(Accurate) Predictions for New Strong Dynamics at colliders

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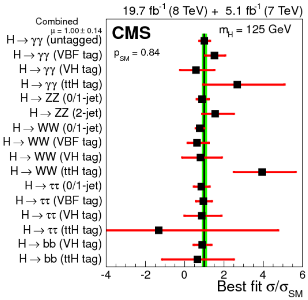
Introduction

If New Strong Dynamics (NSD) is present in Nature, we expect...

1. Low energy deviations: EWPT, Higgs, top couplings
2. Several composite states at $m \sim 4\pi f$
   e.g.: η, σ , ρ^μ, a^μ, ω^μ, composite fermions (e.g. top partner), etc
3. Strong Vector Boson Scattering

Low energy deviations



- Discovered Higgs h very SM-like
- Can be accomodated if h is a pseudo-NGB (Composite Higgs)
- Techni-dilaton component can be SM-like, $\sigma\pi\pi$ in QCD is misteriously described by linear sigma model
- top correction reduces h mass Foadi, Frandsen, Sannino 12'

- EWPT several studies including loop of composite resonances in CH SO(5)/SO(4)
  e.g. Contino, Salvarezza 15'
- top-Higgs sector still open to BSM (and the most prone for it)
- h-electron constrained by EDM measurements Altmannshofer, Brod, Schmaltz 15', but to light quarks harder task
- Higgs self-coupling completely unknown and open for BSM contributions - di-Higgs searches

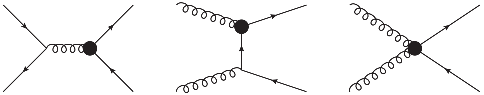
Indirect probes beyond EW precision: Top quark chromomagnetic dipole moment at NLO in QCD DBF, C.Zhang 15'

$$\mathcal{L}_{ttg} = g_s \bar{t}\gamma^\mu T^A t G^A_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}\left(d_V + i d_A \gamma_5\right) T^A t G^A_{\mu\nu}$$

- Naturally arises in various models of new physics, in particular in composite models (e.g. Martnez et al 08', Atwood et al 94') e.g. $d_V \gtrsim 0.001$.
- To go beyond LO calculation, a theoretical framework based on the dimension-six Lagrangian of the SM is required.

$$O_{tG} = y_t g_s \left(\bar{Q}\sigma^{\mu\nu} T^A t\right) \tilde{\phi} G^A_{\mu\nu} \ ,$$

- Main constrain comes from $t\bar{t}$ production.



Renormalization

O_{tG} contribution to top-quark and gluon fields renormalization

$$\delta Z_2^{(t)} = \delta Z_{2,SM}^{(t)} - C_{tG} \frac{2\alpha_s m_t^2}{\pi \Lambda^2} D_\varepsilon \left(\frac{1}{\varepsilon_{UV}} + \frac{1}{3} \right)$$

$$\delta m_t = \delta m_{t,SM} - C_{tG} \frac{4\alpha_s m_t^3}{\pi \Lambda^2} D_\varepsilon \left(\frac{1}{\varepsilon_{UV}} + \frac{1}{3} \right)$$

$$\delta Z_2^{(g)} = \delta Z_{2,SM}^{(g)} - C_{tG} \frac{2\alpha_s m_t^2}{\pi \Lambda^2} D_\varepsilon \frac{1}{\varepsilon_{UV}} \,,$$

g_s renormalization

$$\delta Z_{g_s} = \delta Z_{g_s,SM} + C_{tG} \frac{\alpha_s m_t^2}{\pi \Lambda^2} D_\varepsilon \frac{1}{\varepsilon_{UV}}$$

Running of C_{tG}.

$$\delta Z_{C_{tG}} = \frac{\alpha_s}{6\pi} \Gamma(1+\varepsilon)(4\pi)^\varepsilon$$

Framework

- Calculation in MadGraph5_aMC@NLO framework - O_{tG} implemented via FeynRules into UFO format.
- UV counterterms (from below) and the rational R2 terms (from NLOCT package) required by the OPP technique
- Matched to parton shower via the MC@NLO formalism.

Total Cross Section

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2 \qquad \mu_{R,F} = (\mu/2, \mu, 2\mu),\ \mu = m_t$$

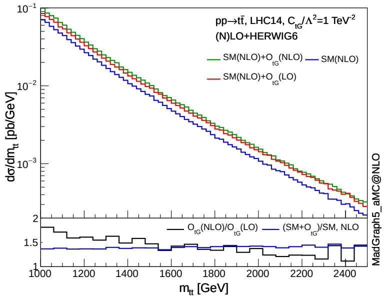
β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ $(+41\%)$ (-27%)	$1.810^{+0.073}_{-0.197}$ $(+4.05\%)$ (-10.88%)	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ $(+34\%)$ (-25%)	$72.62^{+9.26}_{-10.53}$ $(+12.7\%)$ (-14.5%)	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $(+29.7\%)$ (-22.4%)	$239.5^{+29.0}_{-31.8}$ $(+12.1\%)$ (-13.3%)	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $(+29.0\%)$ (-22.0%)	$283.0^{+33.6}_{-36.9}$ $(+11.9\%)$ (-13.1%)	1.48

C_{tG}/Λ^2	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

Distributions

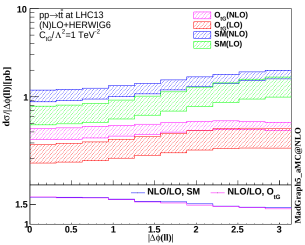
High mass cut suggested to enhance CMDM contribution, but...

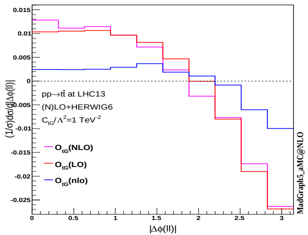
	no cuts	$m_{t\bar{t}} > 1$ TeV	$m_{t\bar{t}} > 2$ TeV
K (SM)	1.49	1.16	0.77
K (O_{tG})	1.49	1.14	0.69
O_{tG}(LO)/SM(LO)	0.32	0.28	0.29
O_{tG}(NLO)/SM(NLO)	0.32	0.28	0.26
O_{tG}(LO)/SM(NLO)	0.21	0.24	0.37



Decayed top distributions(MadSpin)

- Example: azimuthal difference of leptons - CMDM affect spin correlation;
- Sometimes perturbation expansion used incorrectly.





Test of a dynamical SM-fermion mass generation

Based on Alanne, DBF, Frandsen 16' and work in progress.

The observation of a η_X can shed light on the mass generation of SM-fermions

The possibilities:

1. High scale Extended Technicolor (ETC) $\to$ large coupling to top
2. Low scale induced *vev* to a scalar doublet (composite origin) $\to$ small coupling to top
3. Partial compositeness $\to$ intermediate (small?) see Flacke's talk

Exponential map of NGB of G/H SB pattern
Example $SU(2) \times SU(2)$ of G

$$\Sigma = \exp(i\pi/f), \quad \pi = \begin{pmatrix} \eta_X + \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & \eta_X - \pi^0 \end{pmatrix}$$

LO term:

$$\mathcal{L}_{\mathrm{K}} = \frac{f^2}{4}\mathrm{Tr}[D_\mu^\dagger \Sigma D^\mu \Sigma]$$

η anomaly-induced mass:

$$\mathcal{L}_m = \frac{m_{\eta_X}^2}{32} f^2 \mathrm{Tr}[\ln\Sigma - \ln\Sigma^\dagger]^2$$

ETC

- Four-fermion operator $\mathcal{O} \sim qqQQ$ generate by integrating out heavy vector or scalar

$$\mathcal{L}_{\rm ETC} = -Y_1 F_\pi f_1(h/F_\pi)\,(\bar{q}_{\rm L}\Sigma q_{\rm R}) - Y_2 F_\pi f_2(h/F_\pi)\,\left(\bar{q}_{\rm L}\Sigma\tau^3 q_{\rm R}\right) + {\rm h.c.}$$

- Fixing the masses $m_t = (Y_1 + Y_2)F_\pi$, and $m_b = (Y_1 - Y_2)F_\pi$ fixes also η coupling Higgs-ish, *e.g.*

$$\mathcal{L}_{\eta\bar{q}q} = -i\frac{m_t}{F_\pi}\eta_{\rm NMWT}\,\bar{t}\gamma^5 t - i\frac{m_b}{F_\pi}\eta_{\rm NMWT}\,\bar{b}\gamma^5 b$$

- $Y_{1,2}$ can be generated via integrating out a heavy scalar doublet

$$\mathcal{L}_{\rm Yuk} = -y_t\bar{q}_{\rm L}\tilde{\Phi}t_{\rm R} - y_b\bar{q}_{\rm L}\Phi b_{\rm R} - y_U\bar{Q}_{\rm L}\tilde{\Phi}U_{\rm R} - y_D\bar{Q}_{\rm L}\Phi D_{\rm R} + {\rm h.c.}$$

- $T \sim \delta^2 Y^4$, $Y \equiv \frac{1}{2}(y_U + y_D)$, $\delta \equiv \frac{y_U - y_D}{y_U + y_D}$
- alternatively can be generated by vector-current.

