\delta m_h^2|}{m_h^2} \gg 1$, if $\Lambda \gg \mathcal{O}(2-3)\,\text{TeV}$

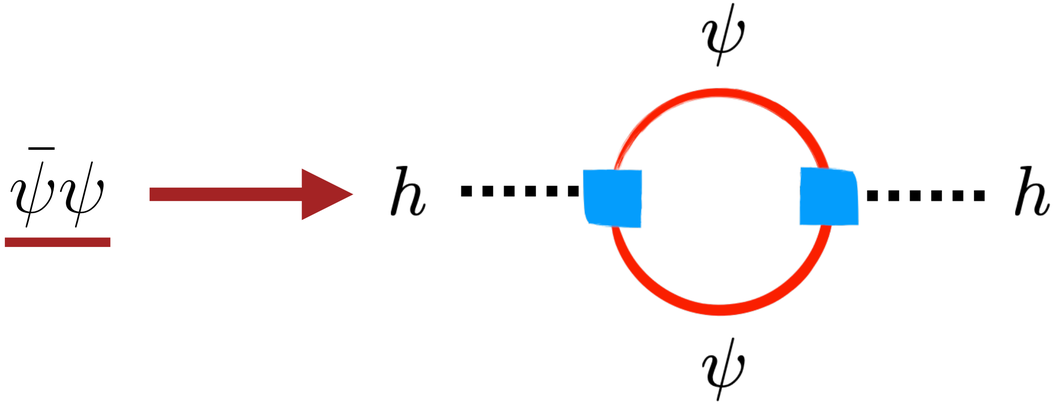
expect solutions to arise **close to TeV** scale

And indeed, there are approaches...

1) Higgs no relevant degree of freedom above some TeV (Composite Higgs)

2) Higgs couples to BSM top partner (SUSY, Little Higgs, **Twin Higgs**)

$$\mathcal{L}_{\text{int}} \supset \frac{c_\psi}{f} |H|^2 \bar{\psi}\psi$$



How to probe a Twin Top at Colliders?

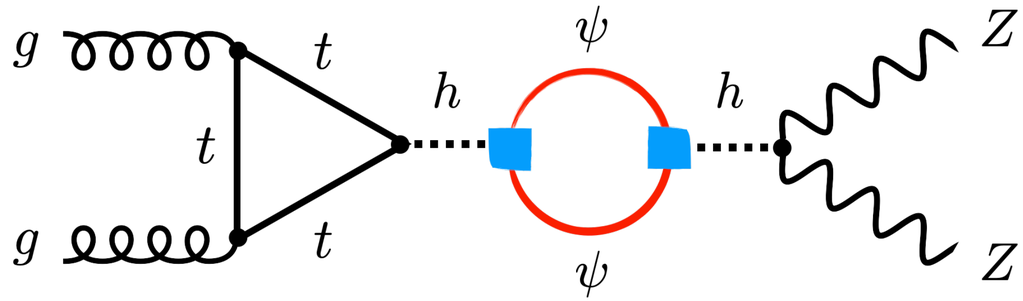
Twin Higgs: ψ is SM singlet ⟶ motto: exploit coupling to Higgs

