Form Factor Effects in Higgs Couplings

Pedro Bittar and Gustavo Burdman
University of São Paulo

May 24-26, 2021
PHENO 2021

BSM Momentum Dependence

- **Heavy BSM physics alters the SM Higgs couplings.**

$$\underline{\text{i.e.}}\ \text{CHMs with } \xi = \frac{v^2}{f^2},\ \text{2HDM with } \tan\tilde{\alpha} \simeq \mathcal{O}\left(\frac{v^2}{M_\pm^2}\right), \dots\ .$$

$$\boxed{\text{In general an } \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \text{ effect.}}$$

- **Momentum effects assumed to decouple.**

Might not happen for high off-shell momenta.

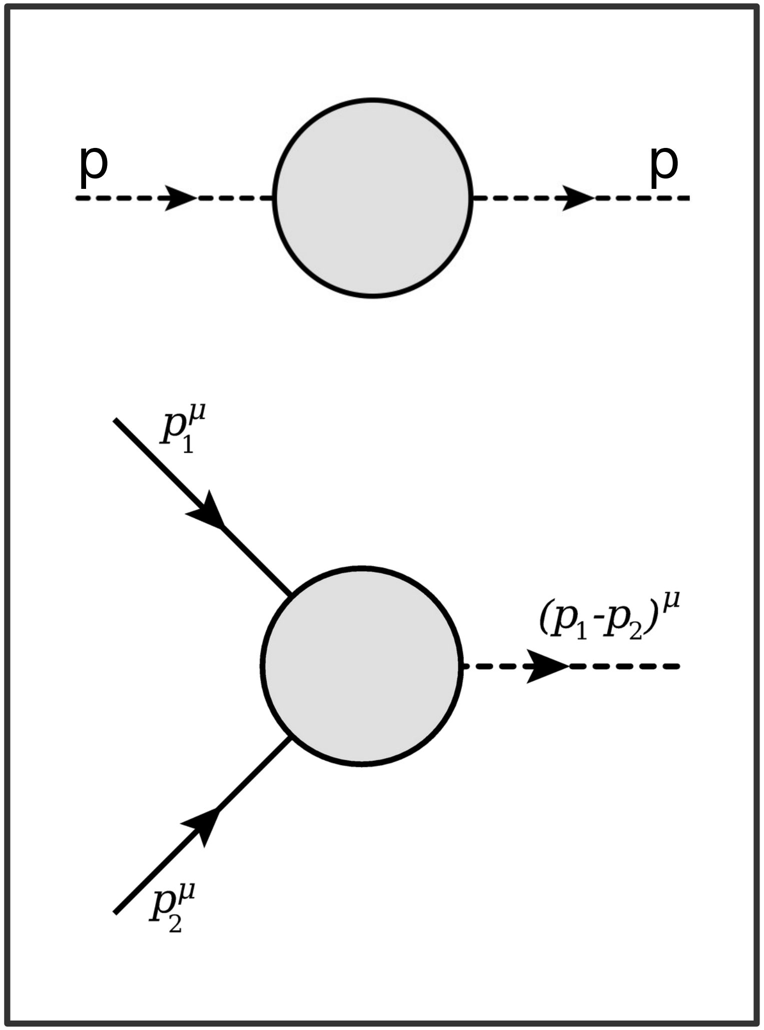
How to explore momentum dependence in a general manner?

What are the consequences of momentum dependent Higgs couplings?

We expect an enhancement of order p^2/Λ^2 over the v^2/Λ^2 coupling modification in off-shell channels.

pedro.bittar.souza@usp.br

Higgs Form Factors



- 2-point functions: Spectral decomposition.

$$\Pi(p^2) = \int_0^\infty dm^2 \, \frac{\rho(m^2)}{p^2 - m^2}$$

- 3-point functions: ?

$$\Gamma(p_1^\mu, p_2^\nu) = \Gamma(p_1^2, p_2^2, p_1 \cdot p_2)$$

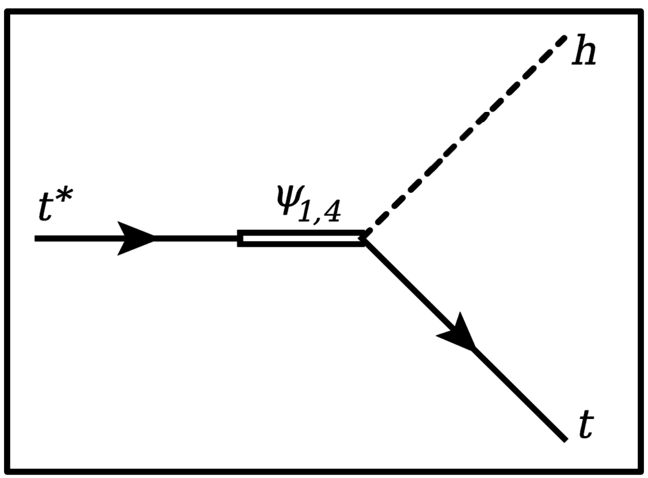
Need to assume Higgs interactions with BSM states.

