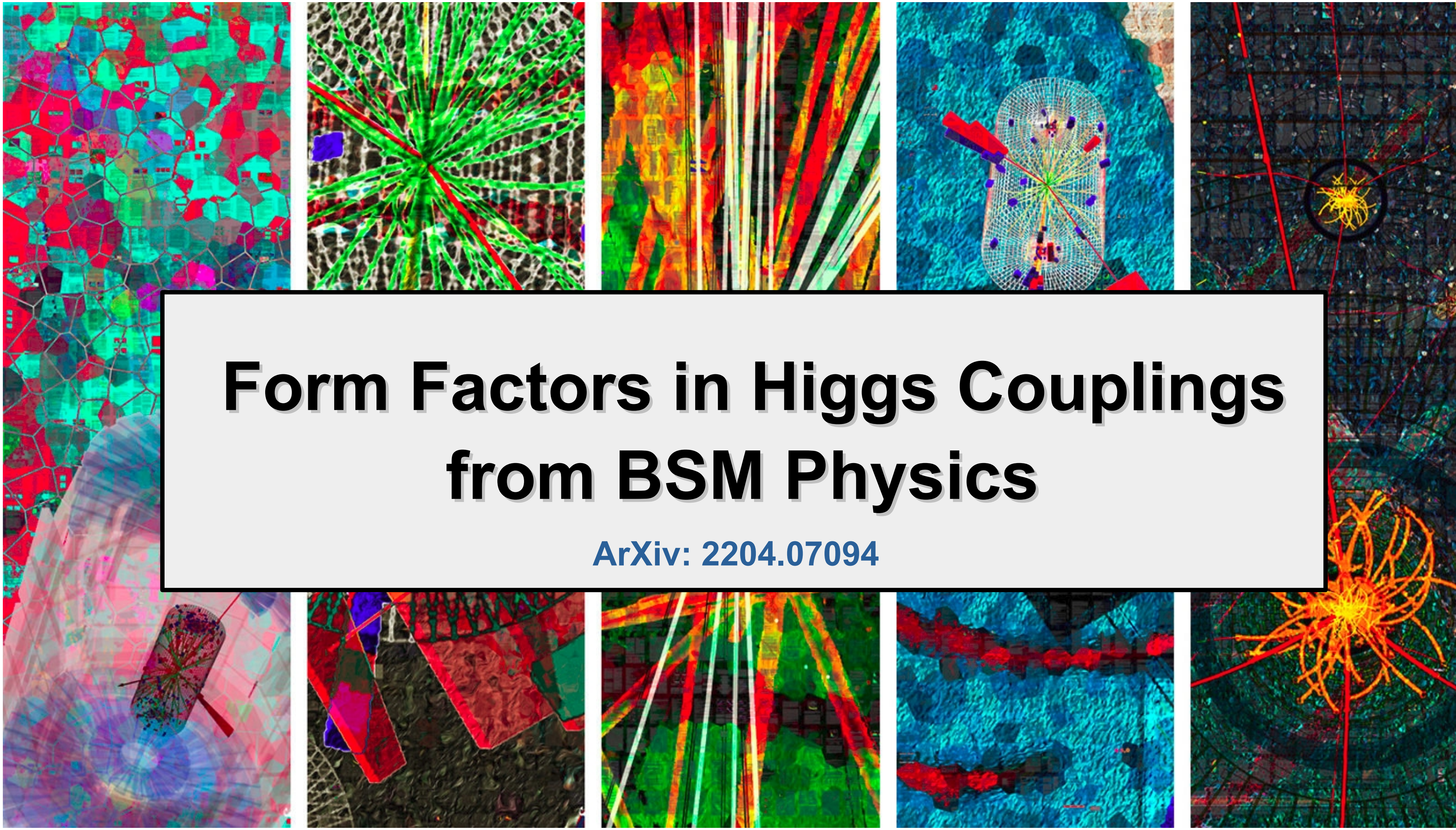

Form Factors in Higgs Couplings from BSM Physics

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Planck 2022 - *24th International Conference From the Planck Scale to the Electroweak Scale*

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Outline

1. Higgs Form Factors
2. Form Factor Examples
3. Signals at the LHC
4. Conclusions

The Higgs at the LHC

Hierarchy problem → Resonances at the TeVs

Future of the LHC: First **precision** then **Energy**

BSM → Deviations in the Higgs couplings

- κ framework
- EFTs (SMEFT ,...)

↳ **Constant shifts**

Higgs Form Factors

Higgs Form Factors = (Non-local) BSM momentum dependence in the Higgs couplings

Examples → Model dependent approach to momentum effects

⤷ **Complementary to the EFT program**

Higgs Form Factors

- Heavy BSM physics $\sim \mathcal{O}\left(\frac{v^2}{M^2}\right)$ (On-shell)

i.e. CHMs with $\xi = \frac{v^2}{f^2}$,
2HDM with $\tan\alpha \simeq \frac{v^2}{M_\pm^2}$, *etc...*

- **Off-shell effects** $\sim \mathcal{O}\left(\frac{q^2}{M^2}\right)$

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

On-shell normalization: $F(0, m_X) = 1$

Off-shellness to disentangle q² effects

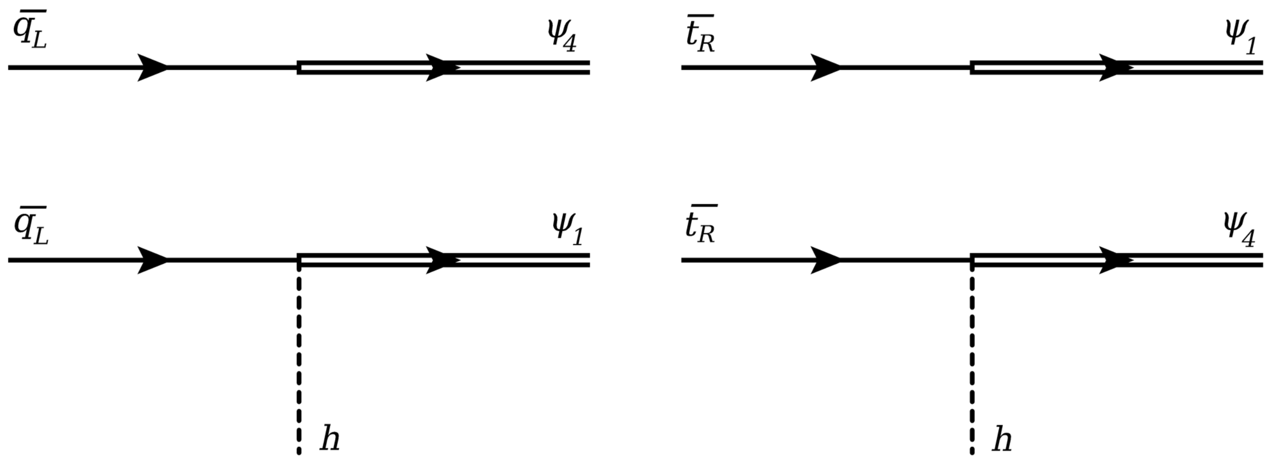
Example: Composite Higgs

Composite Higgs: **pNGB** from a new strongly interacting sector

EWSB is triggered by explicit breakings that generate the Higgs couplings and its potential