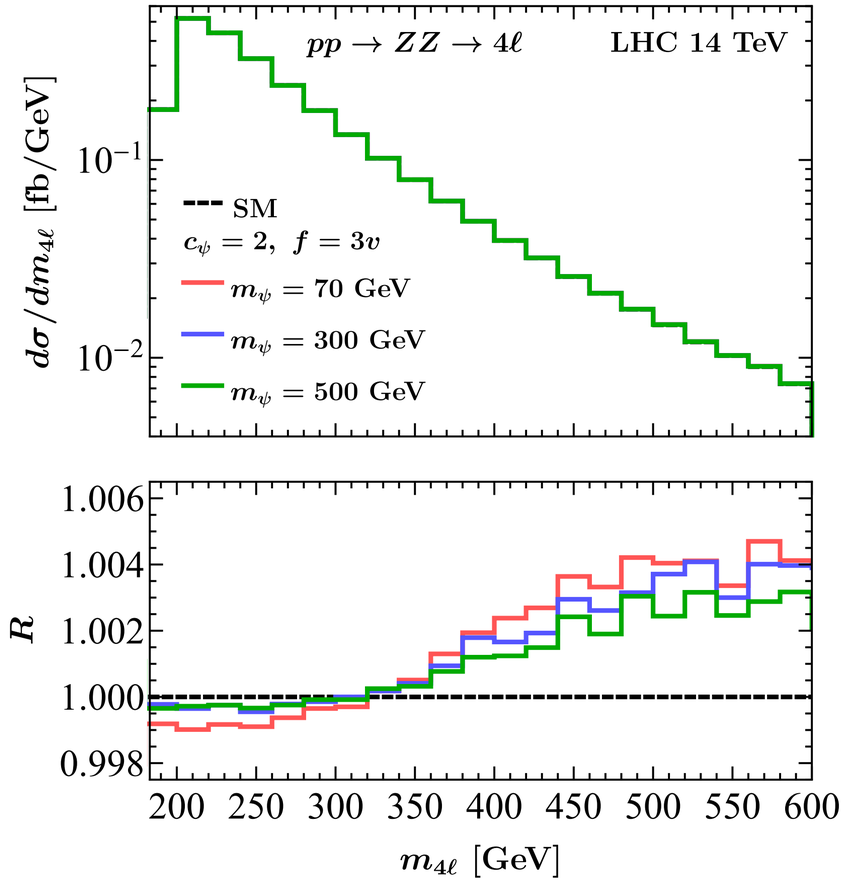
1) Higgs self-energy in $gg \to 4\ell$

2) Di-Higgs production

3) direct production of ψ-pairs in off-shell Higgs decays (VBF)

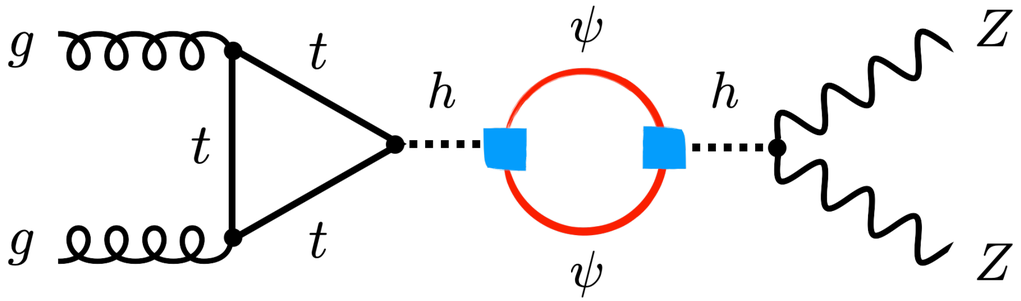
1) Higgs self-energy





- main modifications in the tail
- larger for smaller fermion masses
- relative deviations small: $\mathcal{O}(0.5)\%$

1) Higgs self-energy



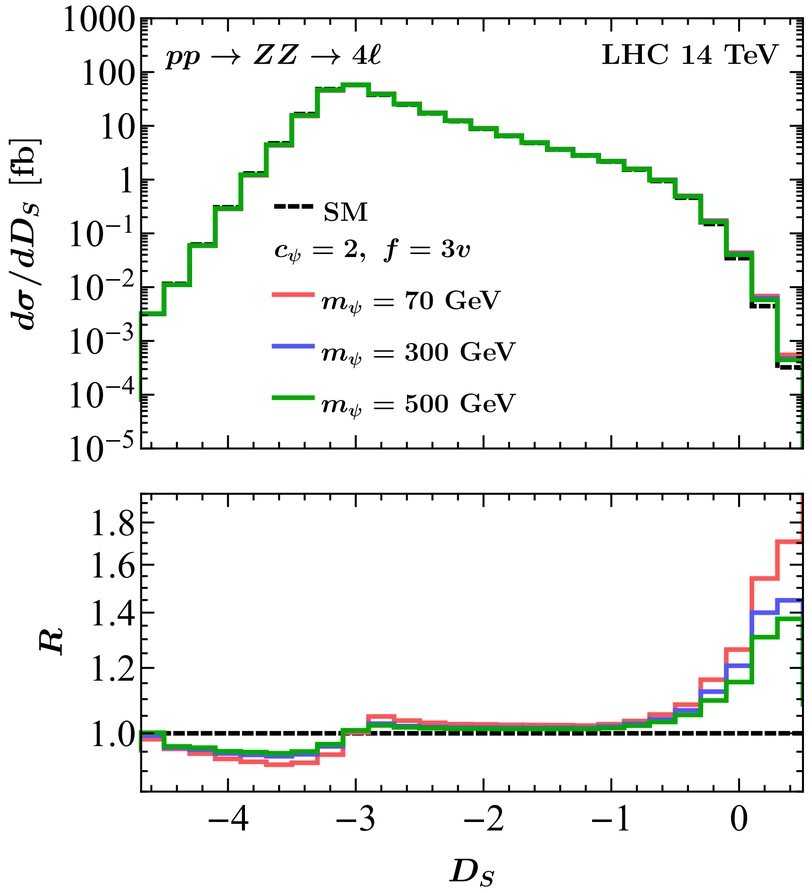
$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

