# Momentum Dependent Effects in Higgs Couplings

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# Outline

- Physics Beyond the Standard Model in the next decade: Energy vs. Precision
- Exploring BSM in the Higgs Couplings

  How do we study sensitivity to extensions of the SM ?

  EFTs

  Explicit Models

- Form Factors in Higgs Couplings from BSM physics
- Models and Signals
- Conclusions

# The Transition from Energy to Precision

Looking for new physics beyond the SM

- Look for new particles at energy frontier: LHC.
- Look for hidden/dark sectors: dark sector/DM searches at various energies
- Test the SM with precision, low(er) energies: Flavor Physics, Electroweak tests
- Precision Tests of the Higgs Sector: Higgs Couplings to everything

$$\left.\begin{array}{c}\text{Higgs as a window to new dynamics BSM} \\ + \\ \text{Energy Frontier: at } \sqrt{s} \simeq 14\ \mathrm{TeV} \text{ for a while}\end{array}\right\} \Rightarrow \begin{array}{c}\text{Understand Higgs couplings} \\ \text{at the LHC/HL-LHC}\end{array}$$

# Higgs Couplings and New Physics

## Effective Field Theory approach

- New physics encoded in expansion in local HDOs

$$\mathcal{L}_{\rm SM} + \sum_{i,n>4} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

SMEFT *Brivio and Trott (2019)*

or

HEFT *Alonso, Gavela, Merlo, Rigolin, Yepes (2013)*

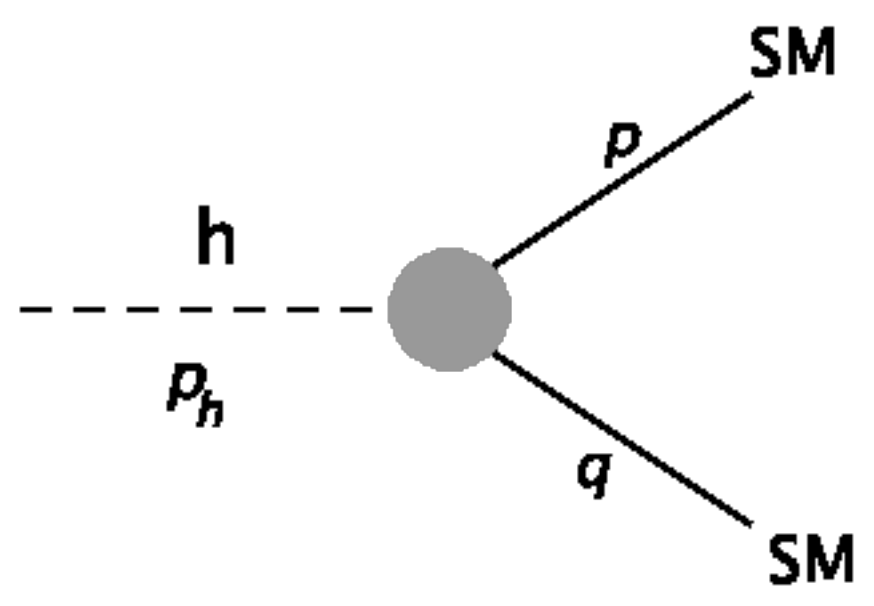
- Model Independent
- Correlated constraints from EW and Higgs data
- Are dim-6 operators enough ? Do we need dim-8 in some cases ?
- Reconstruction of non-local effects

  Are dim-6 enough to be as sensitive to them as the HL-LHC data ?

# Momentum Dependence in Higgs Couplings

## Higgs as a window to BSM physics

New physics can generate momentum dependence in couplings




Requires off shell momentum

$\Rightarrow$ Form factor in Higgs couplings $\Bigg\{$

*Isidori, Trott (2014)*

*Bellazzini, Csaki, et al. (2016)*

*Gonçalves, Han, Mukhopadhyay (2018)*

Is the EFT approach ideal to deal with momentum dependence effects ?

*Englert, Soreq, Spannowsky (2014)*

*Azatov, Grojean, Paul, Salvioni (2014)*

# Form Factors in Higgs Couplings from BSM

## Model dependent approach

Compute the Higgs form factors in a specific model → full momentum dependence

Matching with EFT may require operators of dim > 6 to capture full non-local features

**Loose** generality, **Gain** in power of data to constrain specific BSM not directly accessible

“Scan" over models so as to cover all signals : where is the momentum dependence coming from ?

- Higgs line
- Gauge boson line
- Fermion line

# Form Factors in Higgs Couplings from BSM

## General features of Higgs Form Factors

In general, Higgs coupling to SM particle X in an extension of the SM

$$c_{h,X}(q,p) = c_{h,X}^{\mathrm{SM}}\,\kappa_X\,F(q,p)$$

with $F(0,m_X) = 1$ couplings defined at zero momentum

But on shell modification can always be reabsorbed in $\kappa'_X = \kappa_X\,F(m_h,p)$

$\Longrightarrow$ Need off shell Higgs or X to observe momentum dependence

# Form Factors in Higgs Couplings from BSM

<u>Three Examples</u>

- A Composite Higgs Model

  Fermion and Vector resonances

- Mixing of Higgs with a heavier scalar

  Scalar resonance

- Mixing with an unparticle scalar sector

  No resonances

# Composite Higgs Models

*Agashe, Contino, Pomarol (2005)*

Higgs is a pseudo-Goldstone boson $G \to H$ Coset $G/H$ at scale $f$

Spectrum

$$\mathcal{L} = \mathcal{L}_{\rm ES} + \mathcal{L}_{\rm CS} + \mathcal{L}_{\rm int.}$$

Elementary Sector: SM fermions and gauge bosons

Composite Sector: Resonances and the pNGBs, including Higgs

Higgs couplings to SM from $\mathcal{L}_{\rm int.}$

Integrating out resonances ⟶ form factors

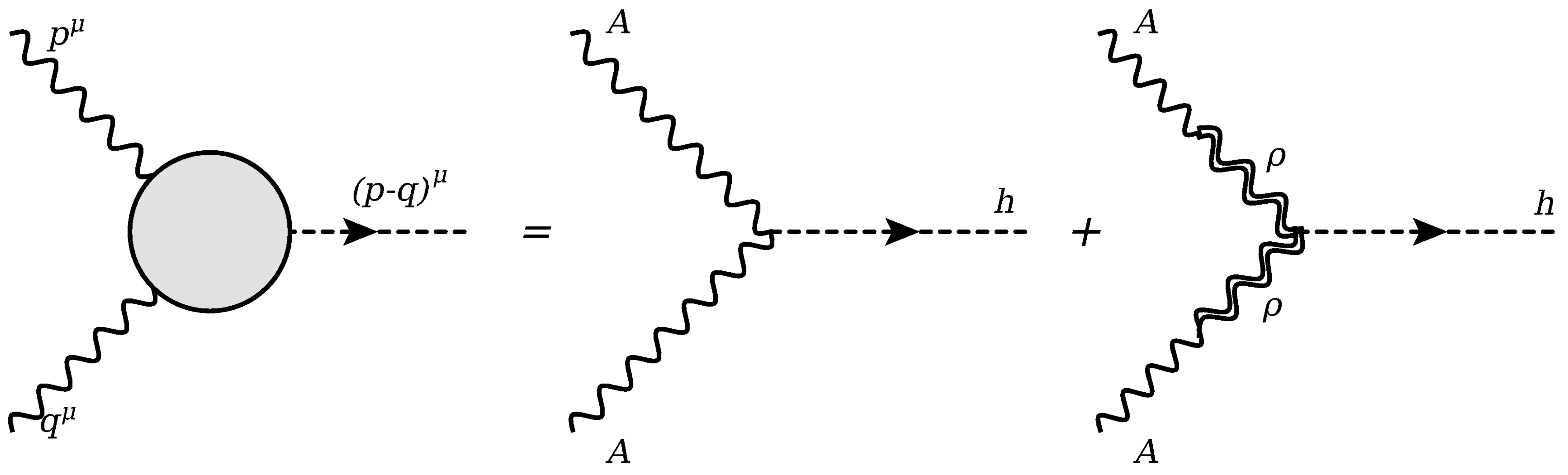
# Composite Higgs Models: MCHM $SO(5)/SO(4)$

<u>Vector Resonances</u> $SO(4) \sim SU(2)_L \times SU(2)_R$

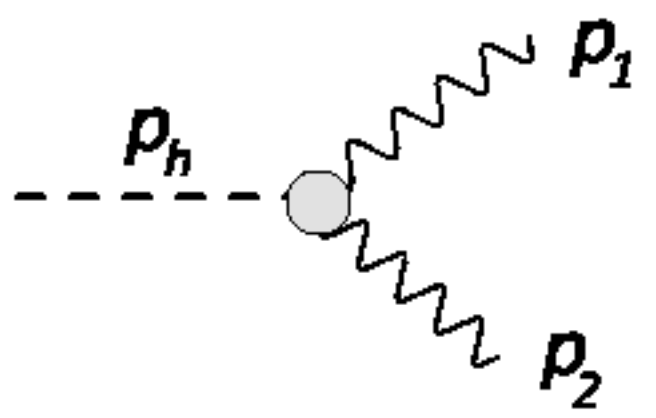
Kinetic Mixing

$$\mathcal{L}^V_{\text{int.}} = \frac{1}{2}\frac{g}{g_\rho} W^{a_L}_{\mu\nu} \rho^{a_L,\mu\nu} + \frac{1}{2}\frac{g'}{g_\rho} B_{\mu\nu} \rho^{3_R,\mu\nu}$$

(equivalent to mass mixing)