Dynamical Higgs couplings

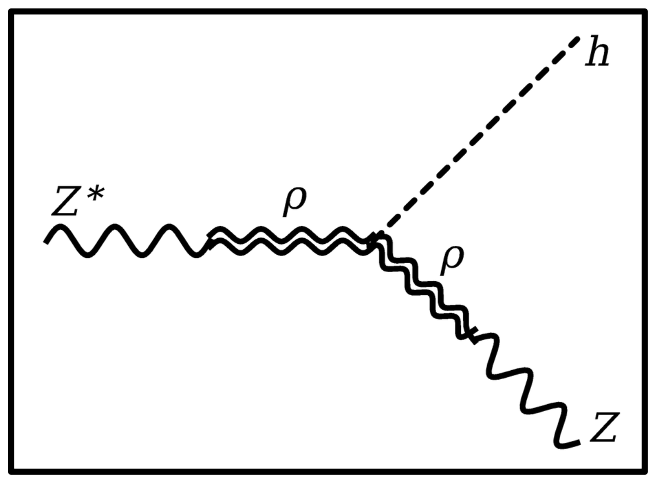
pedro.bittar.souza@usp.br

Higgs Form Factors: Examples

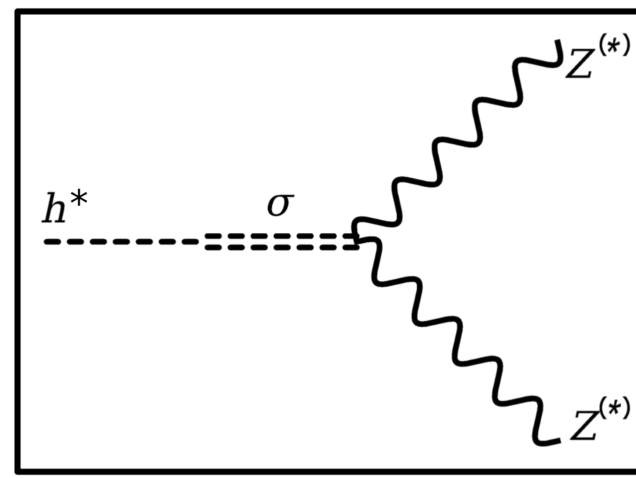
- CHMs → Partial Compositeness
- CHMs → Hidden local symmetry
- Heavy Scalars → Bilinear Couplings



➡ $t\bar{t}h$ Channel



➡ Zh Channel



➡ $h^* \rightarrow Z^{(*)}Z^{(*)}$ Channel

pedro.bittar.souza@usp.br

Higgs Form Factors: Examples

$$\mathcal{L}_{\text{FF}} = \sum_i \Gamma_i(p_1, p_2, p_h)\mathcal{L}_i^{\text{higgs}}$$

i.e. Top-Yukawa form factor:

$$\Gamma_Y(p_1, p_2, p_h)\overline{q}_L \tilde{H} t_R$$

Expect modifications to SM mass-Yukawa relation

$$M(p_t^2)\overline{q}_L t_R + \kappa_\xi \frac{y_t^{SM}}{\sqrt{2}} f(p_1^2, p_2^2, p_1 \cdot p_2)\overline{q}_L h t_R$$

→ $M(m_t^2) = m_t$ (Pole Mass)

→ $\mathcal{O}(v^2/f^2)$

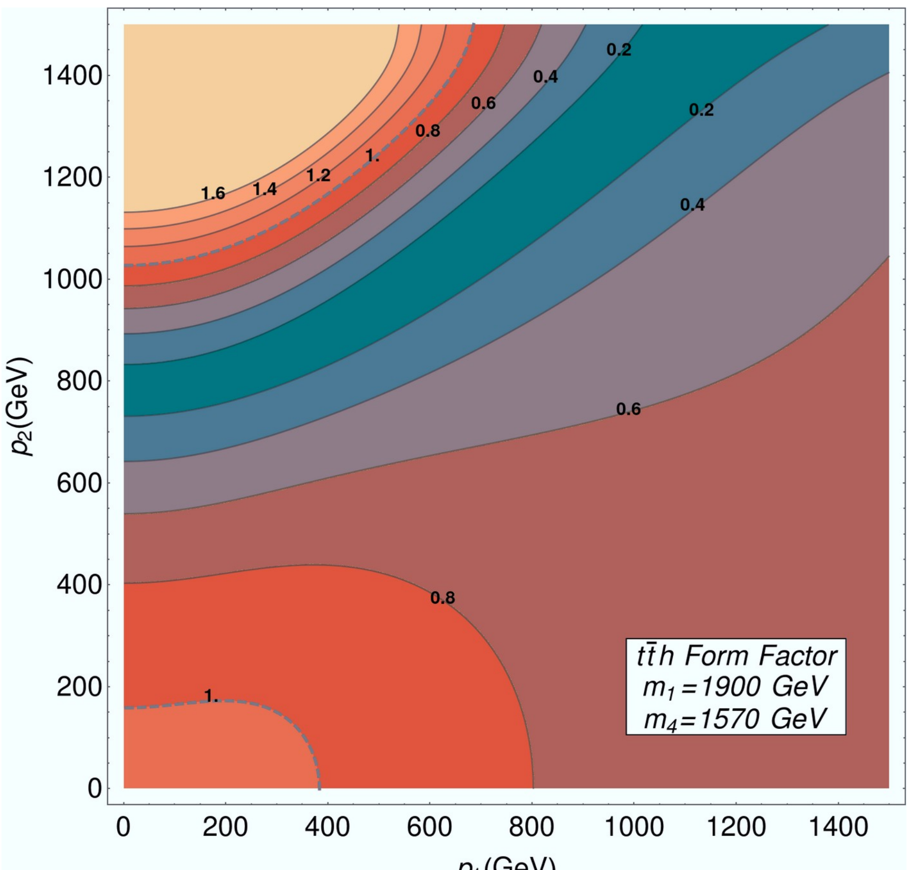
→ $f = 1$ for on-shell momenta.