- $P_h, P_{gg}, P_{q\bar{q}}$ are squared MEs for

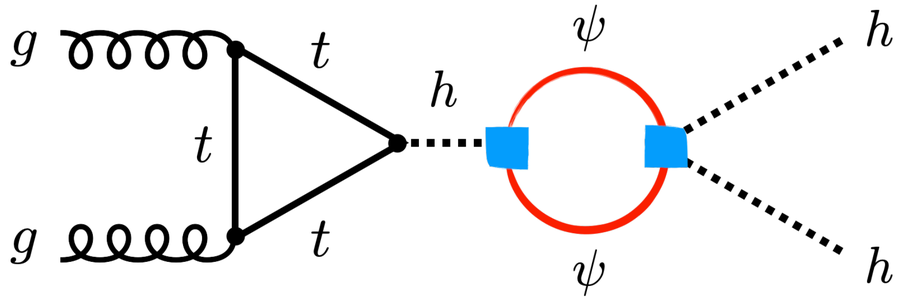
  $gg \to h^* \to ZZ$, $gg \to ZZ$, $q\bar{q} \to ZZ$

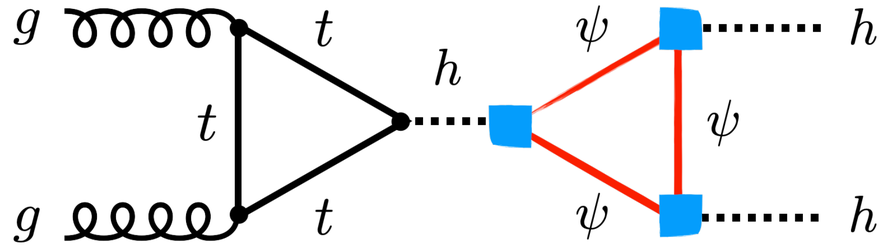
- $c = 0.1$ empirical constant

- deviations can **exceed** $\mathcal{O}(50)\%$



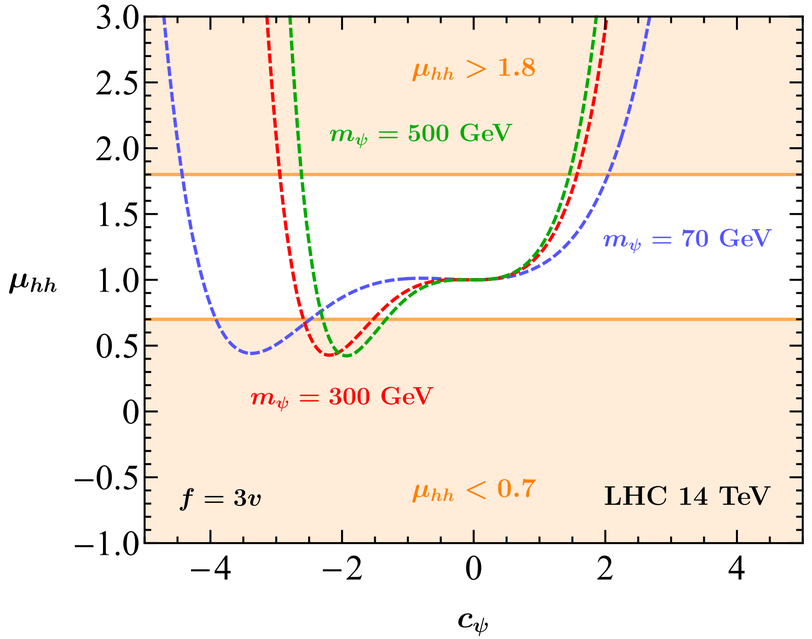
2) Di-Higgs production



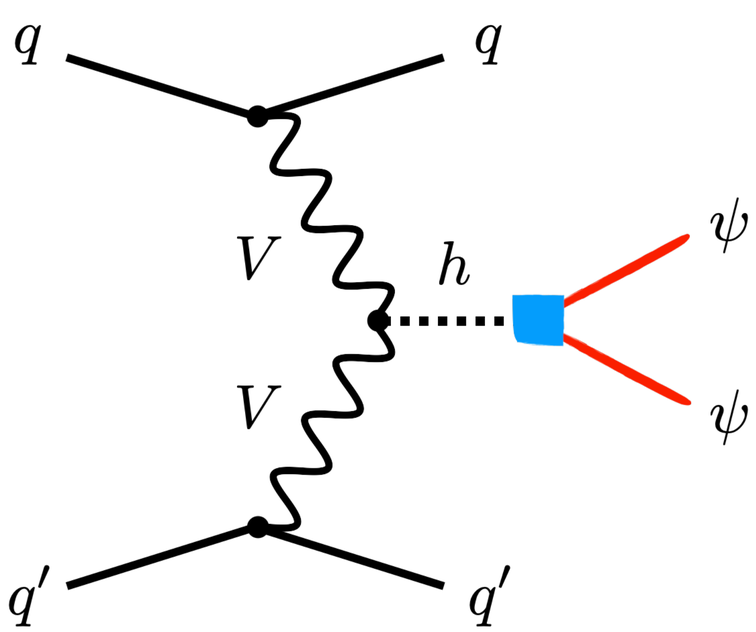


$$\mu_{hh} = \sigma/\sigma_{\rm SM}$$

polynomial in the Wilson coefficient



3) Off-shell Higgs decays (VBF)