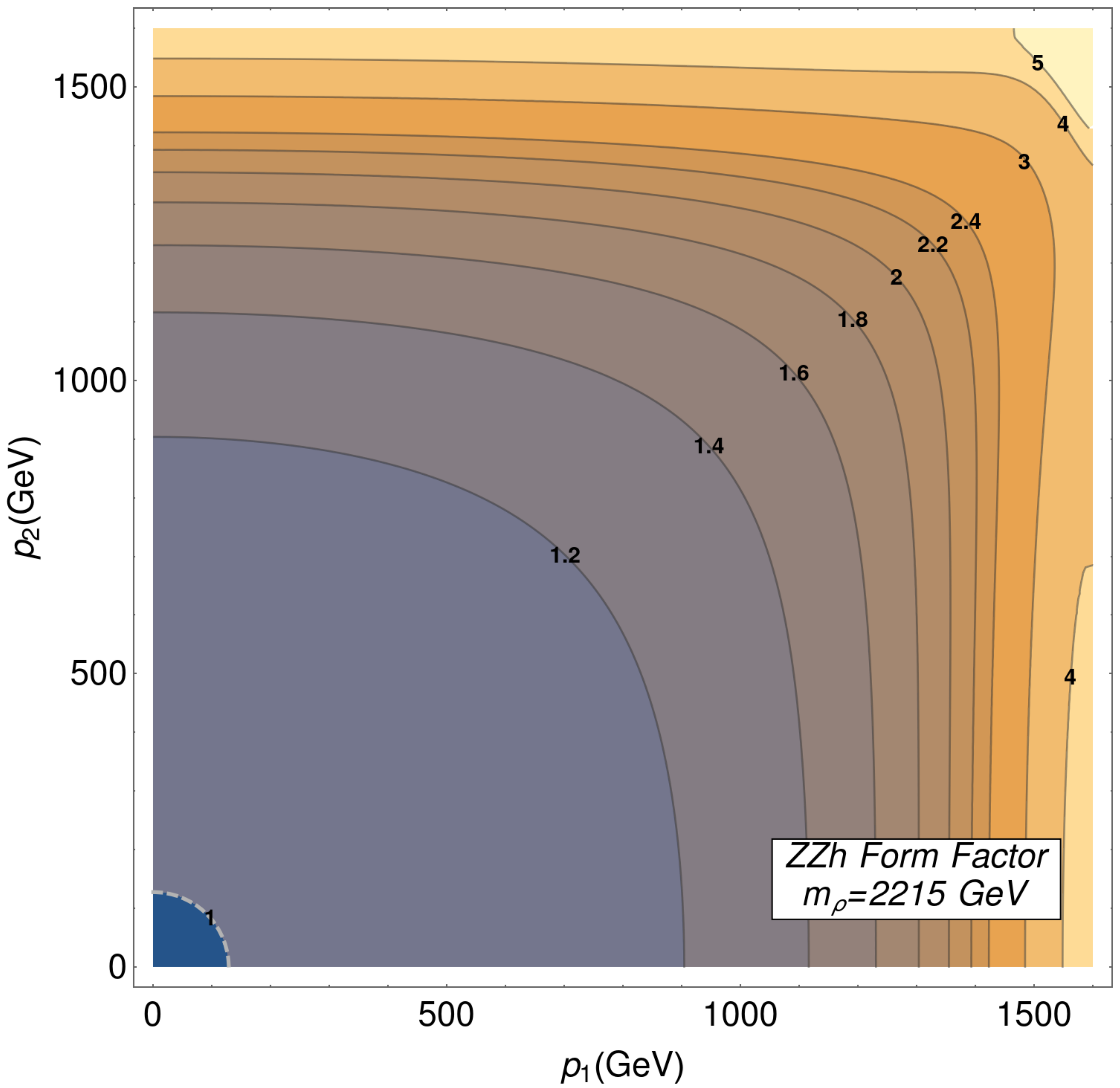
# Gauge Form Factor in  MCHM

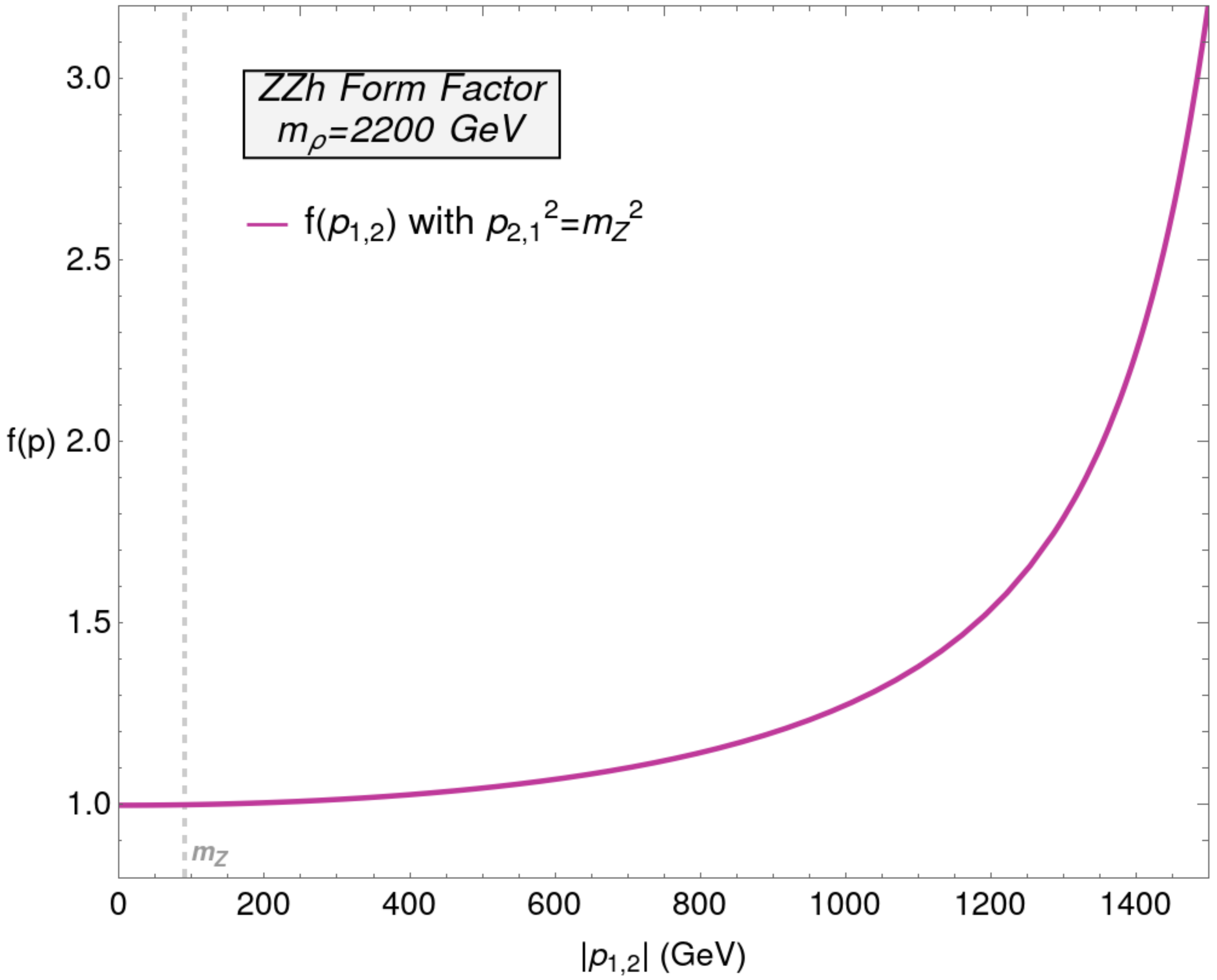



$$= g_V\, M_V\, \kappa_\xi\, f_{VVh}(p_1, p_2)$$

$$\kappa_\xi = \sqrt{1 - v^2/f^2} = \sqrt{1-\xi}$$

$$f_{VVh}(M_V^2, M_V^2) = 1$$



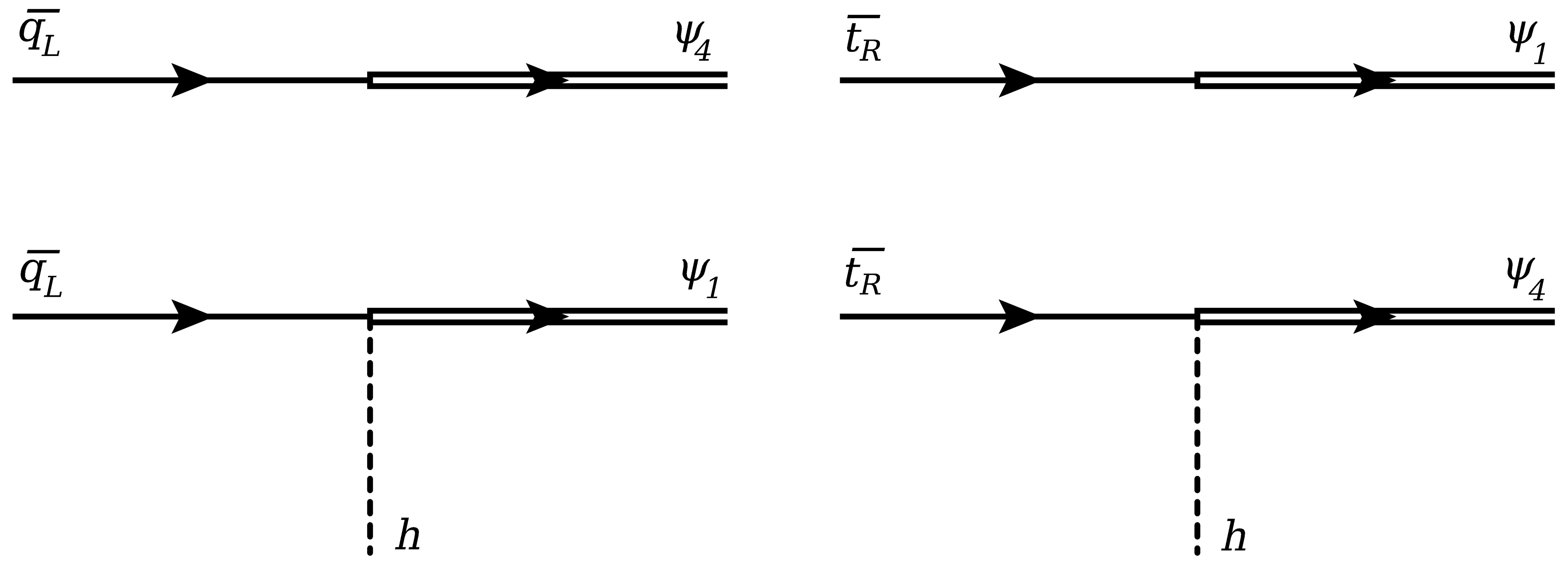
# Fermion Form Factor in MCHM

Fermions   Embed in incomplete **5** of SO(5) ⟶ $MCHM_{\mathbf{5}}$

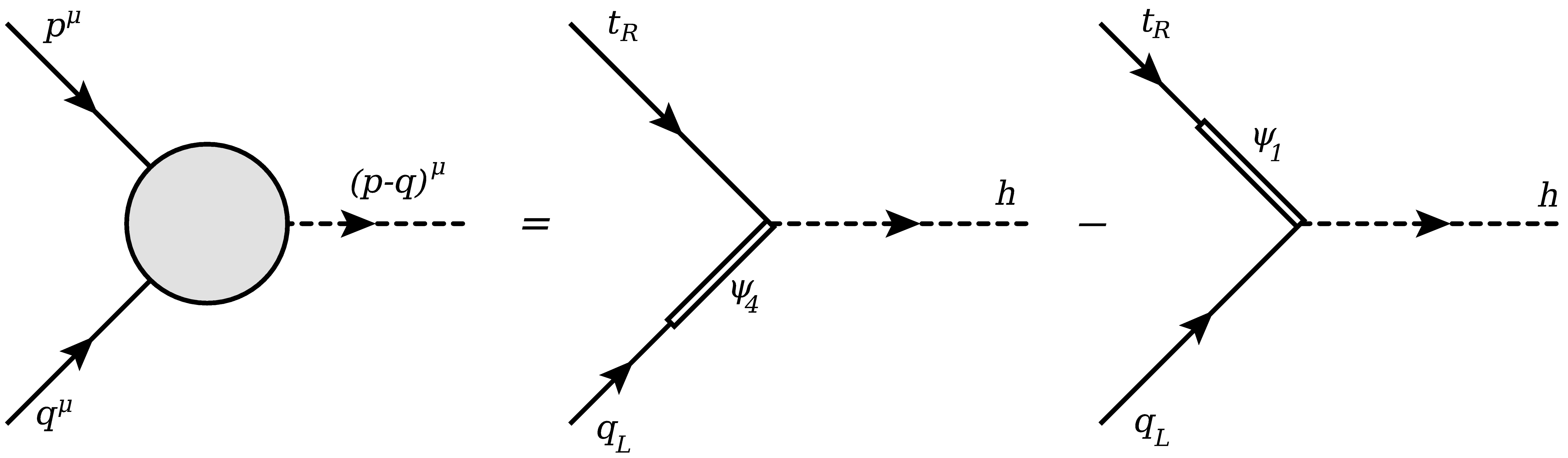
$$q_L^{\mathbf{5}} = \begin{pmatrix} -ib_l \\ -b_l \\ -it_l \\ t_l \\ 0 \end{pmatrix} \qquad t_r^{\mathbf{5}} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_r \end{pmatrix} \qquad b_r^{\mathbf{5}} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_r \end{pmatrix}.$$

Fermion Resonances   **4** and **1** of SO(4)

Partial Compositeness   *Elementary fermions couple linearly to composite operators*

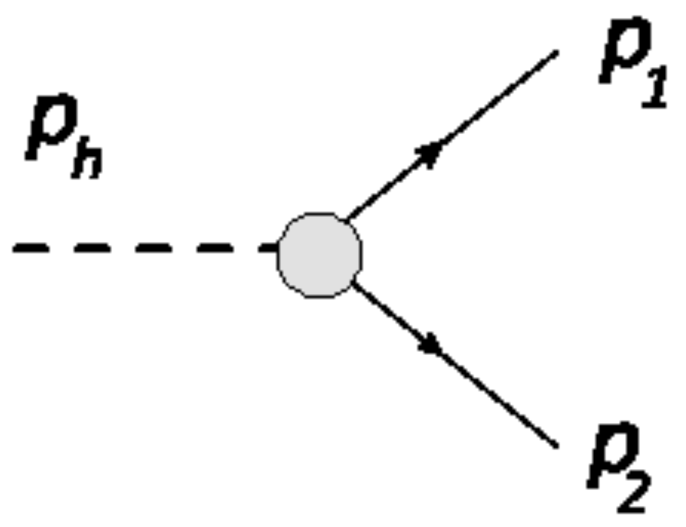


# Fermion Form Factor in MCHM




Integrating out fermion resonances $\Longrightarrow$ Momentum dependence in $\bar{t}th$ coupling