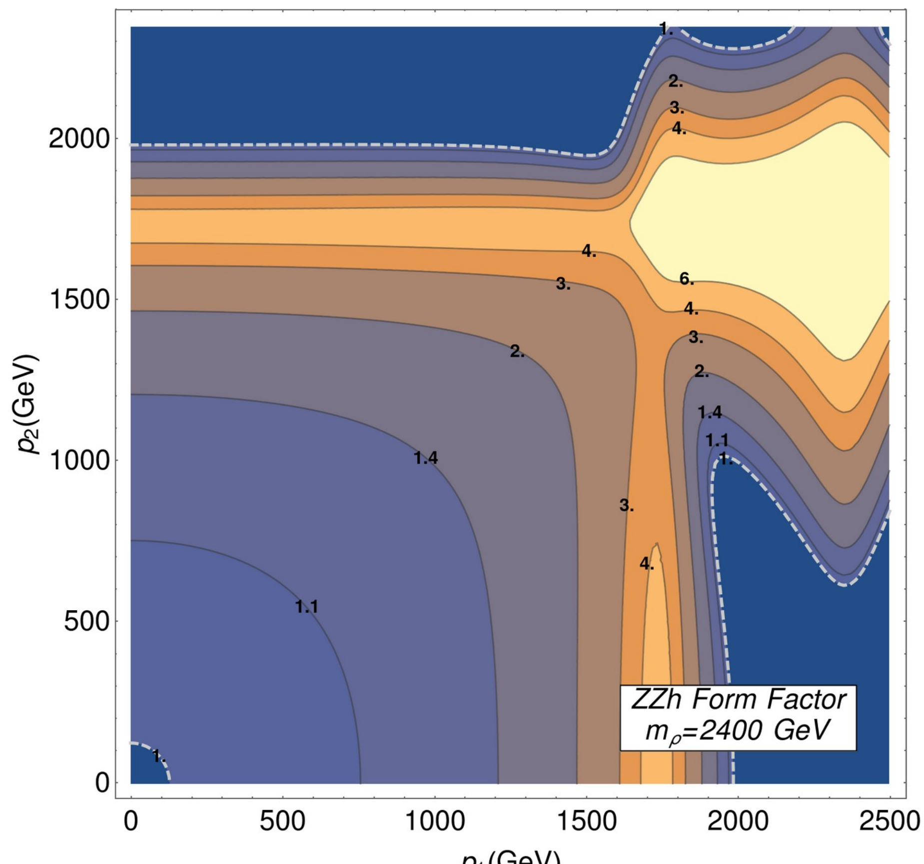
pedro.bittar.souza@usp.br

MCHM$_5$: $$f_{t\bar{t}h}(p_1,p_2) = \frac{M(p_1,p_2)\,(1-2\xi)\,/\sqrt{2}}{\left(\Pi_0^L(p_1)+\Pi_1^L(p_1)\frac{1}{2}\left\langle {S_h}^2\right\rangle\right)\left(\Pi_0^R(p_2)+\Pi_1^R(p_2)\left\langle {C_h}^2\right\rangle\right)}$$

$$M(p_1,p_2) = f^2 y_L y_R \left(\frac{m_4}{p_1^2-m_4^2} - \frac{m_1}{p_2^2-m_1^2}\right) \qquad \kappa_\xi^{\mathbf{5}} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