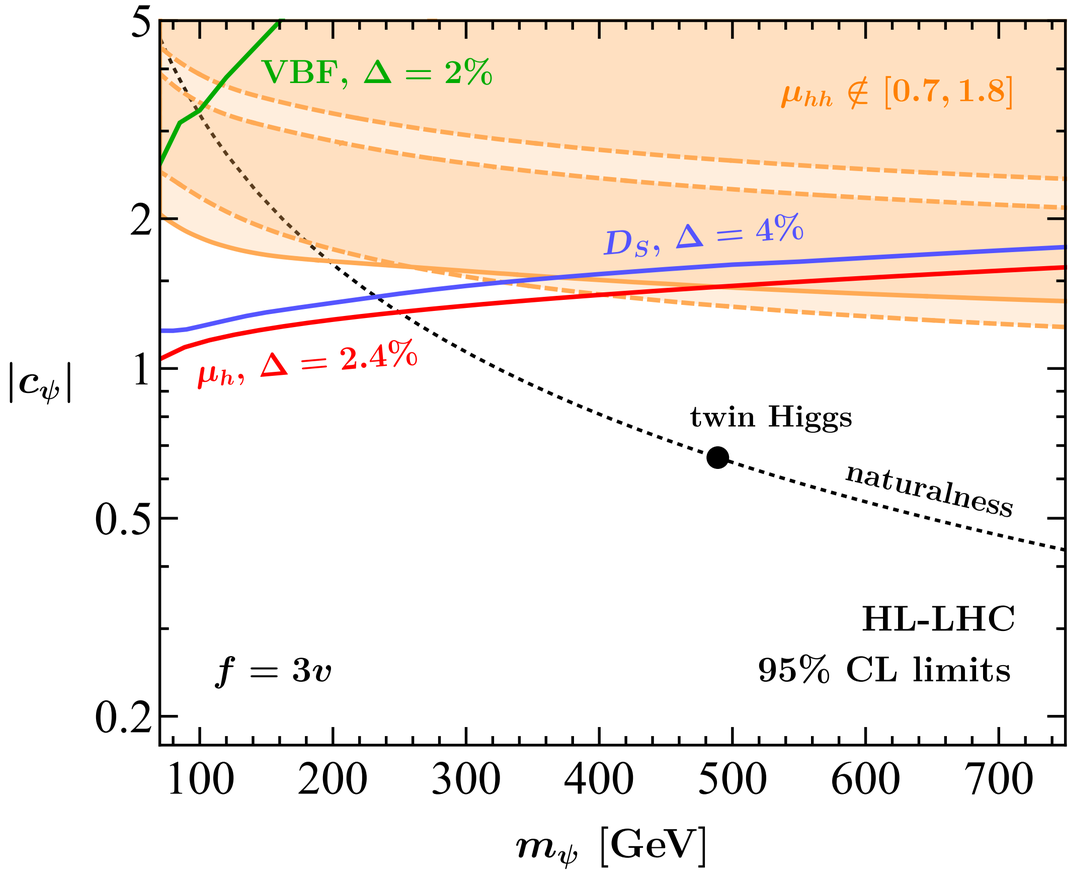


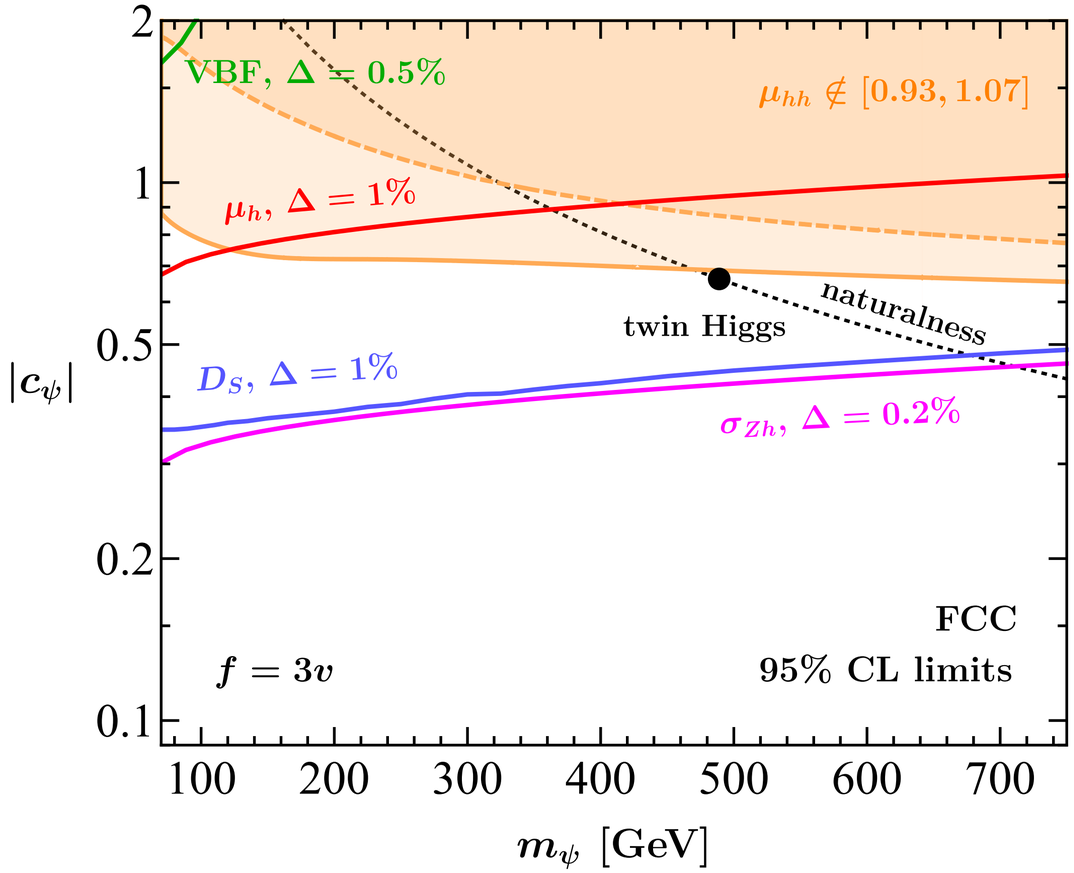
- VBF signature: jets in forward direction
- search for missing transverse energy
- **but:** 2 sources of suppression

  1) Higgs propagator scales as $\sim 1/p^2$

  2) phase space suppression

Results


VBF, $\Delta = 2\%$
$\mu_{hh} \notin [0.7, 1.8]$
D_S, $\Delta = 4\%$
μ_h, $\Delta = 2.4\%$
twin Higgs
naturalness
HL-LHC
95% CL limits
$f = 3v$
$|c_\psi|$
m_ψ [GeV]