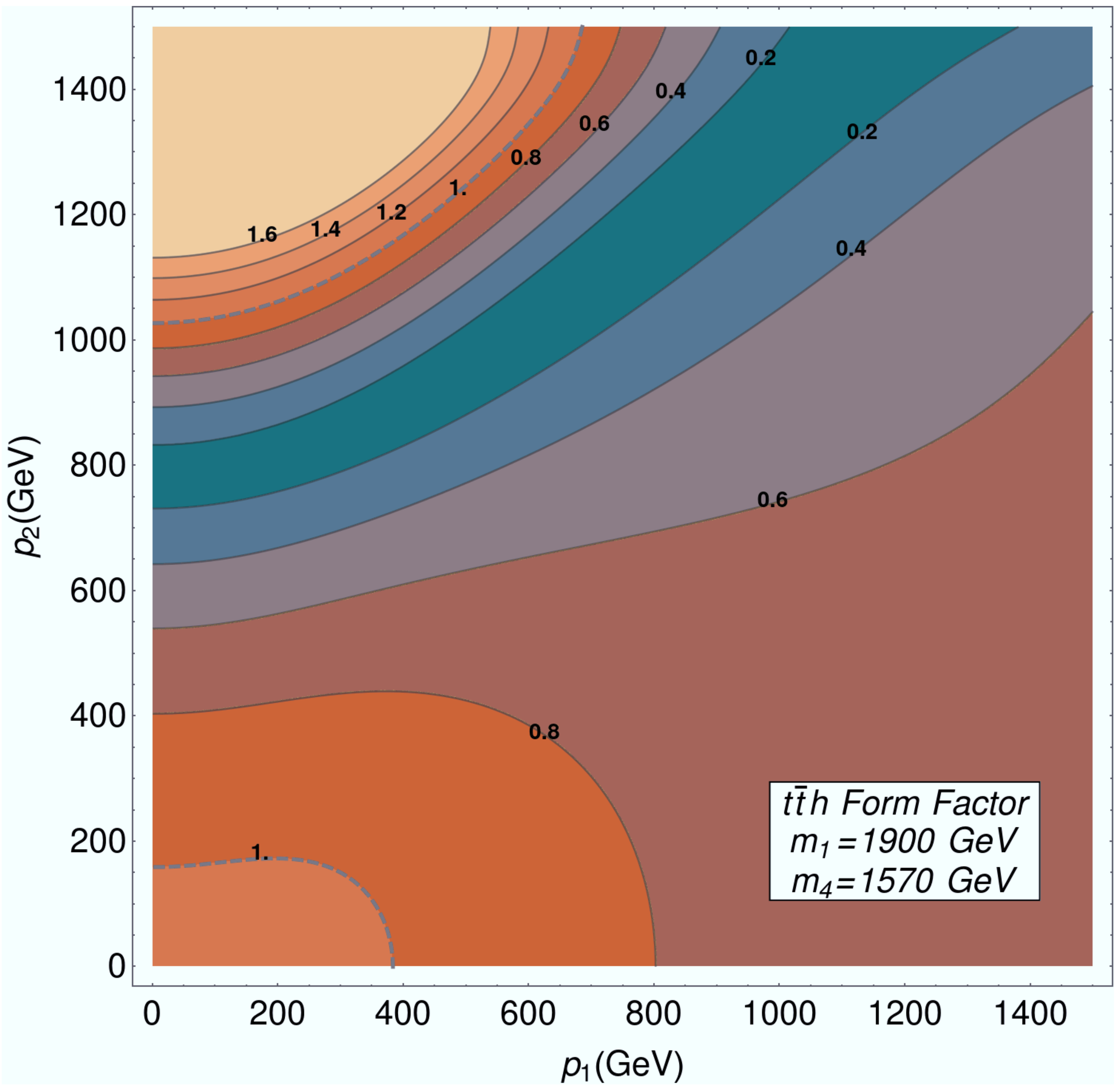
# Fermion Form Factor in MCHM

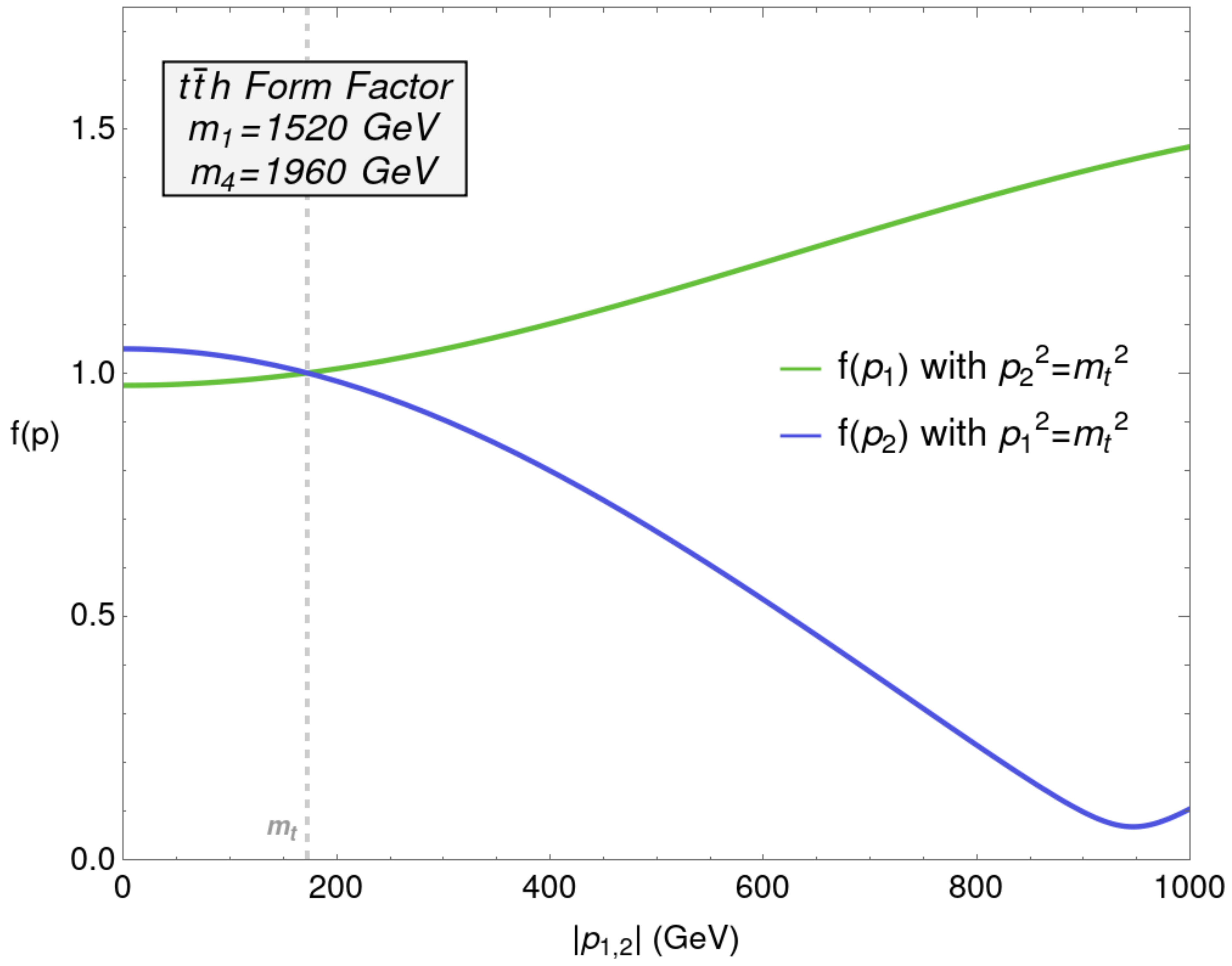



$$= y_t\ \kappa_\xi^{\mathbf{5}}\ f_{\bar{t}th}(p_1, p_2)$$

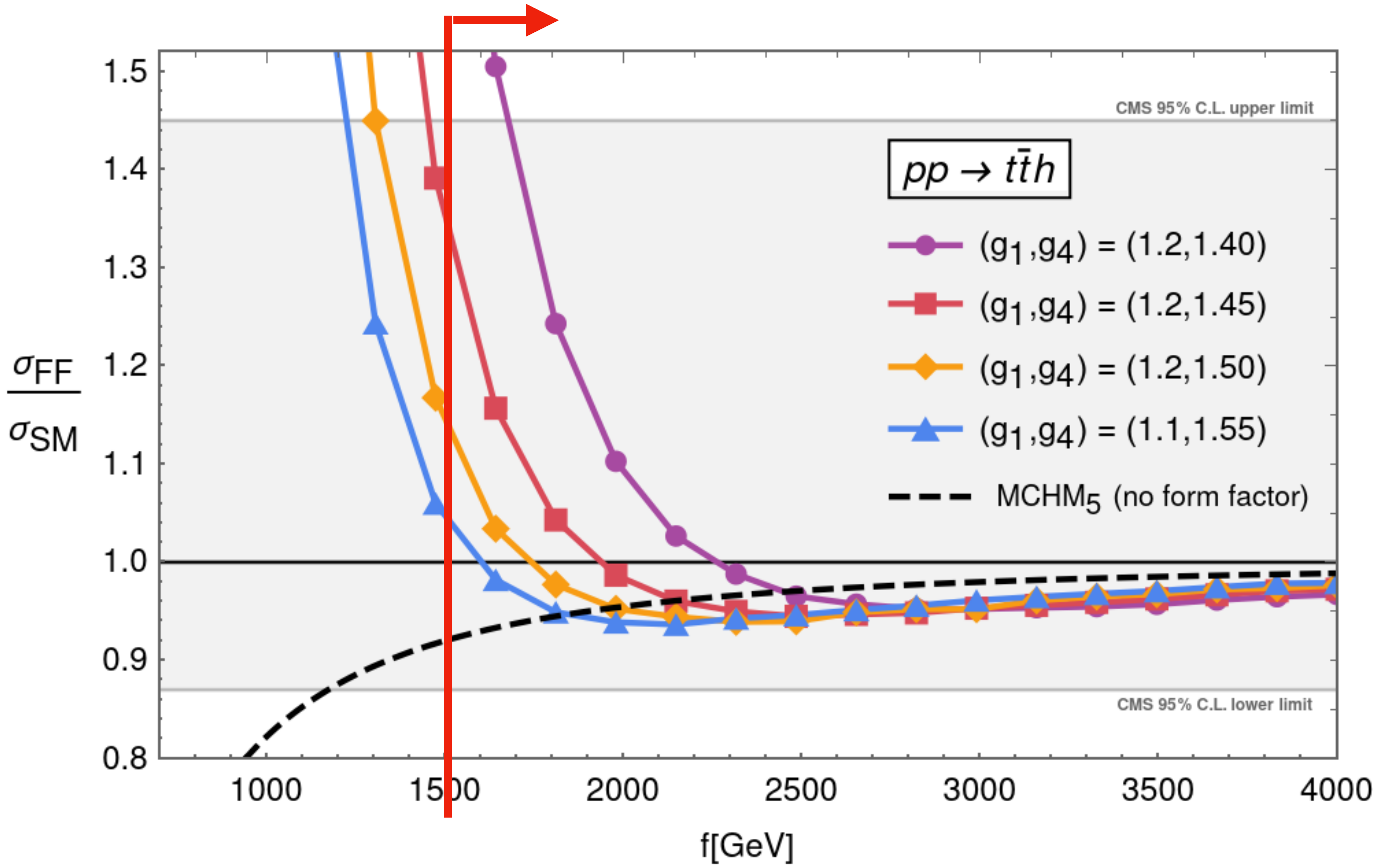
$$\kappa_\xi^{\mathbf{5}} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

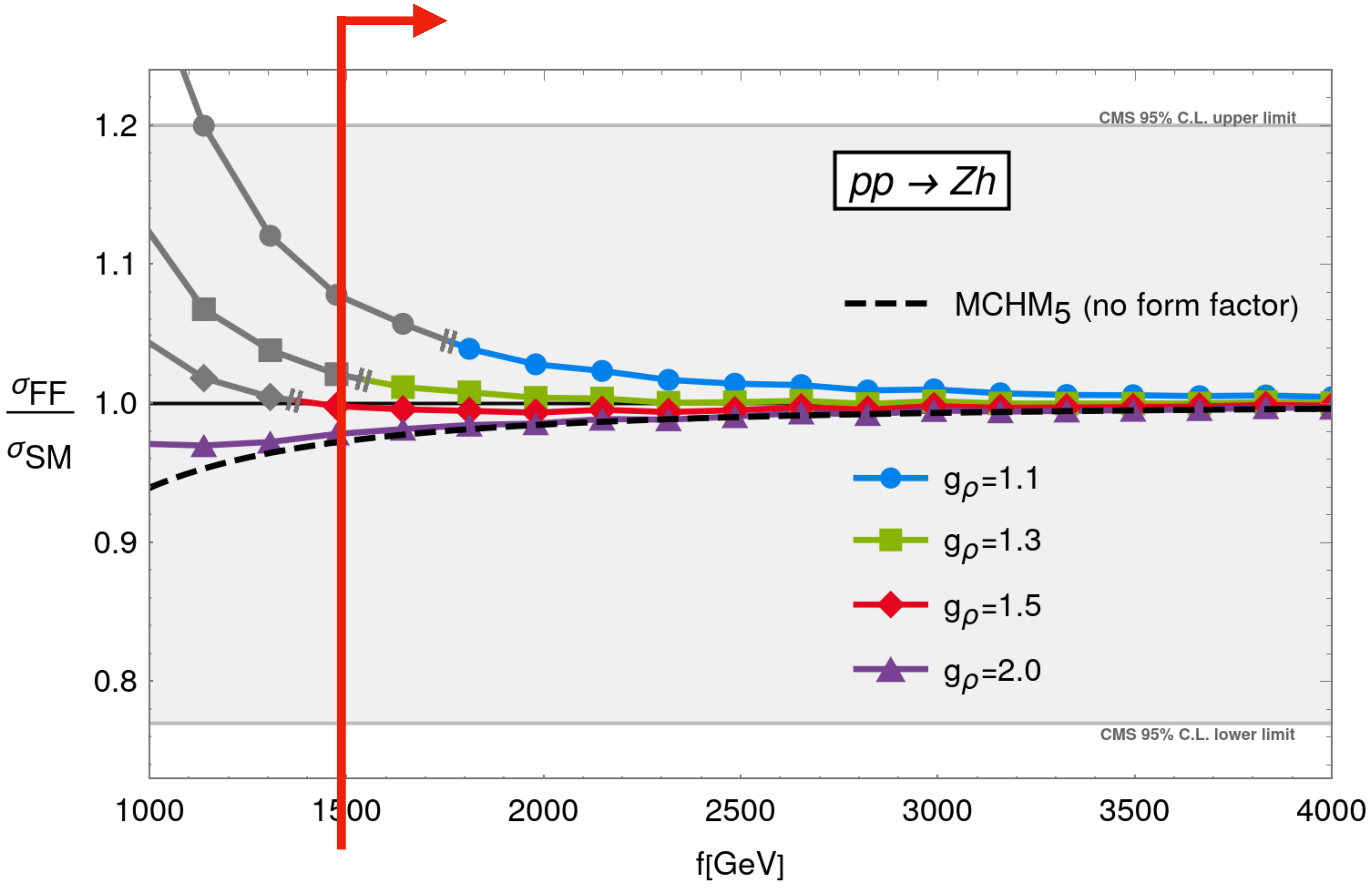
$$f_{\bar{t}th}(m_t^2, m_t^2) = 1$$



# Effects in MCHM

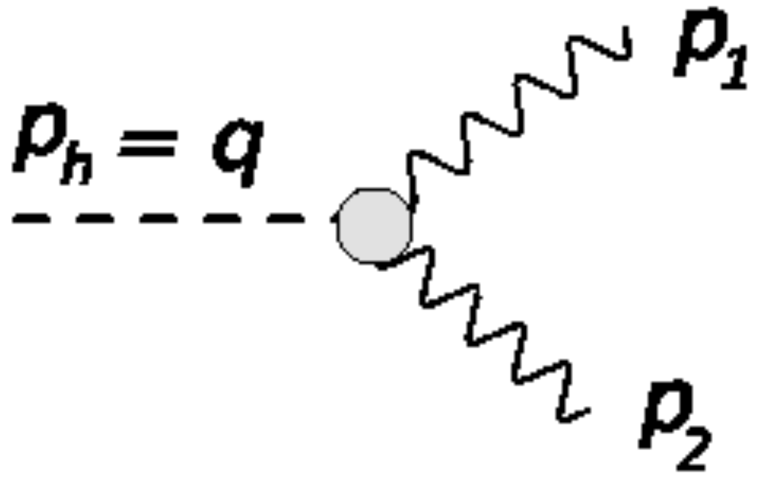


# Mixing with a Scalar

Additional Scalar Doublet *Hill, Machado, Thomsen, Turner (2019)*

$$\mathcal{L} = |D_\mu H_a|^2 + |D_\mu H_b|^2 - M_a^2 H_a^\dagger H_a - M_b^2 H_b^\dagger H_b - \mu^2 (H_a^\dagger H_b + h.c.) - \frac{\lambda}{2}(H_a^\dagger H_a + H_b^\dagger H_b)^2 + \lambda' (H_a^\dagger H_b H_b^\dagger H_a)$$




$$\Rightarrow \quad f_{hVV}(q^2) = \frac{2M_V^2}{v}\left(1 - \frac{\mu^4}{M_b^4}\frac{q^2}{q^2 - M_b^2}\right)$$

