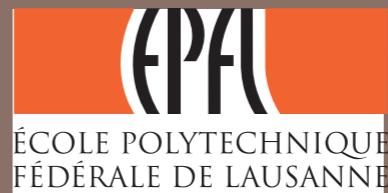


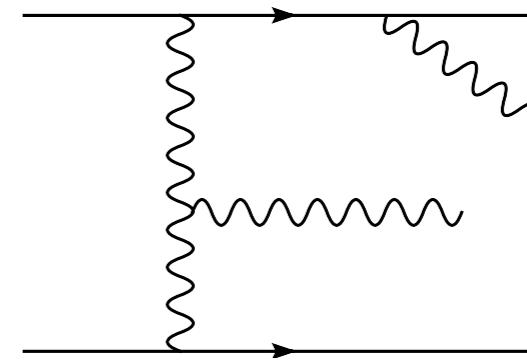
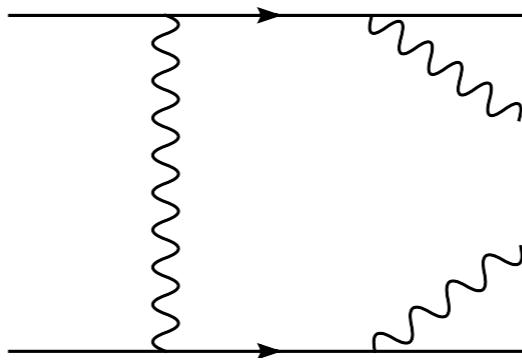
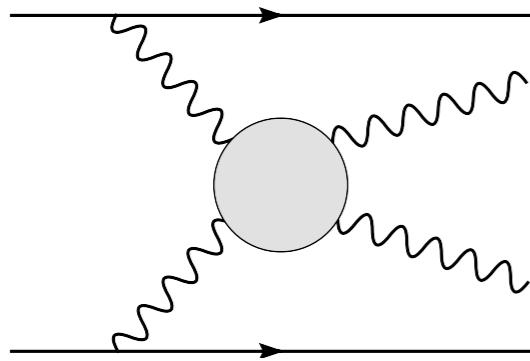
THEORETICAL ASPECTS OF VECTOR BOSON SCATTERING