Induced *vev*

- The doublet can't be integrated out and acquires a *vev*, $v \to v_{\rm w}^2 = N_D F_\pi^2 + v^2$ - SM-fermion mass from v (e.g. Carone 12')
- Φ can be composite (Chivukula, Cohen, Lane 90') or fundamental
- $\sqrt{N_D} F_\pi \lesssim 0.4\, v_{\rm w}$ if the scalar excitation of Φ is interpreted as the Higgs.
- $F_\pi \gtrsim 0.25\, v_{\rm w}$ not to have a very light resonance spectrum in disagreement with direct search constraints.
- The (mostly-)η_X mass eigenstate couples to the top quark only via this mass mixing with π_f^0, $c_X \equiv y_X\, v_{\rm w}/m_t$

$$c_X \approx 8\sqrt{2}\pi c_1\, Y\delta \frac{F_\pi^2}{m_{\eta_X}^2} \frac{v_{\rm w}}{v} + \mathcal{O}(\delta^2)$$

- for $m_\Phi \ll \Lambda$, $T \sim \delta^2 Y^2 \to \delta \cdot Y \lesssim 0.2$ for $F_\pi > 0.25 v_{\rm w} \to c_X < 0.1$

Partial compositeness

- SM-fermion mix with composite state (Kaplan 91')
- $\mathcal{L}_{\rm pc} = (\kappa f QQQ + \tilde{\kappa} f^c Q^c Q^c Q^c) + \text{ h.c.}$
- $B \sim QQQ \to \mathcal{L}_{\rm eff} = \epsilon\,(fB + f^c B^c) - m_B B B^c + h.c.$
- SM-fermion mass: $m_f \approx \frac{\epsilon^2}{m_B}$
- mixing angle: $\alpha \approx \frac{\epsilon}{m_B}$
- The coupling between the η_1 state and the SM top quark arises from $\eta_1 B B^c$ interaction $g_{\eta BB} \approx \frac{C m_t}{f}$
- in QCD $\eta' pp$ coupling is very small, implying $C \ll 1$. On top of mixing suppression.

Benchmark scenarios

- Farhi-Susskind one-family model:
  $Q_L = (T_L, B_L)^T$, $Y = y$, $L_L = (N_L, E_L)^T$, $Y = -3y$,
  (T_R, B_R, N_R, L_R), $Y = (y+1, y-1, -3y+1, -3y-1)$
- S-model: L_L, N_R, E_R, S
- MWTC colorless

state	A_{gg}	$A_{\gamma\gamma}$	c_X^{ETC}
$\eta_1 \sim \frac{1}{4}(\bar{Q}i\gamma_5 Q + \bar{L}i\gamma_5 L)$	1	$\frac{8}{3}$	1
$\eta_{63} \sim \frac{1}{4\sqrt{3}}(\bar{Q}i\gamma_5 Q - 3\bar{L}i\gamma_5 L)$	$\frac{1}{\sqrt{3}}$	$\frac{-4}{3\sqrt{3}}$	$\frac{1}{\sqrt{3}}$
$\eta_S \sim \frac{1}{\sqrt{10}}(\bar{Q}i\gamma_5 Q + \bar{S}i\gamma_5 S)$	$\sqrt{\frac{2}{5}}$	$\sqrt{\frac{2}{5}}$	$\sqrt{\frac{2}{5}}$
$\eta_{25} \sim \frac{1}{2\sqrt{15}}(3\bar{Q}i\gamma_5 Q - 2\bar{S}i\gamma_5 S)$	$\frac{-2}{\sqrt{15}}$	$\sqrt{\frac{3}{5}}$	$\sqrt{\frac{3}{5}}$

$\mathcal{A}_{V_1 V_2} = \mathrm{Tr}[T^a (T_1 T_2 + T_2 T_1)_{\mathrm{L}} + \mathrm{L} \leftrightarrow \mathrm{R}],$

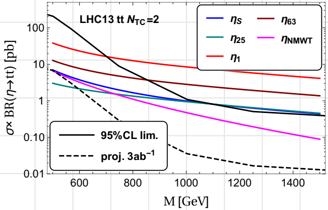
Experimental tests

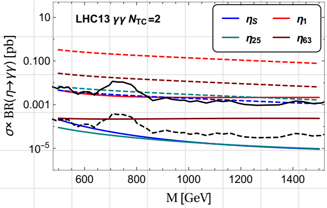
The diagnostic is therefore a large decay into tops in the ETC case and decays into jets and photons (and weak bosons) in the other cases.

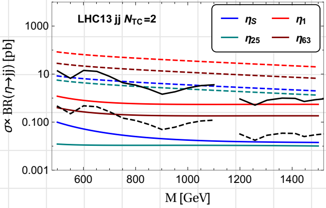
$$\Gamma_{\eta_X \to \bar{t}t} = \frac{3}{8\pi}\frac{m_t^2}{v_{\rm w}^2} c_X^2\, m_{\eta_X} \left(1 - m_t^2/m_{\eta_X}^2\right)^{1/2}$$

$$\Gamma_{\eta_X \to \gamma\gamma} \simeq \frac{\alpha^2 m_{\eta_X}^3}{256\pi^3 v_{\rm w}^2}\left|\frac{4}{3} c_X A_{1/2}^A(\tau_t) + \frac{N_{\rm TC}\, v_{\rm w}}{F_\pi}\mathcal{A}_{\gamma\gamma}^{\eta}\right|^2$$

$$\Gamma_{\eta_X \to gg} \simeq \frac{\alpha_s^2 m_{\eta_X}^3}{128\pi^3 v_{\rm w}^2}\left|c_X A_{1/2}^A(\tau_t) + \frac{2N_{\rm TC}\, v_{\rm w}}{F_\pi}\mathcal{A}_{gg}^{\eta}\right|^2$$







Searching for heavy resonances in top-quark pair production

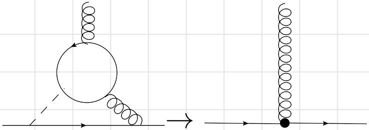
- More robust prediction is necessary
- QCD correction is very important for SM background and for signal (large k-factor)
- Interference effect is also very large
- Hence, QCD correction to interference expected to be important
- Only done in some approximation: e.g. real radiation + fixed k-factor, soft approximation Bernreuther et al. 15', Hespel et al. 16'

QCD corrections for EFT

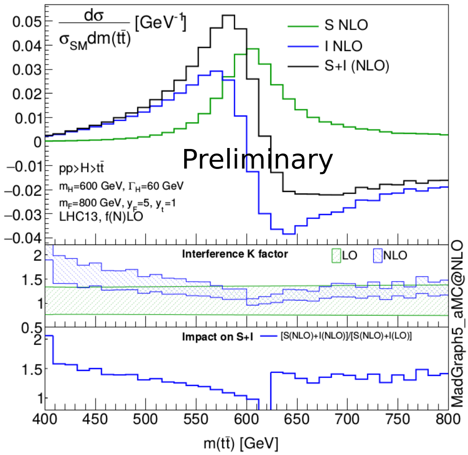
Based on DBF, Zhang (in progress)

$$\mathcal{L}_g = \frac{c_{HG}}{\Lambda}\alpha_S \sigma G^a_{\mu\nu} G^{a\mu\nu} + \frac{c_{HG5}}{\Lambda}\alpha_S \eta G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