VBF, $\Delta = 0.5\%$
$\mu_{hh} \notin [0.93, 1.07]$
μ_h, $\Delta = 1\%$
twin Higgs
naturalness
D_S, $\Delta = 1\%$
σ_{Zh}, $\Delta = 0.2\%$
FCC
95% CL limits
$f = 3v$
$|c_\psi|$
m_ψ [GeV]

Backup

Event Cuts 4-lepton analysis at the LHC

Event Cut	Description
$140\,\text{GeV} < m_{4\ell} < 600\,\text{GeV}$	four-lepton invariant mass
$\lvert\eta_\ell\rvert < 2.5$	pseudorapidity range for the leptons
$p_{T,\ell_1} > 20\,\text{GeV}$	highest lepton transverse momentum
$p_{T,\ell_2} > 15\,\text{GeV}$	second highest lepton transverse momentum
$p_{T,\ell_3} > 10\,\text{GeV}$	third highest lepton transverse momentum
$p_{T,\ell_4} > 6\,\text{GeV}$	fourth highest lepton transverse momentum
$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$	invariant mass of the leading lepton pair
$50\,\text{GeV} < m_{34} < 115\,\text{GeV}$	invariant mass of the subleading lepton pair

QCD-improved spectra 4-lepton analysis

- estimate higher-order QCD effects using K-factors defined as ratio of fiducial cross section to certain order in QCD to LO QCD prediction

- numerical values: $K_{gg}^{\mathrm{NLO}} = 1.83, K_{q\bar{q}}^{\mathrm{NNLO}} = 1.55$

- QCD-improved spectra: $\left(\frac{d\sigma_{pp}}{dO}\right)_{\mathrm{improved}} = K_{gg}^{\mathrm{NLO}} \left(\frac{d\sigma_{gg}}{dO}\right)_{\mathrm{LO}} + K_{q\bar{q}}^{\mathrm{NNLO}} \left(\frac{d\sigma_{q\bar{q}}}{dO}\right)_{\mathrm{LO}}$