Not any breaking: Top and the gauge bosons mix with the their composite partners

$MCHM_5$ partial compositeness:



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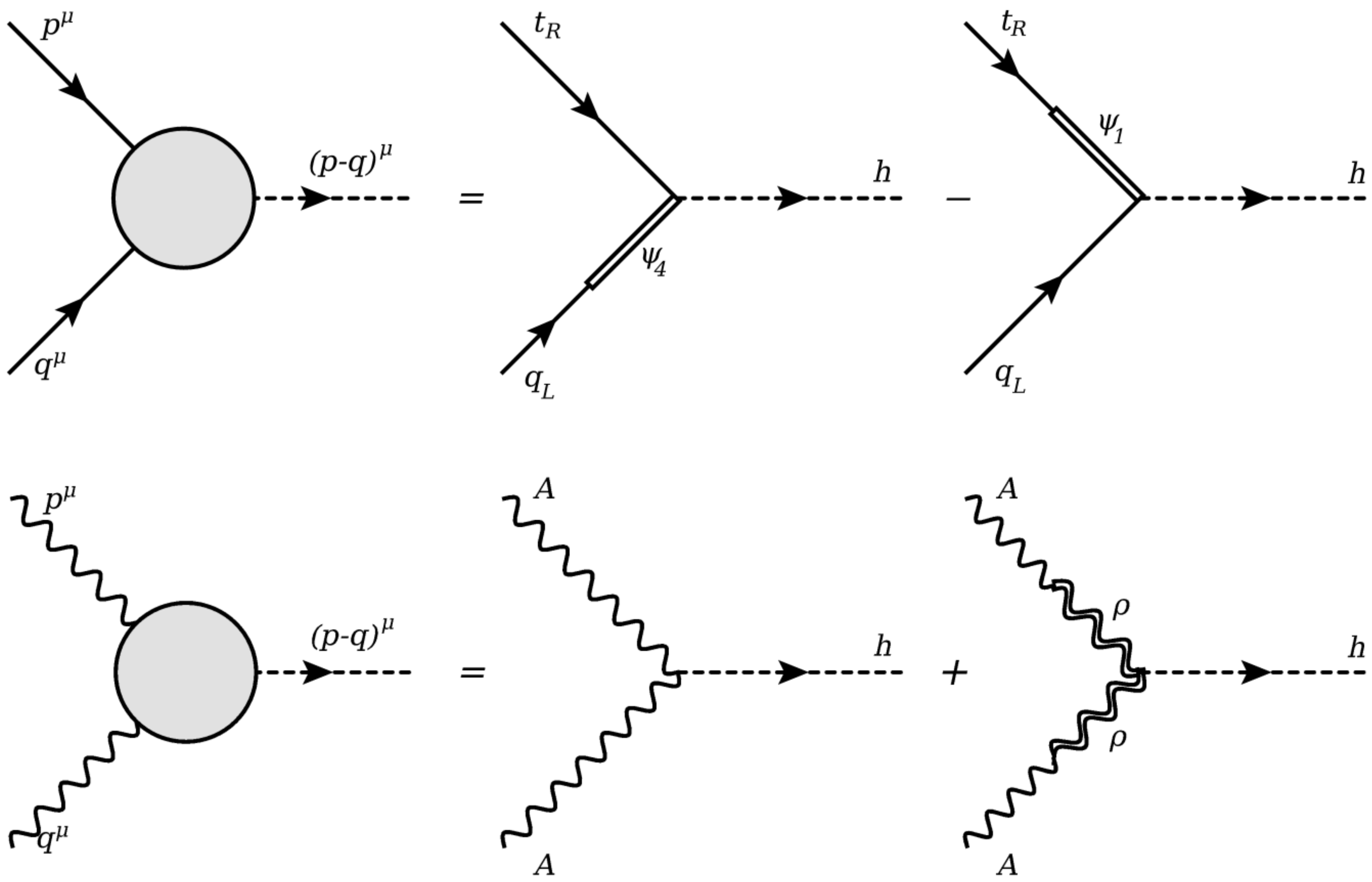
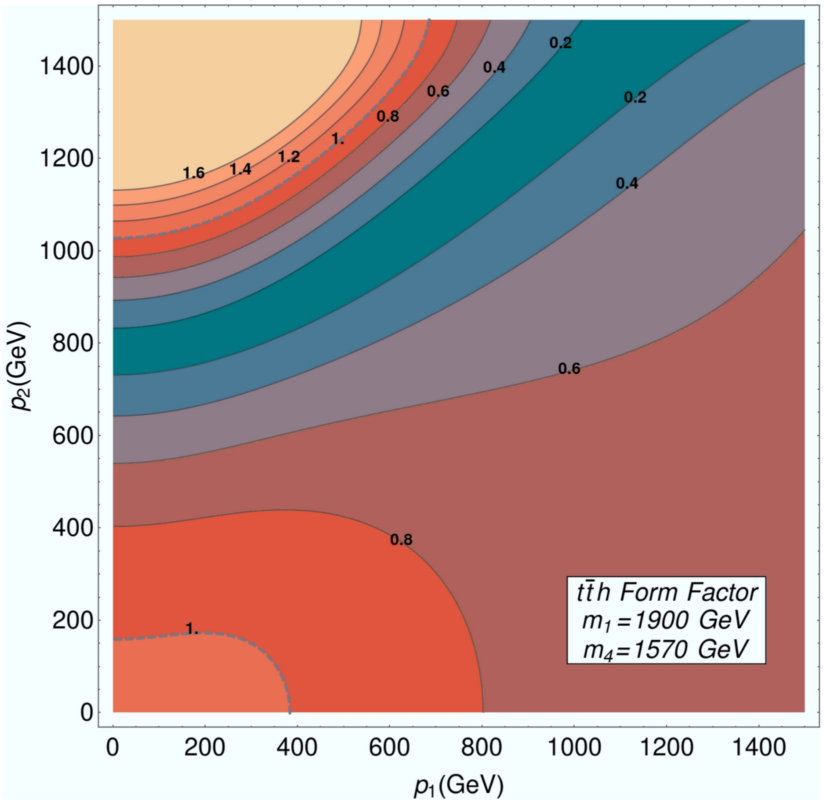
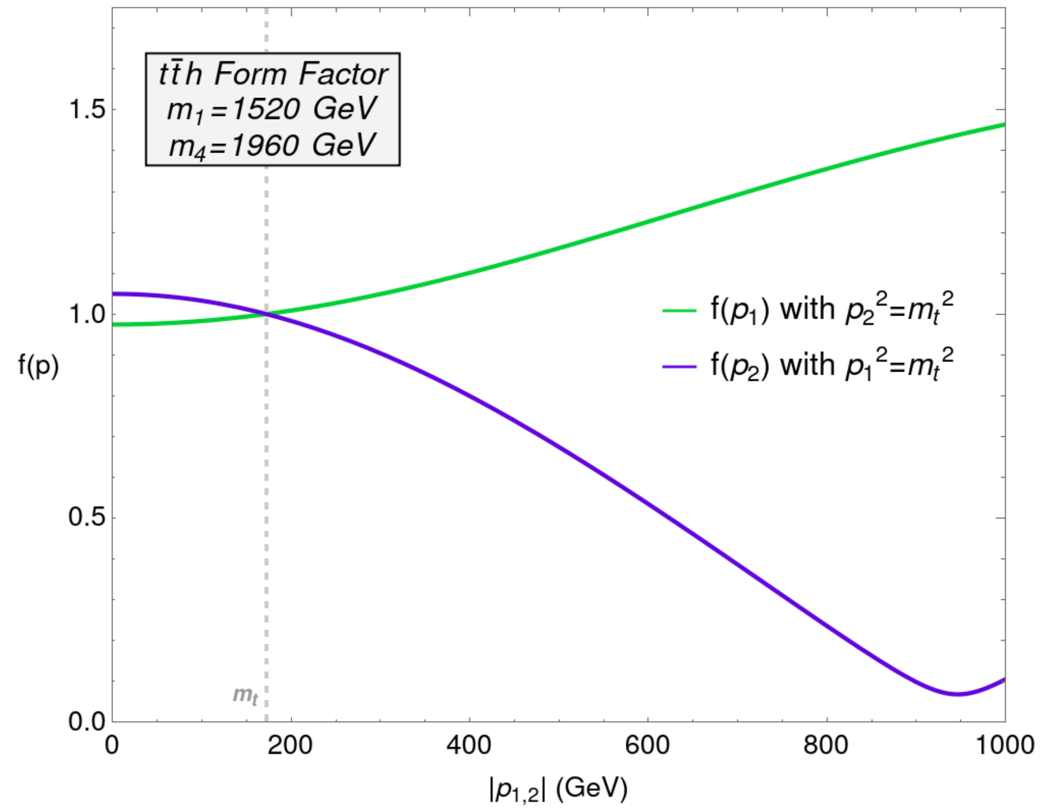
Example: Composite Higgs