Due to operator mixing: $\mathcal{L}_{ttg} = g_s y_t \bar{t} \sigma^{\mu\nu} T^A t G^A_{\mu\nu}$

- Model implemented in the UFO format through the Feynrules package.
- R2 and SM UV counter terms computed with NLOCT package
- EFT UV counter-terms computed via FeynArts + FormCalc
- Matching:  (from 1503.04830)

$\eta \to t\bar{t}$



dσ / σ_SM dm(tt̄) [GeV⁻¹]
S NLO
I NLO
S+I (NLO)
Preliminary
pp>H>tt̄
m_H=600 GeV, Γ_H=60 GeV
m_F=800 GeV, y_F=5, y_t=1
LHC13, f(N)LO
Interference K factor
LO
NLO
Impact on S+I
[S(NLO)+I(NLO)]/[S(NLO)+I(LO)]
MadGraph5_aMC@NLO
m(tt̄) [GeV]

Reconstructed study

Based on DBF, Fabbri, Schumman (in progress)

Goal: Get precise limits and projections for the discovery of scalar particles in top pair production

- experiments use poor BSM modeling (for instance ignore interference effects)
- theory papers usually use simple parton level studies
- Full form factor of top loop hard coded in the helicity amplitudes.

$$y_{t5} = c_t^{\eta} \frac{m_t}{v}$$
$$y_t = c_t^{\eta} \frac{m_t}{v}$$
$$c_{HG}/\Lambda = c_g^{\sigma} \frac{\alpha_S}{12\pi v}$$
$$c_{HG5}/\Lambda = -c_g^{\eta} \frac{\alpha_S}{8\pi v}$$
$$c_g^{\eta} = N_{TC} \mathcal{A}_{gg}(v/F_{\pi})$$

Simulation framework:

- Process: semi-leptonic top pair produciton
  $pp \to t\bar{t} \to b\bar{b}jj\ell\nu$ + jets
- Sherpa MC, ME+PS, Merging at LO and NLO - compared with aMC@NLO+Pythia8

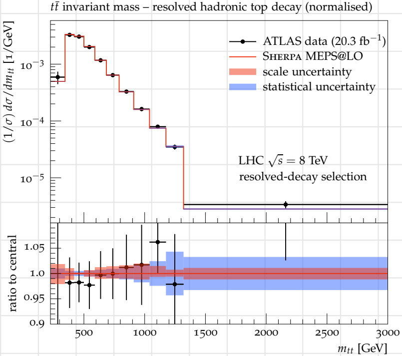
Analyses (using the Rivet program):

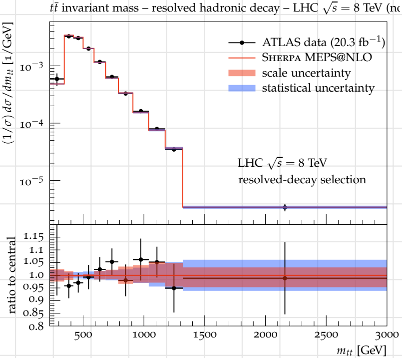
- Based on two ATLAS analyses
- The observed yield is corrected for detector effects to obtain a cross-section at particle level in a fiducial region close to the event selection.
- This allows us to use the particle level simulation to compare our predictions with data.
- Boosted: (1510.03818) The hadronically decaying top quark is reconstructed as an anti-k_t jet with radius parameter $R = 1.0$ and identified with jet substructure techniques.
- Resolved: (1511.04716) hadronic top decay can be resolved in three jets.

SM predictions

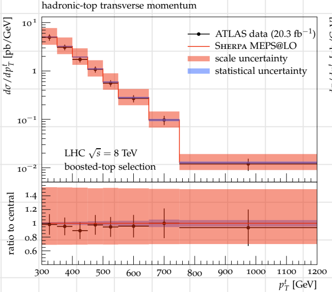
- The normalized distribution gives very robust theory prediction Czakon et al. 16'

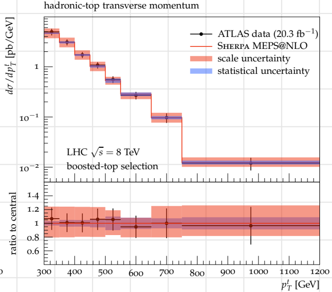
Resolved:





Boosted:


hadronic-top transverse momentum
ATLAS data (20.3 fb^{-1})
SHERPA MEPS@LO
scale uncertainty
statistical uncertainty
LHC $\sqrt{s}$ = 8 TeV
boosted-top selection
$d\sigma/dp_T^t$ [pb/GeV]
ratio to central
p_T^t [GeV]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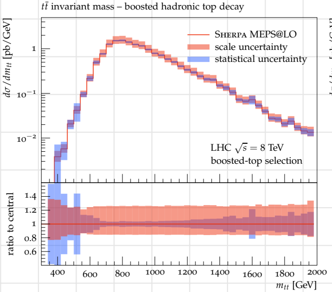
$t\bar{t}$ invariant mass – boosted hadronic top decay
SHERPA MEPS@LO
scale uncertainty
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LHC $\sqrt{s}$ = 8 TeV
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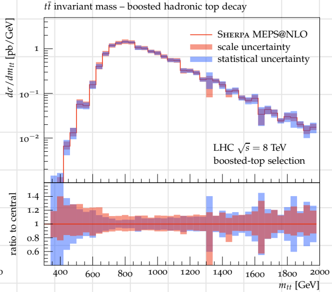
$d\sigma/dm_{tt}$ [pb/GeV]
ratio to central
m_{tt} [GeV]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scale uncertainty
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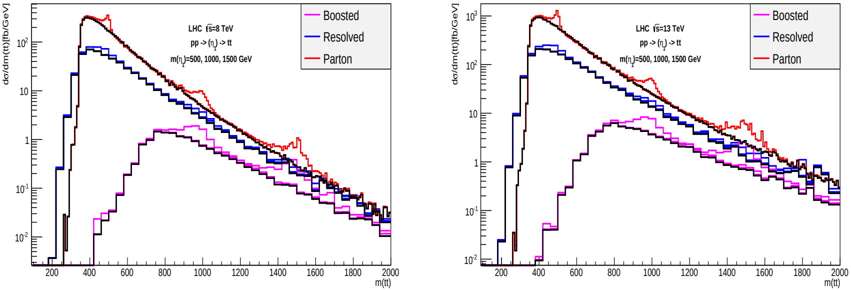
$d\sigma/dm_{tt}$ [pb/GeV]
ratio to central
m_{tt} [GeV]

BSM modeling

- the BSM part is only a small correction on top of SM background. We used a event-by-event reweighting by the amplitudes summed and averaged (including extra radiation)
- the PS has a SM profile. Interference color flow cannot be described by PS.