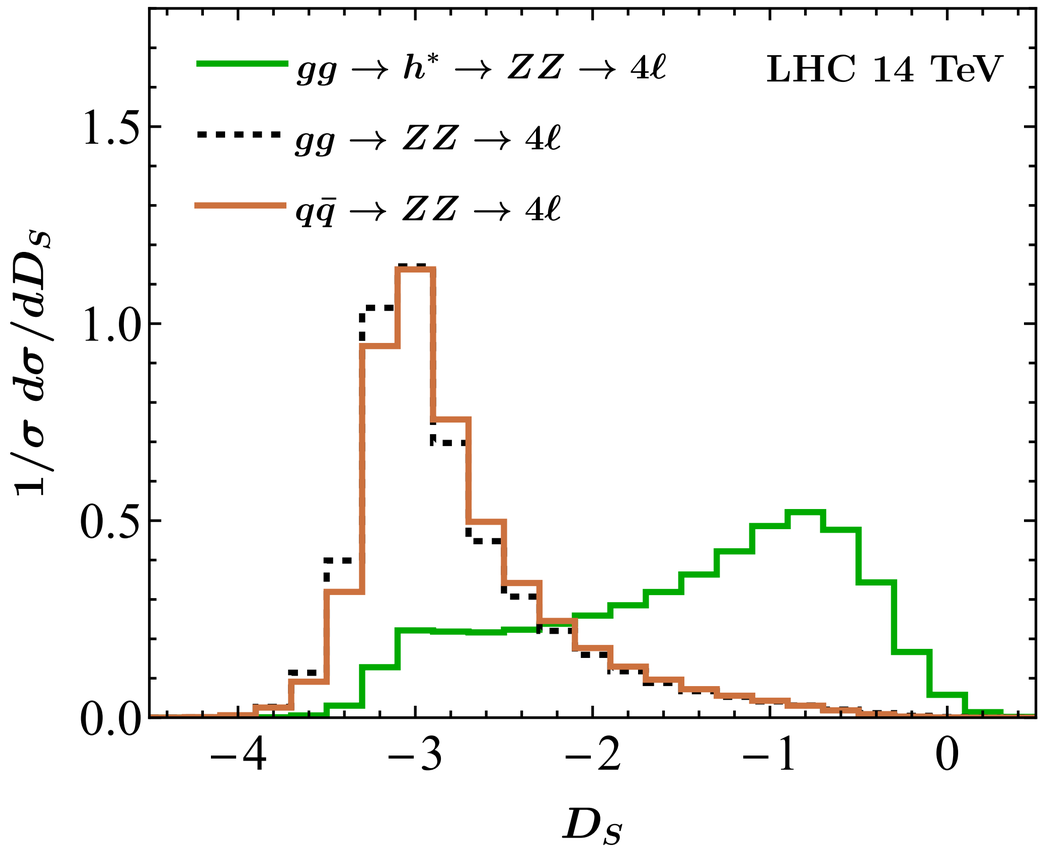
Matrix-element based discriminant

$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

- $P_h, P_{gg}, P_{q\bar{q}}$ are squared MEs for

  $gg \to h^* \to ZZ$, $gg \to ZZ$, $q\bar{q} \to ZZ$

- $c = 0.1$ empirical constant



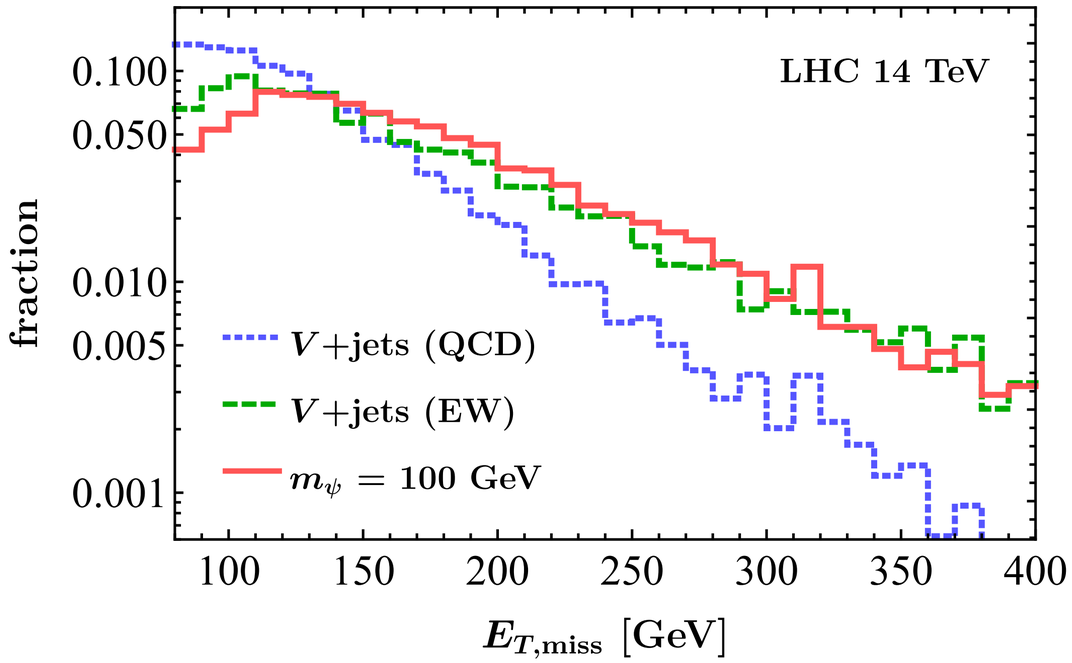
Statistical analysis

- Poisson distribution to construct likelihood and profile-likelihood ratio
- Asimov data set: counts in bin correspond to expectation value
- Asimov approximation for significance including background uncertainty:

$$Z_i = \sqrt{2\left((s_i + b_i)\ln\left[\frac{(s_i + b_i)(b_i + \sigma_{b_i}^2)}{b_i^2 + (s_i + b_i)\sigma_{b_i}^2}\right] - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left[1 + \frac{\sigma_{b_i}^2 s_i}{b_i(b_i + \sigma_{b_i}^2)}\right]\right)}$$

- condition: $Z > \sqrt{2}\,\mathrm{erf}^{-1}(\mathrm{CL})$ with $\mathrm{CL} = 95\%$

Off-shell Higgs decays (VBF)



- $E_{T,\mathrm{miss}} > 180\,\mathrm{GeV}$ (trigger efficiency)
- optimize cuts on $\Delta\eta_{j_1 j_2}$ and $m_{j_1 j_2}$