Example: Composite Higgs

$$\frac{f_{t\bar{t}h}(p_1,p_2)}{y_t} = \left(1 - \frac{M_L(p_1) - m_t}{\not{p}_1 - m_t}\right)^{-1} \left(1 - \frac{M_R(p_2) - m_t}{\not{p}_2 - m_t}\right)^{-1}$$
$$\frac{M(p_1,p_2)\,(1-2\xi)/\sqrt{2}}{\left(\Pi_0^L(p) + \Pi_1^L(p)\frac{1}{2}\langle {S_h}^2\rangle\right)\left(\Pi_0^R(q) + \Pi_1^R(q)\langle {C_h}^2\rangle\right)}.$$

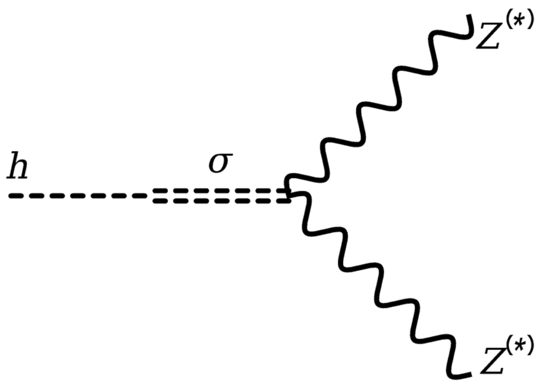




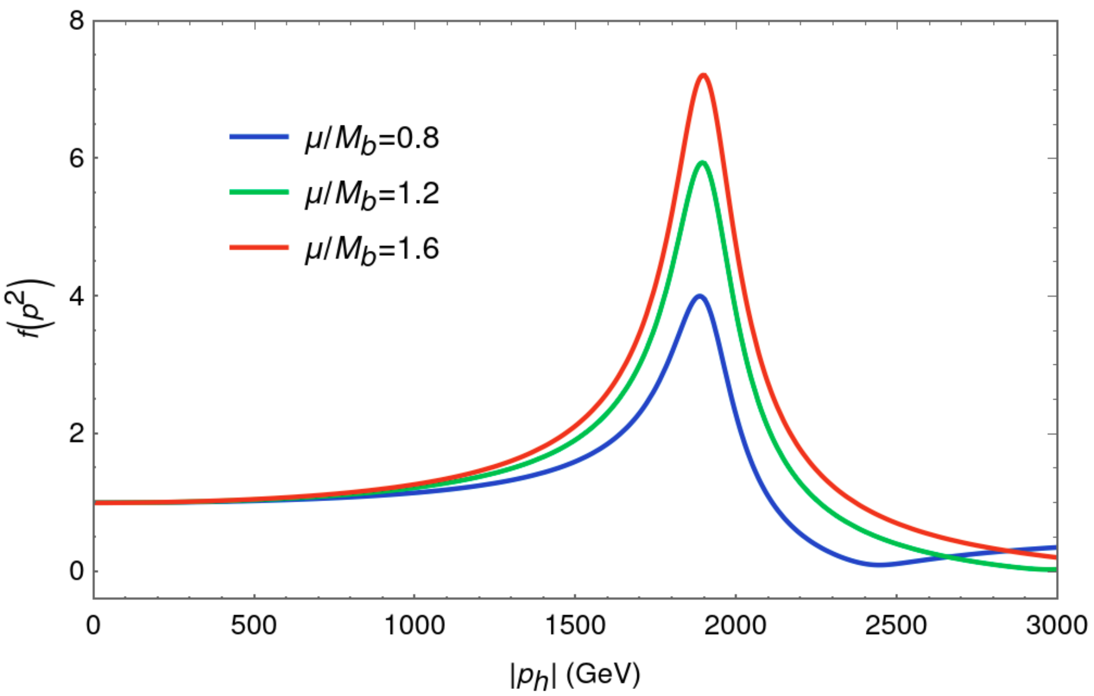
Example: Scalar Form Factor

CHMs → Illustrative but not exaustive

Mixing with a Scalar to generate the Higgs couplings: $-\mu^2(H_a^\dagger H_b + h.c.)$



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



Example: Unparticle Form Factor

No resonances in the LHC so far

- Form factor examples presented so far have **poles**
- Explore effects from the continuum part of the amplitude → **Branch cuts**

Assume a **new conformal sector**

CFT is broken at a scale μ

Scalar unparticle operator: $\phi(x)$,*d*

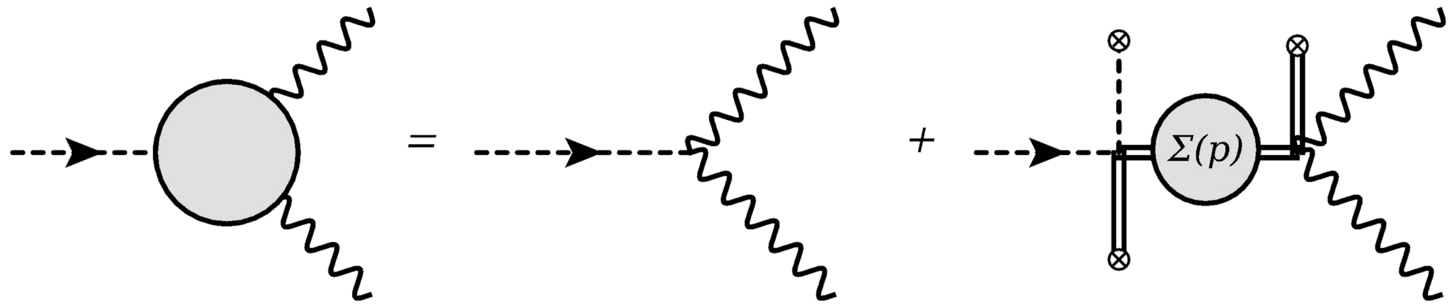
Unparticle scalar 2-point function: $\Delta(p,\mu,d) = \frac{A_d}{2\sin d\pi}\frac{i}{(\mu^2 - p^2 - i\epsilon)^{2-d}}$

Unscalar with the same quantum numbers as the Higgs.

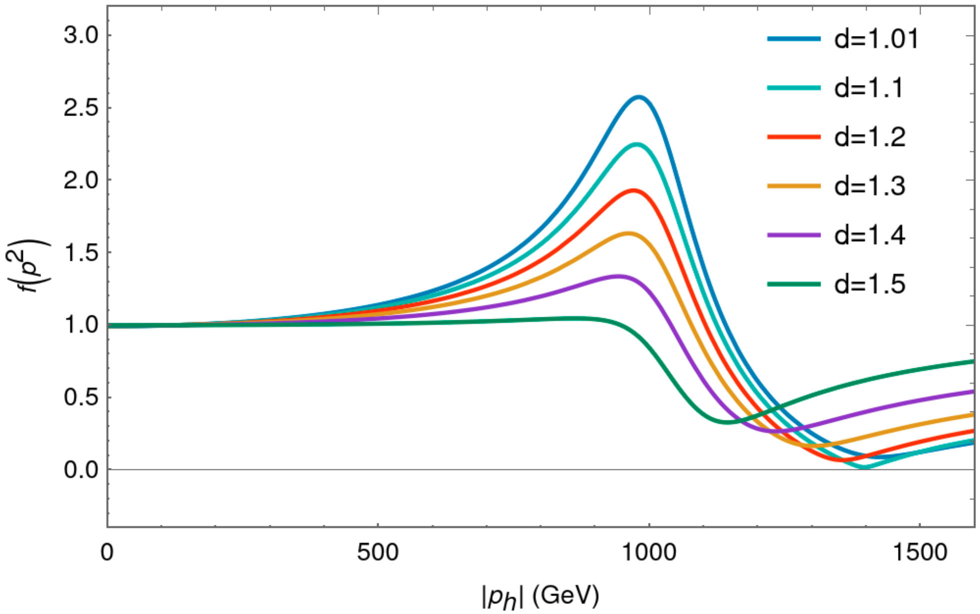
$$S_{\rm NL} = \int d^4x \left\{ \phi^\dagger (D^2 - m^2)^{2-d}\phi - \lambda_t \overline{u}_R \frac{\phi^\dagger}{\Lambda^{d-1}} q_L + h.c. + \alpha |H|^2 \frac{|\phi|^2}{\Lambda^{2(d-1)}} \right\}$$