Roberto Contino
EPFL & CERN

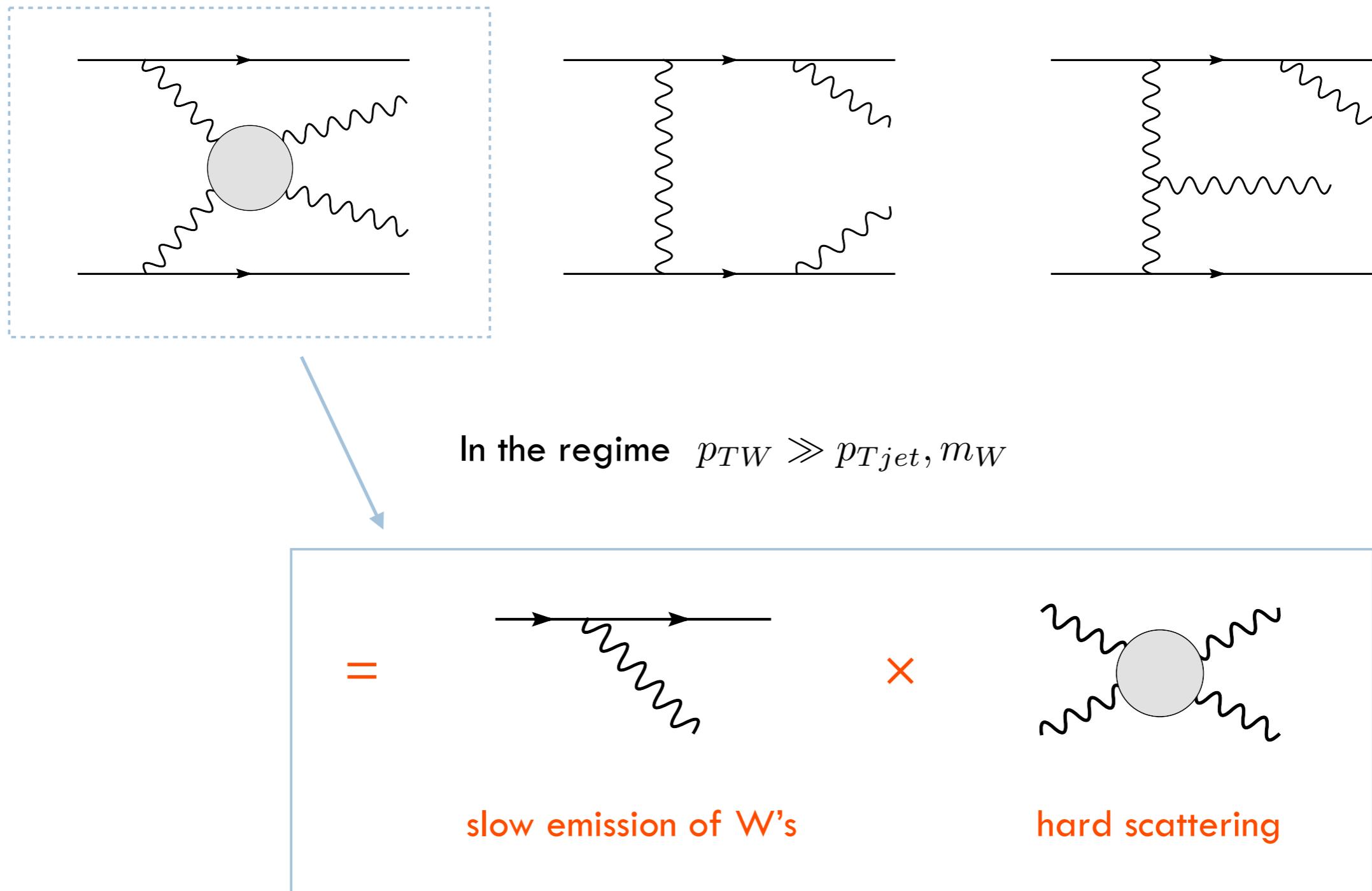


‘Physics at the High-Luminosity LHC’, May 11-13, 2015, CERN

Anatomy of WW scattering

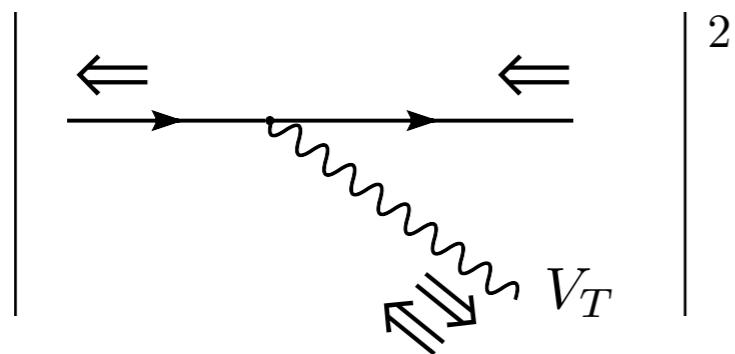


Anatomy of WW scattering



Luminosity of W_T , W_L inside the proton

- Transversely polarized W's

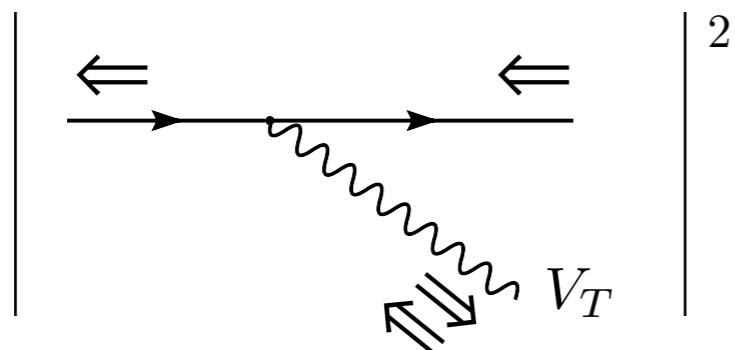


$$f_T(x) = \frac{g_V^2 + g_A^2}{4\pi^2} \frac{1 + (1-x)^2}{x} \int d^2 p_T \frac{p_T^2}{[p_T^2 + (1-x)m_V^2]^2}$$
$$\simeq \frac{g_V^2 + g_A^2}{4\pi^2} \frac{1 + (1-x)^2}{x} \log \frac{p_{Tmax}^2}{(1-x)m_V^2}$$