- QCD radiation and reconstruction effects are important and must be taken into account from theory predictions
- A statistical study is in progress for scanning several scenarios
- This search is important for composite dynamics

Vectors in $SU(4)/Sp(4)$

Based on DBF, Cacciapaglia, Cai, Deandrea, Frandsen

- In NSD the Higgs boson can also be part of a pseudo-Goldstone boson. Minimal scenario (FCD) $SU(4) \to Sp(4)$ - 2 Dirac flavours fund. of $SU(2)$ gauge theory.
- Vaccum alignment (1402.0233, 1001.1361, ...):

$$\Sigma_0 = \sin\theta \underbrace{\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}}_{\text{TC}} + \cos\theta \underbrace{\begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}}_{\text{CH (no EW breaking)}}$$

- GB+σ sector: 5 GB (3 eaten+ h, η) + 1 σ mixing w/ h (Arbey et al. 15')
- Loop induced and explicit techni-quark masses in the potential fix θ giving mass to h, η (η phenomenology hard, $\sigma \lesssim 1fb$)

Effective Lagrangian

- Follow Hidden Gauge symmetry approach
- $SU(4)_0 \times SU(4)_1 \to Sp(4)_0 \times Sp(4)_1 \to Sp(4)$
- 2 copies of pion matrix U_i to $SU(4) \to Sp(4)$
  $D_\mu U_0 = (\partial_\mu - ig\widetilde{\mathbf{W}}_\mu - ig'\mathbf{B}_\mu)U_0$
  $D_\mu U_1 = (\partial_\mu - i\tilde{g}\boldsymbol{\mathcal{V}}_\mu - i\tilde{g}\boldsymbol{\mathcal{A}}_\mu)U_1$
- K introduced to break $Sp(4) \times Sp(4) \to Sp(4)$
- $p_{\mu\,i} = 2\sum_a \text{Tr}\left(Y_a \omega_{R\,i,\mu}\right) Y_a$, transform homogeneously
  $p_{\mu\,i} \to h(g_i,\pi_i)\, p_{\mu\,i}\, h^\dagger(g_i,\pi_i)$

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{2g^2}\,\text{Tr}\,\widetilde{\mathbf{W}}_{\mu\nu}\widetilde{\mathbf{W}}^{\mu\nu} - \frac{1}{2g'^2}\,\text{Tr}\,\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{\kappa_F(\sigma)}{2\tilde{g}^2}\,\text{Tr}\,\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu} \\
&+ \frac{1}{2}\kappa_{G_0}(\sigma) f_0^2\,\text{Tr}\,p_{0\mu}p_0^\mu + \frac{1}{2}\kappa_{G_1}(\sigma) f_1^2\,\text{Tr}\,p_{1\mu}p_1^\mu + r(\sigma) f_1^2\,\text{Tr}\,p_{0\mu}Kp_1^\mu K^\dagger \\
&+ \frac{1}{2}\kappa_K(\sigma) f_K^2\,\text{Tr}\,\mathcal{D}^\mu K\,\mathcal{D}_\mu K^\dagger + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \mathcal{V}(\sigma) \\
&+ \mathcal{L}_{fermions}
\end{aligned}$$

Properties

$$\mathcal{F}_\mu = \boldsymbol{\mathcal{V}}_\mu + \boldsymbol{\mathcal{A}}_\mu = \sum_{a=1}^{10} \mathcal{V}_\mu^a V_a + \sum_{a=1}^{5} \mathcal{A}_\mu^a Y_a .$$

		$SU(2)_V$	$SU(2)_L \times SU(2)_R$	TC	CH
$\mathcal{V}$	$v_\mu^{0,\pm}$	3	$(3,1) \oplus (1,3)$	$\vec{\rho}_\mu$	$\vec{\rho}_\mu$
	$s_\mu^{0,\pm}$	3			$\vec{a}_\mu$
	$\tilde{s}_\mu^{0,\pm}$	3	$(2,2)$		
	$\tilde{v}_\mu^{0}$	1			
$\mathcal{A}$	$a_\mu^{0,\pm}$	3	$(2,2)$	$\vec{a}_\mu$	
	x_μ^{0}	1			
	$\tilde{x}_\mu^{0}$	1	$(1,1)$		

- $\widetilde{s}_\mu^{\pm,0}$, $\widetilde{v}_\mu^0$, x_μ^0 and $\widetilde{x}_\mu^0$ do not mix $M_{\widetilde{s}} = M_{\widetilde{v}^0} = M_V$ and $M_{x^0} = M_{\widetilde{x}^0} = M_A$
- Masses: $M_{A^+}^2 = M_A^2 \left[1 + \frac{1}{2}\left(\frac{g}{\widetilde{g}}\right)^2 r^2 s_\theta^2 + \mathcal{O}\left(1/\widetilde{g}^4\right)\right]$ $M_{S^+}^2 = M_V^2$

  $M_{V^+}^2 = M_V^2 \left[1 + \frac{1}{2}\left(\frac{g}{\widetilde{g}}\right)^2 (2 - s_\theta^2) + \mathcal{O}\left(1/\widetilde{g}^4\right)\right]$

  $M_{A^0}^2 = M_A^2 \left[1 + \frac{r^2(g^2+g'^2)s_\theta^2}{2\widetilde{g}^2} + \mathcal{O}\left(1/\widetilde{g}^4\right)\right]$

  $M_{V^0/S^0}^2 =$

  $M_V^2 \left[1 + \frac{g^2+g'^2}{4\widetilde{g}^2}\left(1 + c_\theta^2 \pm \sqrt{1 + 2\frac{(g'^4 - 6g'^2g^2+g^4)}{(g^2+g'^2)^2}c_\theta^2 + c_\theta^4}\right) + \mathcal{O}\left((1/\widetilde{g})^4\right)\right]$
- $v^2 \equiv \frac{1}{\sqrt{2}G_F} = \frac{-4}{g^2}\Pi_{W^+W^-}(0) = \frac{4}{g^2}\frac{1}{\left[\mathcal{M}_{\mathrm{C}}^{2\,-1}\right]^{11}} =$

  $2(M_V^2\frac{f_0^2}{f_K^2} - M_A^2 r^2)s_\theta^2/\tilde{g}^2$

  $v^2 = \left(f_0^2 - r^2 f_1^2\right)\sin^2\theta = f_\pi^2 \sin^2\theta$

EWPT

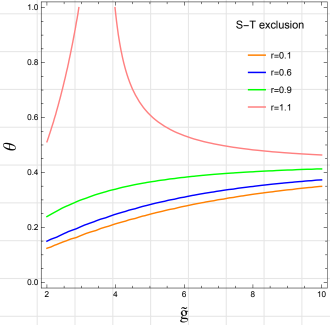
Vector contribution:

$$\hat{S} = -\frac{g^2\left(r^2-1\right)s_\theta^2}{2\tilde{g}^2+g^2\left[2+(r^2-1)s_\theta^2\right]}$$

$$W = \frac{g^2 M_W^2\left[s_\theta^2\left(r^2 M_V^2 - M_A^2\right)+2M_A^2\right]}{M_A^2 M_V^2\left\{g^2\left[\left(r^2-1\right)s_\theta^2+2\right]+2\tilde{g}^2\right\}}$$

$$Y = \frac{g'^2 M_W^2\left[s_\theta^2\left(r^2 M_V^2 - M_A^2\right)+2M_A^2\right]}{M_A^2 M_V^2\left\{2\tilde{g}^2+g'^2\left[\left(r^2-1\right)s_\theta^2+2\right]\right\}}$$

$$X = \frac{g g' s_\theta^2 M_W^2\left(M_A^2 - r^2 M_V^2\right)}{M_A^2 M_V^2\sqrt{\left\{g^2\left[\left(r^2-1\right)s_\theta^2+2\right]+2\tilde{g}^2\right\}\left\{2\tilde{g}^2+g'^2\left[\left(r^2-1\right)s_\theta^2+2\right]\right\}}}$$



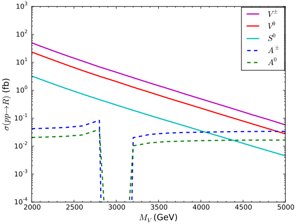
Higgs loop contribution:

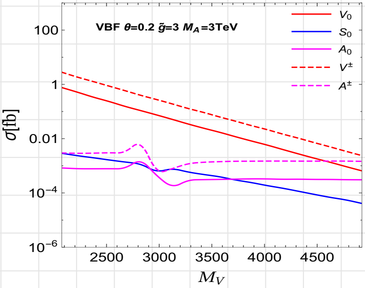
$$\Delta S = \frac{1}{6\pi}\left[(1-\kappa_V^2)\log\left(\frac{\Lambda}{m_h}\right)+\log\left(\frac{m_h}{m_{h,ref}}\right)\right]$$