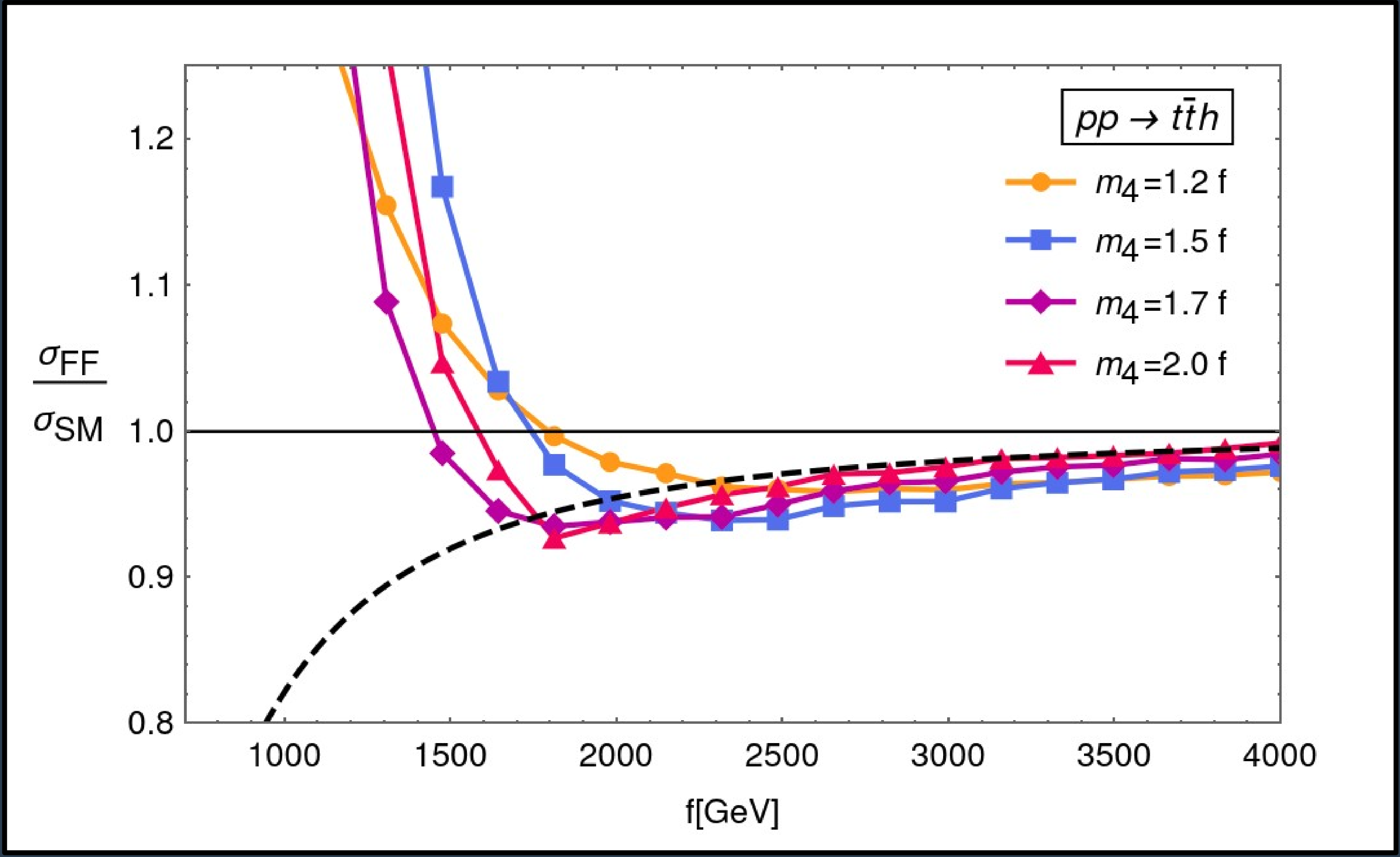
Absolute value of the form factors



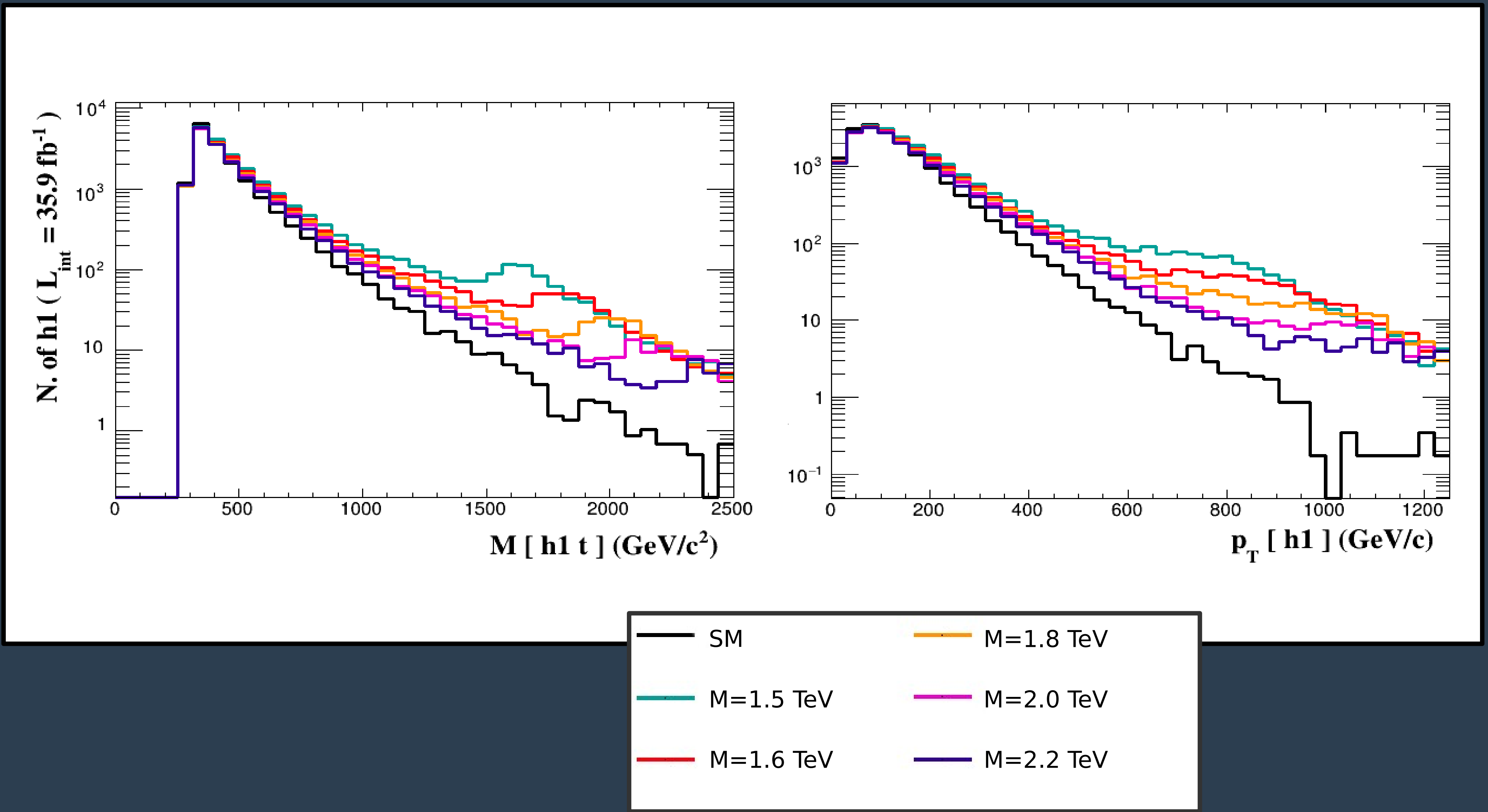


- **Implementation:** Include form factors in **UFO** file. **MADGRAPH** @ parton level.