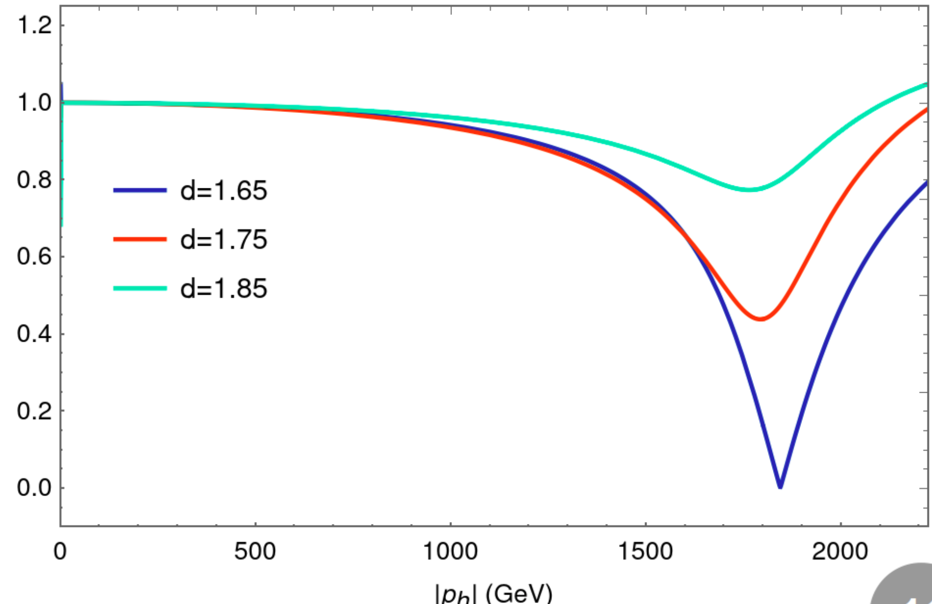
(Mandelstam's Method)

Example: Unparticle Form Factor



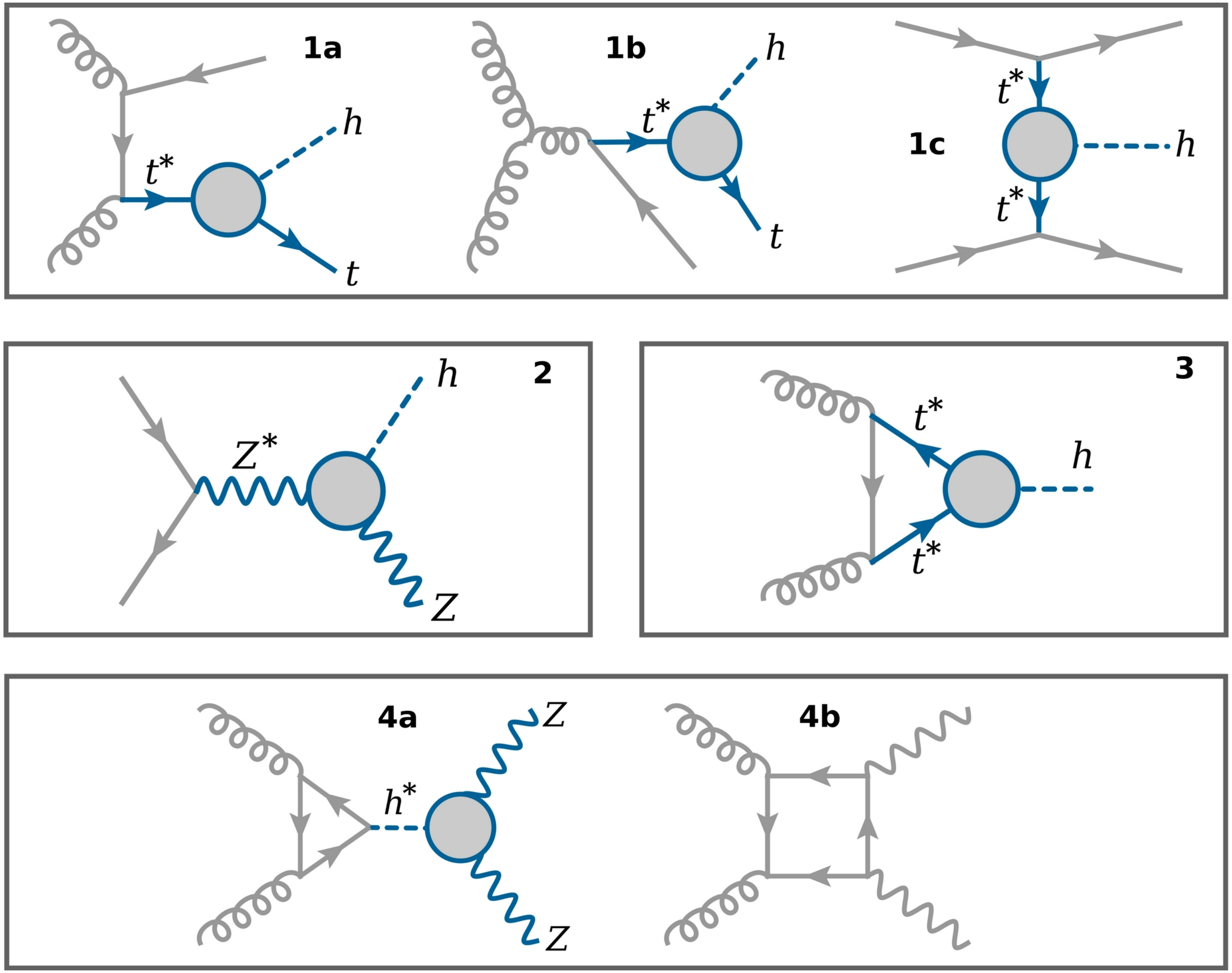
$$f_{unp}(p, q_1, q_2) = \frac{g^2 v}{2c_w^2} + \frac{\alpha v f^{2d}}{\Lambda^{2(d-1)}} \frac{g_*^2}{2} \frac{A_d}{2\sin d\pi} \frac{i\mathcal{F}(0, q_1+q_2)}{(p_h^2 - m^2)^{2-d}}$$





