Probing Electroweak Symmetry Breaking in the TeV region

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EW Effective Lagrangian & WW Scattering @ LHC

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The Road Map

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Energy Scale:	preSpS	SpS	LEP	Tevatron
Effective Theory:	4-fermi Lag. below WZ	Chiral Lag. below Higgs	Chiral Lag prefer light higgs	Chiral Lag with top

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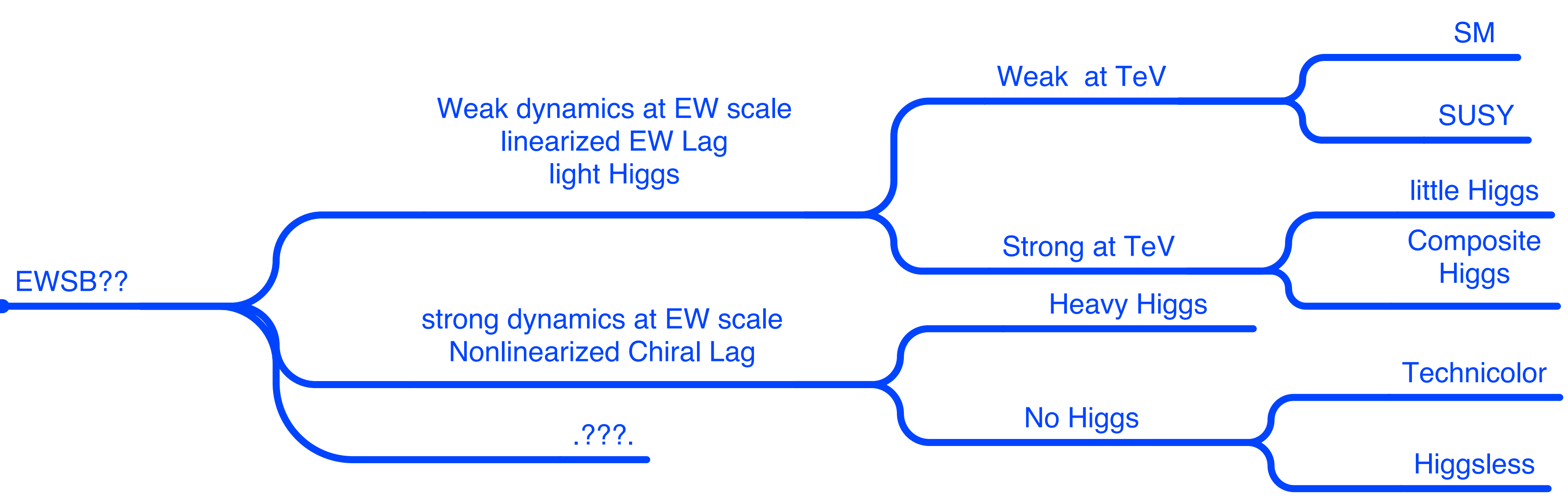
Energy Scale:	LHC	ILC?	???

Effective Theory:



Observable & Parametrization

- LEP I & II, SLD, Tevatron Data:

	Notation	Value	SM prediction
Atomic parity violation	$Q_W(Cs)$	-72.62 ± 0.46	-73.17 ± 0.03
	$Q_W(Tl)$	-116.6 ± 3.7	-116.78 ± 0.05
Muon $g-2$	$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})[10^{-9}]$	4511.07 ± 0.82	4509.82 ± 0.10
ν-nucleon scattering	g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021
	g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003
ν-e scattering	$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003
	$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001
$e^+e^- \to f\bar{f}$ at Z-pole	$\Gamma_Z[\mathrm{GeV}]$	2.4952 ± 0.0023	2.4968 ± 0.0011
	$\sigma_h^0[\mathrm{nb}]$	41.541 ± 0.037	41.467 ± 0.009
	R_e^0	20.804 ± 0.050	20.756 ± 0.011
	R_μ^0	20.785 ± 0.033	20.756 ± 0.011
	R_τ^0	20.764 ± 0.045	20.801 ± 0.011
	R_b	0.21629 ± 0.00066	0.21578 ± 0.00010
	R_c	0.1721 ± 0.0030	0.17230 ± 0.00004
	$A_{fb}^{0,e}$	0.0145 ± 0.0025	0.01622 ± 0.00025
	$A_{fb}^{0,\mu}$	0.0169 ± 0.0025	0.01622 ± 0.00025
	$A_{fb}^{0,\tau}$	0.0188 ± 0.0017	0.01622 ± 0.00025
	$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1031 ± 0.0008
	$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0737 ± 0.0006
	$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2319 ± 0.0012	0.23152 ± 0.00014
	A_e	0.1514 ± 0.0019	0.1471 ± 0.0011
	A_μ	0.142 ± 0.015	0.1471 ± 0.0011
	A_τ	0.1433 ± 0.0041	0.1471 ± 0.0011
Fermion pair production at LEP 2	$\sigma_f(f = q, \mu, \tau)$	Ref. 3	Ref. 3
	$A_{fb}^f(f = \mu, \tau)$	Ref. 3	Ref. 3
	$d\sigma_e/d\cos\theta$	Ref. 26	Ref. 27
W pair	$d\sigma_W/d\cos\theta$	Ref. 28	Ref. 28
W mass	$M_W[\mathrm{GeV}]$	80.410 ± 0.032	80.376 ± 0.017

PDG

- Parametrization: bosonic sector

Oblique 2-point function:

Peskin, Takeuchi

$$\frac{\alpha}{4s^2c^2}S = \Pi'_{ZZ} - \frac{c^2-s^2}{cs}\Pi'_{Z\gamma} - \Pi'_{\gamma\gamma},$$

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2},$$

$$\frac{\alpha}{4s^2}(S+U) = \Pi'_{WW} - \frac{c}{s}\Pi'_{Z\gamma} - \Pi'_{\gamma\gamma}.$$

$$S = -0.13 \pm 0.10$$
$$T = -0.17 \pm 0.12$$
$$U = 0.22 \pm 0.13$$
$$(m_h = 117\ \mathrm{GeV})$$

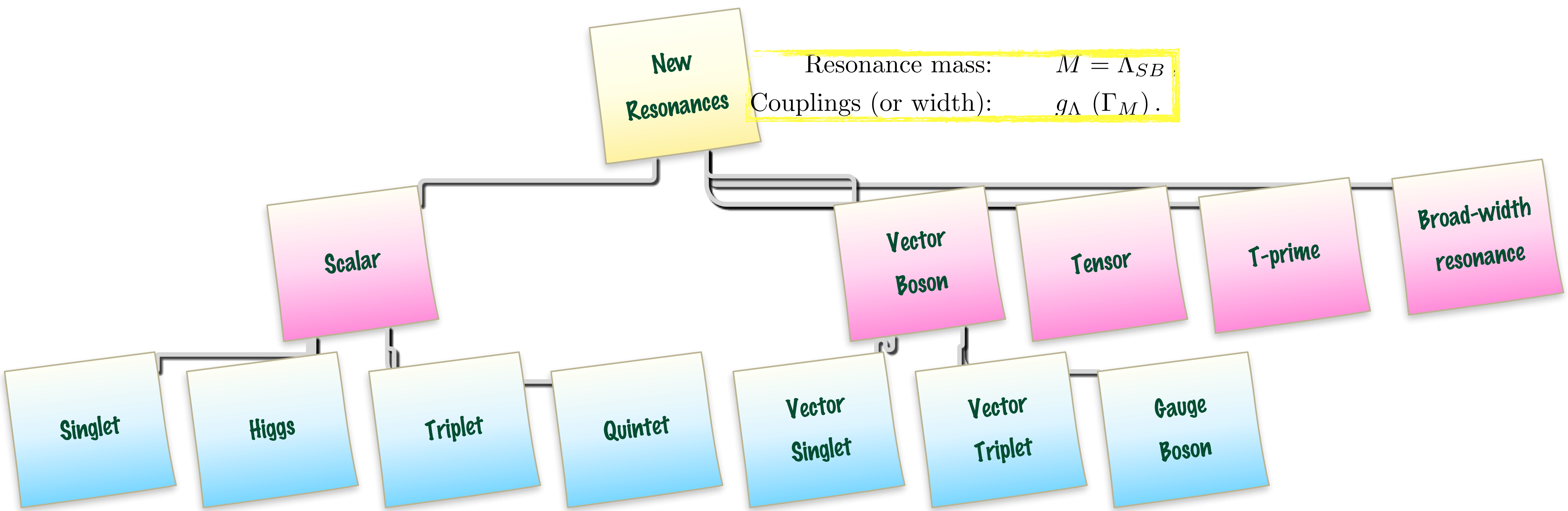
Triple GB Coupling 3-point function:

$$\mathcal{L}_{TGC} = \mathrm{ie}\left[g_1^\gamma A_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu}\right) + \kappa^\gamma W_\mu^- W_\nu^+ A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_\mu^{-\nu} W_{\nu\rho}^+ A^{\rho\mu}\right]$$
$$+ \mathrm{ie}\frac{c_w}{s_w}\left[g_1^Z Z_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu}\right) + \kappa^Z W_\mu^- W_\nu^+ Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W_\mu^{-\nu} W_{\nu\rho}^+ Z\right.$$

couplings	PDG bounds	indirect limits	Unit. W^+W^-	Unit. $W^\pm Z$
Δg_1^Z	$-0.016^{+0.022}_{-0.019}$	$[-0.051\ ,\ 0.0092]$	2.7	0.22
$\Delta\kappa_Z$	$-0.076^{+0.059}_{-0.056}$	$[-0.050\ ,\ 0.0039]$	0.22	3.5
λ_Z	$-0.088^{+0.060}_{-0.057}$	$[-0.061\ ,\ 0.10]$	0.15	0.14
g_5^Z	-0.07 ± 0.09	$[-0.085\ ,\ 0.049]$	2.7	1.7
g_4^Z	-0.30 ± 0.17	—	2.7	0.22
$\tilde\kappa_Z$	$-0.12^{+0.06}_{-0.04}$	—	2.7	3.5
$\tilde\lambda_Z$	-0.09 ± 0.07	—	0.15	0.14

New-Physics Resonance

- Model independent new physics:



- Low-energy effects (integrate out resonances):

$$\mathcal{L}_\Phi = \frac{z}{2}\left[\Phi(M^2 + A)\Phi + 2\Phi J\right] \quad \longrightarrow \quad \mathcal{L}_\Phi^{\text{eff}} = -\frac{z}{2M^2} JJ + \frac{z}{2M^4} JAJ + O(M^{-6}).$$

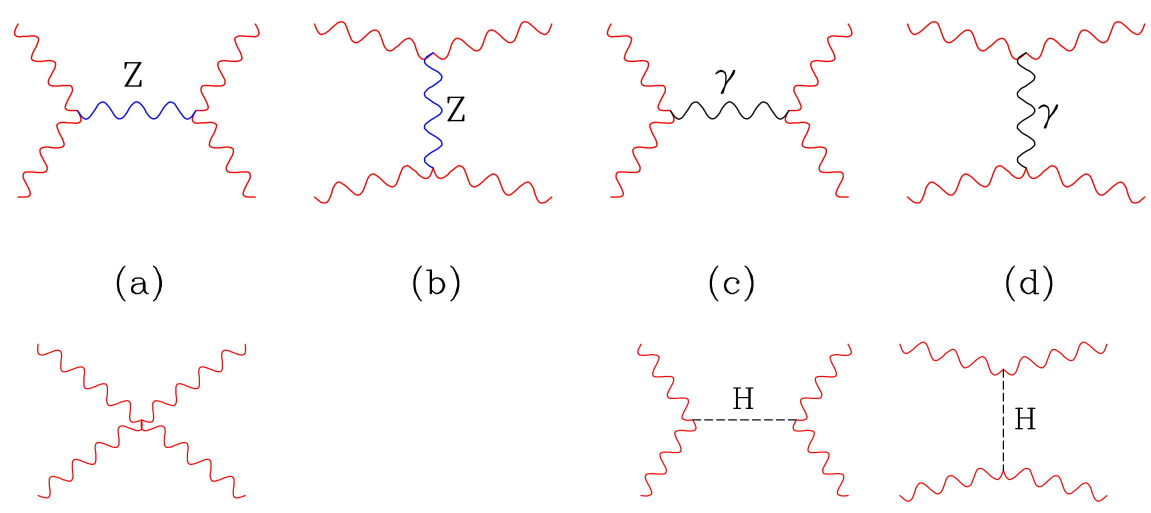
Appelquist, Carrazzone

Usually, the effects from heavy resonance are either suppressed by inverse powers of M, or renormalize parameters of the low-energy theory. (Decoupling Theorem)

Special case: Non-decoupling effects! (example: oblique(chiral fermion), zbb, K/B-mixing...)

WW Scattering (Non-decoupling Channel)

$W_L^+(p_+) + W_L^-(p_-) \to W_L^+(q_+) + W_L^-(q_-)$ Scattering in COM frame



(a) (b) (c) (d)

(e) (f) (g)

$$\varepsilon_L(p_\pm) = \left(\frac{p}{M_W}, 0, 0, \pm\frac{E}{M_W}\right),$$

$$\varepsilon_L(q_\pm) = \left(\frac{p}{M_W}, 0, \pm\frac{E}{M_W}\sin\theta, \pm\frac{E}{M_W}\cos\theta\right).$$

$$\mathcal{T}^{a-d} = g_W^2\left\{\frac{p^4}{M_W^4}\left[3 - 6\cos\theta - cos^2\theta\right] + \frac{p^2}{M_W^2}\left[\frac{9}{2} - \frac{11}{2}\cos\theta - 2cos^2\theta\right]\right\},$$

$$\mathcal{T}^{e} = g_W^2\left\{\frac{p^4}{M_W^4}\left[-3 + 6\cos\theta + cos^2\theta\right] + \frac{p^2}{M_W^2}\left[-4 + 6\cos\theta + 2cos^2\theta\right]\right\},$$

$$\mathcal{T}^{f-g} = g_W^2\left\{ 0 + \frac{p^2}{M_W^2}\left[-\frac{1}{2} - \frac{1}{2}\cos\theta\right] - \frac{M_H^2}{4M_W^2}\left[\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2}\right]\right\}.$$

The differential cross section (neglecting particle masses)

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|\mathcal{T}|^2.$$

Performing a partial wave expansion

$$\mathcal{T}(s,t) = 16\pi\sum_J (2J+1)a_J(s)P_J(\cos\theta),$$

The total cross section is

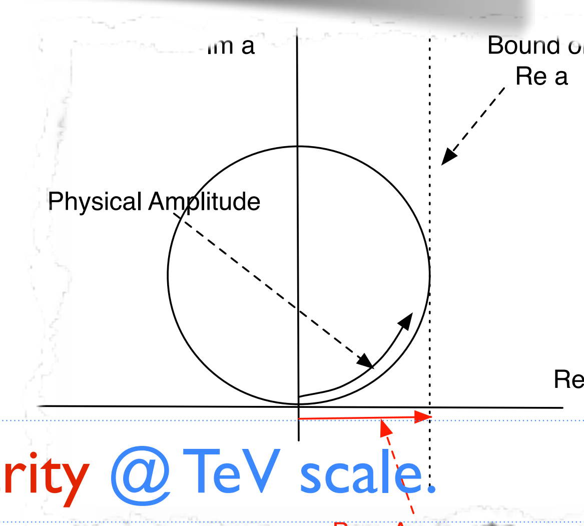
$$\sigma = 16\pi\sum_J(2J+1)|a_J(s)|^2.$$

Using the optical theorem

$$\sigma = \frac{1}{s}\mathrm{Im}\mathcal{T}(s,t=0),$$

the unitarity bound is

$$|a_J(s)|^2 = \mathrm{Im}(a_J(s)), \quad \text{or} \quad , |\mathrm{Re}\, a_J(s)| \le 1/2.$$

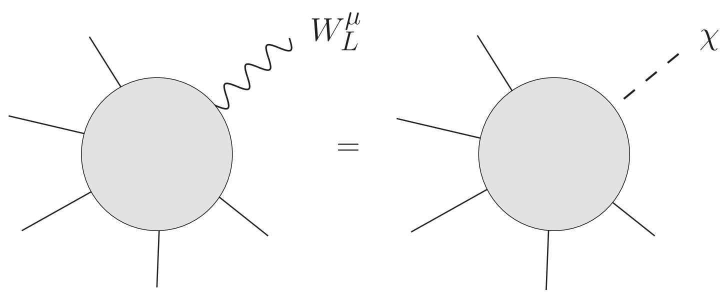


Nondecoupling: In the $M_H \to \infty$ limit, $\mathcal{T}^{tot} = -g_W^2\frac{M_H^2}{4M_W^2}\left[\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2}\right] \to \frac{u}{v^2} + \mathcal{O}(1/M_H^2).$

The Partial wave amplitude, without Higgs or other new physics, violate unitarity @ TeV scale.

Goldstone Boson Scattering

- To simplify our calculation, use the equivalent theorem:



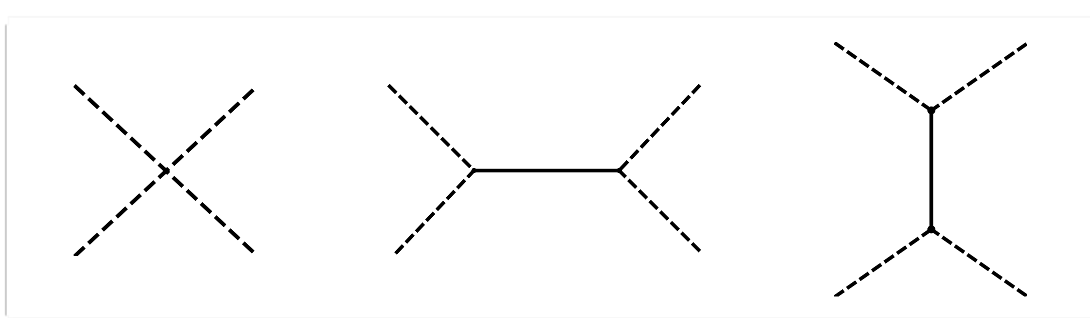
$$\times \left(1+O\left(\frac{m_W^2}{E^2}\right)\right).$$

Lee, Quigg and Thacker

$$\mathcal{T}(W_L^+W_L^- \to W_L^+W_L^-) \simeq \mathcal{T}(\pi^+\pi^- \to \pi^+\pi^-)$$

Chanowitz, Gaillard   Yao, Yuan   Bagger, Schmidt   He, Kuang, Li

- Goldstone boson scattering process:



$$\mathcal{L}_{Goldstone} = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{2}\partial_\mu \pi^0 \partial^\mu \pi^0 + \partial_\mu \pi^+ \partial^\mu \pi^- - \frac{m_H^2}{2}H^2 - \frac{m_H^2}{2v}H\left(H^2 + (\pi^0)^2 + 2\pi^+\pi^-\right) - \frac{m_H^2}{8v^2}\left(H^2 + (\pi^0)^2 + 2\pi^+\pi^-\right)^2$$

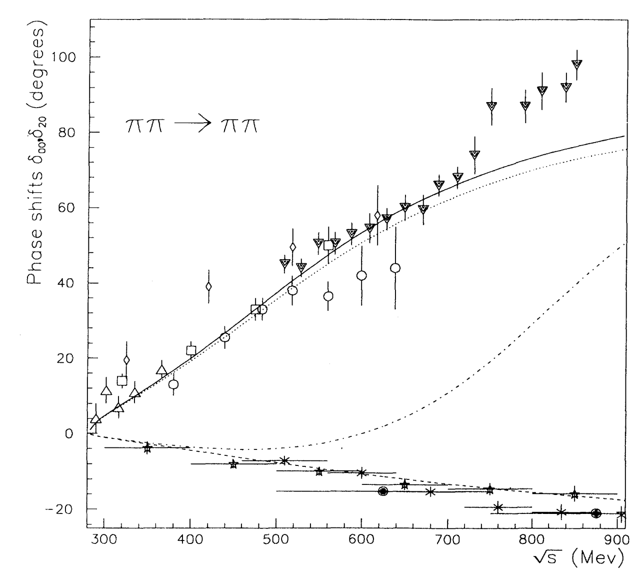
Low-energy Theorem (LET) (integrate out Higgs)

In the $m_H \to \infty$ limit, still $\mathcal{T}(\pi\pi \to \pi\pi) \to \frac{u}{v^2} \simeq \frac{s}{v^2}$

$$\mathcal{T}(\pi^+\pi^- \to \pi^+\pi^-) = -\frac{m_H^2}{v^2}\left(2 + \frac{m_H^2}{s - m_H^2} + \frac{m_H^2}{t - m_H^2}\right)$$

Similar to Pi-Pi Scattering in low-energy QCD
(Understand chiral symmetry breaking)

Study WW scattering in EW chiral Lag.
(Understand EW symmetry breaking)



EW Effective Theories

EW Chiral Lagrangian

- The SM Higgsless Lagrangian below the EW scale

$$\mathcal{L}_{SM} = \mathcal{L}_{kin}(A, W, Z) + \mathcal{L}_{kin}(f, D_\mu f) + \mathcal{L}_{mass}(f) + \mathcal{L}_{mass}(GB)$$

Full EW gauge symmetry!