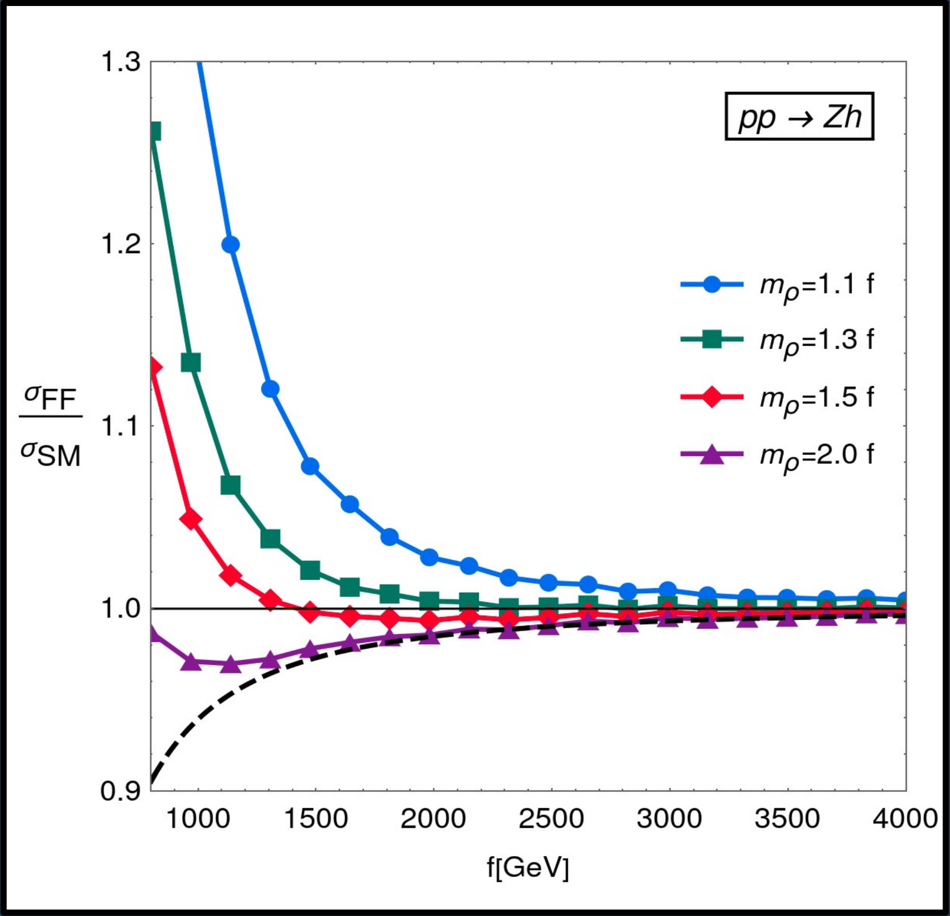
Fermionic resonances: $MCHM_5$ Form factor