Luminosity of W_T, W_L inside the proton

- Transversely polarized W's

Log enhancement as in the
Weizsäcker-Williams
photon spectrum



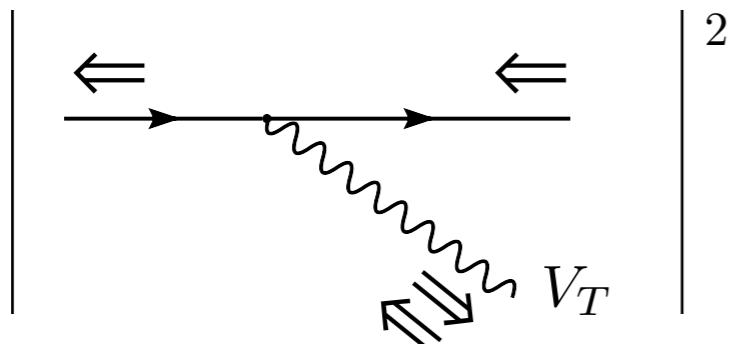
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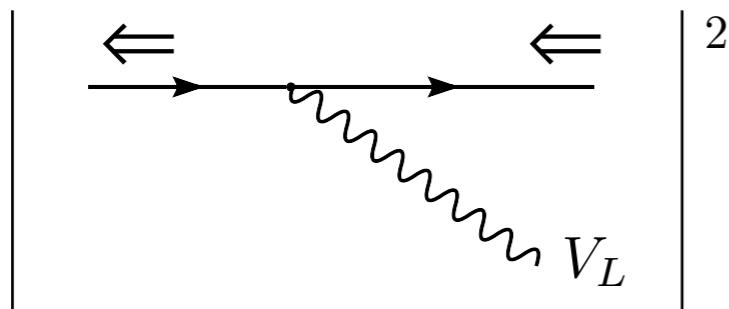
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$$\simeq \frac{g_V^2 + g_A^2}{4\pi^2} \frac{1 + (1-x)^2}{x} \log \frac{p_{Tmax}^2}{(1-x)m_V^2}$$

- Longitudinally polarized W's



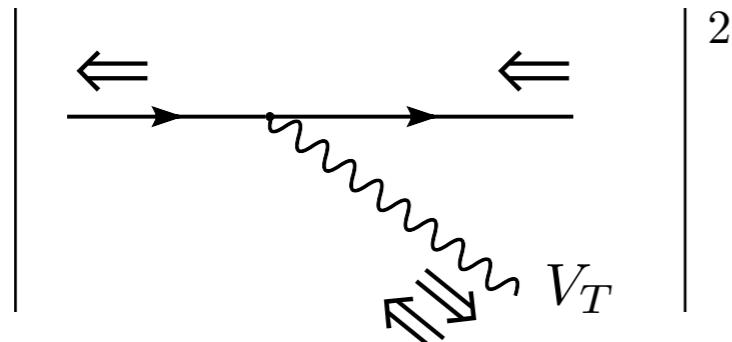
$$f_L(x) = \frac{g_V^2 + g_A^2}{4\pi^2} \frac{(1-x)}{x} \int d^2 p_T \frac{(1-x)m_V^2}{[p_T^2 + (1-x)m_V^2]^2}$$

$$\simeq \frac{g_V^2 + g_A^2}{4\pi^2} \frac{(1-x)}{x}$$

Luminosity of W_T, W_L inside the proton

- Transversely polarized W's

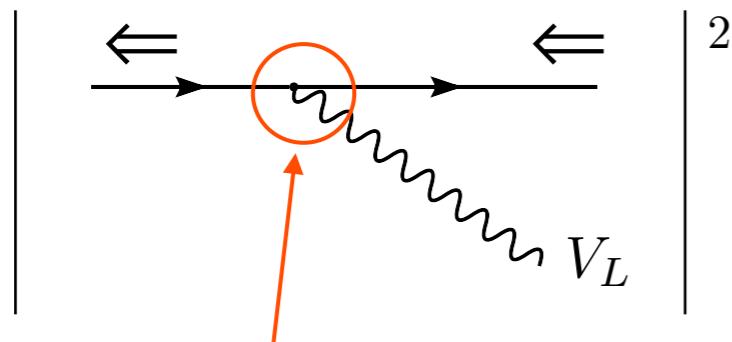
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- Longitudinally polarized W's