Violate EW gauge symmetry!

➡ How to build an EW effective theory below EW scale with EW gauge symmetry?

- Introduce extra field to parametrize ignorance on EWSB

$$\begin{aligned}
\Sigma(x) = e^{-i\pi^a(x)\tau^a/v} &\rightarrow g_L(x)\Sigma(x)g_R(x)^\dagger, \quad \text{with } SU(2)_L \otimes U(1)_Y \text{ trans.} \\
V_\mu = \Sigma(D_\mu\Sigma)^\dagger &\rightarrow g_L(x)V_\mu g_L(x)^\dagger, \quad D_\mu = \partial_\mu\Sigma + igW_\mu T^a\Sigma - \frac{i}{2}g'\Sigma\tau^3 B_\mu, \\
T = \Sigma\tau^3\Sigma^\dagger &\rightarrow g_L(x)Tg_L(x)^\dagger, \quad \text{violate } SU(2)_C \text{ symmetry.}
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{mass}(f) &= -\bar{Q}_L\Sigma M_Q Q_R - \bar{L}_L\Sigma M_L L_R + h.c. \\
\mathcal{L}_{mass}(GB) &= -\frac{v^2}{4}\mathrm{Tr}[V_\mu V^\mu].
\end{aligned}$$

Invariant under EW gauge symmetry now!

Anomalous Couplings (Bosonic Sector)

$$
\begin{aligned}
\mathcal{L}_0 &\equiv l_0 \frac{v^2}{\Lambda^2}\frac{v^2}{4}[\mathrm{Tr}(TV_\mu)]^2, && SU(2)_C\text{-violation, T-parameter } (\Delta\rho)\\
\mathcal{L}_1 &\equiv l_1 \frac{v^2}{\Lambda^2}\frac{gg'}{2}B_{\mu\nu}\mathrm{Tr}(TW^{\mu\nu}), && \text{S-parameter, TGC}\\
\mathcal{L}_2 &\equiv l_2 \frac{v^2}{\Lambda^2}\frac{ig'}{2}B_{\mu\nu}\mathrm{Tr}(T[V^\mu,V^\nu]), && \text{TGC}\\
\mathcal{L}_3 &\equiv l_3 \frac{v^2}{\Lambda^2} ig\mathrm{Tr}(W_{\mu\nu}[V^\mu,V^\nu]), && \text{TGC}\\
\mathcal{L}_4 &\equiv l_4 \frac{v^2}{\Lambda^2}[\mathrm{Tr}(V_\mu V_\nu)]^2, && \text{QGC}\\
\mathcal{L}_5 &\equiv l_5 \frac{v^2}{\Lambda^2}[\mathrm{Tr}(V_\mu V^\mu)]^2, && \text{QGC}\\
\mathcal{L}_6 &\equiv l_6 \frac{v^2}{\Lambda^2}\mathrm{Tr}(V_\mu V_\nu)\mathrm{Tr}(TV^\mu)\mathrm{Tr}(TV^\nu), && SU(2)_C\text{-violation, QGC}\\
\mathcal{L}_7 &\equiv l_7 \frac{v^2}{\Lambda^2}\mathrm{Tr}(V_\mu V^\mu)\mathrm{Tr}(TV_\nu)\mathrm{Tr}(TV^\nu), && SU(2)_C\text{-violation, QGC}\\
\mathcal{L}_8 &\equiv l_8 \frac{v^2}{\Lambda^2}\frac{g^2}{4}[\mathrm{Tr}(TW_{\mu\nu})]^2, && SU(2)_C\text{-violation, U-parameter, TGC}\\
\mathcal{L}_9 &\equiv l_9 \frac{v^2}{\Lambda^2}\frac{ig}{2}\mathrm{Tr}(TW_{\mu\nu})\mathrm{Tr}(T[V^\mu,V^\nu]), && SU(2)_C\text{-violation, TGC}\\
\mathcal{L}_{10} &\equiv l_{10} \frac{v^2}{\Lambda^2}\frac{1}{2}[\mathrm{Tr}(TV_\mu)\mathrm{Tr}(TV_\nu)]^2, && SU(2)_C\text{-violation, QGC}\\
\mathcal{L}_{11} &\equiv l_{11} \frac{v^2}{\Lambda^2} g\epsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(TV_\mu)\mathrm{Tr}(V_\nu W_{\rho\lambda}), && \text{P-vilation, TGC}\\
\mathcal{L}_{12} &\equiv l_{12} \frac{v^2}{\Lambda^2} 2g\mathrm{Tr}(TV_\mu)\mathrm{Tr}(V^\nu W^{\mu\nu}), && \text{CP-vioaltion, TGC}\\
\mathcal{L}_{13} &\equiv l_{13} \frac{v^2}{\Lambda^2}\frac{gg'}{4}\epsilon^{\mu\nu\rho\lambda}B_{\mu\nu}\mathrm{Tr}(TW_{\rho\lambda}), && \text{CP-vioaltion, TGC}\\
\mathcal{L}_{14} &\equiv l_{14} \frac{v^2}{\Lambda^2}\frac{g^2}{8}\epsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(TW_{\mu\nu})\mathrm{Tr}(TW_{\rho\lambda}), && \text{CP-vioaltion, TGC}
\end{aligned}
$$

Appelquist, Bernard

Longhitano

$$
\begin{aligned}
\beta_1 &= l_0\frac{v^2}{\Lambda^2},\\
\alpha_i &= l_i\frac{v^2}{\Lambda^2},\\
\Lambda &= \mathrm{Min}(M_{SB}, 4\pi f).
\end{aligned}
$$

Oblique

$$
\begin{aligned}
S &\equiv -16\pi\frac{d}{dq^2}\Pi_{3B}(q^2)|_{q^2=0} = -16\pi\alpha_1,\\
\alpha T &\equiv \frac{e^2}{c^2s^2m_Z^2}(\Pi_{11}(0)-\Pi_{33}(0)) = 2g^2\beta_1,\\
U &\equiv 16\pi\frac{d}{dq^2}[\Pi_{11}(q^2)-\Pi_{33}(q^2)]|_{q^2=0} = -16\pi\alpha_8.
\end{aligned}
$$

TGC

$$
\begin{aligned}
\Delta\kappa_\gamma &= g^2\alpha_2 + g^2\alpha_3 + g^2\alpha_9,\\
\Delta\kappa_Z &= -g'^2\alpha_2 + g^2\alpha_3 + g^2\alpha_9,\\
\Delta g_1^Z &= \tfrac{1}{c_w^2}g^2\alpha_3,\\
\Delta g_5^Z &= \tfrac{1}{c_w^2}g^2\alpha_{11},\\
\Delta g_1^\gamma &= \Delta g_5^\gamma = 0,\\
\Delta\lambda_\gamma &= \Delta\lambda_Z = 0.
\end{aligned}
$$

VVVV (with custodial sym):

$$
\begin{aligned}
\mathcal{L}_4 &= \alpha_4\left[\frac{g^4}{2}\left[(W_\mu^+W^{-\mu})^2 + (W_\mu^+W^{+\mu})(W_\nu^-W^{-\nu})\right]\right.\\
&\quad \left.+\frac{g^4}{c_w^2}(W_\mu^+Z^\mu)(W_\nu^-Z^\nu) + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2\right]\\
\mathcal{L}_5 &= \alpha_5\left[g^4(W_\mu^+W^{-\mu})^2 + \frac{g^4}{c_w^2}(W_\mu^+W^{-\mu})(Z_\nu Z^\nu) + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2\right]
\end{aligned}
$$

WW Scattering in Chiral Lag.

- ## WW scattering at LO

$$A(W_L^- W_L^- \to W_L^- W_L^-) = -s/v^2$$
$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = -u/v^2$$
$$A(W_L^+ W_L^- \to Z_L Z_L) = s/v^2$$
$$A(Z_L Z_L \to Z_L Z_L) = 0$$

Low-energy Theorem

- ## WW scattering at NLO

$$\mathrm{Re}\, A(s,t,u) = \frac{s}{v^2} + \frac{1}{16\pi^2 v^4}\left\{-\frac{(t-u)}{6}\left[t\ln\frac{-t}{\mu^2} - u\ln\frac{-u}{\mu^2}\right] - \frac{s^2}{2}\ln\frac{s}{\mu^2}\right\} + \alpha_4^0\frac{4(t^2+u^2)}{v^4} + \alpha_5^0\frac{8s^2}{v^4}.$$

Custodial Symmetry Relations:

$$A(W_L^- W_L^- \to W_L^- W_L^-) = A(t,s,u) + A(u,t,s)$$
$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = A(s,t,u) + A(t,s,u)$$
$$A(W_L^+ W_L^- \to Z_L Z_L) = A(s,t,u)$$
$$A(W_L^- Z_L \to W_L^- Z_L) = A(t,s,u)$$
$$A(Z_L Z_L \to Z_L Z_L) = A(s,t,u) + A(t,s,u) + A(u,t,s)$$

$$A^{(0)} = 3A(s,t,u) + A(t,s,u) + A(u,t,s)$$
$$A^{(1)} = A(t,s,u) - A(u,t,s)$$
$$A^{(2)} = A(t,s,u) + A(u,t,s)$$

- ## Unitarity Constraints

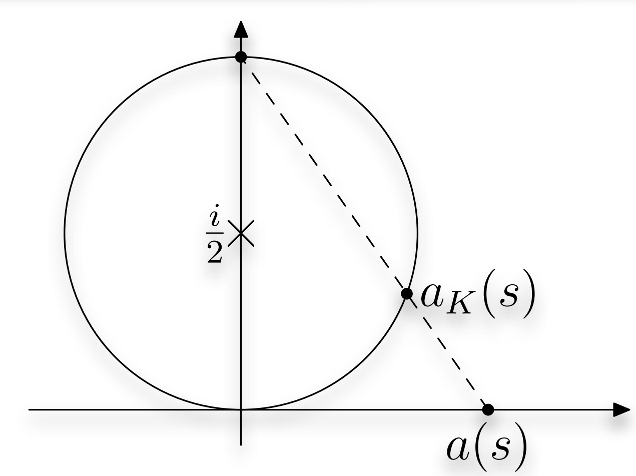
S wave:
$$a_0^0 = \frac{1}{64\pi}\left[+\frac{4s}{v^2} + \frac{16}{3}(7\alpha_4 + 11\alpha_5)\frac{s^2}{v^4}\right]$$
$$a_0^2 = \frac{1}{64\pi}\left[-\frac{2s}{v^2} + \frac{32}{3}(2\alpha_4 + \alpha_5)\frac{s^2}{v^4}\right]$$

P wave:
$$a_1^1 = \frac{1}{64\pi}\left[+\frac{2s}{3v^2} + \frac{8}{3}(\alpha_4 - 2\alpha_5)\frac{s^2}{v^4}\right]$$

D wave:
$$a_2^0 = \frac{1}{64\pi}\left[0 + \frac{16}{15}(2\alpha_4 + \alpha_5)\frac{s^2}{v^4}\right]$$
$$a_2^2 = \frac{1}{64\pi}\left[0 + \frac{8}{15}(\alpha_4 + 2\alpha_5)\frac{s^2}{v^4}\right]$$

$$|a_\ell^I| \lesssim 1/2$$

Unitarization Models: K-matrix / Pade / IAM



K matrix construction for projecting a real scattering amplitude

New Vector Resonance?

- Adding Vector Triplet to delay unitarity violation:

$$\mathcal{L}_\rho = \frac{1}{4}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\left(M_\rho^2 g^{\mu\nu} + \mathbf{D}^2 g^{\mu\nu} - \mathbf{D}^\nu\mathbf{D}^\mu + 2\mathrm{i}\mu_\rho g\mathbf{W}^{\mu\nu} + 2\mathrm{i}\mu'_\rho g'\mathbf{B}^{\mu\nu}\right)\boldsymbol{\rho}_\nu + 2\boldsymbol{\rho}_\mu\mathbf{j}^\mu\right\}$$

$$\mathbf{j}_\mu = \mathrm{i}g_\rho v^2\mathbf{V}_\mu + \mathrm{i}g'_\rho v^2\mathbf{T}\,\mathrm{tr}\left\{\mathbf{TV}_\mu\right\}$$

→

$$\beta_1 = 4h_\rho(g_\rho + h_\rho)\frac{v^2}{2M_\rho^2}$$

$$\alpha_i = \mathcal{O}\left(\frac{v^4}{M_\rho^4}\right) \text{ or } 0$$

$$A^\rho(s,t,u) = -g_\rho^2\left(\frac{s-u}{t-M^2} + \frac{s-t}{u-M^2} + 3\frac{s}{M^2}\right)$$

Still need UV cancellation

- CCWZ Reparametrization of Vector Triplet:

$$\xi\tilde{\xi}^\dagger = \xi^2 = \Sigma = e^{i\pi^a\tau^a/v}$$

$$\mathcal{V}_\mu = \frac{i}{2}\left(\xi^\dagger D_\mu\xi + \xi D_\mu\xi^\dagger\right) \quad \text{and} \quad \mathcal{A}_\mu = \frac{i}{2}\left(\xi^\dagger D_\mu\xi - \xi D_\mu\xi^\dagger\right).$$

$$\mathcal{V} \to U_C\mathcal{V}U_C^\dagger - (D_\mu U_C)U_C^\dagger \quad \text{and} \quad \mathcal{A} \to U_C\mathcal{A}U_C^\dagger.$$

Gauge Field

$$\boldsymbol{\rho} \to U_C\boldsymbol{\rho}U_C^\dagger - i\frac{2g_\rho v}{M}(D_\mu U_C)U_C^\dagger,$$

$$\mathcal{L}_{\rm int} = -g_\rho^2 v^2\,\mathrm{tr}\left[\left(\mathcal{V} + i\frac{M}{2g_\rho v}\boldsymbol{\rho}\right)^2\right] = -g_\rho^2 v^2\,\mathrm{tr}\left[\mathcal{V}\mathcal{V}\right] - ig_\rho vM\,\mathrm{tr}\left[\mathcal{V}\boldsymbol{\rho}\right] + \frac{M^2}{4}\,\mathrm{tr}\left[\boldsymbol{\rho}\boldsymbol{\rho}\right]$$

Higgsless, BESS, Three Site...

Matter Field

$$\boldsymbol{\rho}_\mu \to \xi^\dagger\boldsymbol{\rho}_\mu\xi$$

$$\mathcal{L}_{\rm kin} = -2v^2\,\mathrm{tr}\left[\mathcal{A}_\mu\mathcal{A}^\mu\right] \quad \text{and} \quad \mathcal{L}_{\rm int} = -g_\rho v^2\,\mathrm{tr}\left[\boldsymbol{\rho}_\mu\mathcal{A}^\mu\right.$$

Technicolor, HLS...

- Adding a Vector Singlet:

Alboteanu, Kilian, Reuter

$$\mathcal{L}_\omega = \frac{1}{2}\left[\omega_\mu\left((M^2 + \partial^2)g^{\mu\nu} - \partial^\nu\partial^\mu\right)\omega_\nu + 2\omega_\mu j^\mu\right]$$

$$j_\mu = \mathrm{i}\frac{h_\omega v^2}{2}\,\mathrm{tr}\left\{\mathbf{TV}_\mu\right\}$$

New Scalar Resonance?