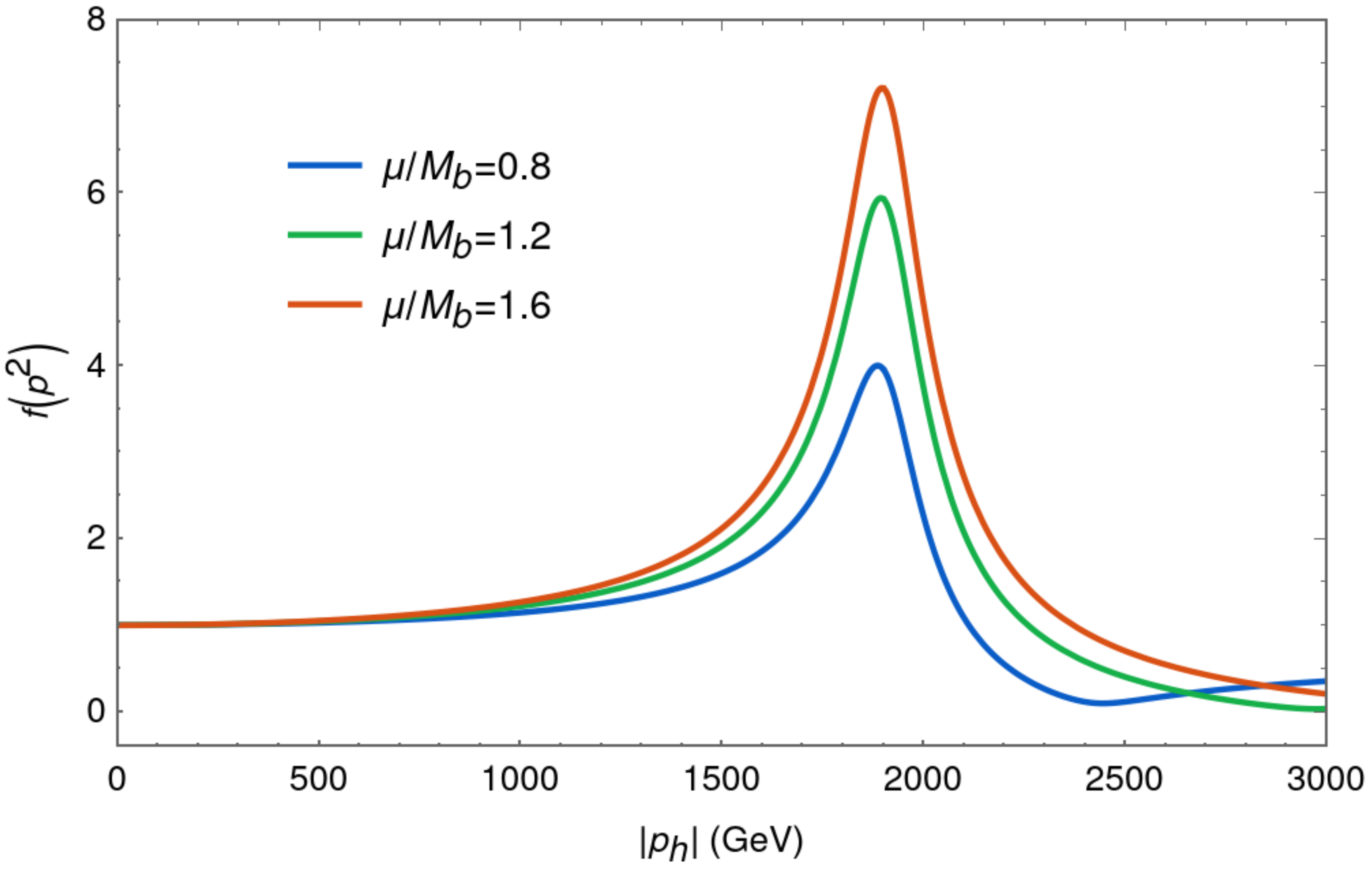
Note: on shell deviation

$$f_{hVV}(m_h^2) = \frac{2M_V^2}{v}(1 + c_b \xi)$$

$$\begin{cases} \xi = \dfrac{v^2}{M_b^2} \\ c_b = 2\lambda \dfrac{\mu^4}{M_b^4} \end{cases}$$

# Mixing with a Scalar

$M_b = 2$ TeV



# Mixing with an Unparticle Scalar Sector

Scalar unparticle operator $\phi(x)$ of dimension $d$ $\quad 1 < d < 2$

*Fox, Rajaraman, Shirman (2007)*

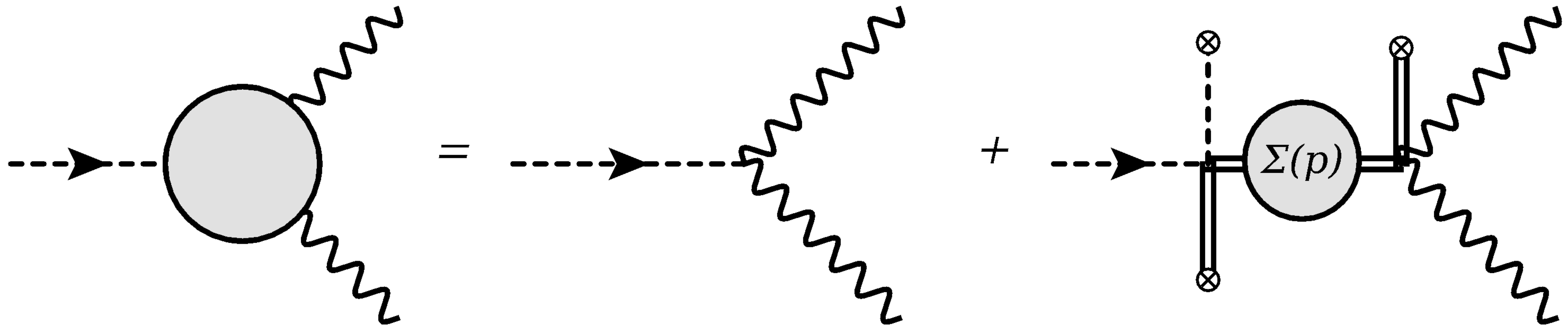
*Cacciapaglia, Marandella, Terning (2008)*

2-point function with IR cutoff $\mu$

$$\Delta(p,\mu,d) = \int d^4x \langle 0|\mathcal{T}\phi(x)\phi^\dagger(0)|0\rangle = \frac{A_d}{2\pi}\int_{\mu^2}^{\infty} ds(s-\mu^2)^{d-2}\frac{i}{p^2-s+i\epsilon},$$

Non-local action

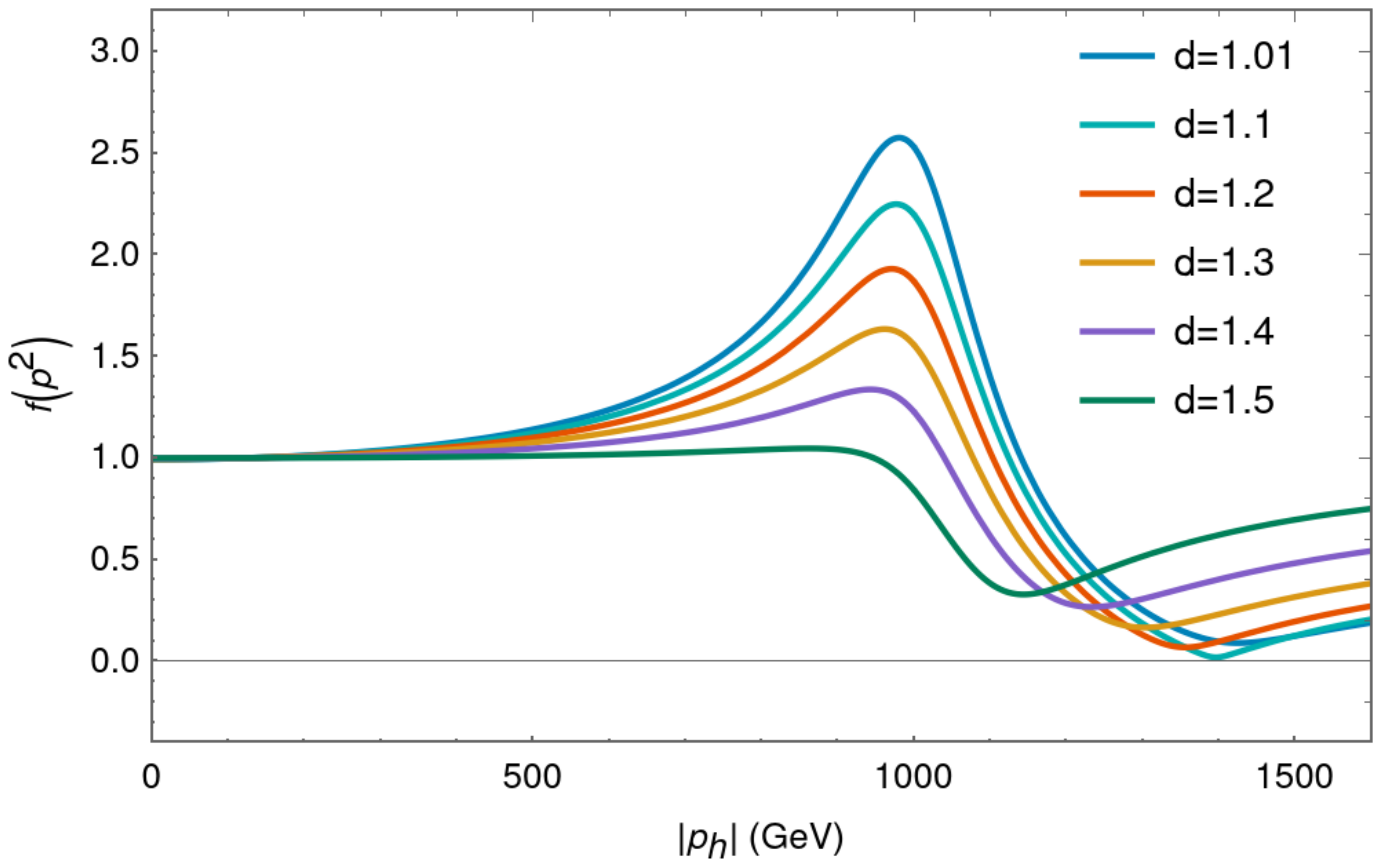
$$S_{\rm NL} = \int d^4x \left\{ \phi^\dagger(D^2-\mu^2)^{2-d}\phi + \alpha|H|^2\frac{|\phi|^2}{\Lambda^{2(d-1)}} \right\}$$