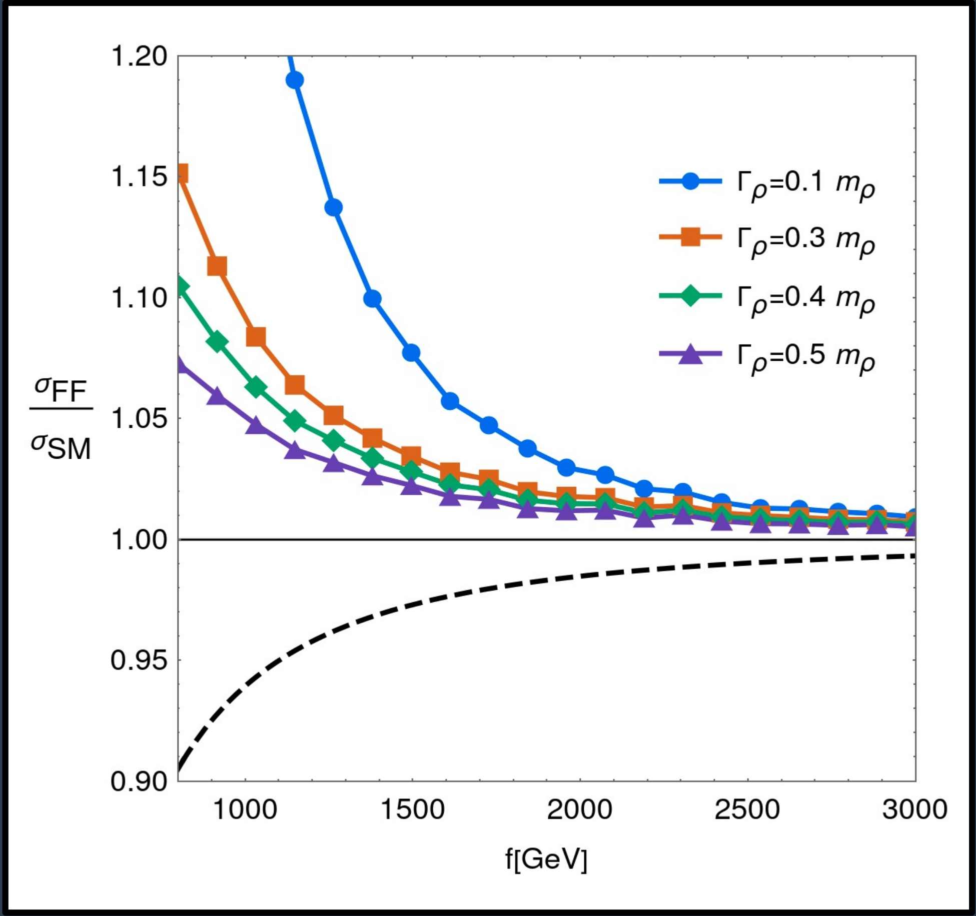


Modification of kinematic distribution shapes



Vectorial resonances: $MCHM_5$ Form factor





Narrow resonances: m_ρ>2.5 TeV

Eur. Phys. J. C (2014) 74:3181

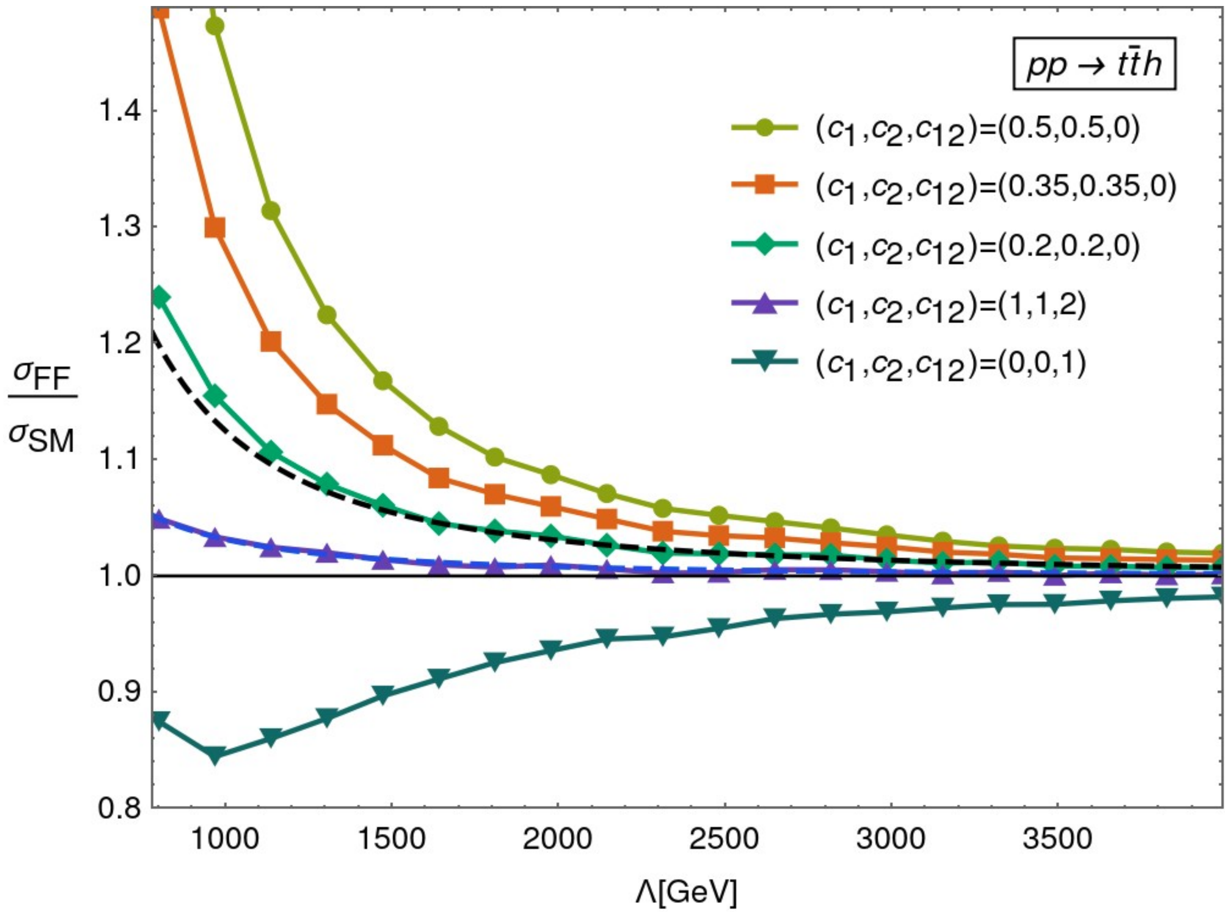
Weaker bounds for broad resonances: m_ρ>1 TeV

Fully composite 3rd generation of quarks, g_ρ>3

ArXiv:1901.01674

Local EFT expansion

$$\Gamma(p_1, p_2, p_h) = \Gamma_0 + c_1 \frac{p_1^2}{\Lambda^2} + c_2 \frac{p_2^2}{\Lambda^2} + c_{12} \frac{p_1 \cdot p_2}{\Lambda^2} + \dots \quad .$$



Conclusions

- Form factor couplings in CHMs promote a **competition between** **misalignment suppression** **and** **momentum enhancement.**
- Signal enhancement valid for **generic BSM states**.
- Modification of kinematic distribution shapes → HL-LHC strategy
- We verify the **off-shell enhancement** of order $\mathbf{p^2/\Lambda^2}$ over $\mathbf{v^2/\Lambda^2}$ coupling modifications.
- Presence of momentum effects in local and non-local formulations.

pedro.bittar.souza@usp.br

Form Factor Effects in Higgs Couplings **(Soon!)**

Pedro Bittar and Gustavo Burdman

Department of Mathematical Physics,
Institute of Physics,
University of Sao Paulo,
R. do Matao 1371, Sao Paulo,
SP 05508-090, Brazil

E-mail: bittar@if.usp.br, burdman@fma.if.usp.br

Thank You!

References

- Agashe, Kaustubh, Roberto Contino, and Alex Pomarol. "**The minimal composite Higgs model.**" Nuclear Physics B 719.1-2 (2005): 165-187.
- Marzocca, David, Marco Serone, and Jing Shu. "**General composite Higgs models.**" Journal of High Energy Physics 2012.8 (2012): 13.
- Gonçalves, D., Han, T., & Mukhopadhyay, S. (2018). **Higgs couplings at high scales**. Physical Review D, 98(1), 015023.
- Gonçalves, Dorival, et al. "**Off-shell Higgs Couplings in $ H^*\to ZZ\to\ell\ell\nu\nu$.**" arXiv preprint arXiv:2012.05272 (2020).
- Liu, Da, Lian-Tao Wang, and Ke-Pan Xie. "**Broad composite resonances and their signals at the LHC.**" Physical Review D 100.7 (2019): 075021.