(m_V^2/E^2) suppression from

$$\epsilon_L^\mu(p) = \frac{p^\mu}{m_V} + O\left(\frac{m_V}{E}\right)$$

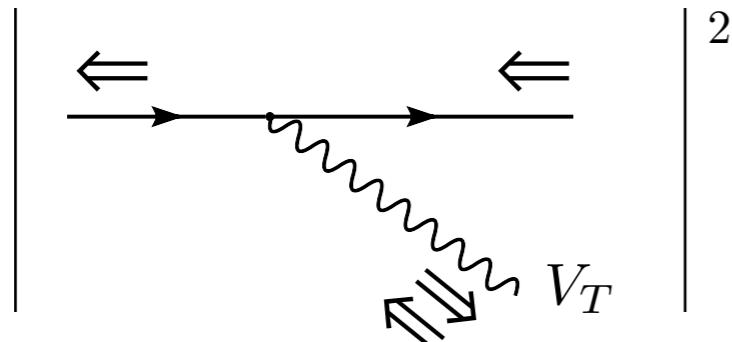
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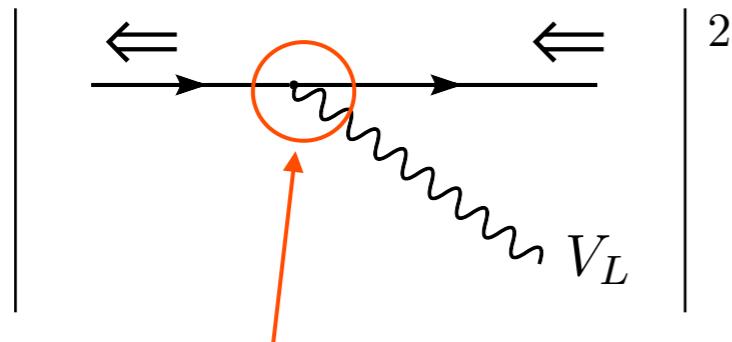
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$$\simeq \frac{g_V^2 + g_A^2}{4\pi^2} \frac{(1-x)}{x}$$

compensated by (E^2/m_V^2)