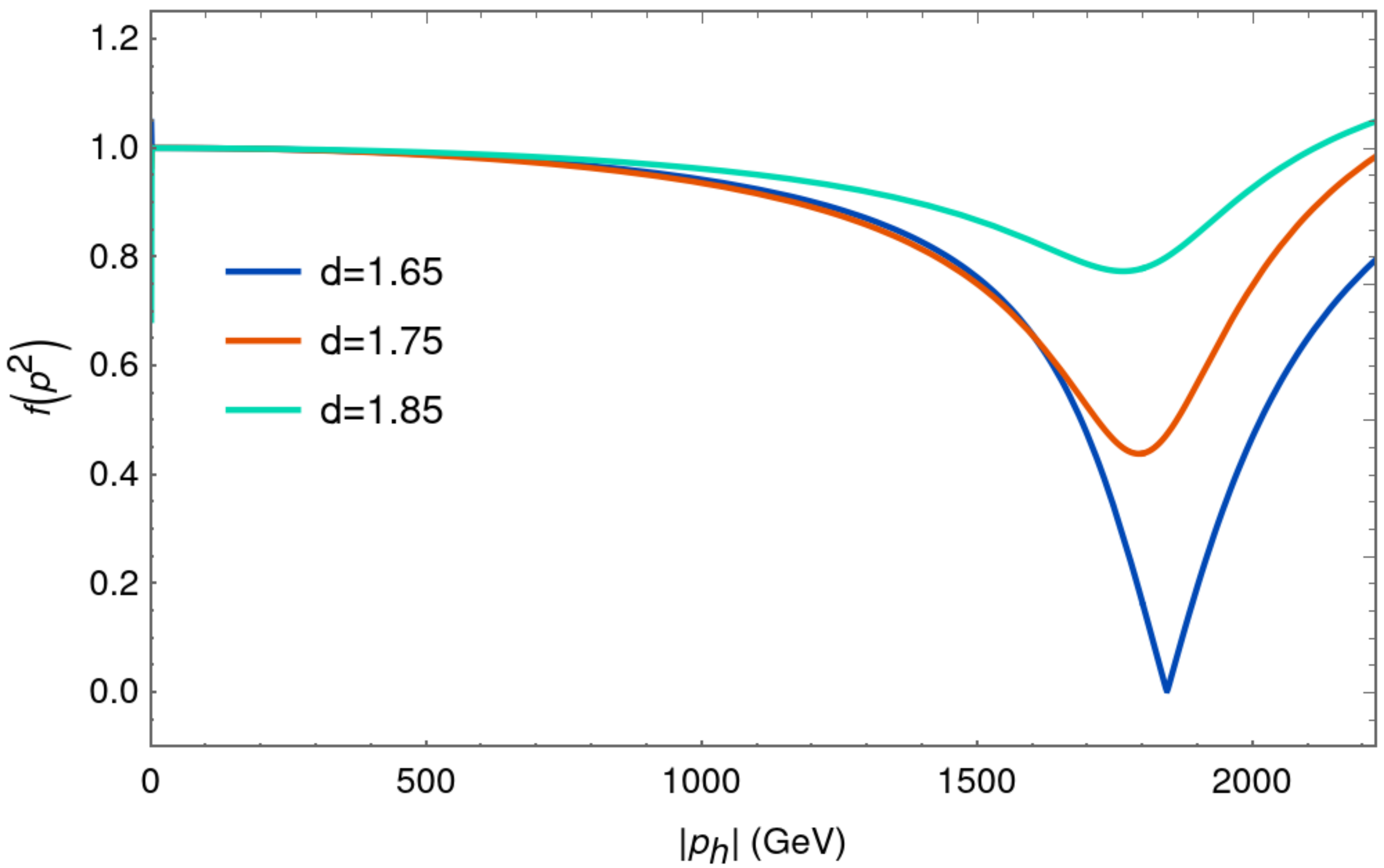


# Form Factor from an Unparticle Scalar Sector

Results for $f_{hVV}(q^2)$ with off shell Higgs, on shell gauge bosons

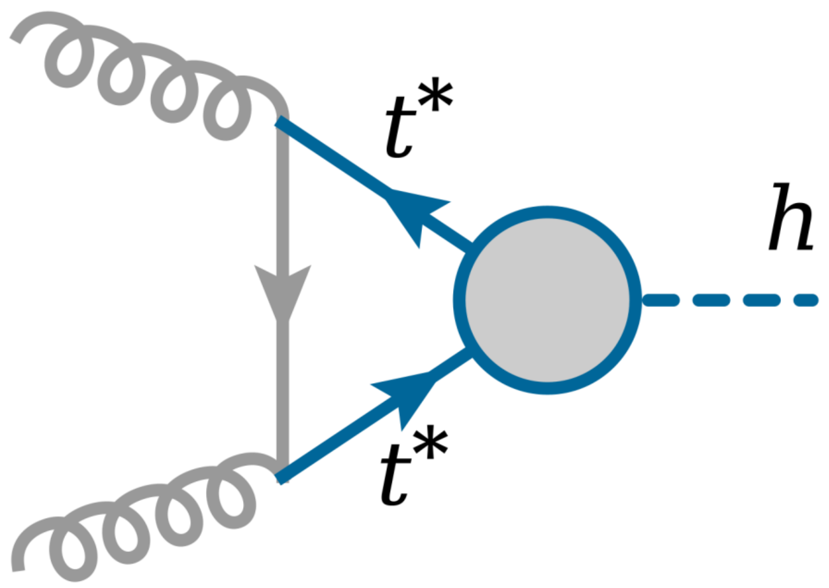
$\mu = 1\ \text{TeV}$



# Constraints from Higgs Production

If top line affected




bounds on form factor scale from $gg \to h \to \gamma\gamma,\ ZZ^*,\ WW^*$

Current ATLAS/CMS data compatible with $M > 1.5\ \mathrm{TeV}$ for generic form factor

MCHM$_5$: $f > 1.5\ \mathrm{TeV}$ if only top coupling affected

But need to perform full study including gauge boson form factor (may relax bound a bit)

# Signals

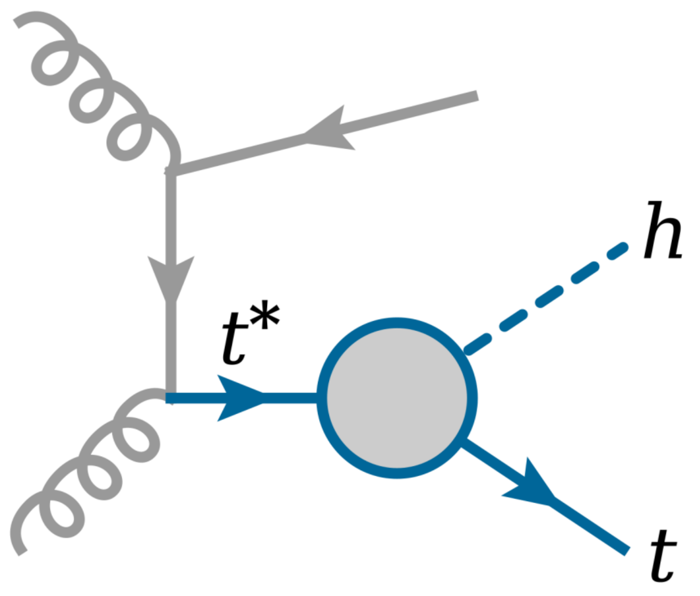
Sensitivity of channels to different sources of momentum dependence

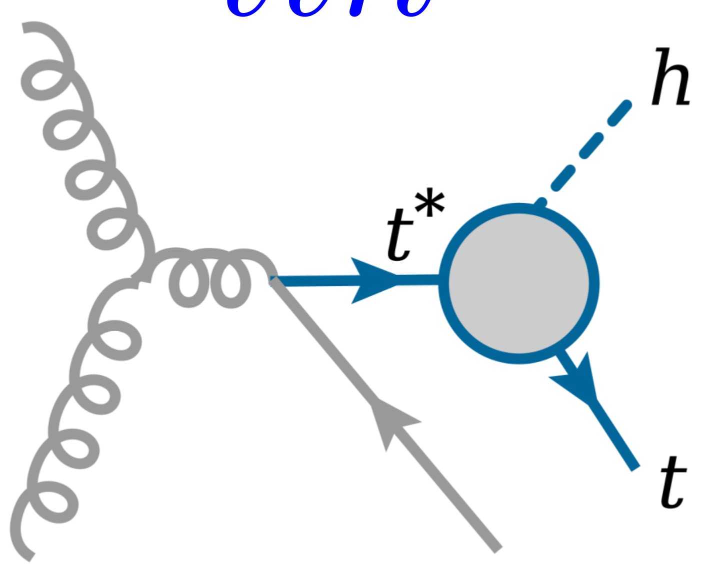
1. Momentum dependence in gauge boson or fermion lines coupled to Higgs

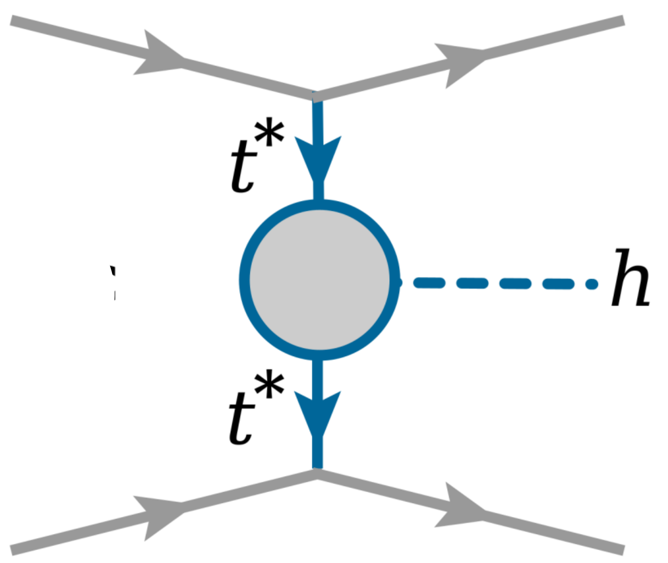
 - Example: CHMs. Vector and Fermion resonances