pedro.bittar.souza@usp.br

Backup

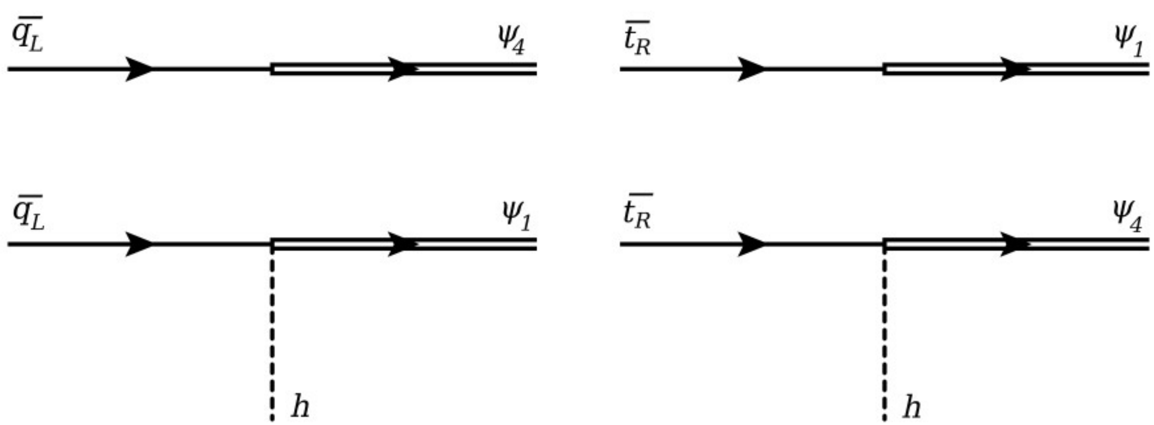
MCHM$_5$ Form Factors

$$U[h] = \exp\left(\frac{i\sqrt{2}}{f} h^{\hat{a}} T^{\hat{a}}\right)$$

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

Partial Compositeness:

$$\mathcal{L}_{int}^F = f\left[y_{L1}(\overline{q_L^{\mathbf{5}}} U[\pi])_5 \psi_1 + y_{L4}(\overline{q_L^{\mathbf{5}}} U[\pi])_j \psi_{4,j}\right] + h.c.$$
$$+ f\left[y_{R1}(\overline{t_r^{\mathbf{5}}} U[\pi])_5 \psi_1 + y_{R4}(\overline{t_r^{\mathbf{5}}} U[\pi])_j \psi_{4,j}\right] + h.c.$$



MCHM$_5$ Form Factors

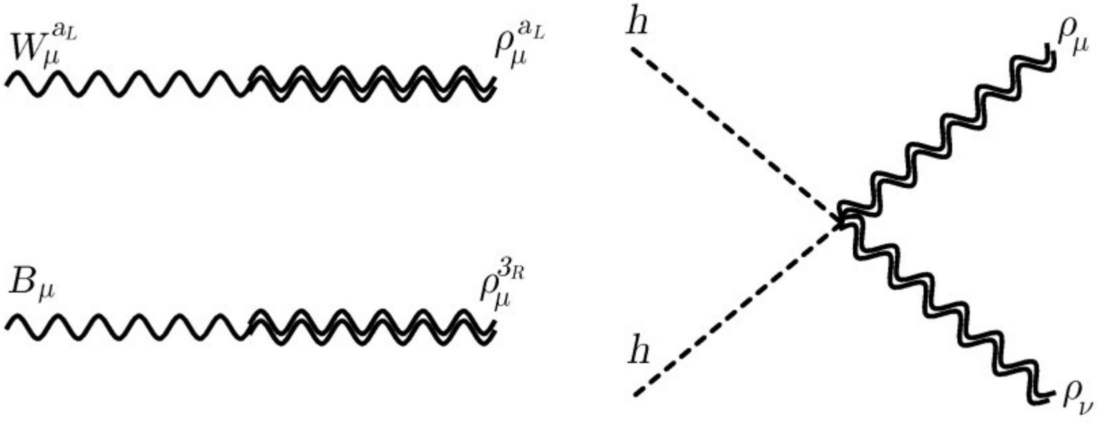
Vector Meson dominance/ Hidden Local Symmetry:

$$\mathcal{L}_{CS}^{V} = -\frac{1}{4}\rho_{\mu\nu}^{a}\rho^{a,\mu\nu} + \frac{m_\rho^2}{2}\rho_{\mu}^{a}\rho^{a,\mu} + g_\rho\rho_\mu^a J^{a,\mu} + \frac{g_\rho^2}{2}\rho_\mu^a\rho^{a,\mu}h^2,$$

$$\mathcal{L}_{ES}^{V} = -\frac{1}{4}W_{\mu\nu}^{a_L}W^{a_L,\mu\nu} + g_0 W_\mu^{a_L}J^{a_L,\mu} + \frac{g_0^2}{2}W_\mu^{a_L}W^{a_L,\mu}h^2$$