Scalar Singlet

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma\left(M_\sigma^2 + \partial^2\right)\sigma + 2\sigma j\right]$$

$$j = -\frac{g_\sigma v}{2}\,\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}^\mu\right\} - \frac{h_\sigma v}{2}\left(\mathrm{tr}\left\{\mathbf{T}\mathbf{V}_\mu\right\}\right)^2$$

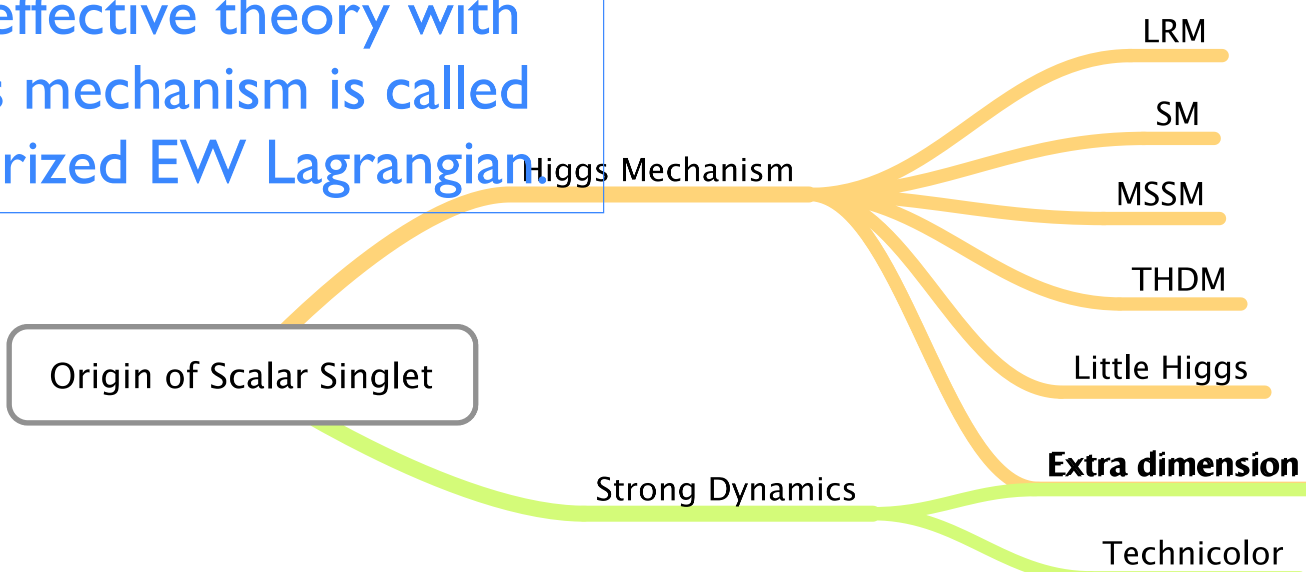
$$\alpha_4 = 0 \qquad \alpha_6 = 0$$

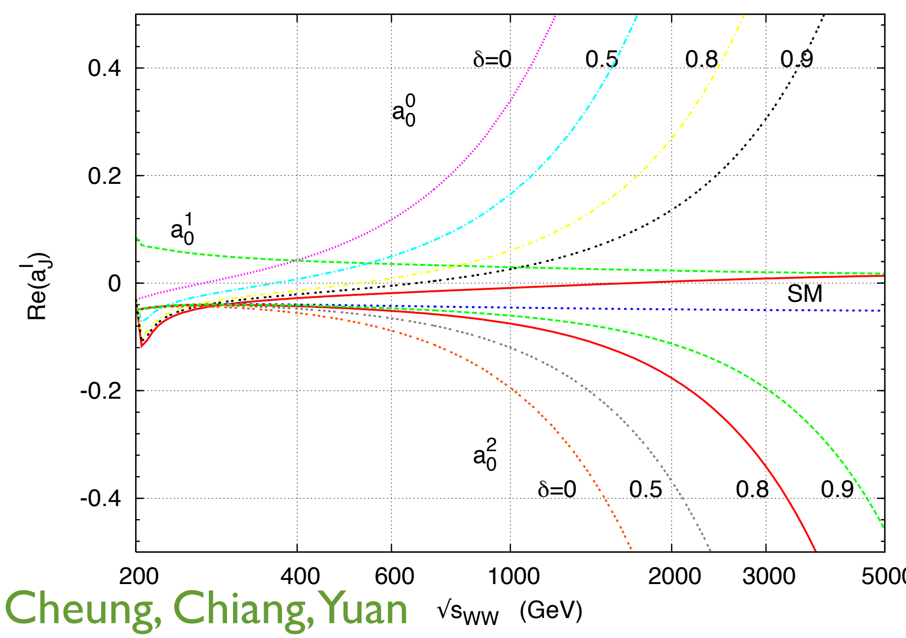
$$\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2g_\sigma h_\sigma\left(\frac{v^2}{8M_\sigma^2}\right)$$

$$A^\sigma(s,t,u) = -\frac{g_\sigma^2}{v^2}\frac{s^2}{s-M^2} \qquad \alpha_{10} = 2h_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$$

g=1, strong cancellation for s term (Higgs mechanism offers g=1)

The effective theory with Higgs mechanism is called Linearized EW Lagrangian.





Cheung, Chiang, Yuan

Scalar Triplet

$$\mathcal{L}_\pi = -\frac{1}{4}\,\mathrm{tr}\left\{\boldsymbol{\pi}(M_\pi^2 + \mathbf{D}^2)\boldsymbol{\pi} + 2\boldsymbol{\pi}\mathbf{j}\right\}$$

$$\mathbf{j} = \frac{h_\pi v}{2}\mathbf{V}_\mu\,\mathrm{tr}\left\{\mathbf{T}\mathbf{V}^\mu\right\} + \frac{h'_\pi v}{2}\mathbf{T}\,\mathrm{tr}\left\{\mathbf{V}_\mu\mathbf{V}^\mu\right\} + \frac{k_\pi v}{2}\mathbf{T}\left(\mathrm{tr}\left\{\mathbf{T}\mathbf{V}_\mu\right\}\right)^2$$

$$\alpha_4 = 0 \qquad \alpha_6 = h_\pi^2\left(\frac{v^2}{16M_\pi^2}\right)$$

$$\alpha_5 = 2h_\pi'^2\left(\frac{v^2}{16M_\pi^2}\right) \qquad \alpha_7 = 2h'_\pi(h_\pi + 2k_\pi)\left(\frac{v^2}{16M_\pi^2}\right)$$

$$\alpha_{10} = 4k_\pi(h_\pi + k_\pi)\left(\frac{v^2}{16M_\pi^2}\right)$$

$$A^\phi(s,t,u) = -\frac{g_\phi^2}{4v^2}\left(\frac{t^2}{t-M^2} + \frac{u^2}{u-M^2} - \frac{2}{3}\frac{s^2}{s-M^2}\right)$$

Linearized EW Lagrangian

- Effective theory with Higgs mechanism above EW scale:
  - Its gauge group contains SU(3) x SU(2) x U(1) symmetry;
  - All the SM particles are incorporated as fund. or composite fields;
  - At low energy, it reduces to SM via decoupling heavy particles;
  - More global and local symmetries can be imposed.
- The linearized EW effective Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Renormalizable SM Lag.

LEP prefers light Higgs

Wilson Coefficients

HVV Anomalous Coupling to distinguish different Higgs scenarios

Dimension-6 operators

Weak or Strong TeV dynamics

Dimension-6 Operators

Buchmuller, Wyler

	Operator	Notation	Operator	Notation
S	$\partial_\mu\left(\phi^\dagger\phi\right)\partial^\mu\left(\phi^\dagger\phi\right)$	$\mathcal{O}_{\partial\phi}$	$\frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$\mathcal{O}_{\phi 6}$
V	$\epsilon^{abc}W_\mu^{a\nu}W_\nu^{b\lambda}W_\lambda^{c\mu}$	$\mathcal{O}_{W3}$	$\epsilon^{abc}G_\mu^{a\nu}G_\nu^{b\lambda}G_\lambda^{c\mu}$	$\mathcal{O}_{G3}$
Oblique	$\phi^\dagger\phi\left(D^\mu\phi\right)^\dagger D_\mu\phi$	$\mathcal{O}_\phi^{(1)}$	$\left(\phi^\dagger D_\mu\phi\right)\left(\left(D^\mu\phi\right)^\dagger\phi\right)$	$\mathcal{O}_\phi^{(3)}$
	$\phi^\dagger\sigma_a\phi\; W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{WB}$		
	$\frac{1}{2}\phi^\dagger\phi\; W_{\mu\nu}^a W_{\mu\nu}^a$	$\mathcal{O}_{WW}$	$\frac{1}{2}\phi^\dagger\phi\; B^{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{BB}$
	$\frac{1}{2}\phi^\dagger\phi\; G_{\mu\nu}^A G_{\mu\nu}^A$	$\mathcal{O}_{GG}$		
SVF	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger\sigma_a iD_\mu\phi\right)\left(\overline{l_L}\gamma^\mu\sigma_a l_L\right)$	$\mathcal{O}_{\phi l}^{(3)}$
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{\phi e}^{(1)}$		
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger\sigma_a iD_\mu\phi\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{\phi q}^{(3)}$
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{\phi d}^{(1)}$
	$\left(\phi^T i\sigma_2 iD_\mu\phi\right)\left(\overline{u_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{\phi ud}$		
LLLL	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\mathcal{O}_{ll}^{(1)}$	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu\sigma_a l_L\right)\left(\overline{l_L}\gamma^\mu\sigma_a l_L\right)$	$\mathcal{O}_{ll}^{(3)}$
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{qq}^{(1,1)}$	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\sigma_a q_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{qq}^{(1,3)}$
	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{lq}^{(1)}$	$\left(\overline{l_L}\gamma_\mu\sigma_a l_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{lq}^{(3)}$
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\lambda_A q_L\right)\left(\overline{q_L}\gamma^\mu\lambda_A q_L\right)$	$\mathcal{O}_{qq}^{(8,1)}$	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\sigma_a\lambda_A q_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a\lambda_A q_L\right)$	$\mathcal{O}_{qq}^{(8,3)}$
RRRR			$\frac{1}{2}\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{ee}$
	$\frac{1}{2}\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{uu}^{(1)}$	$\frac{1}{2}\left(\overline{d_R}\gamma_\mu d_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{dd}^{(1)}$
	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{eu}$	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ed}$
	$\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ud}^{(1)}$		
	$\frac{1}{2}\left(\overline{u_R}\gamma_\mu\lambda_A u_R\right)\left(\overline{u_R}\gamma^\mu\lambda_A u_R\right)$	$\mathcal{O}_{uu}^{(8)}$	$\frac{1}{2}\left(\overline{d_R}\gamma_\mu\lambda_A d_R\right)\left(\overline{d_R}\gamma^\mu\lambda_A d_R\right)$	$\mathcal{O}_{dd}^{(8)}$
	$\left(\overline{u_R}\gamma_\mu\lambda_A u_R\right)\left(\overline{d_R}\gamma^\mu\lambda_A d_R\right)$	$\mathcal{O}_{ud}^{(8)}$		
LRRL	$\left(\overline{l_L}e_R\right)\left(\overline{e_R}l_L\right)$	$\mathcal{O}_{le}$	$\left(\overline{q_L}e_R\right)\left(\overline{e_R}q_L\right)$	$\mathcal{O}_{qe}$
	$\left(\overline{l_L}u_R\right)\left(\overline{u_R}l_L\right)$	$\mathcal{O}_{lu}$	$\left(\overline{l_L}d_R\right)\left(\overline{d_R}l_L\right)$	$\mathcal{O}_{ld}$
	$\left(\overline{q_L}u_R\right)\left(\overline{u_R}q_L\right)$	$\mathcal{O}_{qu}^{(1)}$	$\left(\overline{q_L}d_R\right)\left(\overline{d_R}q_L\right)$	$\mathcal{O}_{qd}^{(1)}$
	$\left(\overline{l_L}e_R\right)\left(\overline{d_R}q_L\right)$	$\mathcal{O}_{qde}$		
	$\left(\overline{q_L}\lambda_A u_R\right)\left(\overline{u_R}\lambda_A q_L\right)$	$\mathcal{O}_{qu}^{(8)}$	$\left(\overline{q_L}\lambda_A d_R\right)\left(\overline{d_R}\lambda_A q_L\right)$	$\mathcal{O}_{qd}^{(8)}$
B-L	$\epsilon_{ABC}\left(\overline{l_L}i\sigma_2 q_L^{c\,A}\right)\left(\overline{d_R^B}u_R^{c\,C}\right)$	$\mathcal{O}_{lqdu}$	$\epsilon_{ABC}\left(\overline{q_L^B}i\sigma_2 q_L^{c\,C}\right)\left(\overline{e_R}u_R^{c\,A}\right)$	$\mathcal{O}_{qqeu}$

Dim-6 Operators (Bosonic Sector)

$\mathcal{O}_i^{(6)}$
$\mathcal{O}_{DW} = \mathrm{Tr}\left(\left[D_\mu, \hat{W}_{\nu\rho}\right]\left[D^\mu, \hat{W}^{\nu\rho}\right]\right)$
$\mathcal{O}_{DB} = -\frac{g'^2}{2}\left(\partial_\mu B_{\nu\rho}\right)\left(\partial^\mu B^{\nu\rho}\right)$
$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$
$\mathcal{O}_{\Phi,1} = \left[\left(D_\mu\Phi\right)^\dagger\Phi\right]\left[\Phi^\dagger\left(D^\mu\Phi\right)\right]$
$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho{}^\mu\right)$
$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$
$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$
$\mathcal{O}_W = \left(D_\mu\Phi\right)^\dagger\hat{W}^{\mu\nu}\left(D_\nu\Phi\right)$
$\mathcal{O}_B = \left(D_\mu\Phi\right)^\dagger\hat{B}^{\mu\nu}\left(D_\nu\Phi\right)$
$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$
$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$
$\mathcal{O}_{\Phi,4} = \left(\Phi^\dagger\Phi\right)\left[\left(D_\mu\Phi\right)^\dagger\left(D^\mu\Phi\right)\right]$

Oblique

TGC

HVV

Pi-Pi Scattering

Higgs Self-coupling

$$\mathcal{L} = \frac{1}{2\Lambda^2}\Big\{ f_{DW}\, g^2\vec{W}_{\mu\nu}\partial^2\vec{W}^{\mu\nu} + f_{DB}\, g'^2 B_{\mu\nu}\partial^2 B^{\mu\nu} + f_{BW}\, m_Z^2 sc W^3_{\mu\nu}B_{\mu\nu} + f_{\Phi,1}\frac{v^2}{2}m_Z^2 Z^\mu Z_\mu \Big\},$$

Barbieri, Pomarol, Rattazzi, Strumia

Adimensional form factors			operators			custodial	$\mathrm{SU}(2)_L$
$g^{-2}\hat{S}$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB}$	$=$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}/gg'$	$+$	$-$
$g^{-2}M_W^2\hat{T}$	$=$	$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$	$-$	$-$
$-g^{-2}\hat{U}$	$=$	$\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)$	$-$			$-$	$-$
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0) - \Pi''_{W^+W^-}(0)$	$-$			$-$	$-$
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$	$-$			$+$	$-$
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$	$+$	$+$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2g^2$	$+$	$+$
$2g_s^{-2}M_W^{-2}Z$	$=$	$\Pi''_{GG}(0)$	$\mathcal{O}_{GG}$	$=$	$(D_\rho G^A_{\mu\nu})^2/2g_s^2$	$+$	$+$

$$\begin{aligned}\mathcal{L}^H_{\rm eff} = &\; g_{H\gamma\gamma}HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}A_{\mu\nu}Z^\mu\partial^\nu H \\ &+ g^{(2)}_{HZ\gamma}HA_{\mu\nu}Z^{\mu\nu} + g^{(1)}_{HZZ}Z_{\mu\nu}Z^\mu\partial^\nu H \\ &+ g^{(2)}_{HZZ}HZ_{\mu\nu}Z^{\mu\nu} + g^{(1)}_{HWW}(W^+_{\mu\nu}W^{-\mu}\partial^\nu H + \text{h.c.}) \\ &+ g^{(2)}_{HWW}HW^+_{\mu\nu}W^{-\mu\nu},\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{\rm WWV}_{\rm eff} = &\; -ig_{\rm WWV}\Big[g_1^V(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})V^\nu \\ &+ \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho \\ &- ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - W^-_\nu\partial_\rho W^+_\mu)V_\sigma\Big]\end{aligned}$$

$$\begin{aligned}\Delta g_1^Z &= g_1^Z - 1 = \frac{1}{2}\frac{m_Z^2}{\Lambda^2}f_W\,, \\ \Delta\kappa_\gamma &= \kappa_\gamma - 1 = 1 + \frac{1}{2}\frac{m_W^2}{\Lambda^2}\left(f_W + f_B\right)\,, \\ \Delta\kappa_Z &= \kappa_Z - 1 = 1 + \frac{1}{2}\frac{m_Z^2}{\Lambda^2}\left(c^2 f_W - c^2 f_B\right) \\ \lambda_\gamma &= \lambda_Z = \frac{3g^2 m_W^2}{2\Lambda^2}f_{WWW}\,.\end{aligned}$$

$$\lambda_Z = \lambda_\gamma \qquad \Delta\kappa_Z = -\Delta\kappa_\gamma\tan^2\theta_W + \Delta g_1^Z$$

Gonzalez-Garcia

$$\begin{aligned}g_{H\gamma\gamma} &= -\left(\frac{gm_W}{\Lambda^2}\right)\frac{s^2(f_{BB}+f_{WW})}{2}, \\ g^{(1)}_{HZ\gamma} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{s(f_W - f_B)}{2c}, \\ g^{(2)}_{HZ\gamma} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{s[s^2 f_{BB} - c^2 f_{WW}]}{c}, \\ g^{(1)}_{HZZ} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2}, \\ g^{(2)}_{HZZ} &= -\left(\frac{gm_W}{\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2}, \\ g^{(1)}_{HWW} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{f_W}{2}, \\ g^{(2)}_{HWW} &= -\left(\frac{gm_W}{\Lambda^2}\right)f_{WW},\end{aligned}$$

Connections between linear and chiral Lag.

Linearized Lag.

$\mathcal{O}^{(n)}_{\rm linear}$	
$-\frac{4\beta_1}{v^2}\mathcal{O}_{\Phi,1}$	$\mathcal{O}_{\Phi,1} = \left[(D_\mu\Phi)^\dagger\Phi\right]\left[\Phi^\dagger(D^\mu\Phi)\right]$
$\frac{4\alpha_1}{v^2}\mathcal{O}_{BW}$	$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$,
$\frac{8\alpha_2}{v^2}\mathcal{O}_B$	$\mathcal{O}_B = \left(D_\mu\Phi\right)^\dagger\hat{B}^{\mu\nu}\left(D_\nu\Phi\right)$,
$\frac{8\alpha_3}{v^2}\mathcal{O}_W$	$\mathcal{O}_W = \left(D_\mu\Phi\right)^\dagger\hat{W}^{\mu\nu}\left(D_\nu\Phi\right)$,
$\frac{4\alpha_4}{v^4}\mathcal{O}^{(8)}_4$	$\mathcal{O}^{(8)}_4 = \left[(D_\mu\Phi)^\dagger(D_\nu\Phi) + (D_\nu\Phi)^\dagger(D_\mu\Phi)\right]^2$,
$\frac{16\alpha_5}{v^4}\mathcal{O}^{(8)}_5$	$\mathcal{O}^{(8)}_5 = \left[(D_\mu\Phi)^\dagger(D^\mu\Phi)\right]^2$,
$-\frac{64\alpha_6}{v^6}\mathcal{O}^{(10)}_6$	$\mathcal{O}^{(10)}_6 = \left[(D_\mu\Phi)^\dagger(D_\nu\Phi)\right]\left[\Phi^\dagger(D^\mu\Phi)\right]\left[\Phi^\dagger(D^\nu\Phi)\right]$,
$-\frac{64\alpha_7}{v^6}\mathcal{O}^{(10)}_7$	$\mathcal{O}^{(10)}_7 = \left[(D_\mu\Phi)^\dagger(D^\mu\Phi)\right]\left[\Phi^\dagger(D_\nu\Phi)\right]\left[\Phi^\dagger(D^\nu\Phi)\right]$,
$-\frac{4\alpha_8}{v^4}\mathcal{O}^{(8)}_8$	$\mathcal{O}^{(8)}_8 = \left[\Phi^\dagger\hat{W}_{\mu\nu}\Phi\right]^2$,
$-\frac{16\alpha_9}{v^4}\mathcal{O}^{(8)}_9$	$\mathcal{O}^{(8)}_9 = \left[\Phi^\dagger\hat{W}_{\mu\nu}\Phi\right]\left[(D^\mu\Phi)^\dagger(D^\nu\Phi)\right]$,
$\frac{128\,\alpha_{10}}{v^8}\mathcal{O}^{(12)}_{10}$	$\mathcal{O}^{(12)}_{10} = \left(\left[\Phi^\dagger(D_\mu\Phi)\right]\left[\Phi^\dagger(D_\nu\Phi)\right]\right)^2$.
$\frac{8\alpha_{11}}{v^4}\mathcal{O}^{(8)}_{11}$	$\mathcal{O}^{(8)}_{11} = i\epsilon^{\mu\nu\rho\sigma}\left[\Phi^\dagger(D_\mu\Phi)\right]\left[\Phi^\dagger\hat{W}_{\rho\sigma}(D_\nu\Phi)\right] + \text{h.c.}$

Hagiwara

$$
\begin{aligned}
2(D_\mu\Phi)^+\Phi &= \partial_\mu h^2 + h^2 Tr(TV_\mu) \\
2\Phi^+W_{\mu\nu}\Phi &= h^2 Tr(TW_{\mu\nu}) \\
2(D_\mu\Phi)^+(D_\nu\Phi) &= h^2[Tr(TV_\mu V_\nu) - Tr(V_\mu V_\nu)] + 2(\partial_\mu h)(\partial_\nu h) \\
2(D_\mu\Phi)^+W^{\mu\nu}(D_\nu\Phi) &= h^2 Tr(W^{\mu\nu}V_\mu V_\nu) - (\partial_\mu h^2)Tr(W^{\mu\nu}V_\nu) \\
2\Phi^+W^{\nu\rho}(D^\mu\Phi) &= h^2[Tr(TV^\mu W^{\nu\rho}) + Tr(V^\mu W^{\nu\rho})] \\
2(D^\mu\Phi)^+W^{\nu\rho}\Phi &= h^2[Tr(TV^\mu W^{\nu\rho}) - Tr(V^\mu W^{\nu\rho})]\ .
\end{aligned}
$$

EW Chiral Lag.