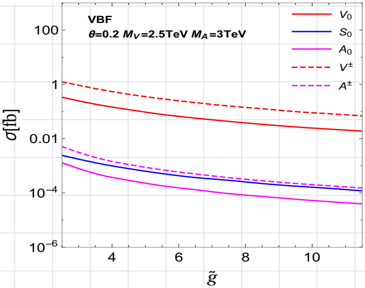
$$\Delta T = -\frac{3}{8\pi\cos^2\theta_W}\left[(1-\kappa_V^2)\ln\frac{\Lambda}{m_h}+\log\left(\frac{m_h}{m_{h,ref}}\right)\right]$$

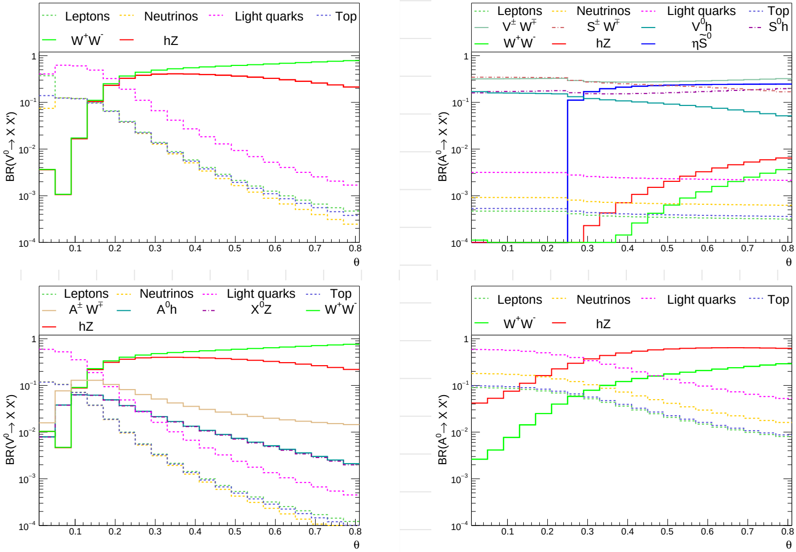
LHC-RunII phenomenology

Model implemented in UFO via FeynRules
available in HEPMDB



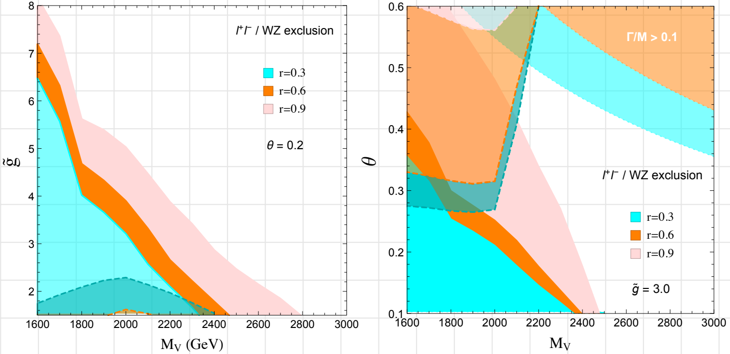






$\tilde{g} = 3$, $r = 0.6$, $M_A = 3$ TeV, $M_A = 2.5(3.5)$ TeV

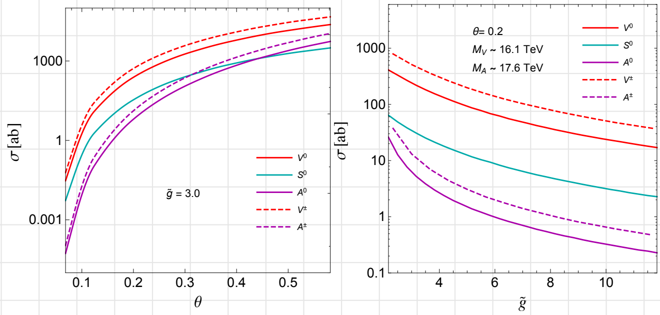
Limits:



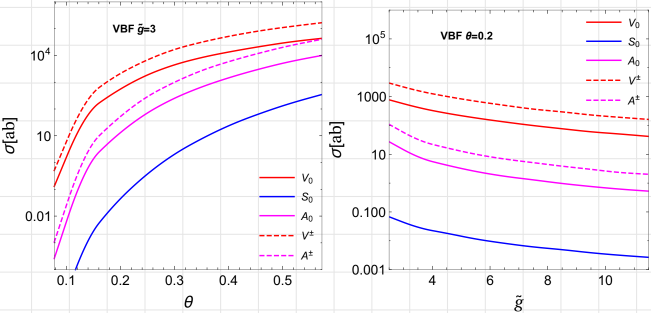
$M_A = M_V$, solid: DY, dashed: WZ

100 TeV collider

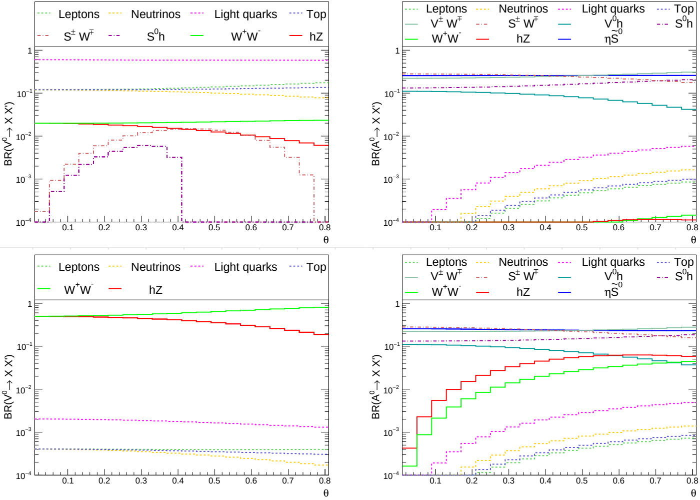
- Benchmark: Lattice result from SU(2)$_{FCD}$, $M_V = 3.2(5)/\sin\theta$ TeV $M_A = 3.6(9)/\sin\theta$ TeV Arthur, Drach, Hansen, Hietanen, Pica, Sannino 16'
- a case for 100 TeV collider



VBF


VBF $\tilde{g}$=3
10^4
10
0.01
σ[ab]
0.1
0.2
0.3
0.4
0.5
θ
V_0
S_0
A_0
$V^\pm$
$A^\pm$
VBF θ=0.2
10^5
1000
10
0.100
0.001
4
6
8
10
$\tilde{g}$

BRs

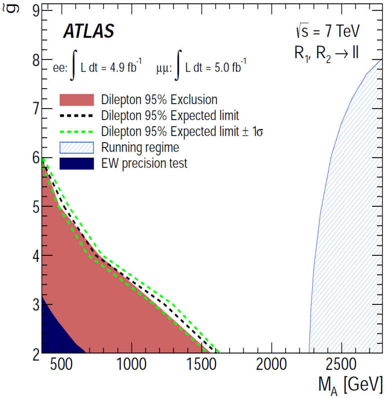

Leptons
Neutrinos
Light quarks
Top
S± W∓
S⁰h
W⁺W⁻
hZ
V± W∓
V⁰h
ηS̃⁰
BR(V⁰→ X X')
BR(A⁰→ X X')
θ

r=1(1.1)

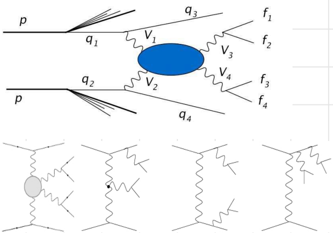
- The model presents a rich phenomenology which cannot be described by other realizations, e.g.:
  - CH SO(5)/SO(4) v, s Contino, D. Marzocca, D. Pappadopulo and R. Rattazzi 11'
  - 1, 2 triplets e.g. Belyaev, Foadi, Frandsen, Jarvinen, Sannino, Pukhov, 08'
- The decay pattern contains "tilded" states, which can generate interesting decay cascates
- Walking dynamics predicts small $S = 4\pi\left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right)$, indicating an extra spectral symmetry $SU(2)'_L \times SU(2)'_R$ (besides the usual custodial symmetry protecting the T parameter) Becciolini, Franzosi, Foadi, Frandsen, Hapola, Sannino 14'
- Near degenerate V A could indicate Walking dynamics

Strong Vector Boson Scattering

- Dominant production of vector resonances through fermion couplings, which are suppressed by $g/\tilde{g}$
- Direct production becomes increasingly kinematically forbidden as the technimesons become heavier;
- VBS may play an important.