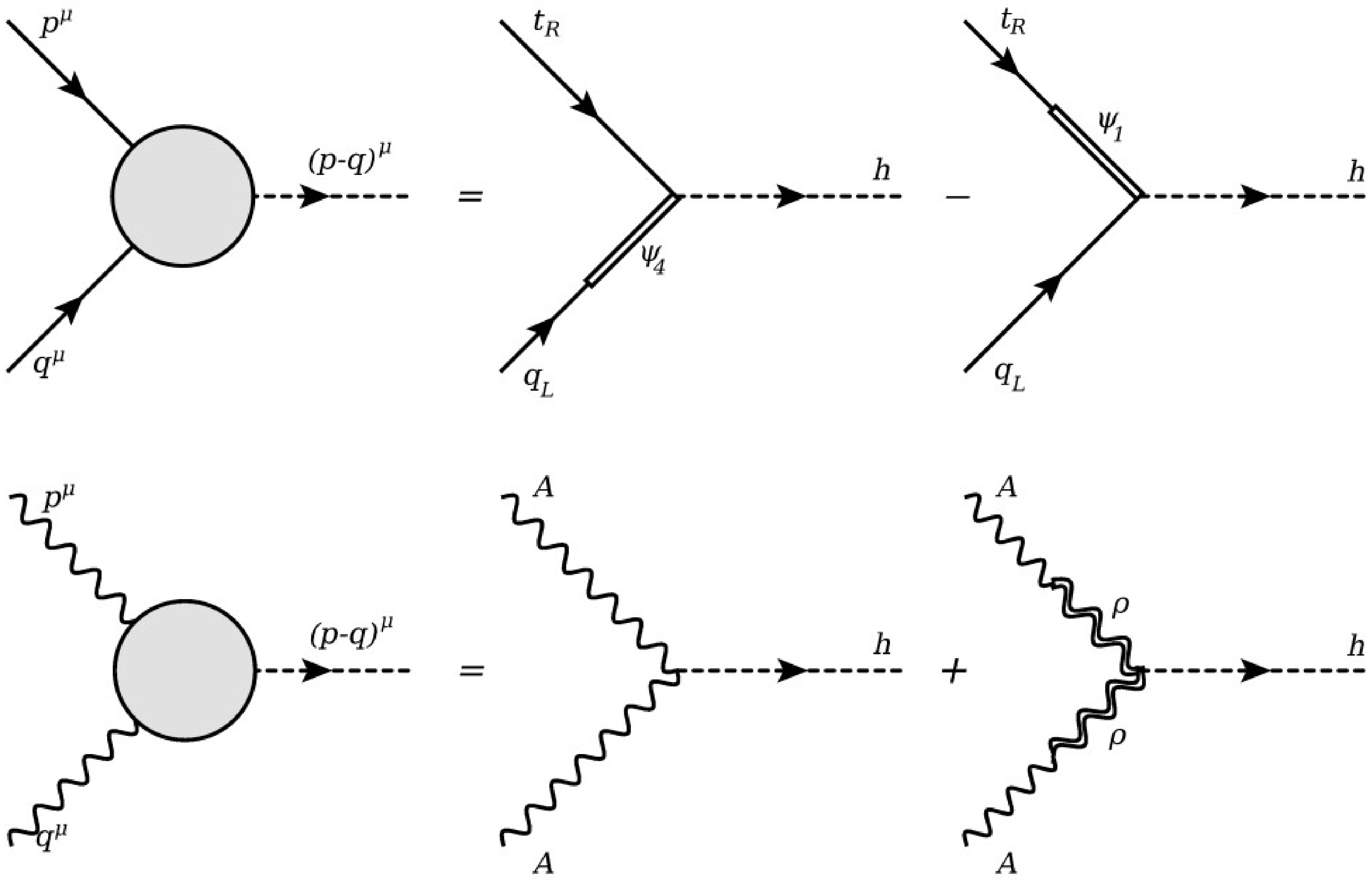
$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + g_0' B_\mu J^{3_R,\mu} + \frac{g_0'^2}{2}B_\mu B^\mu h^2,$$

$$\mathcal{L}_{int}^{V} = \frac{1}{2}\frac{g_0}{g_\rho}W_{\mu\nu}^{a_L}\rho^{a_L,\mu\nu} + \frac{1}{2}\frac{g_0}{g_\rho}B_{\mu\nu}\rho^{3_R,\mu\nu}.$$



pedro.bittar.souza@usp.br

$MCHM_5$ Form Factors



pedro.bittar.souza@usp.br

MCHM$_5$ Form Factors

Form Factor Lagrangian

$$\mathcal{L}^F_{eff} = \overline{q_l} \not{p} \left(\Pi^L_0(p) + \Pi^L_1(p_1, p_2) \Sigma_i \Sigma^i \right) q_l + \overline{t_r} \not{p} \left(\Pi^R_0(p) + \Pi^R_1(p_1, p_2) \Sigma_i \Sigma^i \right) t_r + \\ + \overline{q_l} \left(M_1(p_1, p_2) \Gamma^i \Sigma_i \right) t_r + h.c.$$

$$\mathcal{L}^V_{eff} = \frac{1}{2} \mathcal{P}^{\mu\nu} \left(\Pi_0(p) \, \mathrm{Tr}(A_\mu A_\nu) + \Pi_1(p_1, p_2) \Sigma^T A_\mu A_\nu \Sigma \right)$$

$$\Pi^L_0(p) = 1 + \Pi^L_{\mathbf{4}}(p) = 1 + \frac{f^2 |y_L|^2}{p^2 - m_4^2}, \qquad \Pi^R_0(p) = 1 + \Pi^L_{\mathbf{1}}(p) = 1 + \frac{f^2 |y_L|^2}{p^2 - m_1^2}$$

$$\Pi^L_1(p_1, p_2) = \Pi^L_{\mathbf{1}}(p_1) - \Pi^L_{\mathbf{4}}(p_2) = f^2 |y_L|^2 \left(\frac{1}{p_1^2 - m_1^2} - \frac{1}{p_2^2 - m_4^2} \right), \qquad L \leftrightarrow R$$

$$M(p_1, p_2) = M_{\mathbf{4}}(p_1) - M_{\mathbf{1}}(p_2) = f^2 y_L y_R \left(\frac{m_4}{p_1^2 - m_4^2} - \frac{m_1}{p_2^2 - m_1^2} \right),$$

pedro.bittar.souza@usp.br

Heavy scalars

$$V = M_a^2 H_a^\dagger H_a + M_b^2 H_b^\dagger H_b + \mu^2 (e^{i\theta} H_a^\dagger H_b + h.c.)$$
$$\frac{\lambda}{2} (H_a^\dagger H_a + H_b^\dagger H_b)^2 + \lambda' (H_a^\dagger H_b H_b^\dagger H_a).$$

Form Factor

$$\Gamma_{hVV}(p^2) = g_V^2 v \left(1 - \frac{\mu^4}{4M_b^2} \frac{1}{p^2 - M_b^2} \right)$$

pedro.bittar.souza@usp.br

Broad Resonances

$$G^{(2)}(p^2) = \frac{iZ}{p^2 - M_X^2(p^2) + i\sqrt{s}\Gamma(s)}.$$

Include strong top interaction with resonance.

$$\mathcal{L} = -\frac{1}{4}\rho^a_{\mu\nu}\rho^{a,\mu\nu} + \frac{m_\rho^2}{2}\left(1 + \frac{h^2}{f^2}\right)\rho^a_\mu\rho^{a,\mu} + \frac{1}{2}\frac{g_0^a}{g_\rho}A^a_{\mu\nu}\rho^{a,\mu\nu} + \bar{t}_R\gamma_\mu t_R(g_\rho\rho^\mu - g_0' B_\mu)$$