$\mathcal{L}_{\rm chiral}$
$\mathcal{L}'_1 = \frac{\beta_1 v^2}{4}\left[\text{Tr}\,(TV_\mu)\right]^2$
$\mathcal{L}_1 = \frac{\alpha_1 g g'}{2}B_{\mu\nu}\text{Tr}\left(TW^{\mu\nu}\right)$
$\mathcal{L}_2 = \frac{i\alpha_2 g'}{2}B_{\mu\nu}\text{Tr}\left(T[V^\mu, V^\nu]\right)$
$\mathcal{L}_3 = i\alpha_3 g\,\text{Tr}\left(W_{\mu\nu}[V^\mu, V^\nu]\right)$
$\mathcal{L}_4 = \alpha_4\left[\text{Tr}\,(V_\mu V_\nu)\right]^2$
$\mathcal{L}_5 = \alpha_5\left[\text{Tr}\,(V_\mu V^\mu)\right]^2$
$\mathcal{L}_6 = \alpha_6\text{Tr}\left(V_\mu V_\nu\right)\text{Tr}\left(TV^\mu\right)\text{Tr}\left(TV^\nu\right)$
$\mathcal{L}_7 = \alpha_7\text{Tr}\left(V_\mu V^\mu\right)\text{Tr}\left(TV_\nu\right)\text{Tr}\left(TV^\nu\right)$
$\mathcal{L}_8 = \frac{\alpha_8 g^2}{4}\left[\text{Tr}\,(TW_{\mu\nu})\right]^2$
$\mathcal{L}_9 = \frac{i\alpha_9 g}{2}\text{Tr}\left(TW_{\mu\nu}\right)\text{Tr}\left(T[V^\mu, V^\nu]\right)$
$\mathcal{L}_{10} = \frac{\alpha_{10}}{2}\left[\text{Tr}\,(TV_\mu)\text{Tr}\,(TV_\nu)\right]^2$
$\mathcal{L}_{11} = \alpha_{11}\,g\,\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left(TV_\mu\right)\text{Tr}\left(V_\nu W_{\rho\sigma}\right)$

EW Linearized Lag. ← TeV Chiral Lag.

TeV Chiral Lagrangian

TeV Unknown Dynamics?? (TeV Chiral Lag.)

Higgs singlet + nonlinear triplet

Non-Standard Higgs Lag.

Chivukula, Koulovassilopoulos

$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{\rho^2}{4}A\left(\frac{\rho^2}{f^2}\right)\mathrm{Tr}\,(\partial_\mu\Sigma^\dagger\partial^\mu\Sigma) - \Lambda^2 f^2 B\left(\frac{\rho^2}{f^2}\right),$$

$\rho = \langle\rho\rangle + H,$

$$\mathcal{L} = \frac{1}{4}(v^2 + 2\xi v H + \xi' H^2 + \xi''\frac{H^3}{6v})\,\mathrm{Tr}\,(\partial_\mu\Sigma^\dagger\partial^\mu\Sigma) \quad + \quad \mathcal{L}_H$$

Higgs bidoublet

Strongly-interacting light Higgs

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) \\
& -\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R + \text{h.c.}\right) \\
& +\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu}) \\
& +\frac{ic_{HW}g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB}g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& +\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.
\end{aligned}$$

$$\frac{c_t y_t}{f^2}H^\dagger H\bar{q}_L\tilde{H}t_R + h.c. + \frac{ic_R}{f^2}H^\dagger D_\mu H\bar{t}_R\gamma^\mu t_R + \frac{c_{4t}}{f^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R).$$

Giudice, Grojean, Pomarol Rattazzi

$$U = e^{i\Pi} \qquad \Pi \equiv \Pi^A T^A.$$

$$U^\dagger\partial_\mu U = i\mathcal{D}^A_\mu T^A + i\mathcal{E}^a_\mu T^a \equiv i\mathcal{D}_\mu + i\mathcal{E}_\mu$$

$$\bar{\mathcal{E}}_\mu = A_\mu + \mathcal{E}_\mu(\Pi, D_\nu) = A_\mu - \frac{i}{2}\Pi\overleftrightarrow{D}_\mu\Pi + \mathcal{O}(\Pi^4)$$

$$\bar{\mathcal{D}}_\mu = \mathcal{D}_\mu(\Pi, D_\nu) = D_\mu\Pi - \frac{1}{6}\left[\Pi, \Pi\overleftrightarrow{D}_\mu\Pi\right] + \mathcal{O}(\Pi^5),$$

$$\begin{aligned}
\mathcal{L}^0 & \equiv f^2\mathrm{Tr}\,(\mathcal{D}_\mu\mathcal{D}^\mu) + \cdots \\
& = f^2\mathrm{Tr}\left[\partial_\mu\Pi\partial^\mu\Pi + \frac{1}{3}(\Pi\overleftrightarrow{\partial_\mu}\Pi)(\Pi\overleftrightarrow{\partial^\mu}\Pi) + \cdots\right]
\end{aligned}$$

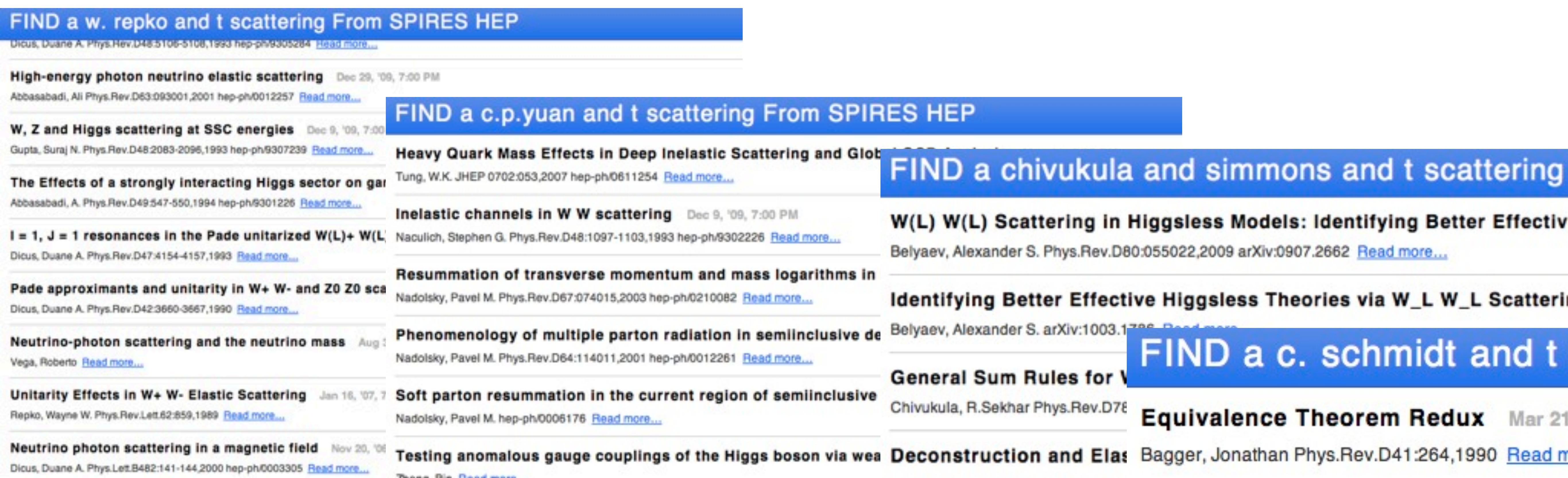
$$\frac{f^2}{2}\mathrm{Tr}(\mathcal{D}^\mu\mathcal{D}_\mu) \supset \frac{1}{f^2}h^a\, h^b\, \partial_\mu h^c\, \partial^\mu h^d\, \mathcal{T}^{abcd};$$

$$\mathcal{T}^{abcd} \equiv -\left(\frac{1}{6f^2}f^{aci}f^{bdi} + \frac{1}{24f^2}f^{ace}f^{bde}\right).$$

WW Scattering @ LHC

Review

- The anomalous 4-point couplings in chiral Lag., and the HVV dim-6 operators in Linearized Lag. are relevant to WW scattering.
- WW scattering offers a way to probe strong TeV dynamics, or probe HVV couplings.
- WW scattering papers in our HEP theory group.


FIND a w. repko and t scattering From SPIRES HEP

High-energy photon neutrino elastic scattering — Dec 29, '09, 7:00 PM
Abbasabadi, Ali Phys.Rev.D63:093001,2001 hep-ph/0012257 Read more...

W, Z and Higgs scattering at SSC energies — Dec 9, '09, 7:00
Gupta, Suraj N. Phys.Rev.D48:2083-2096,1993 hep-ph/9307239 Read more...

The Effects of a strongly interacting Higgs sector on gai
Abbasabadi, A. Phys.Rev.D49:547-550,1994 hep-ph/9301226 Read more...

I = 1, J = 1 resonances in the Pade unitarized W(L)+ W(L
Dicus, Duane A. Phys.Rev.D47:4154-4157,1993 Read more...

Pade approximants and unitarity in W+ W- and Z0 Z0 sca
Dicus, Duane A. Phys.Rev.D42:3660-3667,1990 Read more...

Neutrino-photon scattering and the neutrino mass — Aug
Vega, Roberto Read more...

Unitarity Effects in W+ W- Elastic Scattering — Jan 16, '07, 7
Repko, Wayne W. Phys.Rev.Lett.62:859,1989 Read more...

Neutrino photon scattering in a magnetic field — Nov 20, '0
Dicus, Duane A. Phys.Lett.B482:141-144,2000 hep-ph/0003305 Read more...

FIND a c.p.yuan and t scattering From SPIRES HEP

Heavy Quark Mass Effects in Deep Inelastic Scattering and Glob
Tung, W.K. JHEP 0702:053,2007 hep-ph/0611254 Read more...

Inelastic channels in W W scattering — Dec 9, '09, 7:00 PM
Naculich, Stephen G. Phys.Rev.D48:1097-1103,1993 hep-ph/9302226 Read more...

Resummation of transverse momentum and mass logarithms in
Nadolsky, Pavel M. Phys.Rev.D67:074015,2003 hep-ph/0210082 Read more...

Phenomenology of multiple parton radiation in semiinclusive de
Nadolsky, Pavel M. Phys.Rev.D64:114011,2001 hep-ph/0012261 Read more...

Soft parton resummation in the current region of semiinclusive
Nadolsky, Pavel M. hep-ph/0006176 Read more...

Testing anomalous gauge couplings of the Higgs boson via wea

FIND a chivukula and simmons and t scattering

W(L) W(L) Scattering in Higgsless Models: Identifying Better Effectiv
Belyaev, Alexander S. Phys.Rev.D80:055022,2009 arXiv:0907.2662 Read more...

Identifying Better Effective Higgsless Theories via W_L W_L Scatteri
Belyaev, Alexander S. arXiv:1003.1

General Sum Rules for V
Chivukula, R.Sekhar Phys.Rev.D7

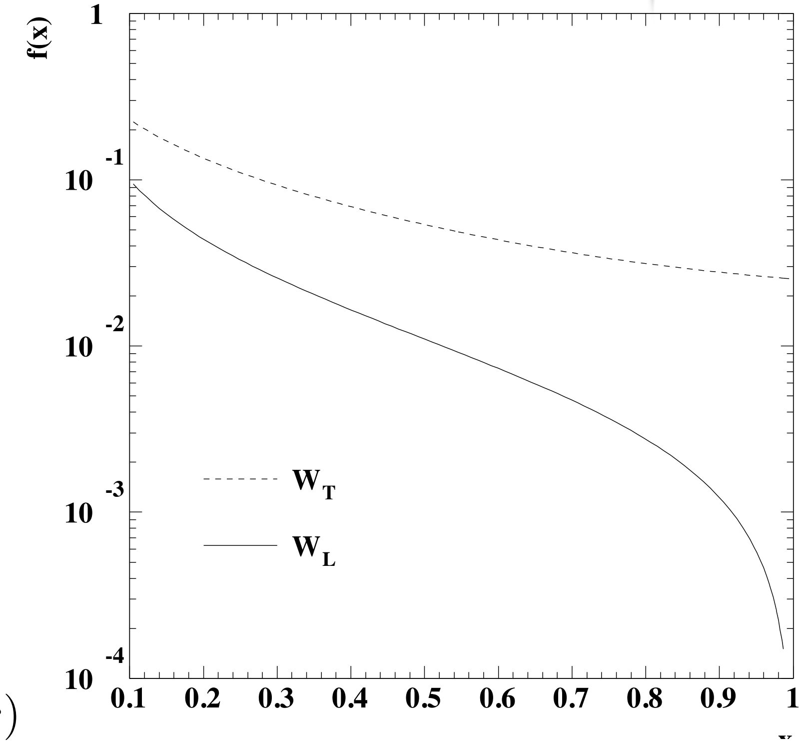
Deconstruction and Elas

FIND a c. schmidt and t

Equivalence Theorem Redux — Mar 21
Bagger, Jonathan Phys.Rev.D41:264,1990 Read m

Cross Section & EWA

$$\sigma(pp \to (q\bar{q}' \to V_3V_4) + X) = \sum_{i,j} \int\int\int dx_1 dx_2 dcos\theta f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}}{dcos\theta}(q\bar{q}' \to V_3V_4)$$



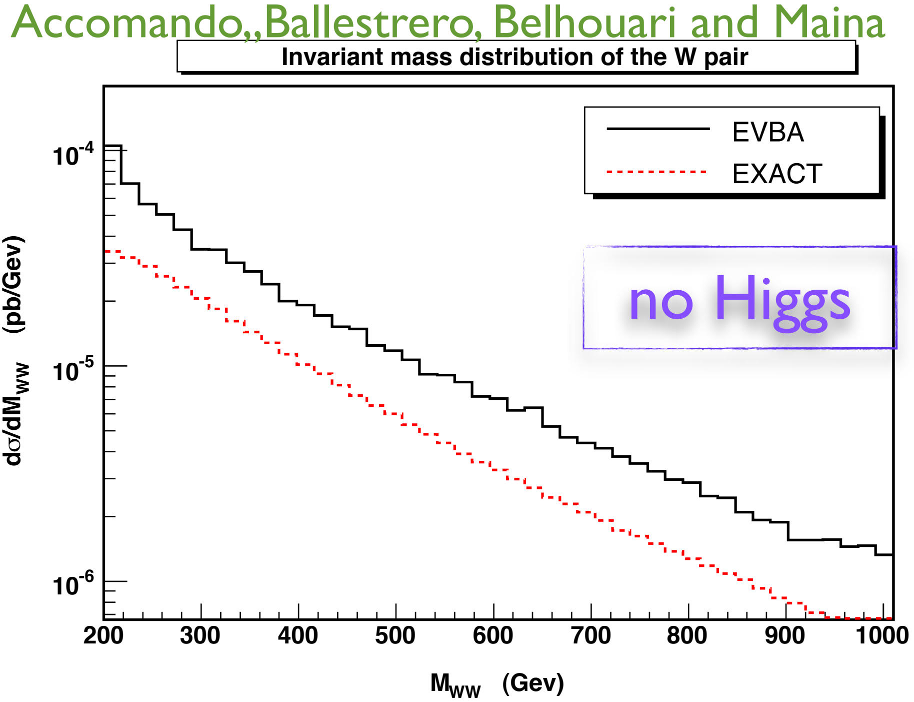
Effective W Approximation (EWA):

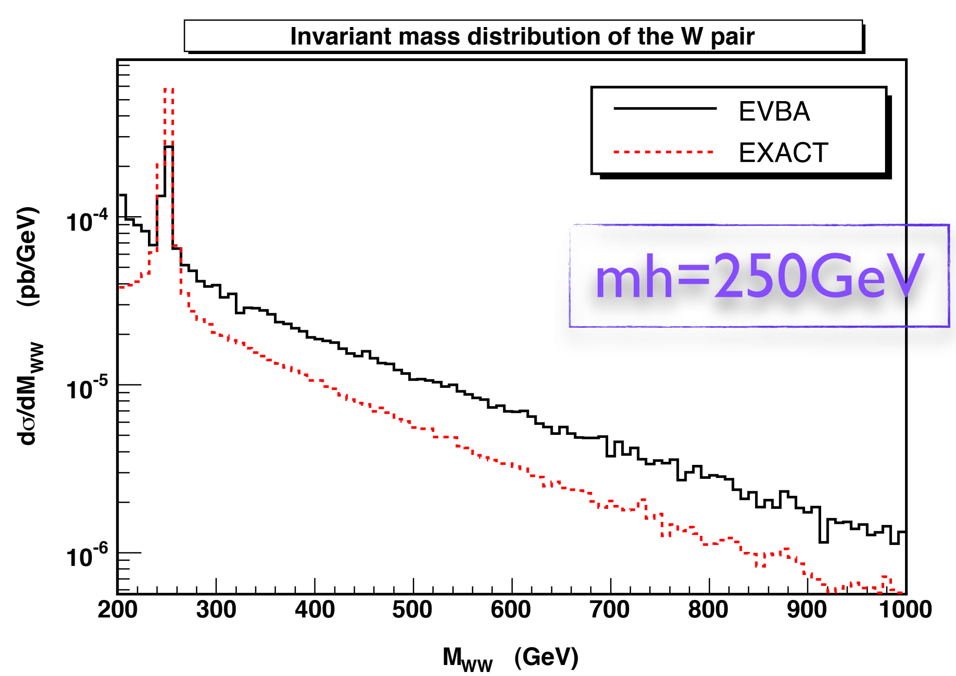
$$\sigma(pp \to (V_1V_2 \to V_3V_4) + X) = \sum_{i,j} \int\int dx_1 dx_2 dcos\theta f_i(x_1, Q^2) f_j(x_2, Q^2) \int\int d\hat{\tau} d\hat{\eta} \frac{\partial^2 L}{\partial\hat{\tau}\partial\hat{\eta}} \frac{d\hat{\sigma}}{dcos\theta}(V_1V_2 \to V_3V_4)$$

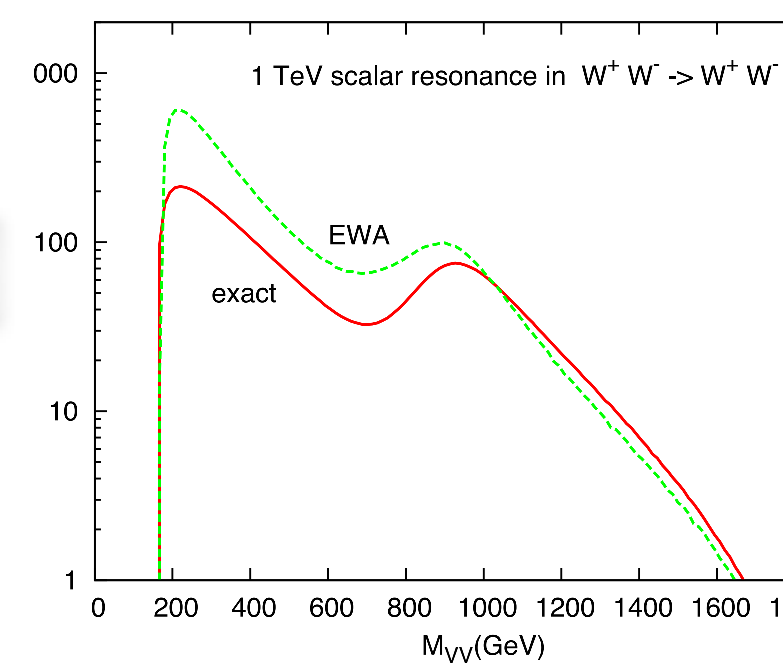
$$\approx \sum_{\lambda_1,\lambda_2} \int dx_1\, dx_2\, F^{\lambda_1}_{q_1 \to q_1' V_1}(x_1)\, F^{\lambda_2}_{q_2 \to q_2' V_2}(x_2)\, \sigma^{\lambda_1 \lambda_2}_{V_1 V_2 \to V_1' V_2'}(x_1 x_2 s)$$

In the exact calculation, the ambiguity for the off-shell W??