from the integral over p_T^2

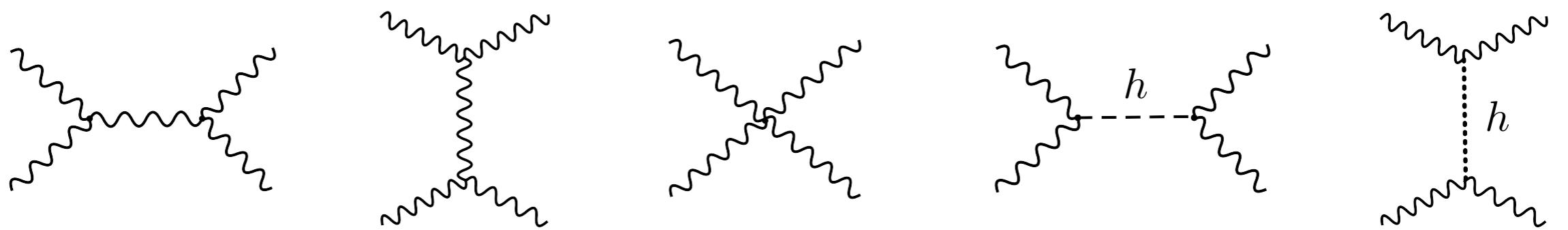
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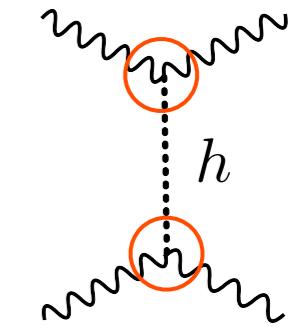
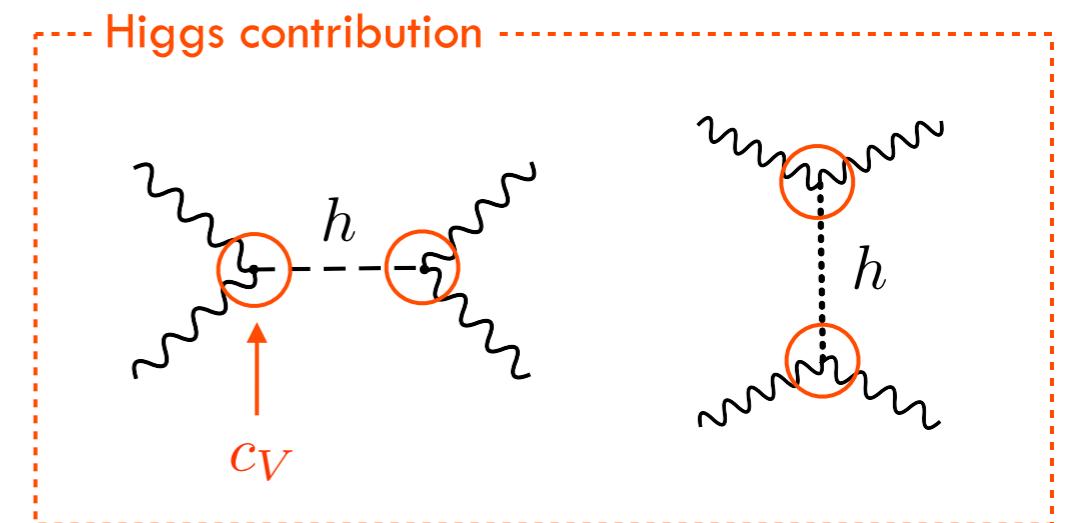
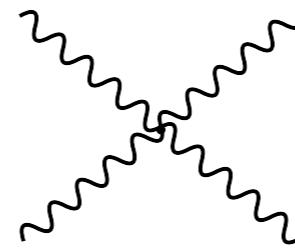
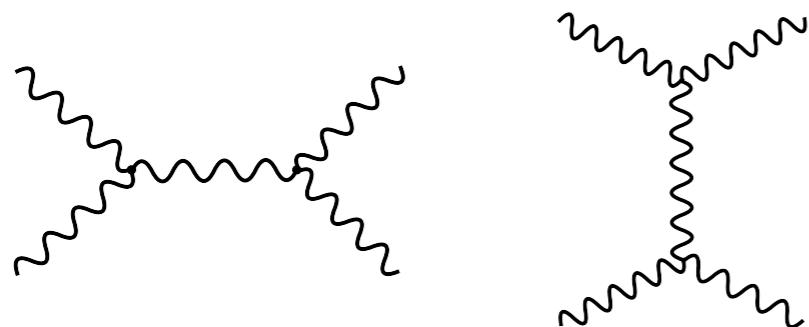
$$f_L(x) = \frac{g_V^2 + g_A^2}{4\pi^2} \frac{(1-x)}{x}$$

1. W_T 's (hence spectator jets) tend to be more forward
2. Smaller luminosity for W_L 's (no log enhancement)

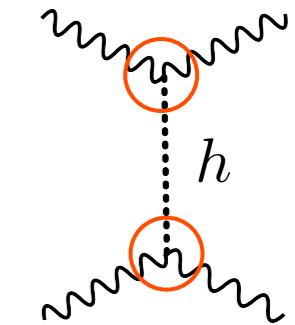
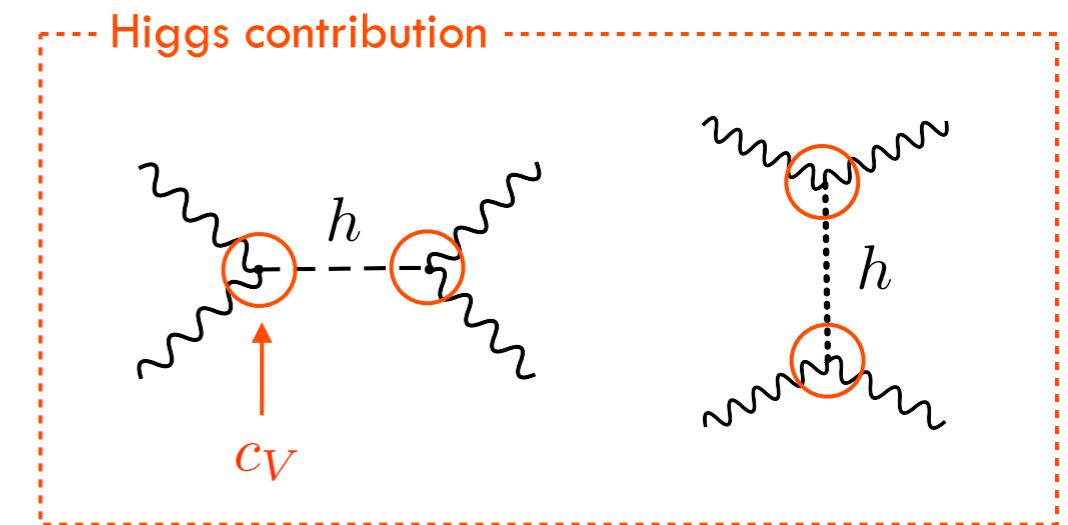
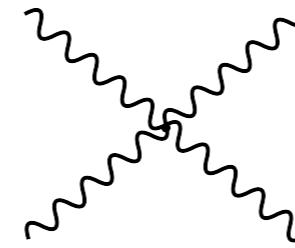
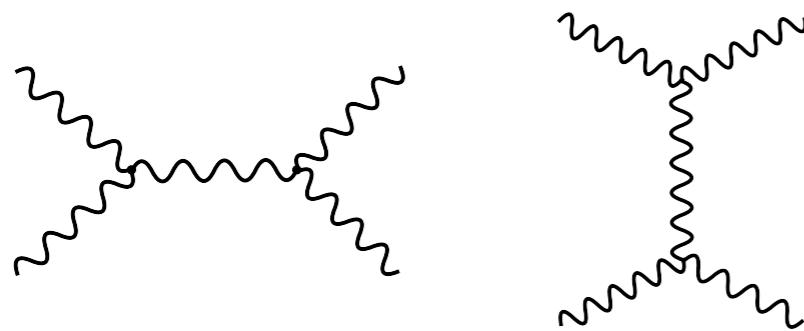
Naive estimate of the hard scattering