 - Channels:

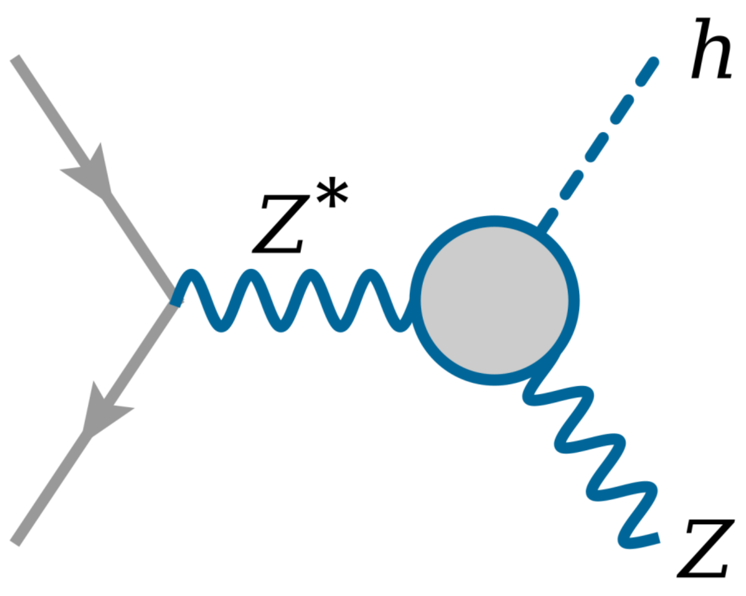
$\bar{t}th$



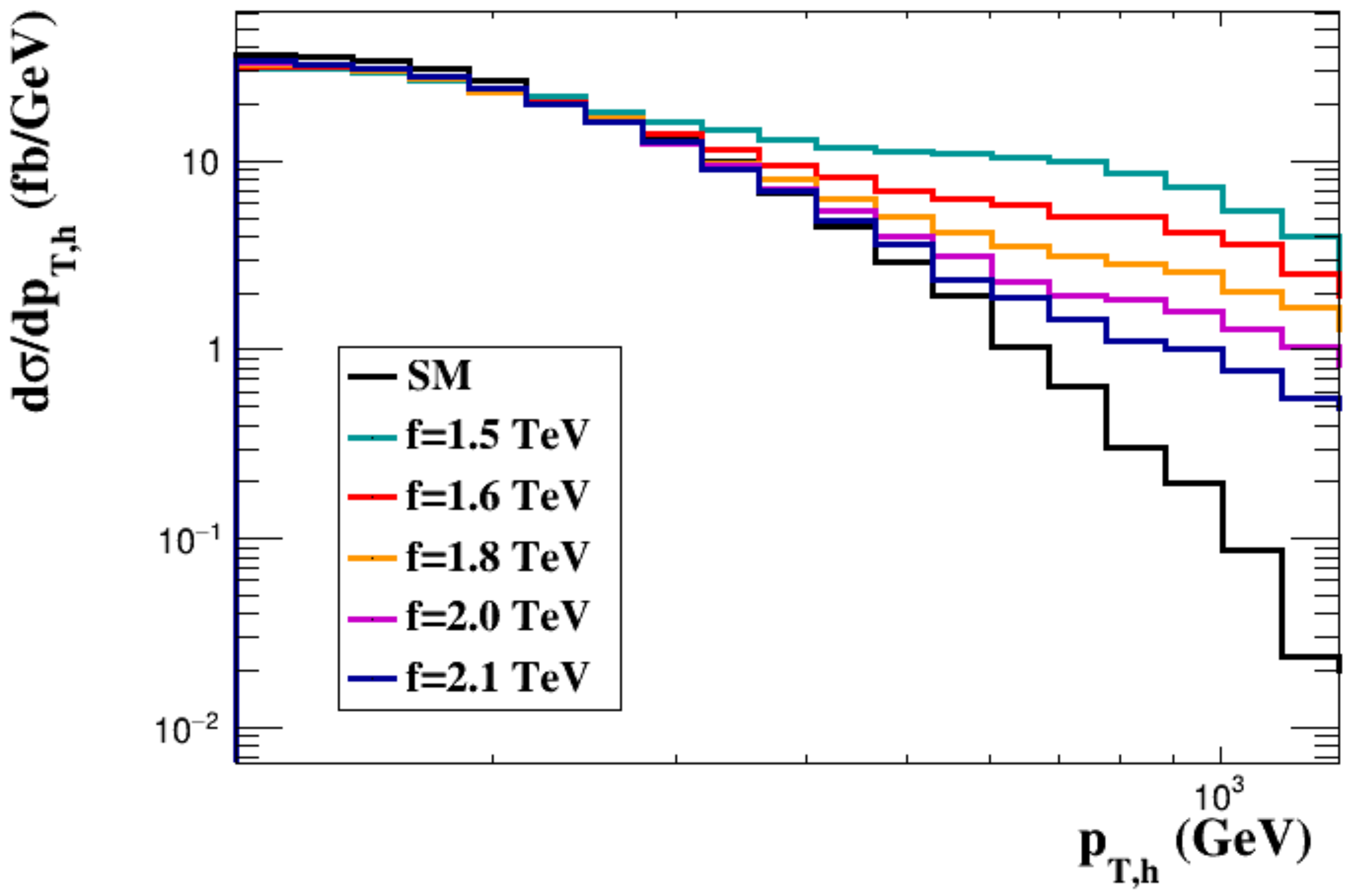




$V^* V h$ E.g.