Accomando,,Ballestrero, Belhouari and Maina



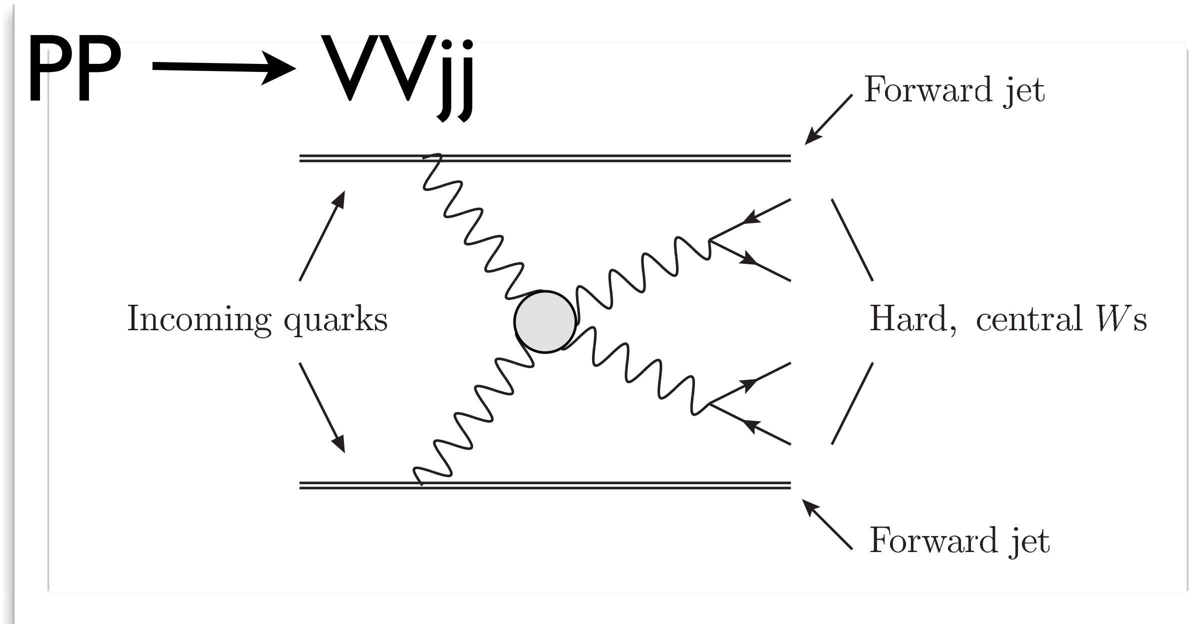




Kilian, et al

Signal & Backgrounds

If strong dynamics at TeV scale, VL VL to VL VL scattering is expected to be enhanced at large invariant mass.



In contrast, VT VT to VT VT, and VT VL to VT VL scattering remain perturbative through the whole invariant mass range. (irreducible BG)

Signal Definition: the enhancement of the cross section over the SM prediction with a light Higgs

$$\sigma_{signal} = \sigma_{newphys} - \sigma_{SM}(m_H = 100 \text{ GeV})$$

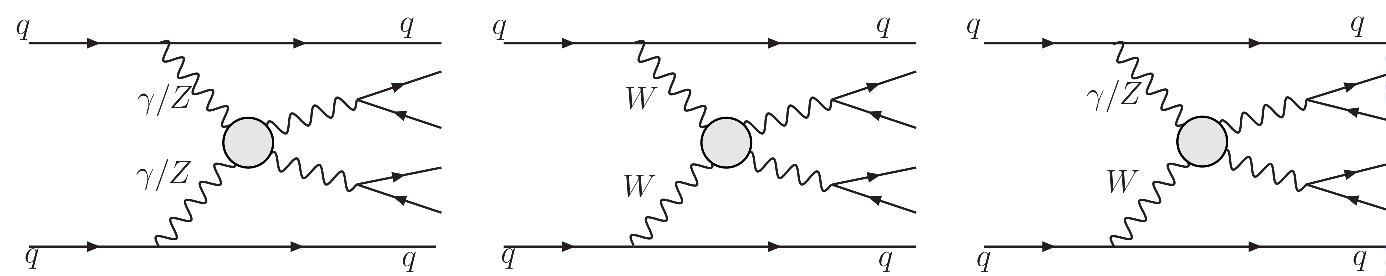
WW Scattering Channels:

4 scattering processes: **W+W-** **W+W+** **W Z** **Z Z**	**X**	**3 decay modes:** **purely leptonic** **semi-leptonic** **purely hadronic**	**=**	**Potentially at least 12 analyses to do!**

Signal & Backgrounds

Bagger, Barger, Cheung, Gunion, Han, Ladinsky, Rosenfeld, Yuan

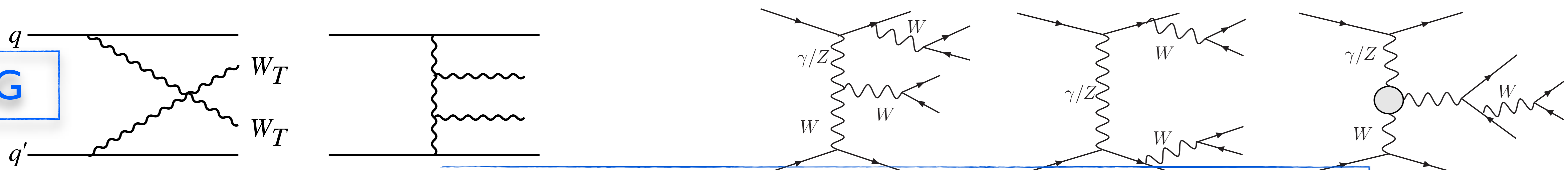
WL-WL Signal



Two Spectator quarks

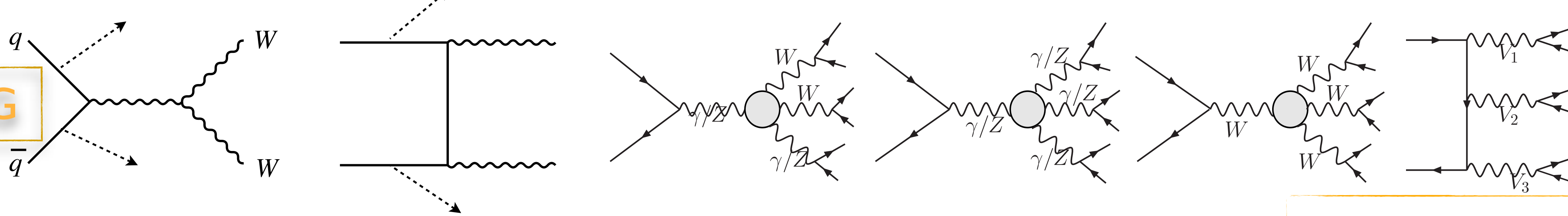
Focus on lepton channel

WT BG



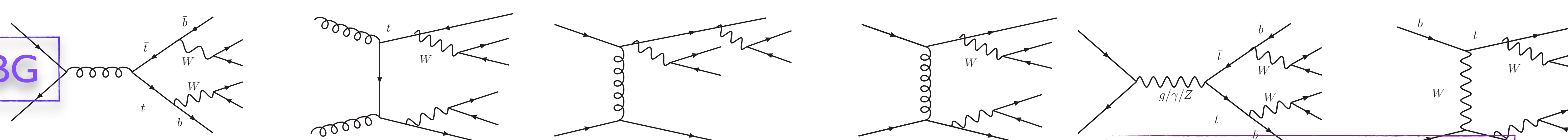
energetic leptons at low rapidity (intrinsic BG)

QCD BG



Forward Jet-Tagging

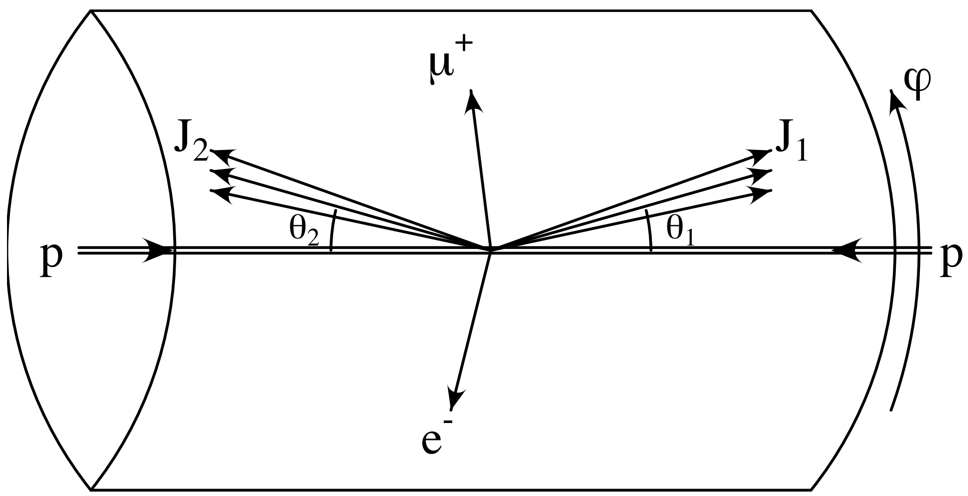
tt-bar BG

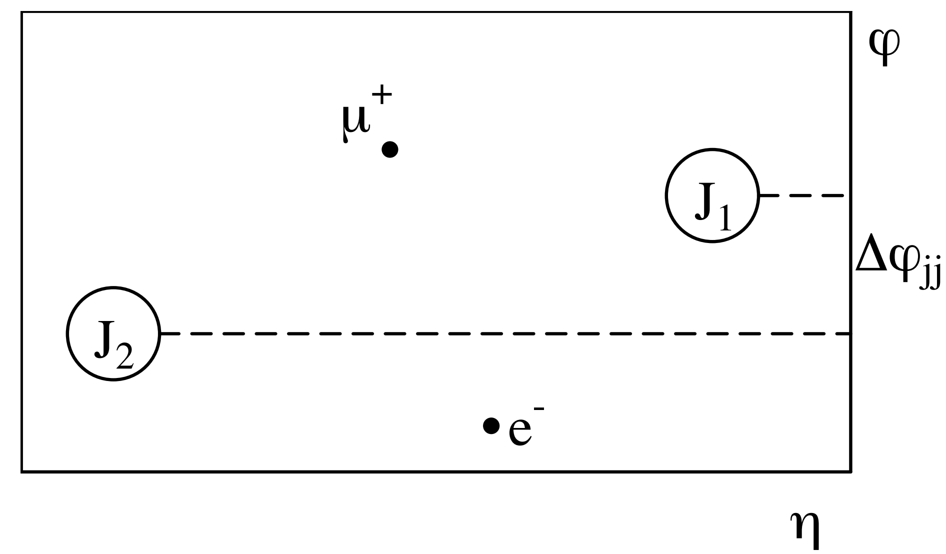


(a) (b) (c) (d)

Central Jet-Veto

Selection of Cuts





Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV) — Jet-Tagging
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets — Central-rapidity leptonic cuts
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$) — Jet-Veto

All jets need to lie in the rapidity-range accessible to the detector,

$$|\eta_j| < 4.5\,,$$

and are supposed to be well-separated,

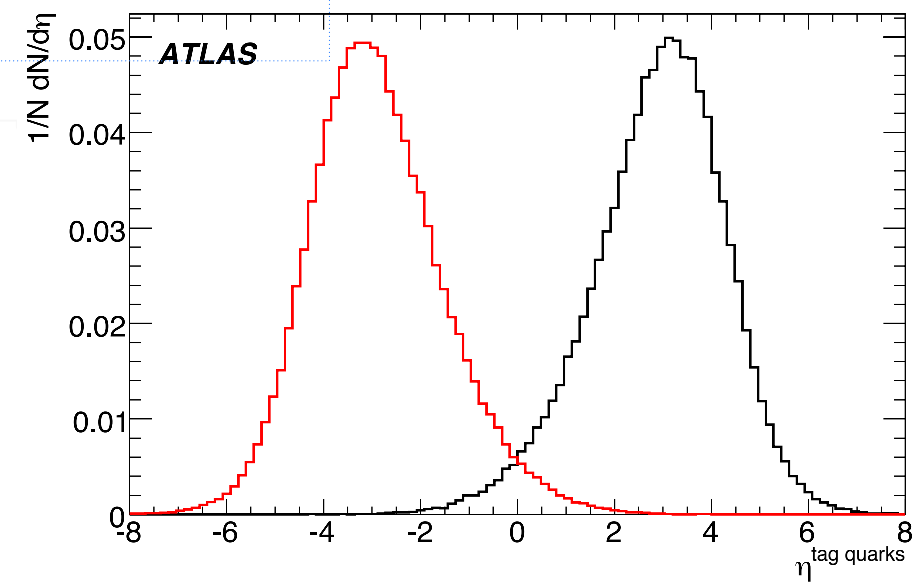
$$\Delta R_{jj} = \sqrt{(\eta_{j_1} - \eta_{j_2})^2 + (\phi_{j_1} - \phi_{j_2})^2} > 0.7\,,$$

Jet-Tagging & Jet-Veto

The two jets of largest Pt are called "tagging jets".

1. Require two jets with
   - $|\eta(jet)| > \eta_{cut}$ and $p_T(jet) > p_{Tcut}$ $\quad p_{Tj}^{tag} > 30$ GeV .
   - opposite signed rapidity $\quad \eta_{j_1}^{tag} \times \eta_{j_2}^{tag} < 0$.
   - at least one of them has an energy greater than a critical value E_{cut} $\quad m_{jj} > m_{jj}^{min}$,
2. If more than one jet with the same sign rapidity satisfies the above cuts, choose the most energetic, labelled FJ1. The next one is labelled FJ2.
   - Require the tag-jet with the opposite sign of rapidity to satisfy $\Delta\eta(FJ1, FJ2) > \Delta\eta_{cut}$ and $E(FJ2) > E_{2cut}$

$$\Delta\eta_{jj} = |\eta_{j_1}^{tag} - \eta_{j_2}^{tag}| > 4 ,$$



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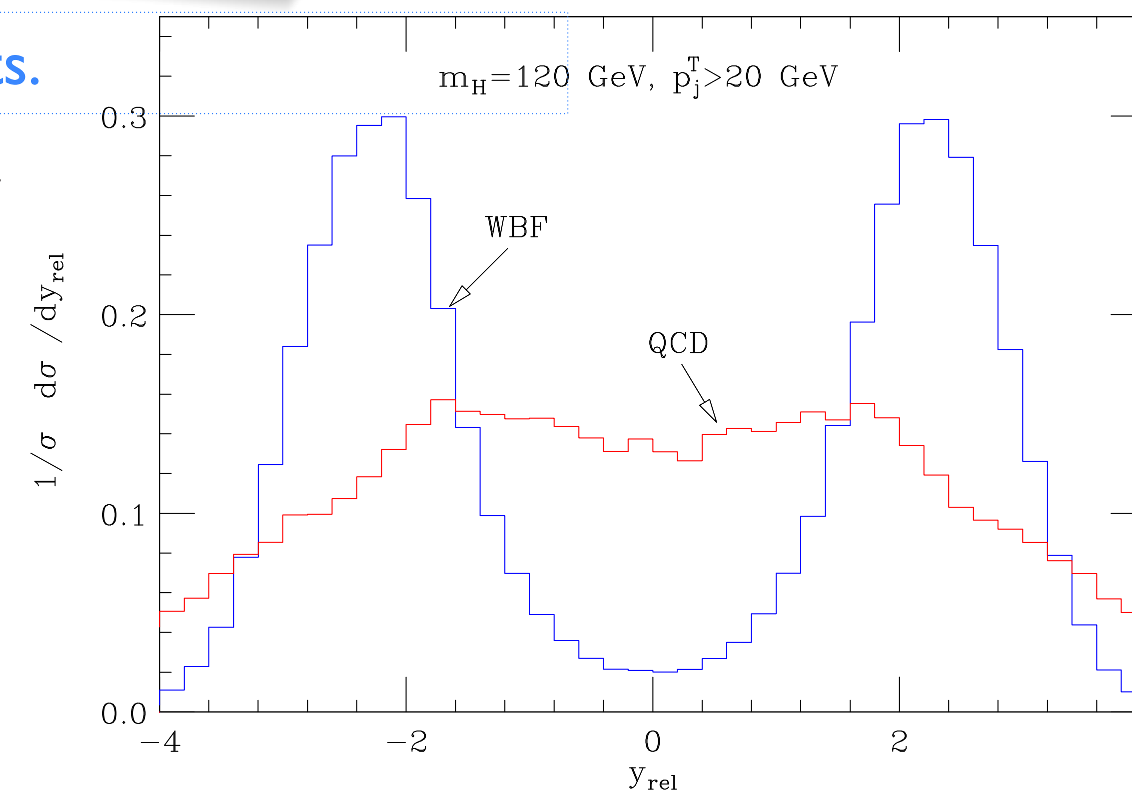
For the central jets with larger Pt, we discards the events.