Signals at the LHC

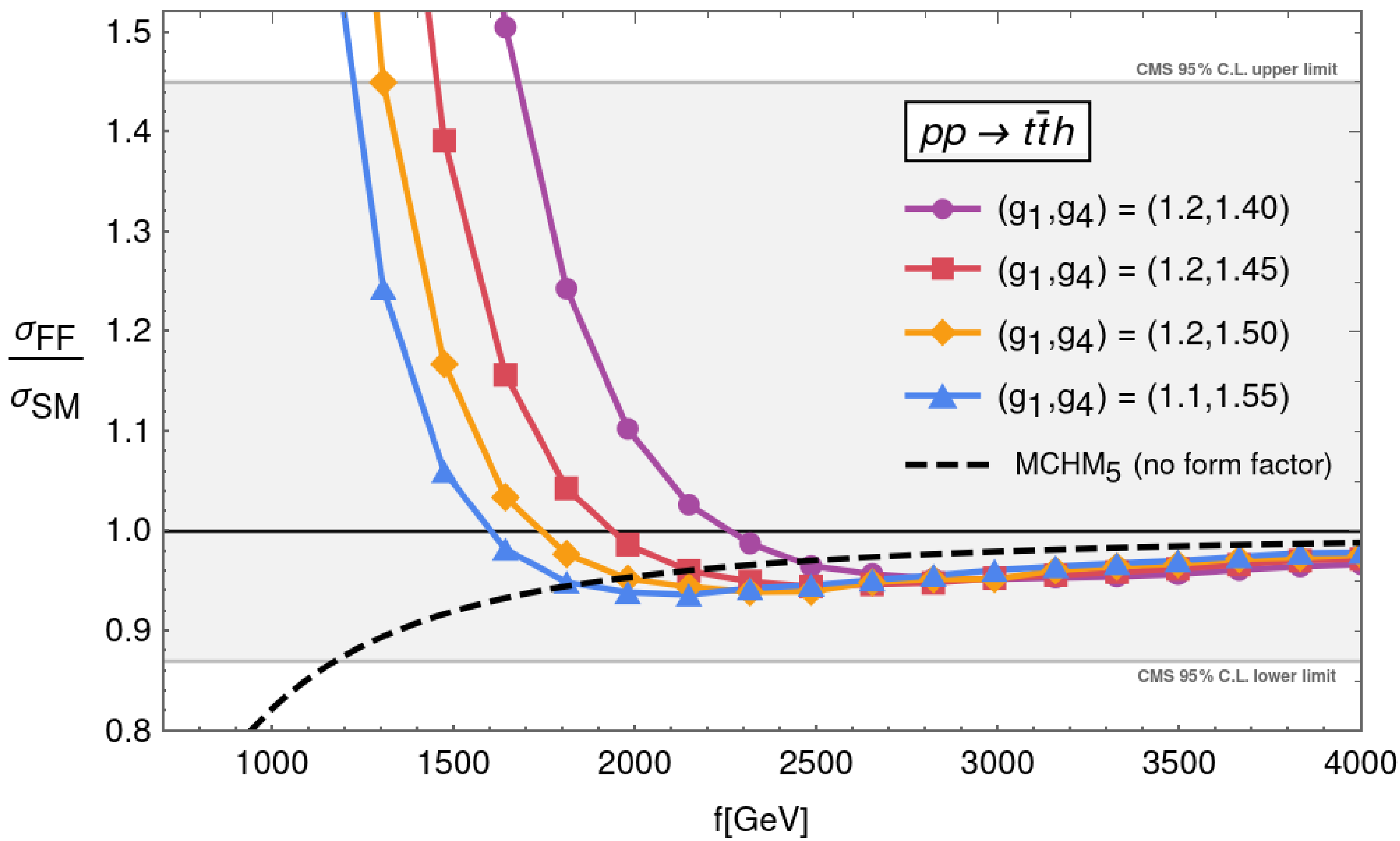
Off-shell probes to the form factors



Signals at the LHC

- Implementation of form factors in MadGraph5_aMC@NLO
- Signal modification: Reach of LHC will be left for future work