# Signals

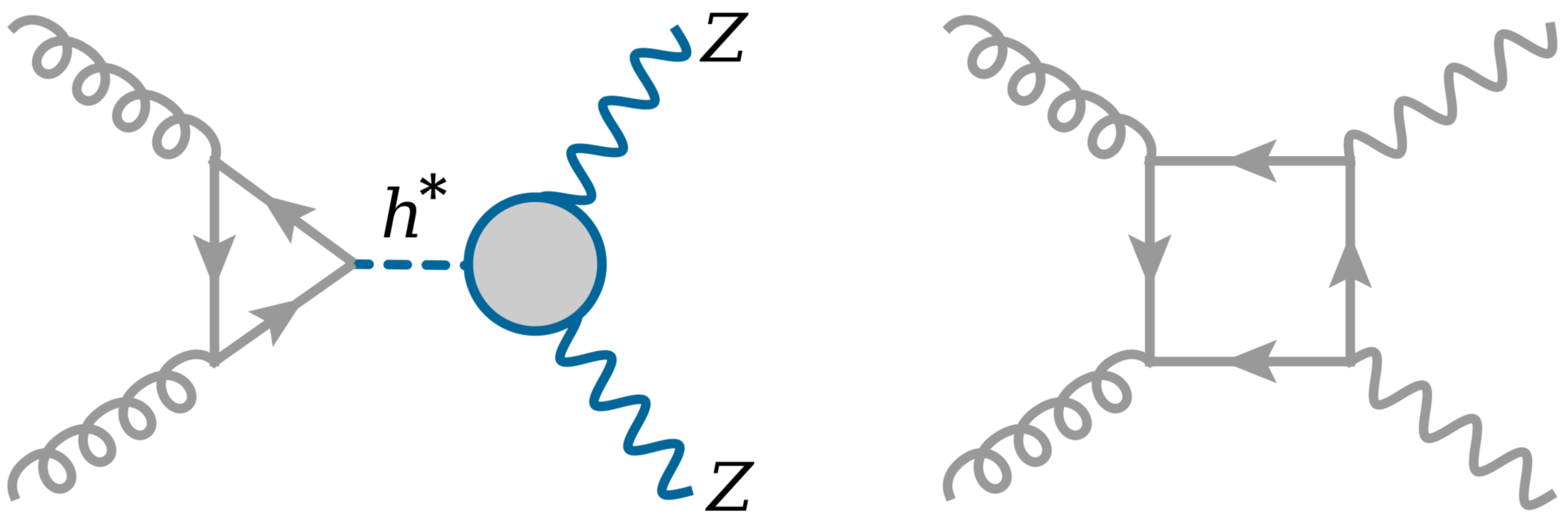
E.g. $\bar{t}th$ in MCHM$_5$



# Signals

2. Momentum dependence in Higgs line

E.g. $pp \to h^* \to 4\ell$

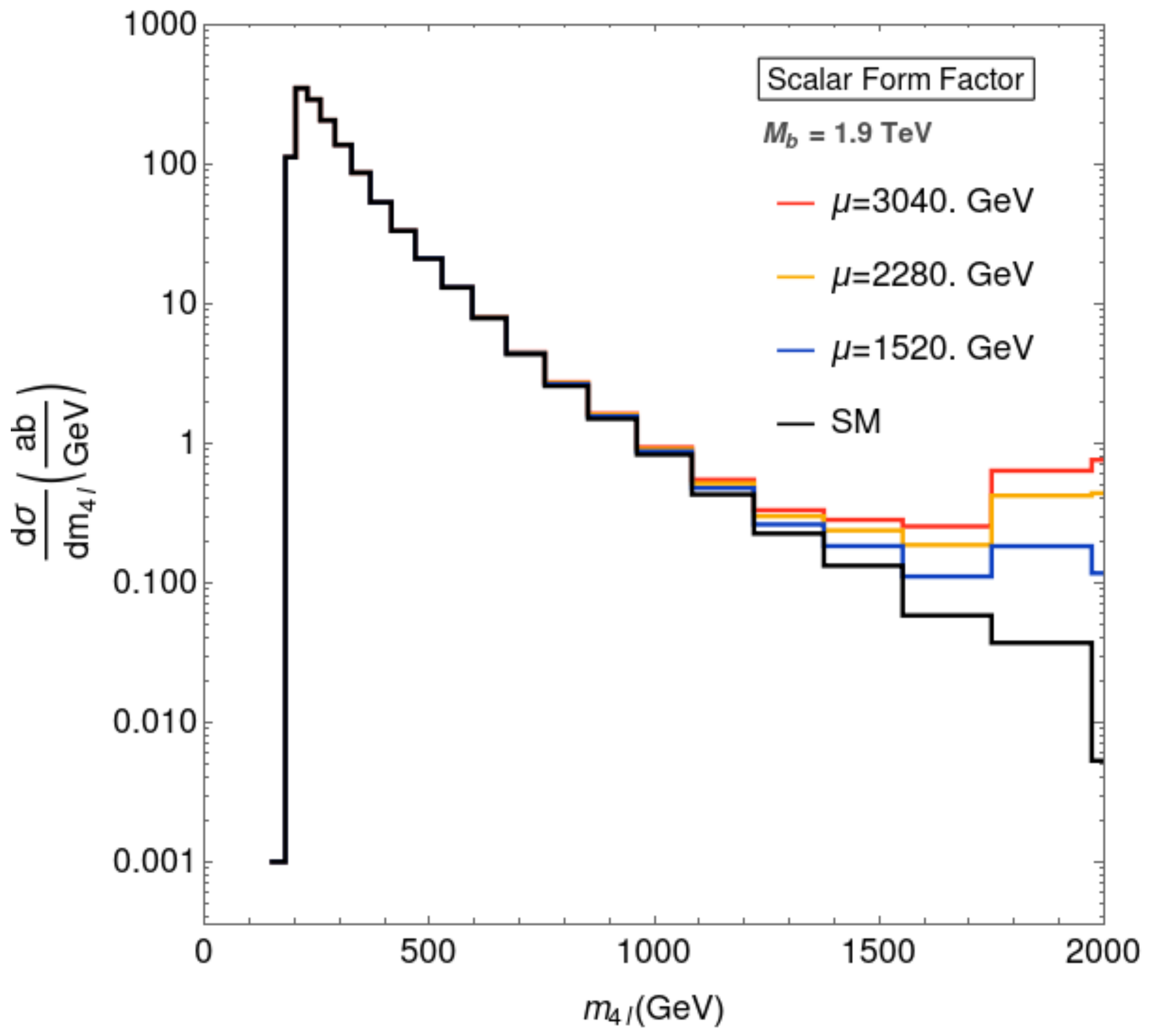



Note: Destructive interference in SM

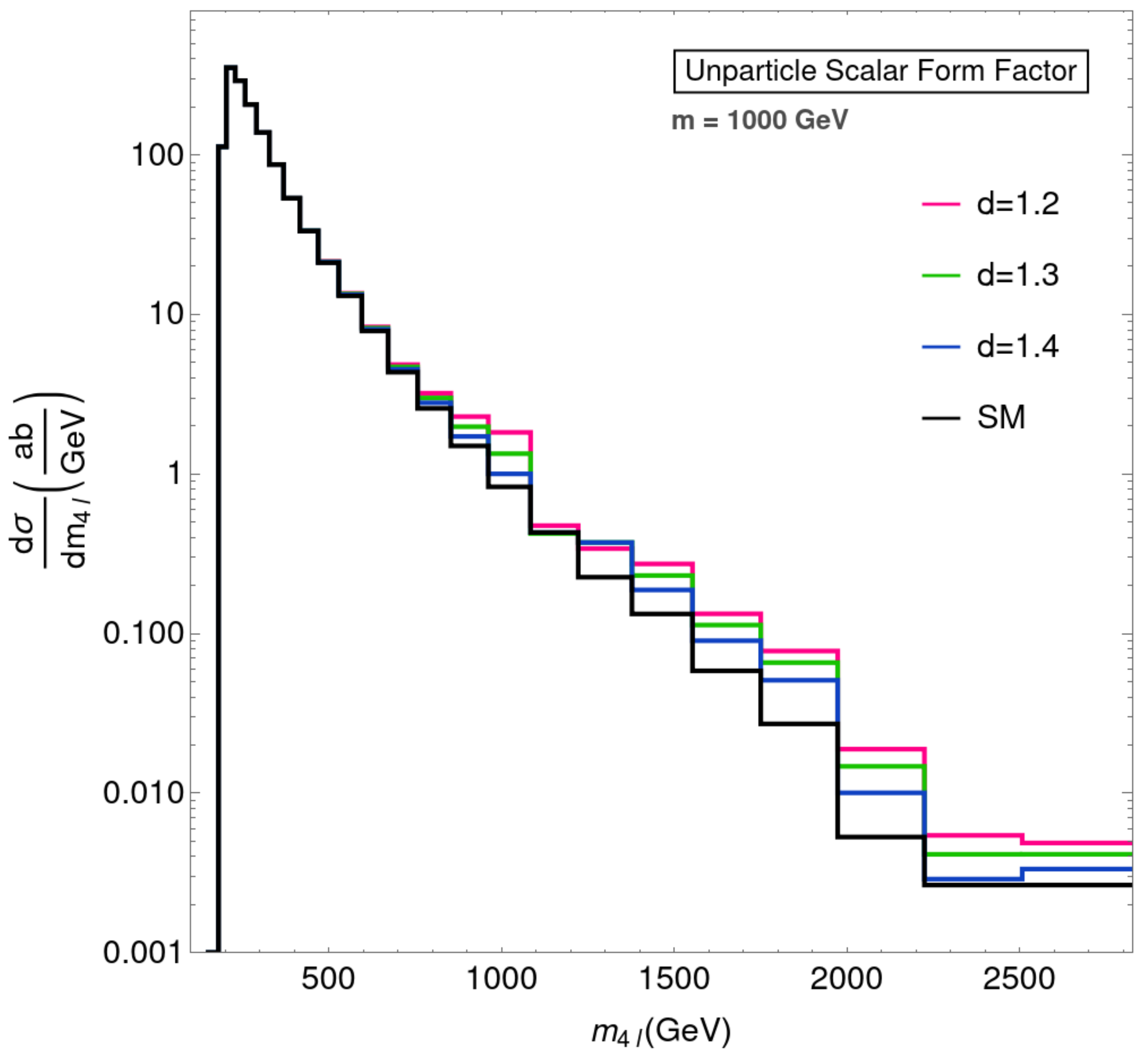
# Signals

In $pp \to h^* \to 4\ell$

## Scalar




## Unparticle Scalar

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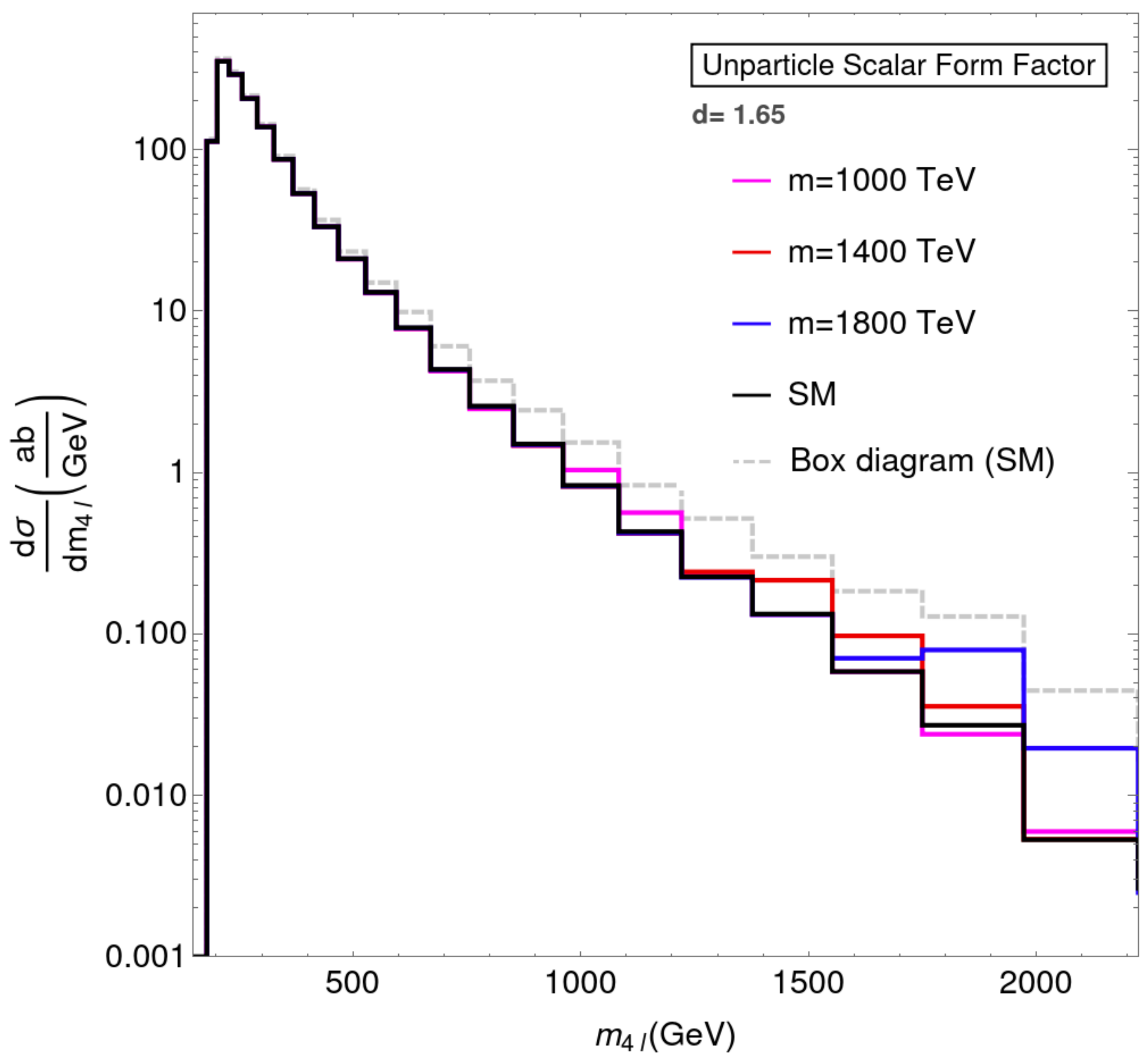


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# Conclusions

- Sensitivity to momentum dependence in Higgs couplings important to test SM at the (HL-)LHC

- Study feasibility of channels with (significantly) off shell Higgs couplings

- Complementary Strategies:

Model-independent EFT approach: more general

Model dependent approach: full momentum dependent known, more amenable to study/simulate signals

- To Do

    More models and their matching the the EFTs

    Explore space-like off shell regions: Signals ?