We veto any such activity by discarding all events with an extra veto jet of

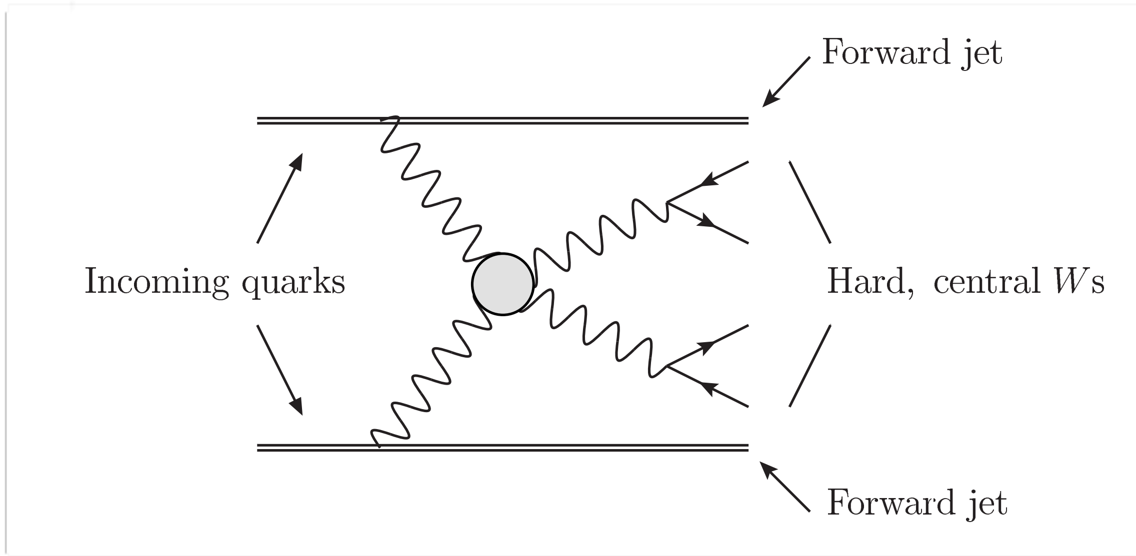
$$p_{Tj}^{veto} > 25 \text{ GeV} ,$$

located in the gap region between the two tagging jets,

$$\eta_{j,min}^{tag} < \eta_j^{veto} < \eta_{j,max}^{tag} .$$



Leptonic Cuts



In order to ensure well-observable isolated charged leptons in the central-rapi
region, we require

$$p_{T\ell} > 20 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad \Delta R_{\ell j} > 0.4\,,$$

The leptons (produced by VV decay) are typically located in the central rapidity region between two tagging jets:

$$\eta_{j,min}^{tag} < \eta_\ell < \eta_{j,max}^{tag}\,,$$

Bagger, Barger, Cheung, Gunion, Han, Ladinsky, Rosenfeld, Yuan

- $ZZjj \to 4\ell\, jj$:

$$m_{ZZ} > 500 \text{ GeV}\,,$$
$$p_T(\ell\ell) > 0.2 \times m_{ZZ}\,.$$

- $ZZjj \to 2\ell 2\nu\, jj$:

$$m_T(ZZ) > 500 \text{ GeV}\,,$$
$$p_T^{miss} > 200 \text{ GeV}\,,$$

with p_T^{miss} being the transverse momentum of the neutrino system and

$$m_T^2(ZZ) = [\sqrt{m_Z^2 + p_T^2(\ell\ell)} + \sqrt{m_Z^2 + (p_T^{miss})^2}]^2 - [\vec{p}_T(\ell\ell) + \vec{p}_T^{miss}]^2\,.$$

- $W^\pm Zjj$:

$$m_T(WZ) > 500 \text{ GeV}\,,$$
$$p_T^{miss} > 30 \text{ GeV}\,,$$

where

$$m_T^2(WZ) = [\sqrt{m^2(\ell\ell\ell) + p_T^2(\ell\ell\ell)} + |p_T^{miss}|]^2 - [\vec{p}_T(\ell\ell\ell) + \vec{p}_T^{miss}]^2\,,$$

- W^+W^-jj:

$$p_{T\ell} > 100 \text{ GeV}\,,$$
$$\Delta p_T(\ell\ell) = |\vec{p}_{T,\ell_1} - \vec{p}_{T,\ell_2}| > 250 \text{ GeV}\,,$$
$$m_{\ell\ell} > 200 \text{ GeV}\,,$$
$$\min(m_{\ell j}) > 180 \text{ GeV}\,,$$

Englert, Jager, Worek, Zeppenfeld

Calculation Tools

Pythia

(1) generate signal in the effective W approximation; (2) scenarios with different resonances are available by choice of input a4, a5; (3)only 2 to 2 + decay, so the BGs are only qq to WW, qq to tt.

MadEvent

(1) handle all processes up to 6 particles in final states; (2)best to generate BGs; (3) not strong TeV models with amplitude unitarization available; (4) too many unwanted diagrams (possible to modify the source code to exclude unwanted diagrams, or specify W polarization).

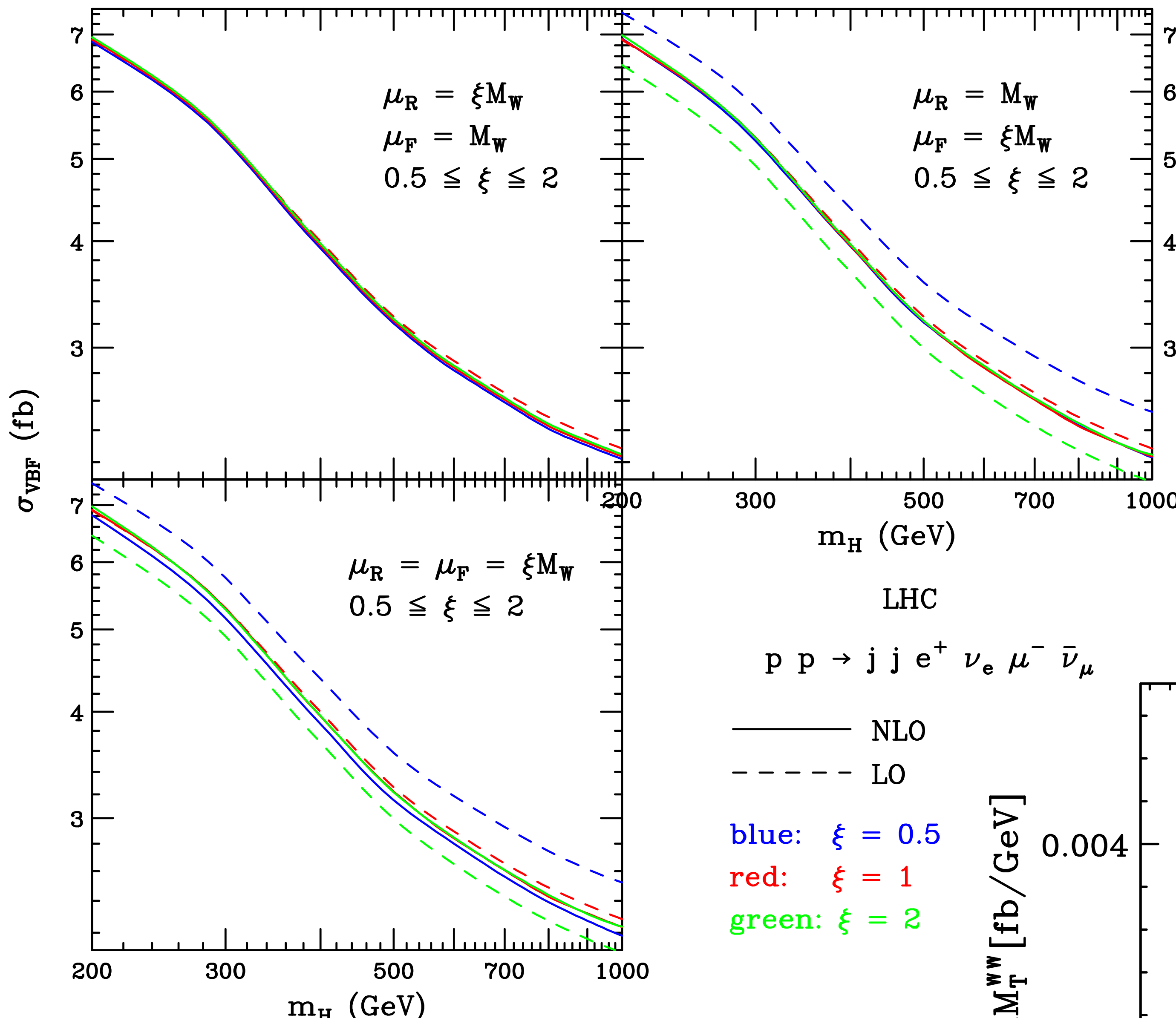
CalcHEP

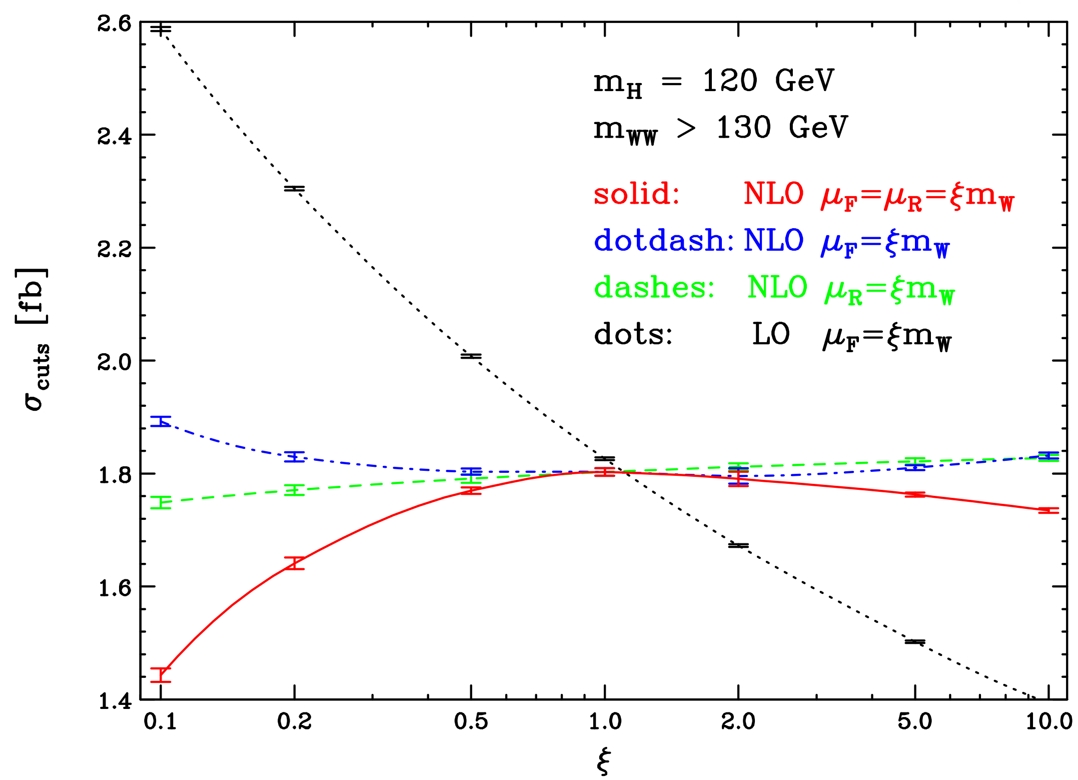
(1) handle all processes up to 6 particles in final states; (2)hard to manipulate the code to modify something.

VBFNLO

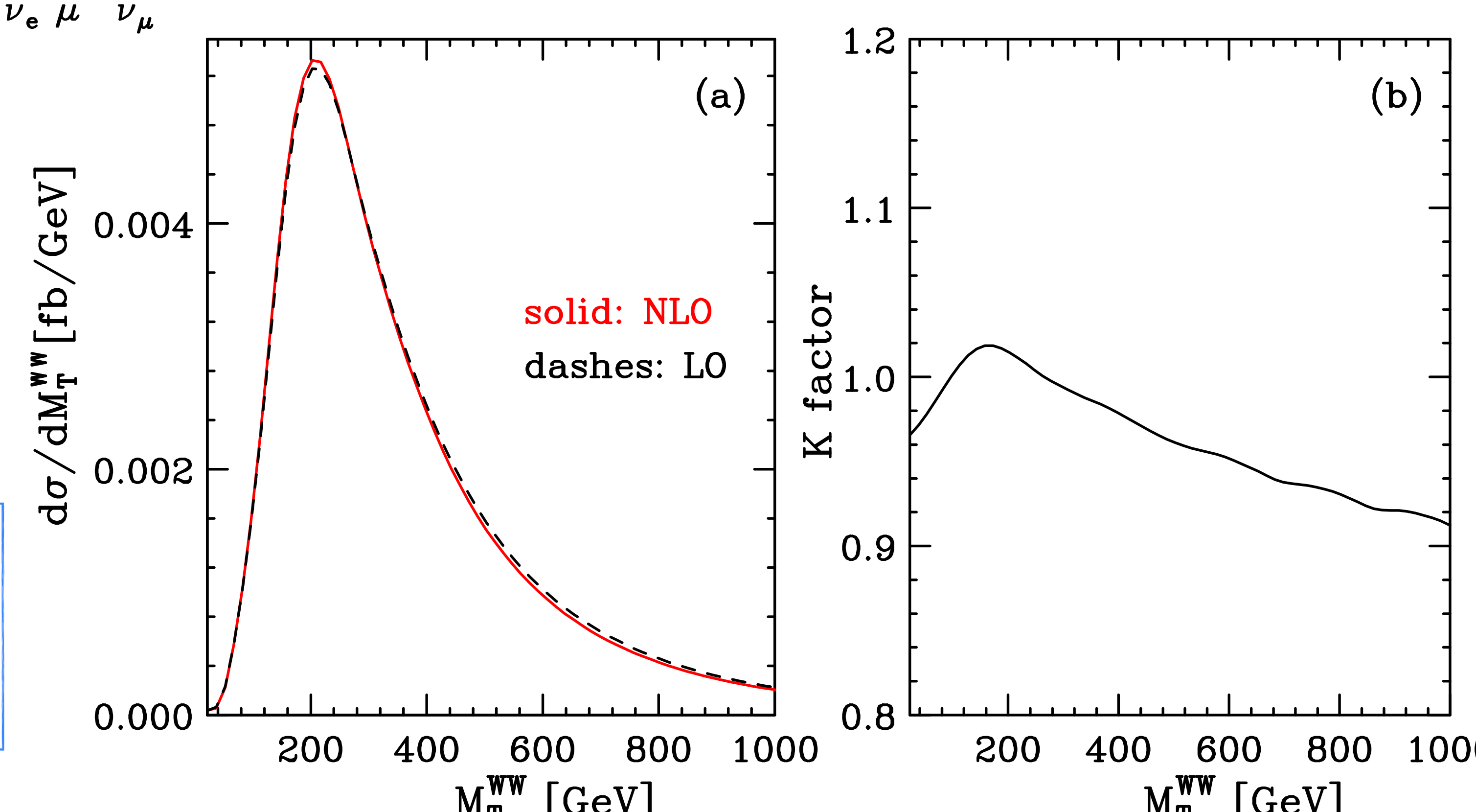
(1) Specific to generate vector boson fusion up to NLO; (2)in LO use HELAS amplitude generated by MadGraph; (3) possible to modify the code to add new physics parameters.

NLO Calculations?





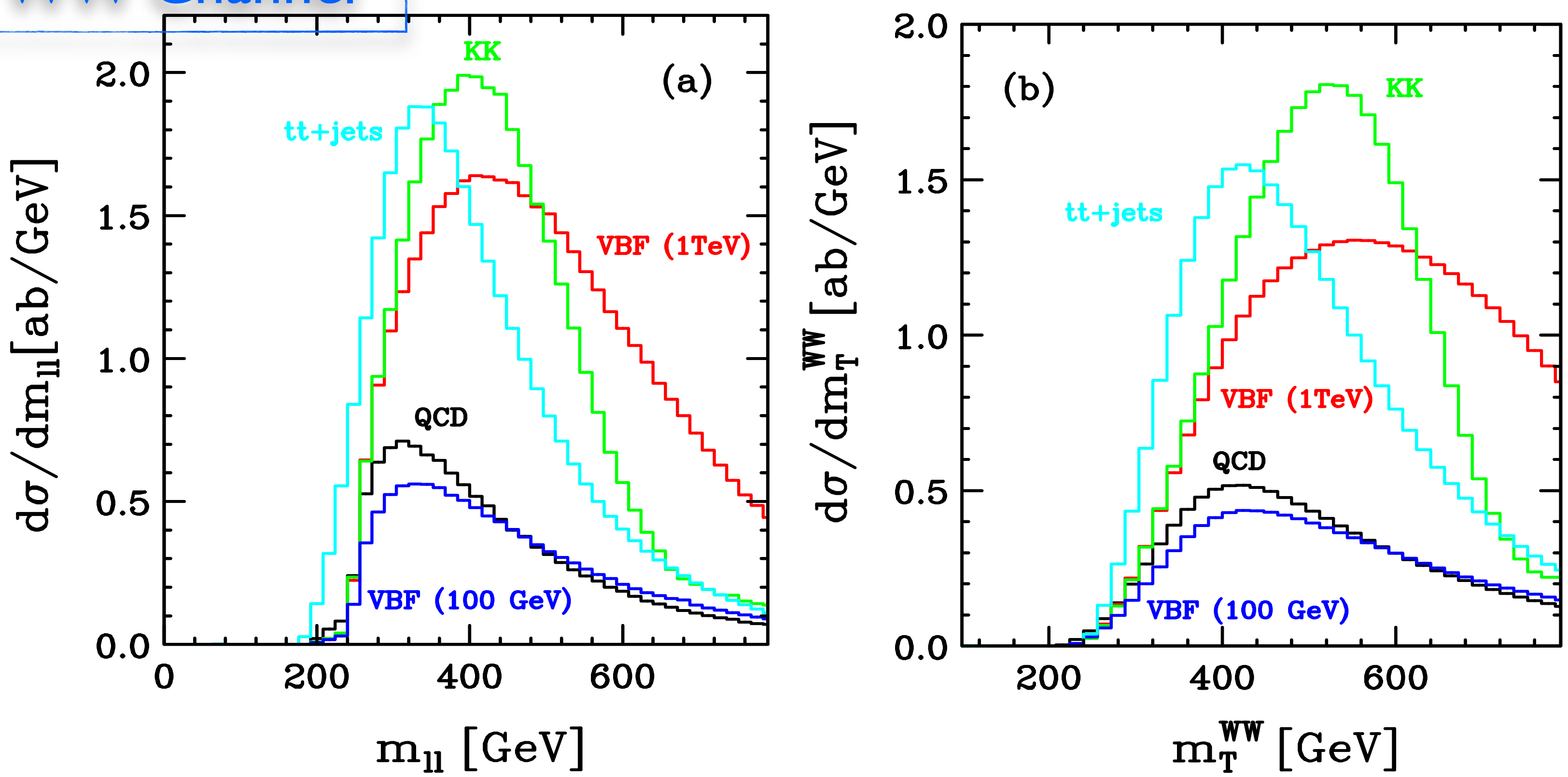
Jager, Oleari, Zeppenfeld



The NLO effects can be well approximated by a proper choice of the factorization scale in the LO calculation.