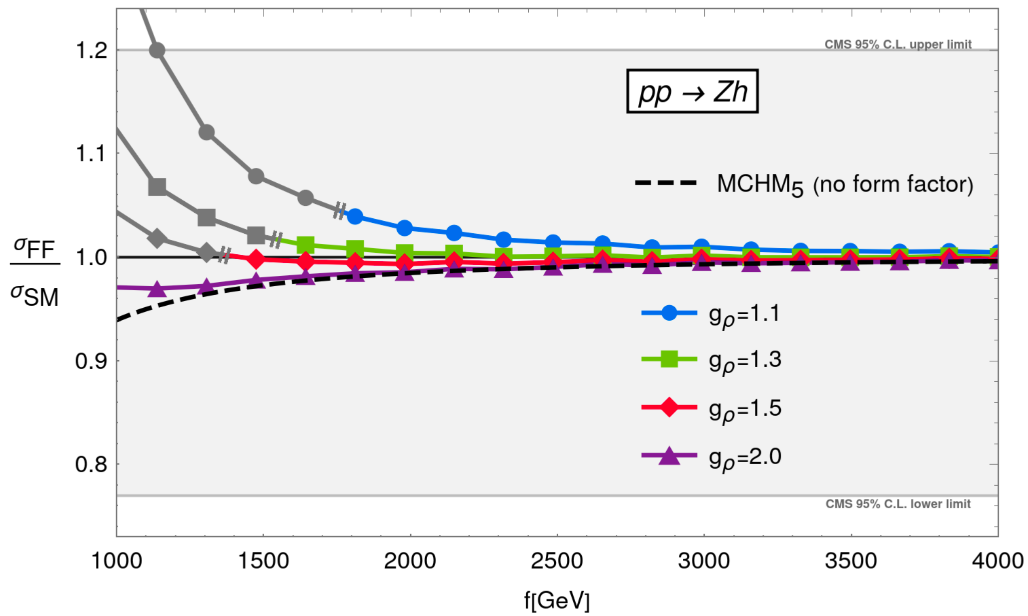
MCHM$_5$ tth Signal

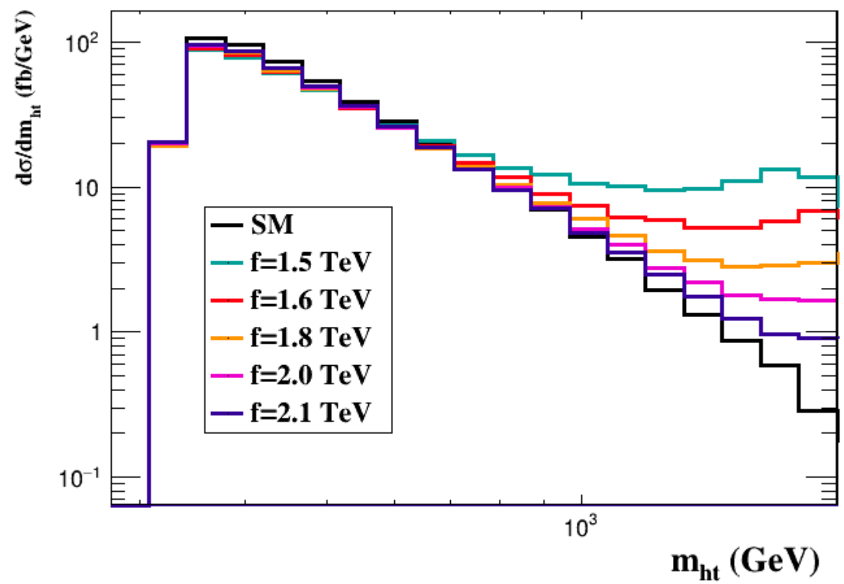


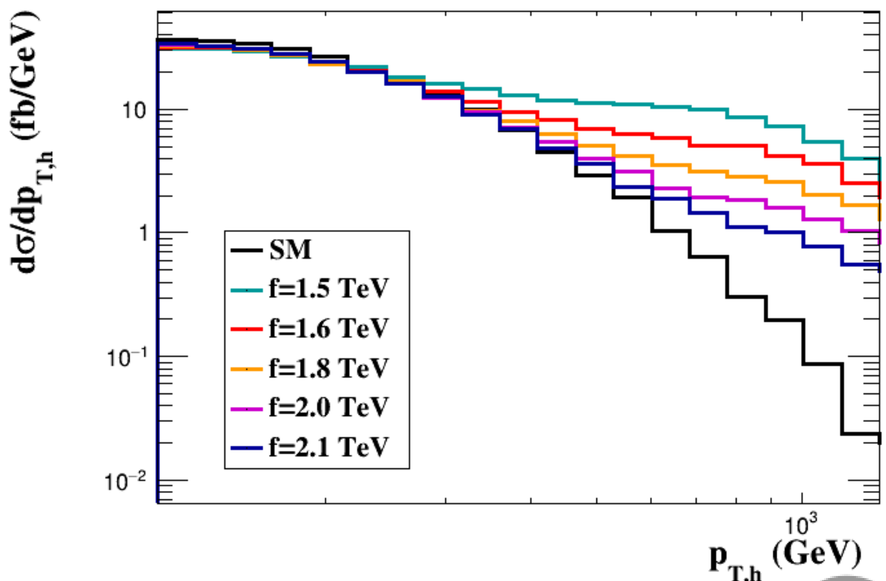
$$\kappa_\xi^{\mathbf{5}} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\xi = v^2/f^2$$

Signals at the LHC



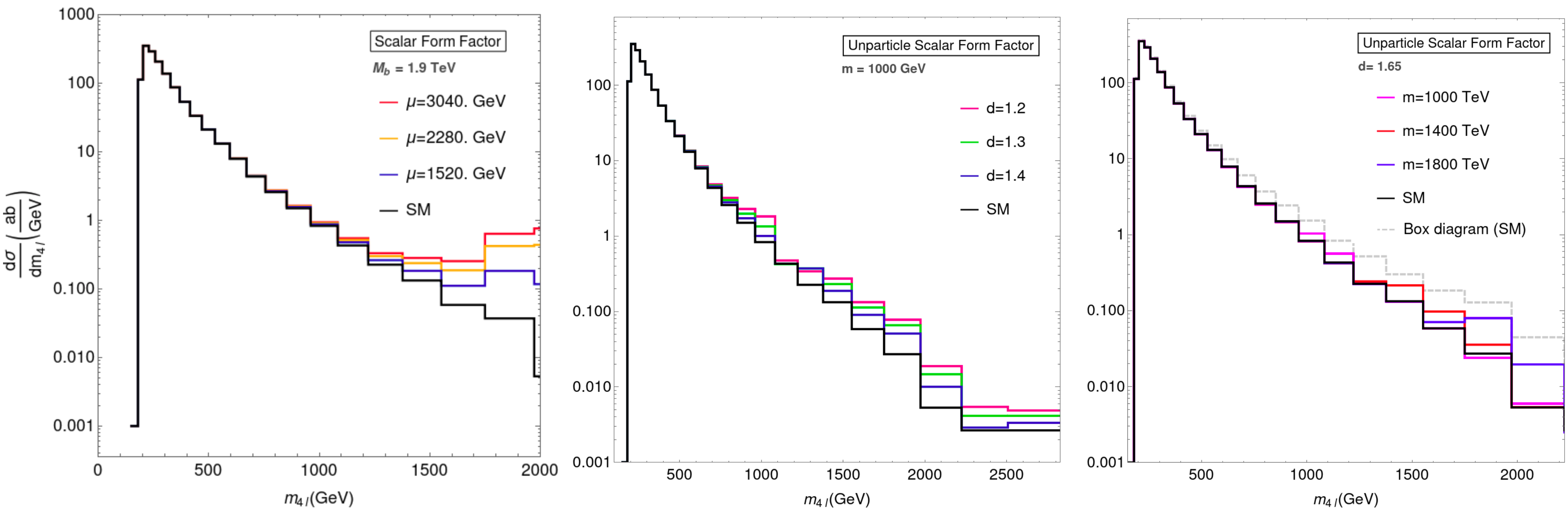




- **Momentum effects do not decouple from the on-shell modifications**
- **Shape modification of Kinematic distributions:** Trademark of composite objects

Example: Composite Higgs

pp→ 4l: $$\frac{d\sigma}{dm_{4l}} = |F(m_{4l})|^2 \frac{d\sigma_{h^*}}{dm_{4l}} + |F(m_{4l})| \frac{d\sigma_{int}}{dm_{4l}} + \frac{d\sigma_{box}}{dm_{4l}}$$



Interference: Both a enhancement and a suppression in the form factor lead to an enhanced signal

Conclusions

- Precision at **future LHC**
- Form Factors as a **model dependent approach** to pinpoint momentum effects
- Need **off-shell channels** (off-shell top, W, Z and h)
- CHM momentum effects do **not decouple at low energies**
- Framework for **non-resonant phenomena**. Continuum effects, CFTs and unparticles

Thank you!