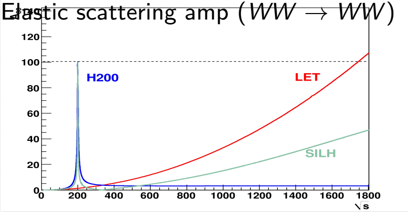


VBS signal (Ballestrero, Bevilacqua, D.B.F, Maina; DBF, Foadi)

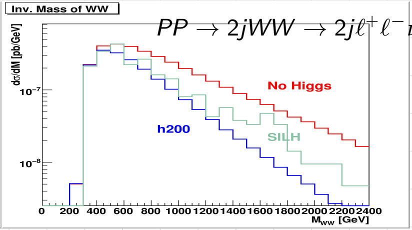


- Longitudinal boson scattering is not fully unitarized by the Higgs boson.
- An excess of events is expected at high energy
- We can observe VB's only through their decays into fermions;

Elastic scattering amp $(WW \to WW)$



$PP \to 2jWW \to 2j\ell^+\ell^-\nu\nu$



Strategy

Our goal is to estimate the power of the LHC in discriminating between the SM and alternative strong-EWSB scenarios through VBS.

The 7 channels:

totally leptonic

$PP \to jj\ell^+\ell^-\ell'\nu$

$PP \to jj\ell^\pm\ell^\pm\nu\nu$

$PP \to jj\ell^+\ell^-\ell^+\ell^-$

$PP \to jjW^+W^- \to jj\ell^+\ell^-\nu\nu$

$PP \to jjZZ \to jj\ell^+\ell^-\nu\nu$

semi-leptonic

$PP \to jjjj\ell\nu$

$PP \to jjjj\ell^+\ell^-$

$\ell = \mu,\, e$

1. Event generation;
2. Study of signal and background;
3. Statistical treatment.

Scenarios of strong VBS:

- NO HIGGS: benchmark scenario used for defining selection cuts. Unitarity violation supressed by steep PDF decrease.
- SILH: $c_H\xi = 1$. Intended as an upper-limit for the effective description.
- Unitarization Models: description of VBS beyond unitarity violation scale. A. Ballestrero, D.B.F., L. Oggero, E. Maina, 11'
  Implementation of EWChL and UM for VBS in PHANTOM in a $2 \to 6$ framework.
- Technicolor: implementation in MadGraph. D.B.F., R. Foadi, 12'

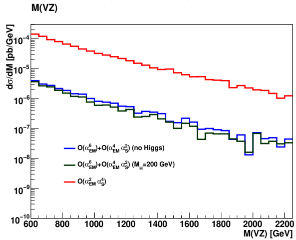
Study of signal and background

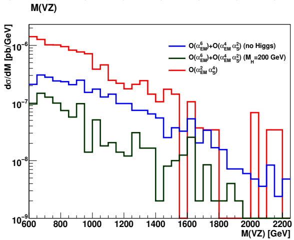
Basic signature:

- tag-jets: two high energetic jets in forward-backward direction;
- two pairs of fermions associated with the two bosons in the central region with high P_T;
- bosons approximately back-to-back in azimuthal plane;
- little color activity close to bosons...

Each channel has its particular properties,

e.g: $PP \to 4j\ell^+\ell^-$

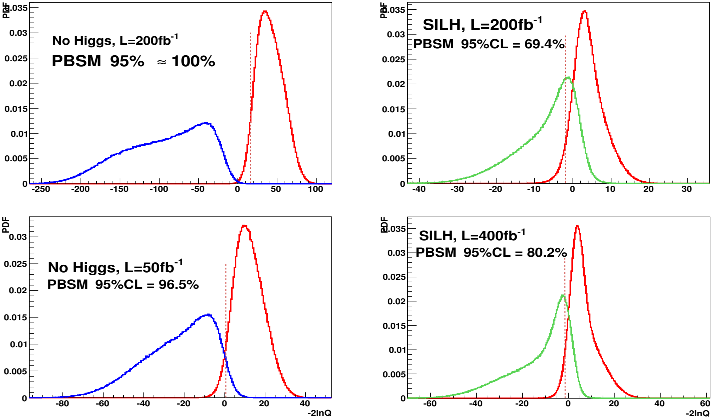




$M(j_f j_b) > 1000$ GeV
$\Delta\eta(j_f j_b) > 4.8$
$\lvert\eta(\ell)\rvert < 2$
$\Delta R(jj) > 0.3$
$p_T(\ell\ell) > 200$ GeV
$\Delta\eta(Vj) > 1.1$
$p_T(j_c) > 60$ GeV
$p_T(j_c j_c) > 200$ GeV
$\max[\eta(j)] > 2.8$
$\Delta R(\ell,\ell) < 1$
$M(j_c j_c \ell\ell) > 600$ GeV

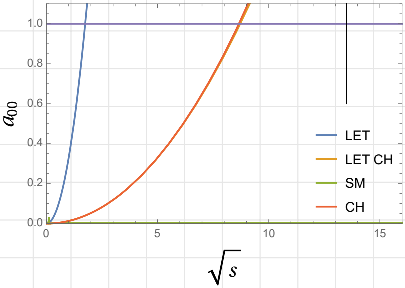
Combination of all 7 channels

- Likelihood ratio defined as $Q(\mathbf{S}; \bar{\mathbf{S}}_{BSM}, \bar{\mathbf{S}}_{SM}) = P(\mathbf{S}; \bar{\mathbf{S}}_{BSM}) / P(\mathbf{S}; \bar{\mathbf{S}}_{\mathbf{SM}})$.



σ

- In $SU(4)/Sp(4)$ $g/g_{SM} = \sin(\theta - \alpha) + (\kappa - 1)\sin\theta\cos\alpha$ (1502.04718)
  Leads to weak constraints
- My naive mass estimate ($\theta = 0.2$, $a_{00} = 2\frac{s}{v^2}\sin^2\theta$)



Effective theory approach to the lineshape of broad resonances D.B.F., F. Maltoni, C. Zhang 13'

- The width of σ turns out to be sizable. A large width induces both a smearing and deformation of the signal line shape;
- The definition of a width, which amounts to a resummation of a specific subset of terms appearing at all orders in perturbation theory becomes problematic, leading to possible violations of gauge symmetry as well as of unitarity;
- We propose to systematically include width effects via a set of gauge invariant higher dimensional terms to the SM lagrangian.

Setting up the stage

- Using the full resumed propagator leads to gauge violation already at tree level.

$$\Delta_H^{-1}(s) = \frac{1}{s - s_H + \Pi_{HH}^R(s)}$$

- in perturbation theory gauge invariance is guaranteed order by order while the presence of a width implies the resummation of a specific subset of higher order contributions, the self-energy corrections.
- The gauge cancellation for example in $V_L V_L$ scattering or in $f_\pm \bar{f}_\pm \to W_L^+ W_L^-$ is guaranteed by WI, e.g.:

$$k_+^\mu k_-^\nu \Gamma_{\mu\nu}^{HWW}(q, k_+, k_-) = -m_W^2 \Gamma^{H\phi^+\phi^-}(q, k_+, k_-) + \frac{igm_W}{2}\Delta_H(q^2)$$

- approaches to restore gauge invariance, such as the complex mass scheme, fermion loop scheme and Pinch Technique do not resum the complete self-energy and running width effects.