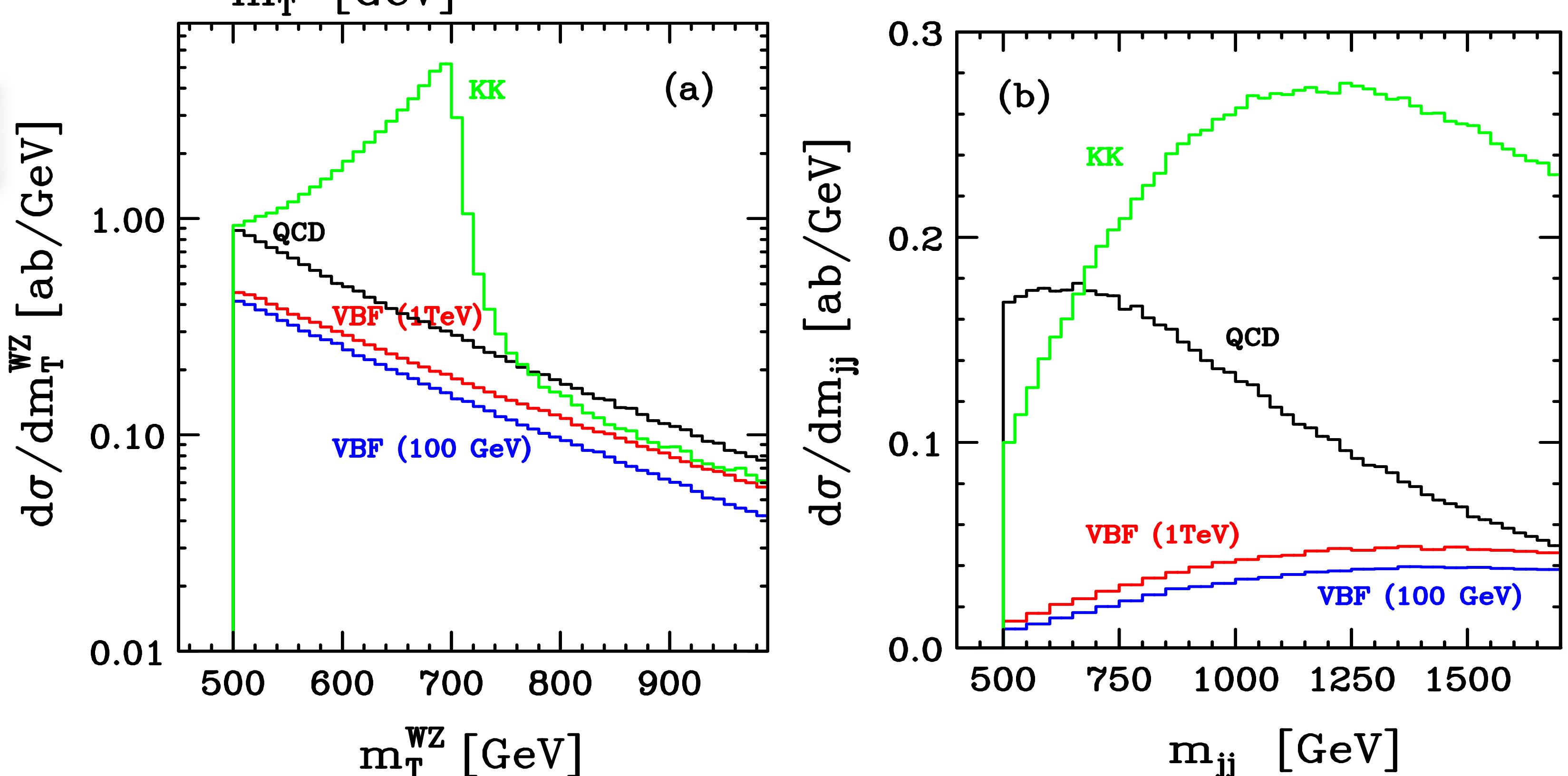
WW/WZ(SM Higgs/Higgsless KK)

WW Channel



Englert, Jager, Worek, Zeppenfeld

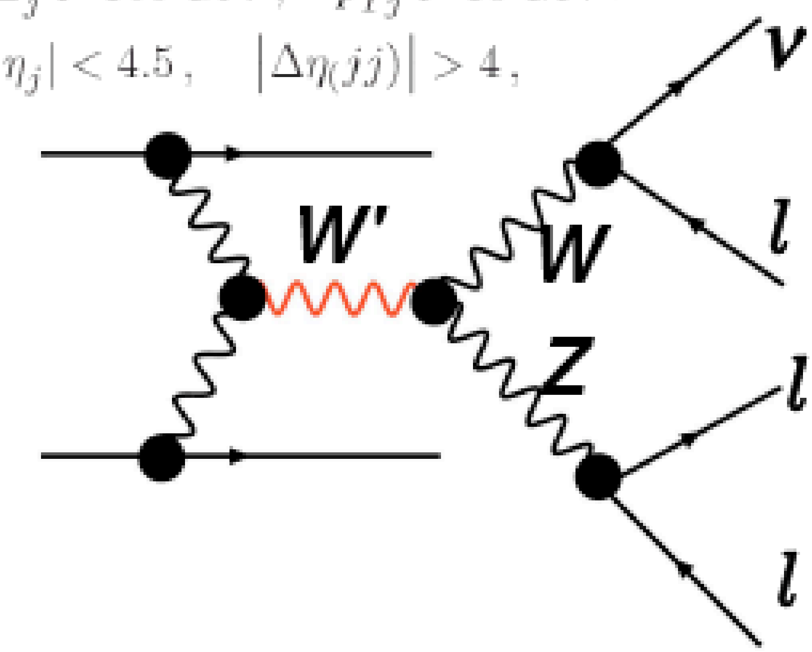
WZ Channel

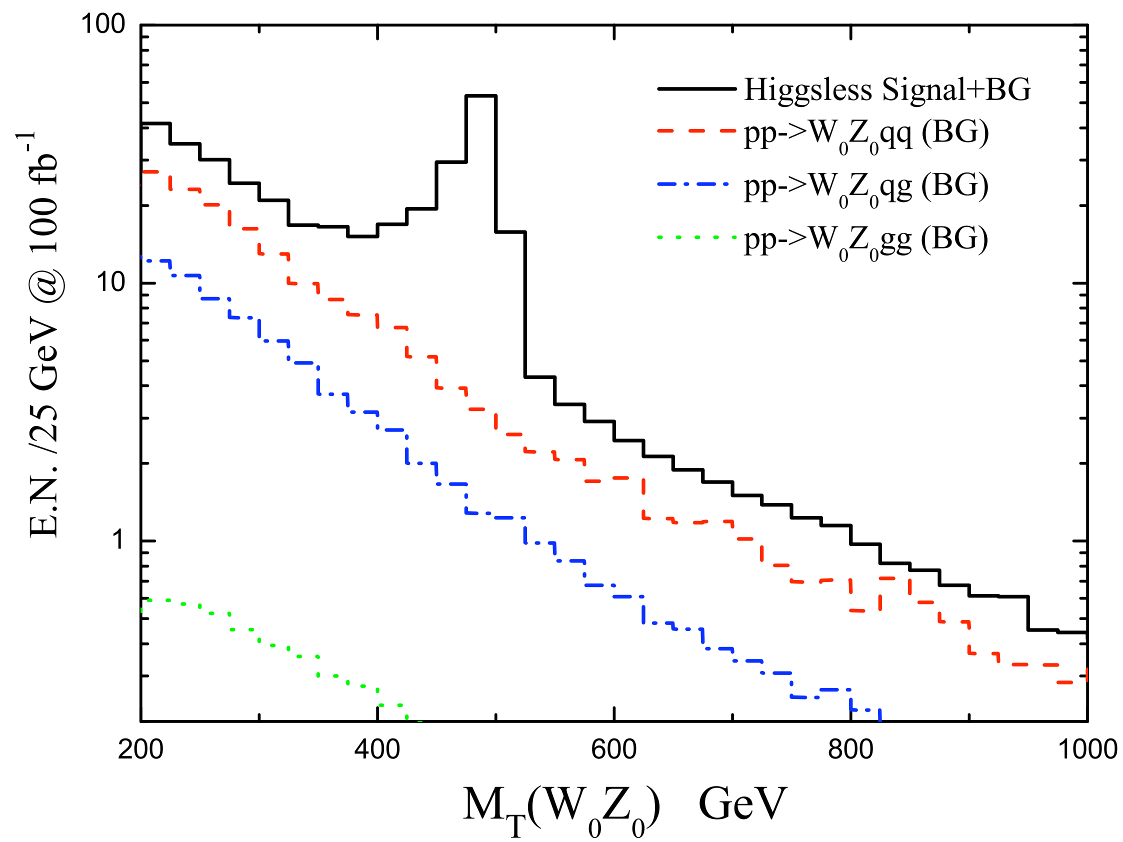


WZ Channel (Three Site/ Higgsless)

Three Site

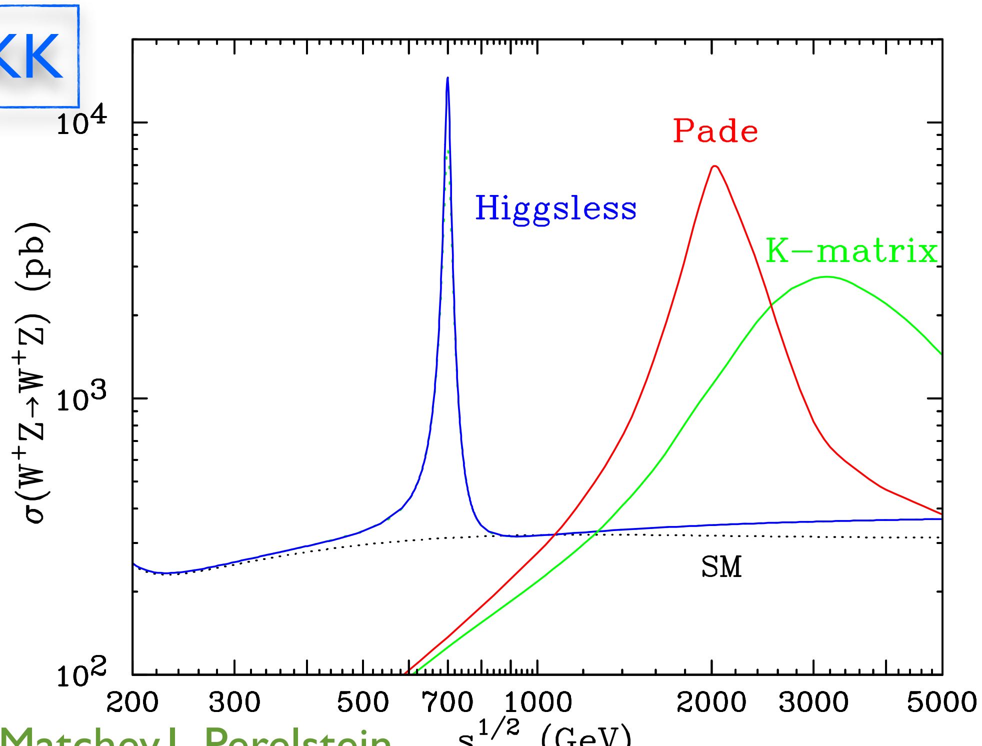
$E_j > 300\,\mathrm{GeV}\,, \quad p_{Tj} > 30\,\mathrm{GeV}$
$|\eta_j| < 4.5\,, \quad |\Delta\eta(jj)| > 4\,,$

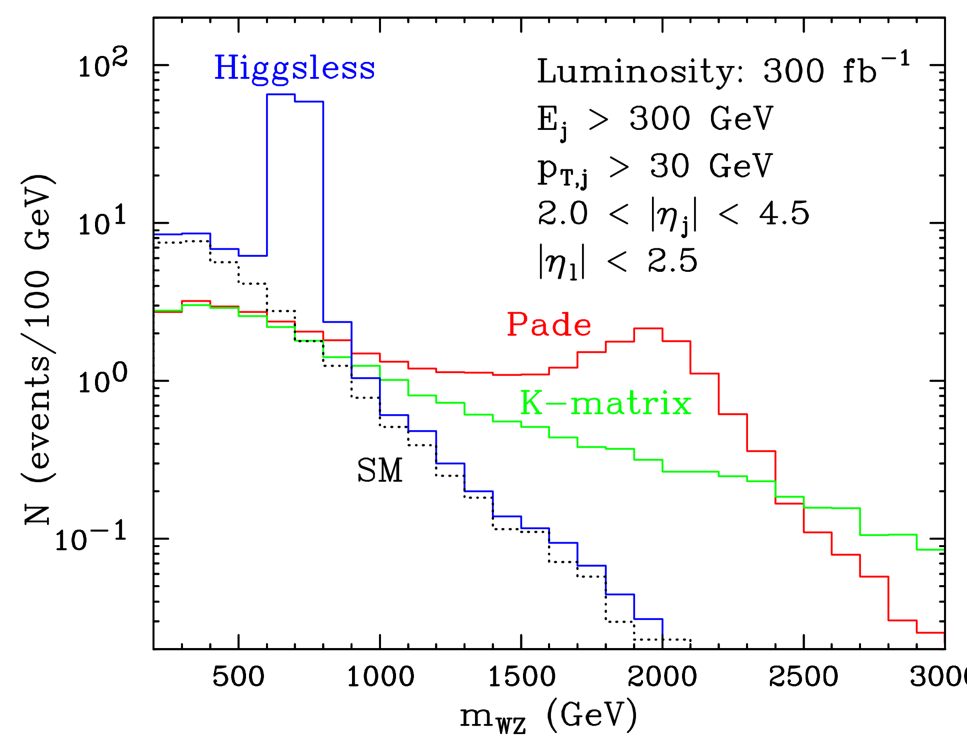




Chivukula, Simmons, et. al.

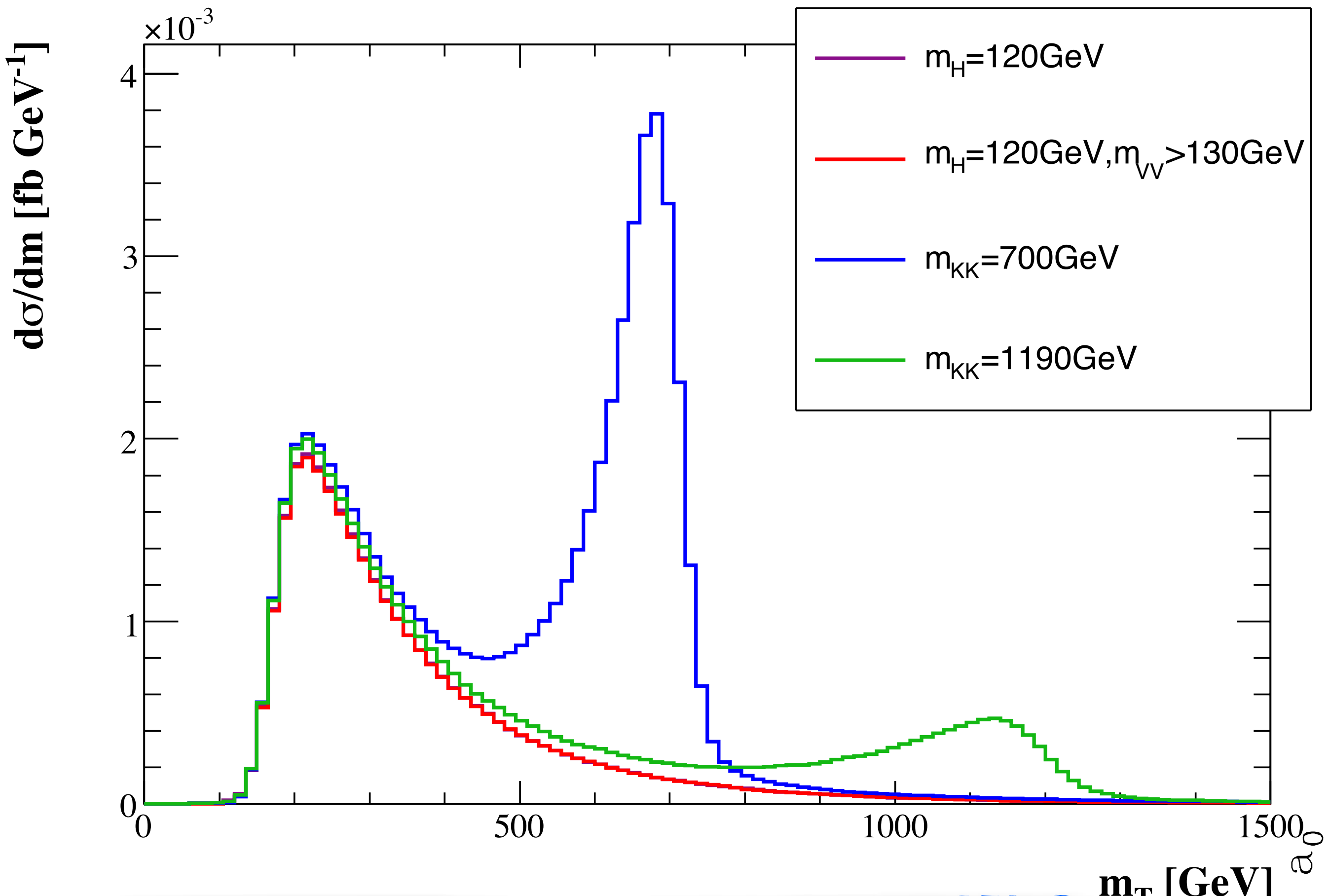
Higgsless KK





Birkedal1, Matchev1, Perelstein

Results from VBFNLO(wz)



$$m_T^2(WZ) = \left(\sqrt{m_{lll}^2 + \vec{p}_{T,lll}^{\,2}} + |\not{p}_T|\right)^2 - (\vec{p}_{T,lll} + \vec{\not{p}}_T)^2$$

In LHC, if there is a bump, how can we know it comes from the enhanced signal or unitarity violation?