PLANCK 2022
Paris, May 30 - June 3, 2022
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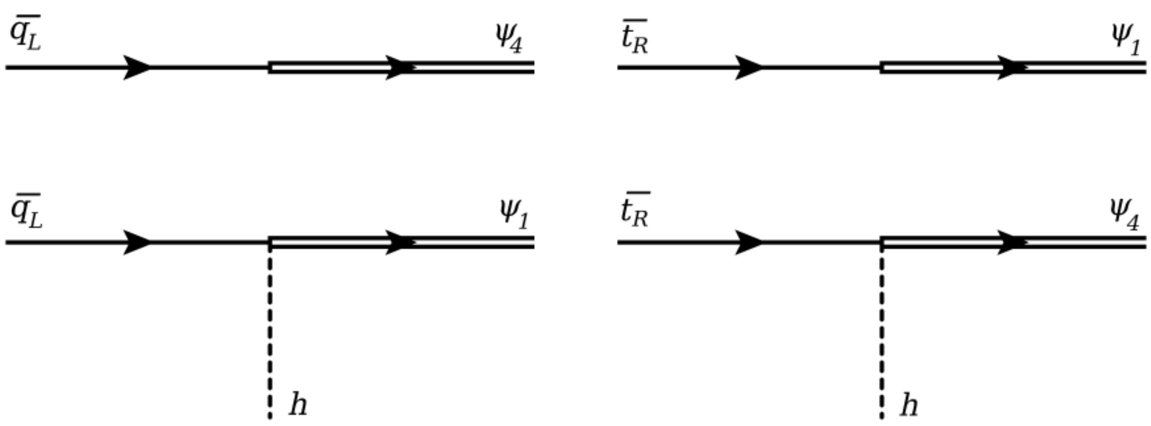
Backup: MCHM$_5$ Form Factors

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

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

Partial Compositeness:

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



Backup: MCHM$_5$ Form Factors

Form Factor Effective Lagrangian

$$\mathcal{L}^F_{eff} = \overline{q_L}\not{p}_1 \left(\Pi^L_0(p_1) + \Pi^L_1(p_1)\frac{S_h^2}{2}\right) q_L + \overline{t_R}\not{p}_2 \left(\Pi^R_0(p_2) + \Pi^R_1(p_2)C_h^2\right) t_R + \\ + \overline{t_R}\left(M_1(p_1, p_2)\frac{S_h C_h}{\sqrt{2}}\right) q_L \, ,$$

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

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

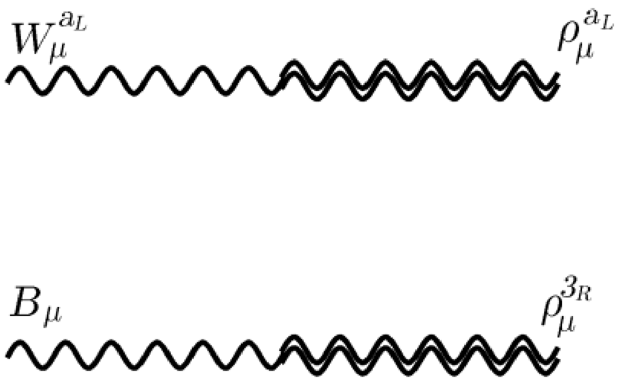
$$M(p_1, p_2) = M_{\mathbf{4}}(p_1) - M_{\mathbf{1}}(p_2) = f^2 y_L y_R \left(\frac{m_4}{p_1^2 - m_4^2} - \frac{m_1}{p_2^2 - m_1^2}\right),$$

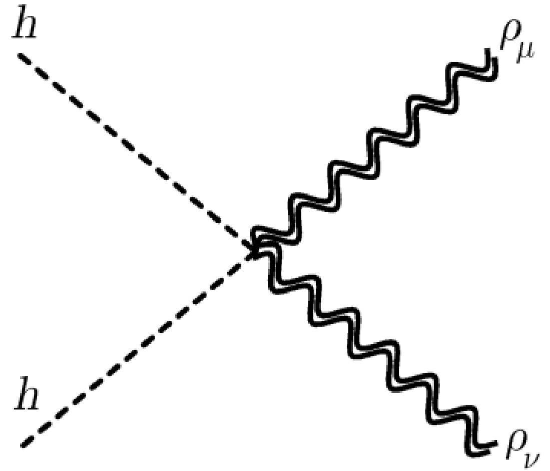
Backup: Hidden Local Symmetry

$$\mathcal{L}^V_{CS} = -\frac{1}{4}\rho^a_{\mu\nu}\rho^{a,\mu\nu} + \frac{m^2_\rho}{2}\rho^a_\mu\rho^{a,\mu} + g_\rho\rho^a_\mu J^{a,\mu} + \frac{g^2_\rho}{2}\rho^a_\mu\rho^{a,\mu}h^2,$$

$$\mathcal{L}^V_{ES} = -\frac{1}{4}W^{a_L}_{\mu\nu}W^{a_L,\mu\nu} + g_0 W^{a_L}_\mu J^{a_L,\mu} + \frac{g^2_0}{2}W^{a_L}_\mu W^{a_L,\mu}h^2$$
$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + g'_0 B_\mu J^{3_R,\mu} + \frac{g'^2_0}{2}B_\mu B^\mu h^2,$$

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





Backup: Mandelstam's Method

Gauge symmetry in the non-local effective Action → Mandelstam's Method

Introduces a wilson line between two unparticle fields. Then, compute the fourth functional derivative to obtain the Higgs-Gauge vertex

$$
\begin{aligned}
ig^2\Gamma^{ab\alpha\beta}(p,q_1,q_2) = & \frac{\delta^4 S_{\mathrm{NL}}}{\delta A^{a\alpha}(q_1)\delta A^{b\beta}(q_2)\delta\phi^\dagger(p+q_1+q_2)\delta\phi(p)} \\
& ig^2\Bigg\{ \quad \left(T^aT^b+T^bT^a\right) g^{\alpha\beta}\mathcal{F}(p,q_1+q_2) \\
& +T^aT^b\frac{(2p+q_2)^\beta(2p+2q_2+q_1)^\alpha}{q_1^2+2(p+q_2)\cdot q_1}\left[\mathcal{F}(p,q_1+q_2)-\mathcal{F}(p,q_2)\right] \\
& +T^bT^a\frac{(2p+q_1)^\alpha(2p+2q_1+q_2)^\beta}{q_2^2+2(p+q_1)\cdot q_2}\left[\mathcal{F}(p,q_1+q_2)-\mathcal{F}(p,q_1)\right]\Bigg\}
\end{aligned}
$$

$$
\mathcal{F}(p,q) = -\frac{\left(m^2-(p+q)^2\right)^{2-d}-\left(m^2-p^2\right)^{2-d}}{q^2+2p\cdot q}
$$

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