The EFT approach

- associate radiative corrections to an ad hoc constructed gauge-invariant operator and match the operator to the one-loop two-point function $\Delta_H(s)$;
- Taylor expansion of the function $\Pi(s) = \Pi^R_{HH}(s)$ and add a series of operators to the Lagrangian:

$$\mathcal{O}_\Pi = \sum_{i=0}^{\infty} c_i \phi^\dagger (-D^2)^i \phi$$

- The addition of this operator to the SM leads to the changes: 1- it gives rise to a resummed propagator and 2- it leads to modifications of the other interactions, in such a way that gauge invariance is maintained.

Improved Operator

- in $VV \to VV$ this operator fixes the high energy behavior but produces an unphysical excess at low energy. The reason for the excess is that the operator does not correctly describe the 1-loop HVV vertex at low energy.
- This can be traced back to the WI. The operator $\tilde{\mathcal{O}}_\Pi$ does not modify $\Gamma^{H\phi^+\phi^-}$, hence, the equality relation is completely satisfied by the HWW vertex;
- the solution is to include the complementary operator:

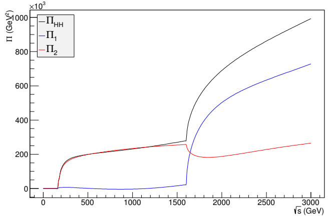
$$\mathcal{O}'_{\Pi_2} = \frac{1}{2v^2}\left(\phi^\dagger\phi - v^2\right)\Pi_2(-\partial^2)\left(\phi^\dagger\phi - v^2\right)$$

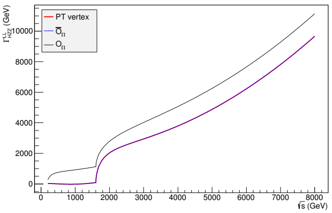
and changing the other one:

$$\mathcal{O}_{\Pi_1} = \phi^\dagger \Pi_1(-D^2)\phi\,.$$

- fixing $\Pi_1(s)$ according to the $\Gamma^{H\phi^+\phi^-}$ and $\Pi(s) = \Pi_1(s) + \Pi_2(s)$, we can extract the contributions from each operators to the total self energy:

$$\bar{\mathcal{O}}_\Pi = \mathcal{O}_{\Pi_1} + \mathcal{O}'_{\Pi_2}$$





Applications

- The treatment of the propagator of a scalar is of immediate relevance for the colliders. As simple testing ground of our proposal and comparisons to the conventional methods, we consider three processes of particular phenomenological importance at the LHC for a scalar boson: vector boson scattering, $t\bar{t}$ production via vector boson fusion and Higgs production via gluon fusion.
- compare the EFT scheme with:

$$\text{Naive propagator: } \frac{i}{\Delta_H(s)} = \frac{i}{s - s_H + \Pi_R(s)}$$

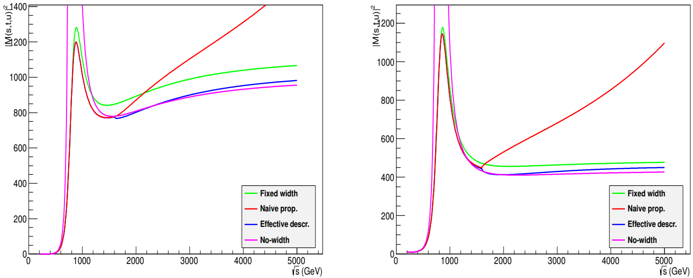
$$\text{Fixed width: } \frac{i}{\Delta_H(s)} = \frac{i}{s - s_H}$$

$$\Pi^R_{HH}(s) = \Pi_{HH}(s) - \Pi_{HH}(s_H) - (s - s_H)\Pi'_{HH}(s_H)$$

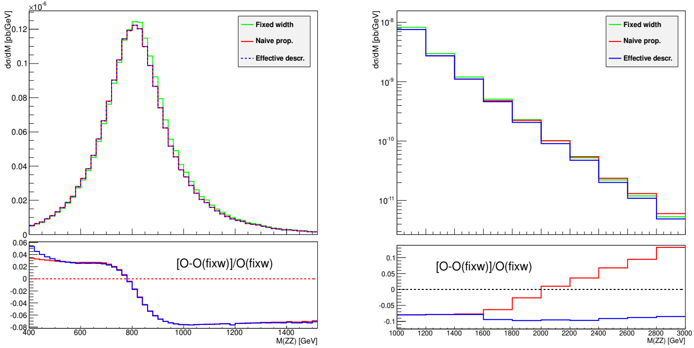
- the EFT scheme has been implemented in MG and MCFM (for gluon fusion).

Vector Boson scattering

- complete description of the Higgs line-shape at the resonance region;
- it corrects the bad high-energy behavior originated from the momenta dependent part of the self energy;
- avoids spurious t-channel widths of the complex-mass scheme also affecting the high energy behavior of amplitudes.

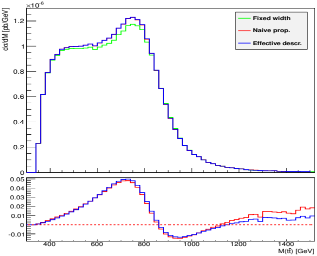


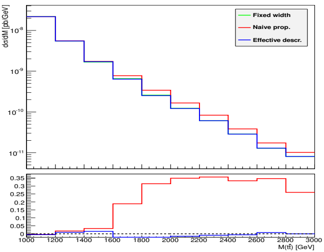
At the LHC, these differences may be important for broad resonance searches.
E.g. $uc \to ucZZ$ (basic kinematical cuts applied):



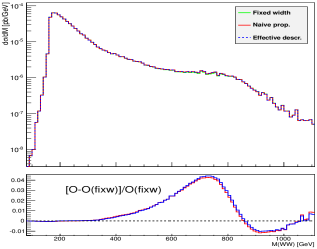
Broad scalars

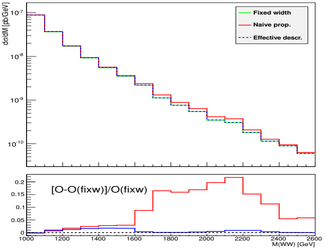
- $us \to dct\bar{t}$





- $gg \to W^+W^-$





Conclusion

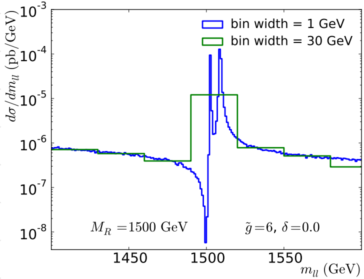
- I discussed several signals of Composite Dynamics expected at colliders...
- and presented methods, tools and techniques to improve their predictions

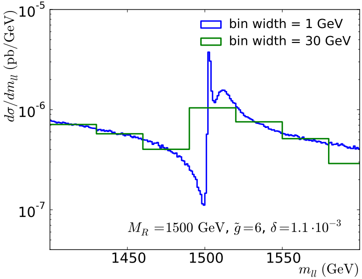
Effective Lagrangian

- Follow Hidden Gauge symmetry approach
- $SU(4)_0 \times SU(4)_1 \to Sp(4)_0 \times Sp(4)_1 \to Sp(4)$
- $U_i = \exp\left[\frac{i\sqrt{2}}{f_i}\sum_{a=1}^{5}(\pi_i^a Y^a)\right]$, $i = 1, 2$
- $U_i \to U_i' = g_i U_i h(g_i, \pi_i)^\dagger$
- $\omega_{R\,i,\mu} = U_i^\dagger D_\mu U_i$
- $D_\mu U_0 = (\partial_\mu - ig\widetilde{\mathbf{W}}_\mu - ig'\mathbf{B}_\mu)U_0$
  $D_\mu U_1 = (\partial_\mu - i\widetilde{g}\boldsymbol{\mathcal{V}}_\mu - i\widetilde{g}\boldsymbol{\mathcal{A}}_\mu)U_1$
- $\mathbf{B}_\mu = B_\mu\ S_6$, $\quad \widetilde{\mathbf{W}}_\mu = \sum_{a=1}^{3}\widetilde{W}_\mu^a\ S_a$
  $\boldsymbol{\mathcal{V}}_\mu = \sum_{a=1}^{10}\mathcal{V}_\mu^a\ V_a$, $\quad \boldsymbol{\mathcal{A}}_\mu = \sum_{a=1}^{5}\mathcal{A}_\mu^a\ Y_a$
- $p_{\mu\,i} = 2\sum_a \mathrm{Tr}\left(Y_a \omega_{R\,i,\mu}\right) Y_a$, $v_{\mu\,i} = 2\sum_a \mathrm{Tr}\left(V_a \omega_{R\,i,\mu}\right) V_a$