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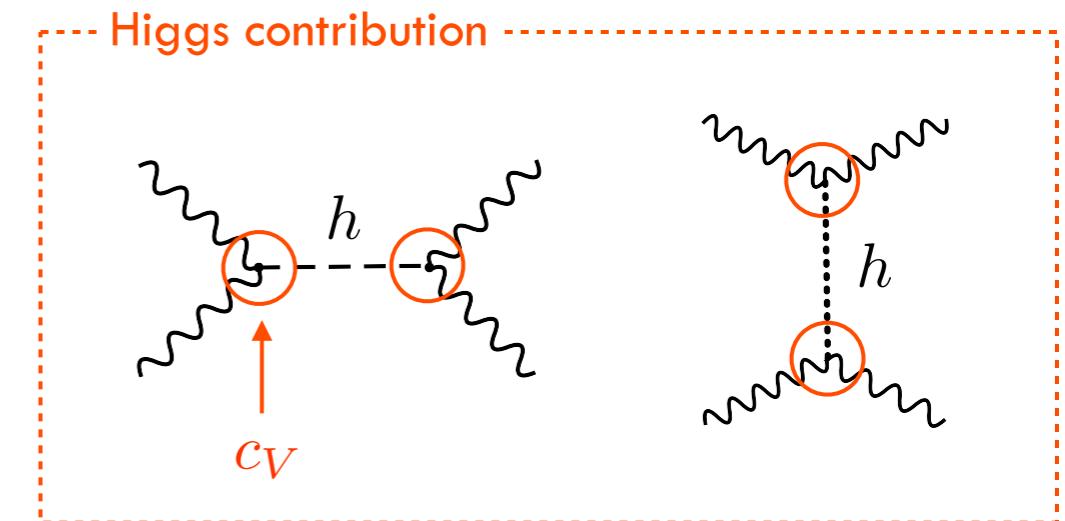
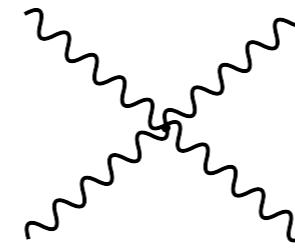
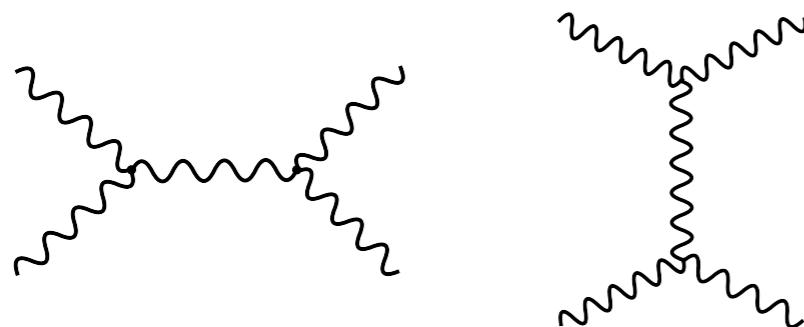


$$\mathcal{A}(V_T V_T \rightarrow V_T V_T) = g^2 f(t/s)$$

$$f(t/s) \sim s/t \quad \text{for } t \rightarrow 0$$

(Coulomb singularity)