Foadi, Gopalakrishna, Schmidt

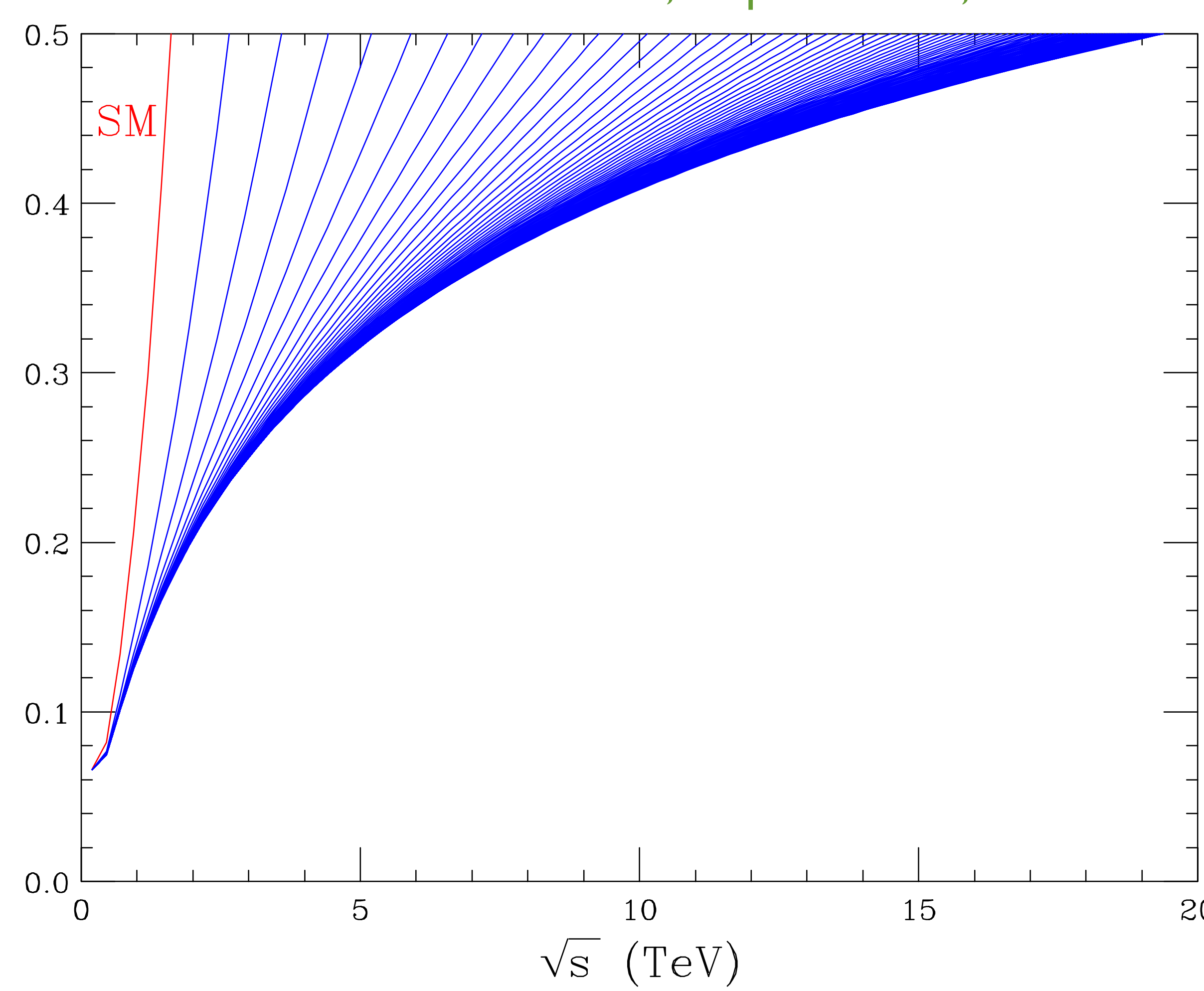
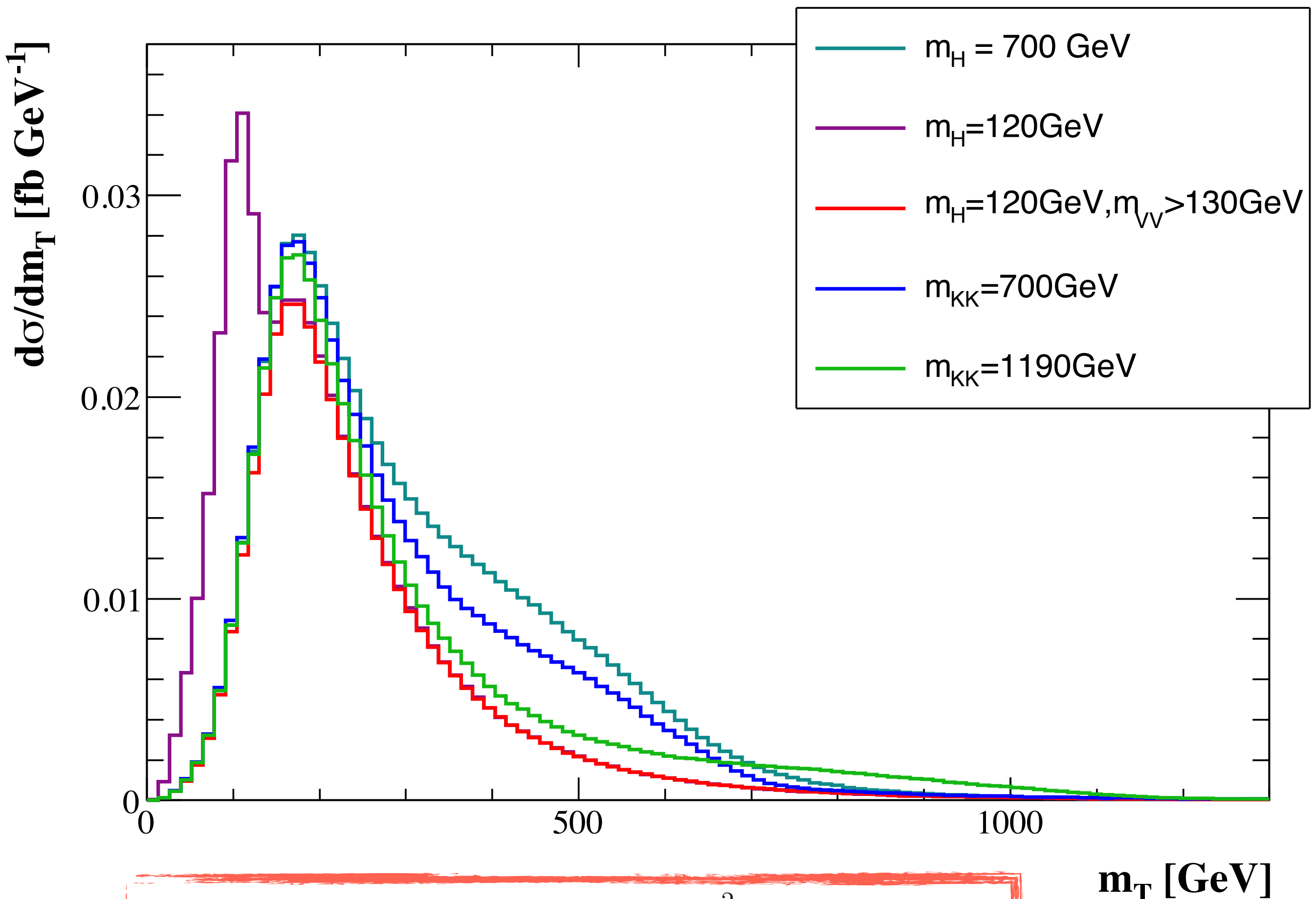
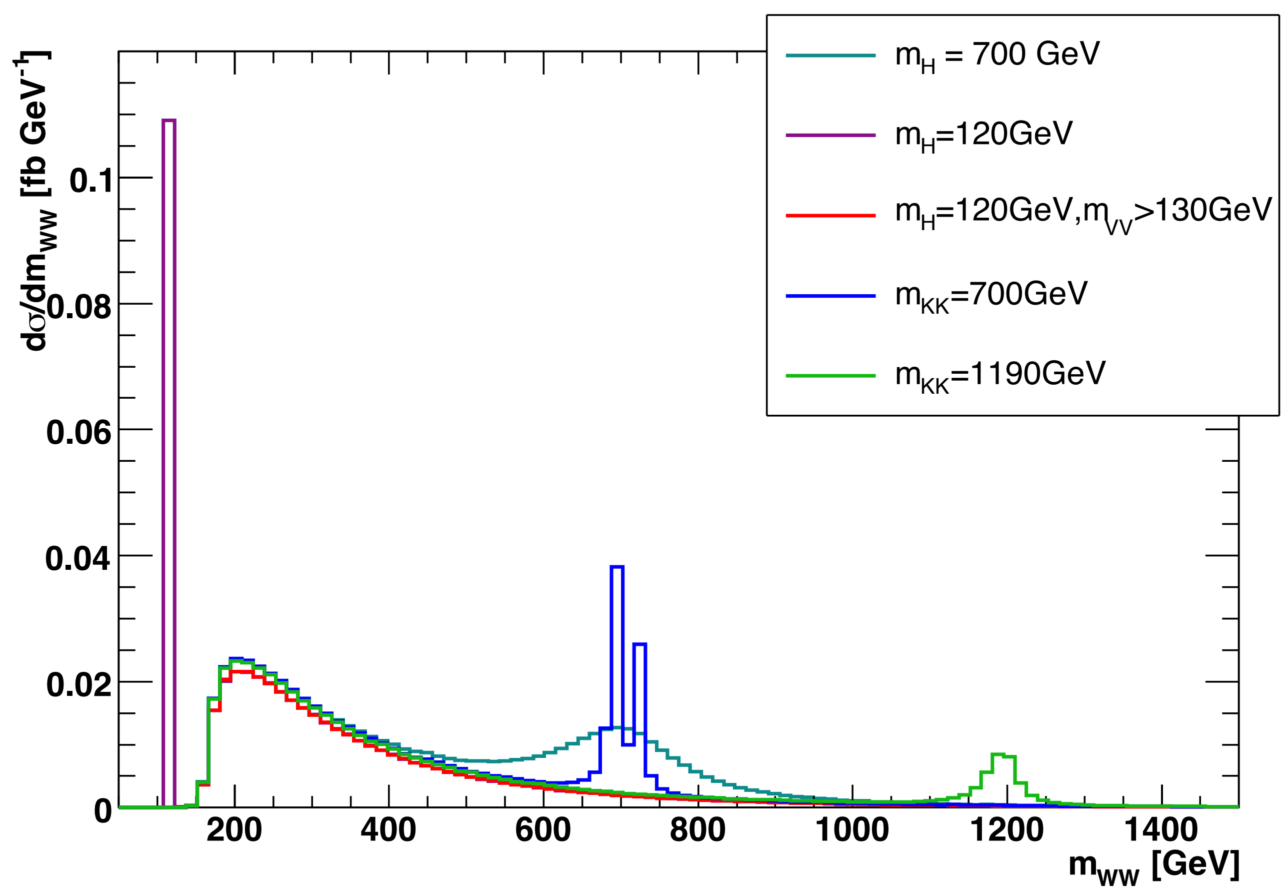


Figure 7: The $J = 0$ partial wave amplitude as a function of $\sqrt{s}$ for the standard model without a Higgs boson (red) and the $U(1) \times [SU(2)]^N \times SU(2)_{N+1}$ model (blue) for $N = 1$ to 100 with $m_{W'} = 500$ GeV.

Results from VBFNLO(ww)



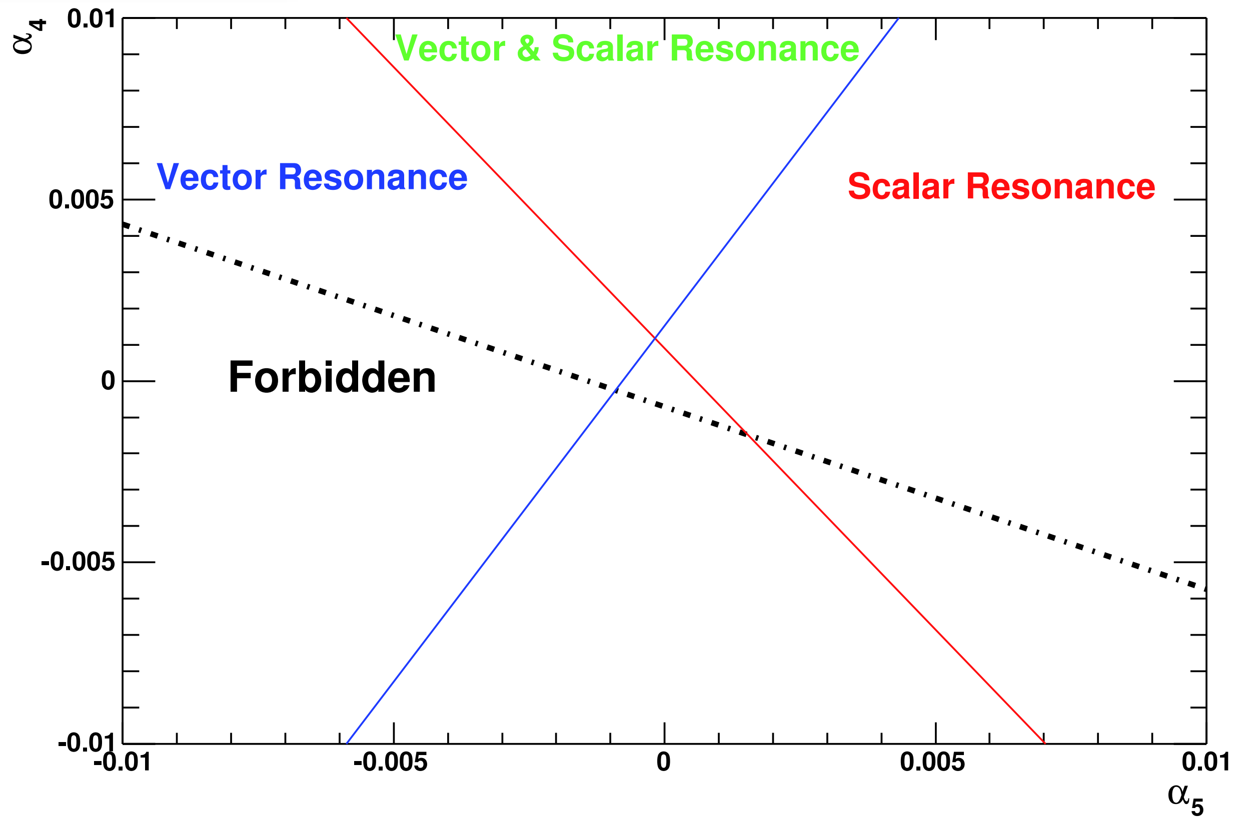
$$m_T^2(WW) = \left(\sqrt{m_{ll}^2 + \vec{p}_{T,ll}^{\,2}} + |\not{p}_T|\right)^2 - (\vec{p}_{T,ll} + \vec{\not{p}}_T)^2$$

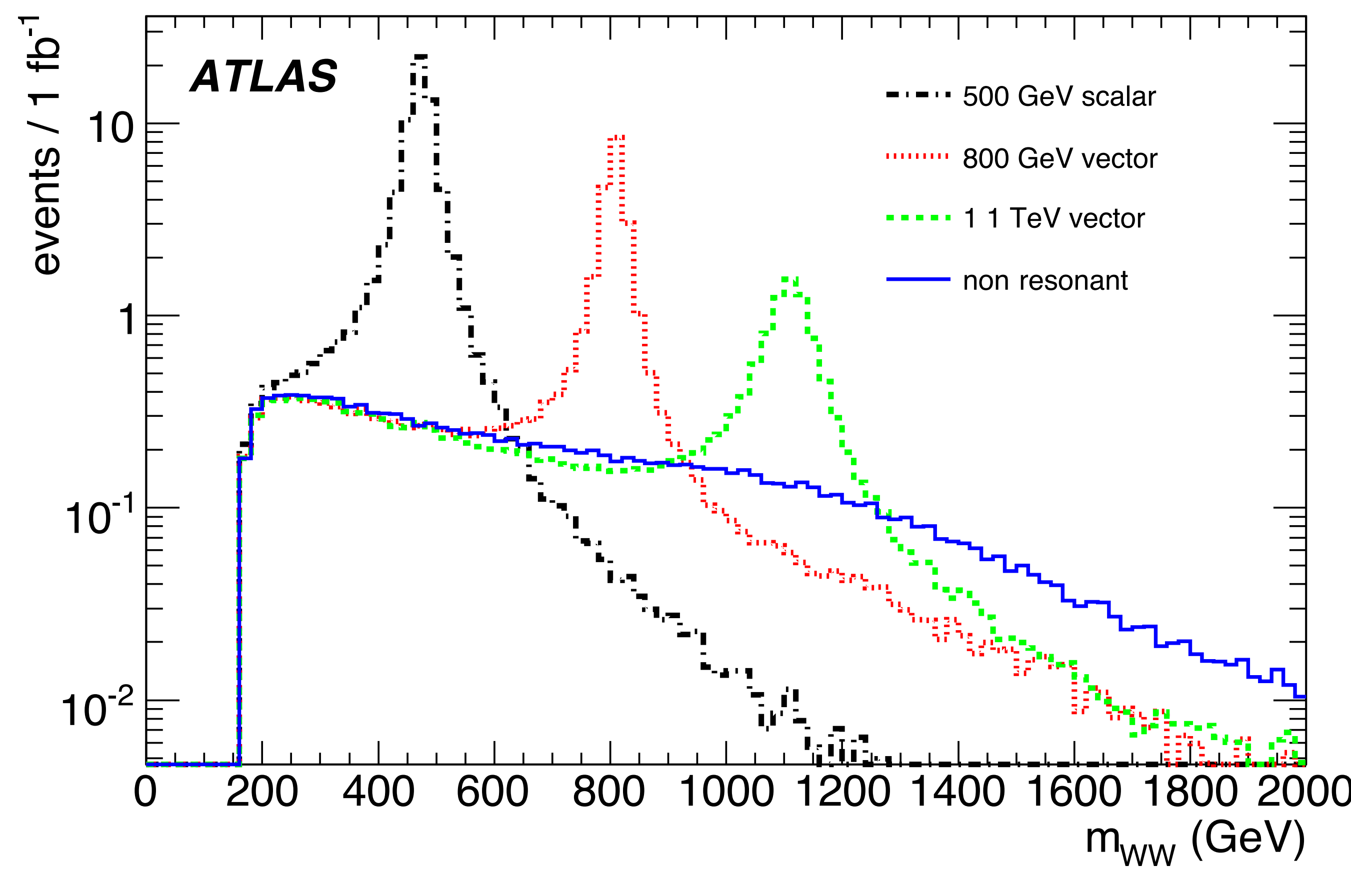


In the WW channel, if we know there is a unitarity violation, how can we identify the unitarity violation scale M(WW) from the MT(ll)??

Other Scenarios?

Chiral Lag





ATLAS TDR

Other Scenarios???

Non-Standard Higgs?

Little Higgs?

Linearized effective Lag.

He, Kuang, Yuan, Zhang

Strongly-Interacting Light Higgs?

Summary

- Before Higgs discovery, WW scattering offers a way to probe the EWSB mechanism.

- Even when Higgs is discovered, WW scattering can still be used to distinguish SM Higgs from other models.

- WW scattering at the LHC (Signal+BG) is reviewed, and new results from MC generator is in progress.

Thank You!!!

New Resonances?

$$\mathcal{L}_s = -\frac{1}{2}\Phi_r^a \Box \Phi_r^a - \frac{1}{2}m_r^2 \Phi_r^a \Phi_r^a + \beta_r f \, \Phi_r^a (\vec{h}^T \; T_L^a T_R^3 \; \vec{h}) + \cdots \; .$$

By integrating out Φ_r^a we find

$$\begin{aligned} \mathcal{L}_{eff} &= \frac{\beta_r^2 f^2}{2} (\vec{h}^T \; T_L^a T_R^3 \; \vec{h}) \frac{1}{\Box + m_r^2} (\vec{h}^T \; T_L^a T_R^3 \; \vec{h}) \\ &= \frac{\beta_r^2 f^2}{2 m_r^2} (\vec{h}^T \; T_L^a T_R^3 \; \vec{h}) \left[1 - \frac{\Box}{m_r^2} + \cdots \right] (\vec{h}^T \; T_L^a T_R^3 \; \vec{h}), \end{aligned}$$