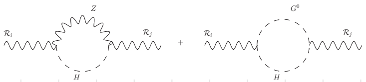
LHC Phenomenology

- Production dominated by Drell-Yan
- Decay to fermions preferred, $\Gamma^{\bar{f}f'}_{\mathcal{R}_i} \sim \Gamma^{VV'}_{\mathcal{R}_i} \sim \frac{1}{a}\Gamma^{HV}_{\mathcal{R}_i} \sim \frac{M_R}{\tilde{g}^2}$
- a-parameter tune the Higgs-weak boson couplings - and total width.
- Peculiar phenomenology in di-lepton - small splitting, $\frac{\Delta M}{M_R} \simeq \frac{0.16}{\tilde{g}^2}$ and overlap resonances for $a \gtrsim 1$.

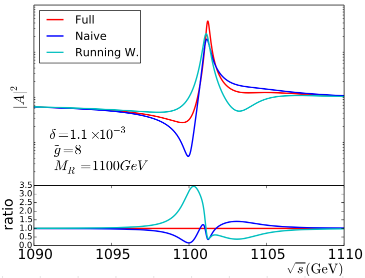




Off-diagonal width



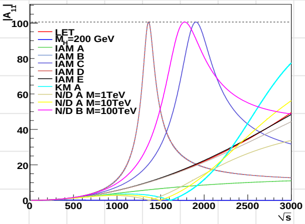
$$i\Delta = \frac{i}{D}\begin{pmatrix} p^2 - m_2^2 + i\Sigma_{22} & -i\Sigma_{12} \\ -i\Sigma_{21} & p^2 - m_1^2 + i\Sigma_{11} \end{pmatrix}$$

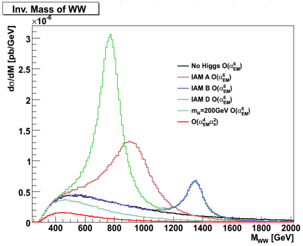


Field	Fermion currents	P	C
Massive spin-1 $\mathcal{V}_\mu$ (unbroken generators)			
v^+	$\overline{D}\gamma^\mu U$		
v^0	$\frac{1}{\sqrt{2}}\left(\overline{U}\gamma^\mu U - \overline{D}\gamma^\mu D\right)$	$-$	$-$
v^-	$\overline{U}\gamma^\mu D$		
$\tilde{v}^0$	$\sqrt{2}\cos\theta\,\Im\left(U^T C\gamma^\mu D\right) + \frac{1}{\sqrt{2}}\sin\theta\,\left(\overline{U}\gamma^\mu U + \overline{D}\gamma^\mu D\right)$	$-$	$-$
s^+	$\cos\theta\,\left(\overline{D}\gamma^\mu\gamma^5 U\right) + \frac{i}{2}\sin\theta\,\left(U^T C\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right)$		
s^0	$-\frac{1}{\sqrt{2}}\cos\theta\,\left(\overline{U}\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu\gamma^5 D\right) - \sqrt{2}\sin\theta\,\Im\left(U^T C\gamma^\mu\gamma^5 D\right)$	$+$	$+$
s^-	$\cos\theta\,\left(\overline{U}\gamma^\mu\gamma^5 D\right) + \frac{i}{2}\sin\theta\,\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T - D^T C\gamma^\mu\gamma^5 D\right)$		
$\tilde{s}^+$	$\frac{i}{2}\left(U^T C\gamma^\mu\gamma^5 U + \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right)$		
$\tilde{s}^0$	$\sqrt{2}\,\Re\left(U^T C\gamma^\mu\gamma^5 D\right)$	$+$	$-$
$\tilde{s}^-$	$\frac{i}{2}\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T + D^T C\gamma^\mu\gamma^5 D\right)$		
Massive spin-1 $\mathcal{A}_\mu$ (broken generators)			
a^+	$\frac{i}{2}\cos\theta\,\left(U^T C\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right) - \sin\theta\,\left(\overline{D}\gamma^\mu\gamma^5 U\right)$		
a^0	$-\sqrt{2}\cos\theta\,\Im\left(U^T C\gamma^\mu\gamma^5 D\right) + \frac{1}{\sqrt{2}}\sin\theta\,\left(\overline{U}\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu\gamma^5 D\right)$	$+$	$+$
a^-	$\frac{i}{2}\cos\theta\,\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T - D^T C\gamma^\mu\gamma^5 D\right) - \sin\theta\,\left(\overline{U}\gamma^\mu\gamma^5 D\right)$		
[illegible]	$\sqrt{2}\,\Re\left(U^T C\gamma^\mu D\right)$		$+$

Unitarization Models

$$\hat{A}_{IJ}^{KM}(s) = \frac{32\pi}{32\pi Re(1/A_{IJ}(s)) - i} \; ; \; \hat{A}_{IJ}^{IAM}(s) = \frac{A_{IJ}^{(1)}(s)}{1 - A_{IJ}^{(2)}(s)/A_{IJ}^{(1)}(s)} \; ; \; \hat{A}_{IJ}^{N/D}(s) = \frac{N_{IJ}(s)}{D_{IJ}(s)} \; ;$$





some Feynman rules:

$$\Delta^{-1}_{W,Z} = \frac{i}{q^2 - m^2_{W,Z}} \left[-g^{\mu\nu} + \frac{\left(1 + \frac{m^2_{W,Z}\Pi''(q^2)}{1+\Pi'(0)}\right) q^\mu q^\nu}{m^2_{W,Z} + q^2 \frac{m^2_{W,Z}\Pi''(q^2)}{1+\Pi'(0)}} \right]$$

$$H(q)W^{+\mu}(k_1)W^{-\nu}(k_2) \to ig\frac{m_W}{\sqrt{1+\Pi'(0)}}\Pi'(q^2)g^{\mu\nu} + \cdots$$

$$Z^\mu(k_1)W^{+\nu}(k_2)W^{-\rho}(k_3) \to i\frac{g}{c_W}\frac{m^2_W}{1+\Pi'(0)}s^2_W\left[\Pi''(k_3^2)g^{\mu\nu}k_3^\rho - \Pi''(k_2^2)g^{\mu\rho}k_2^\nu\right] + \cdots$$

$$Z^\mu(k_1)Z^\nu(k_2)W^{+\rho}(k_3)W^{-\sigma}(k_4)$$

$$\to ig^2\frac{m^2_Z}{1+\Pi'(0)}\left[\Pi''(s)g^{\mu\nu}g^{\rho\sigma} + s^4_W(\Pi''(t)g^{\mu\rho}g^{\nu\sigma} + \Pi''(u)g^{\mu\sigma}g^{\nu\rho})\right] + \cdots$$

$$H\phi^+\phi^-,\ H\phi^0\phi^0 \to -i\frac{g[m^2_H - \Pi(0)]}{2m_W}\sqrt{1+\Pi'(0)}$$

$$\phi^+\phi^-\phi^0\phi^0 \to -i\frac{g^2[m^2_H - \Pi(0)]}{4m^2_W}[1+\Pi'(0)]$$

Operator mixing

- $O_{tG} \to O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ and several four-fermion operators: vanish because O_{tG} is effectively a 5-dim operator after SB.
- $O_{tG} \to O_{\phi G} = g_s^2 \left(\phi^\dagger \phi\right) G_{\mu\nu}^A G^{A\mu\nu}$: $\mathcal{O}(y_t^2)$.