Naive estimate of the hard scattering



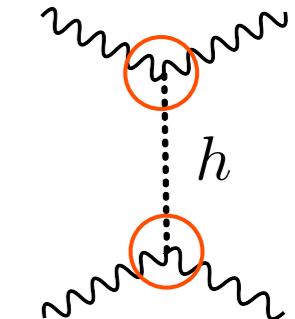
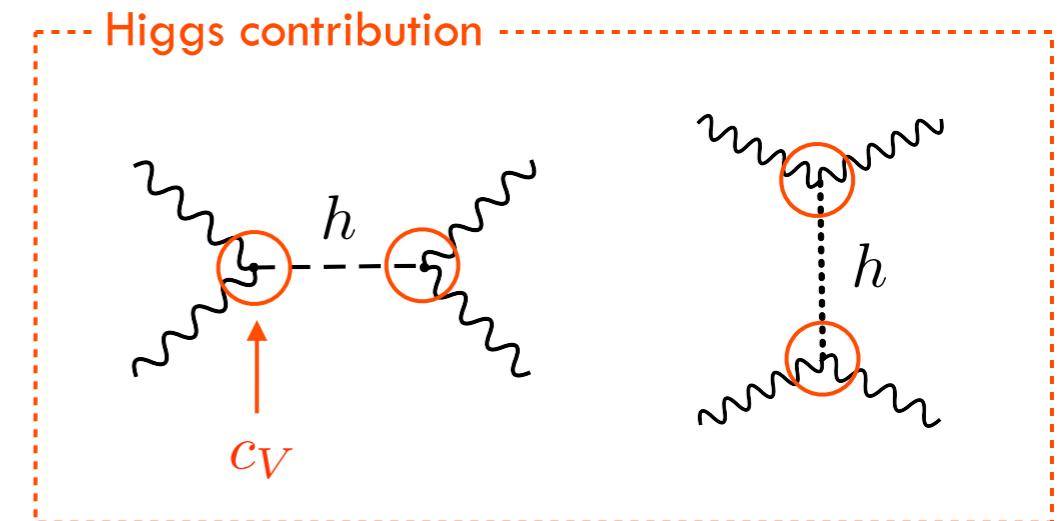
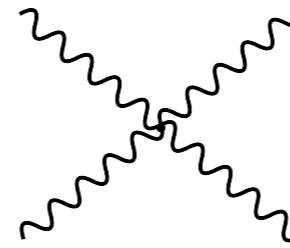
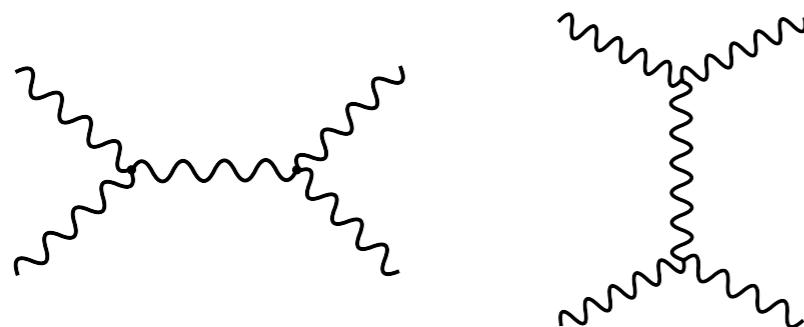
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$$\mathcal{A}(V_L V_L \rightarrow V_L V_L) = \frac{1}{v^2} \left[s - \frac{s^2 c_V^2}{s - m_h^2} \right] + \text{crossed} \sim \frac{s}{v^2} (1 - c_V^2) + \dots$$

Naive estimate of the hard scattering

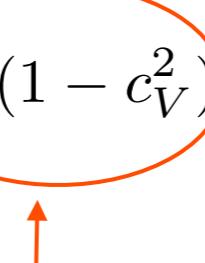


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Energy growth for $c_V \neq 1$

Strong sensitivity on Higgs coupling

Naive estimate of the hard scattering

Total cross section

$$\begin{aligned} -s + Q_{min}^2 &< t < -Q_{min}^2 \\ m_W^2 \ll Q_{min}^2 \ll s \end{aligned}$$

$$\frac{\sigma_{LL \rightarrow LL}}{\sigma_{TT \rightarrow TT}} = N_s \frac{s Q_{min}^2}{m_W^4} (1 - c_V^2)^2$$

Hard scattering in
the central region

$$\frac{d\sigma_{LL \rightarrow LL}/dt}{d\sigma_{TT \rightarrow TT}/dt} \Big|_{t \sim -s/2} = N_h \frac{s^2}{m_W^4}$$

Naive estimate of the hard scattering

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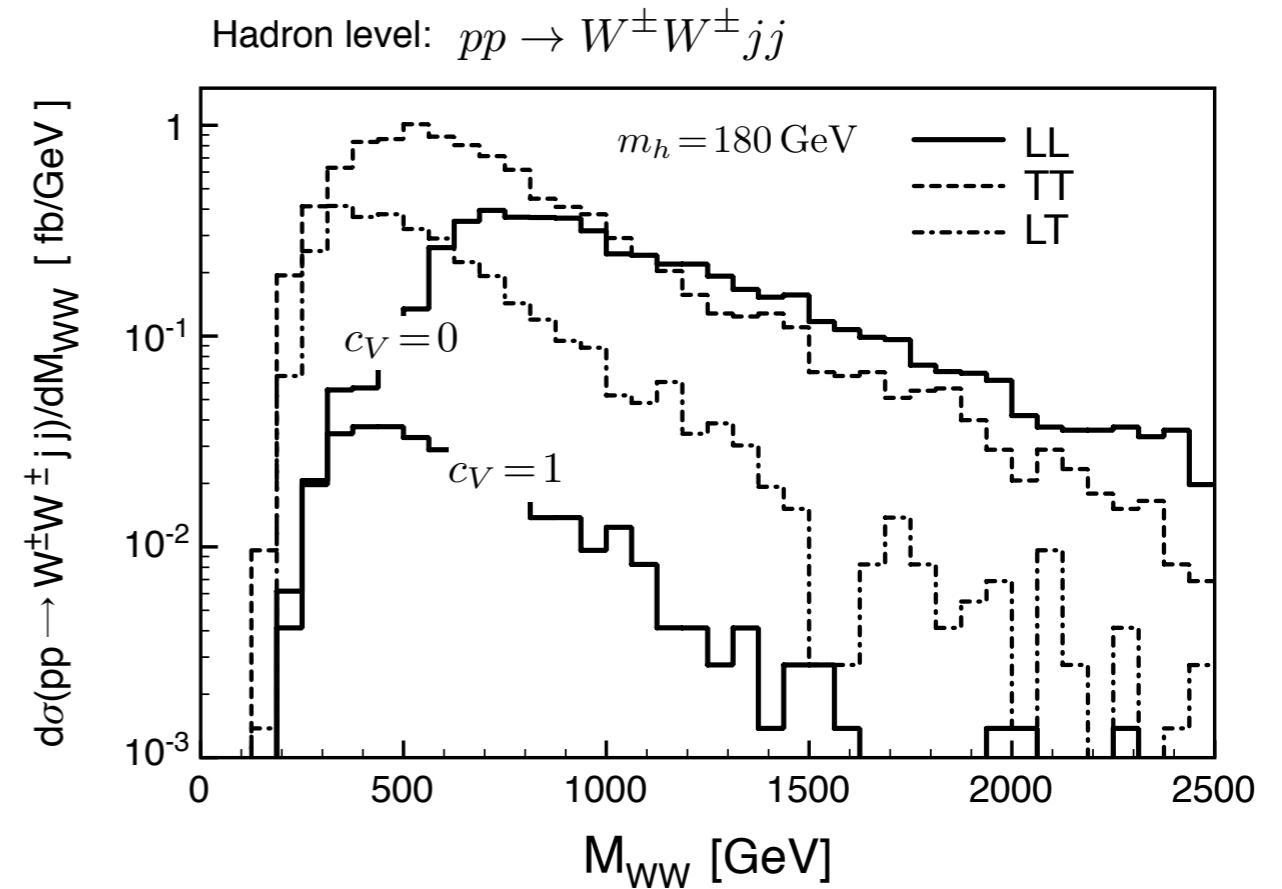
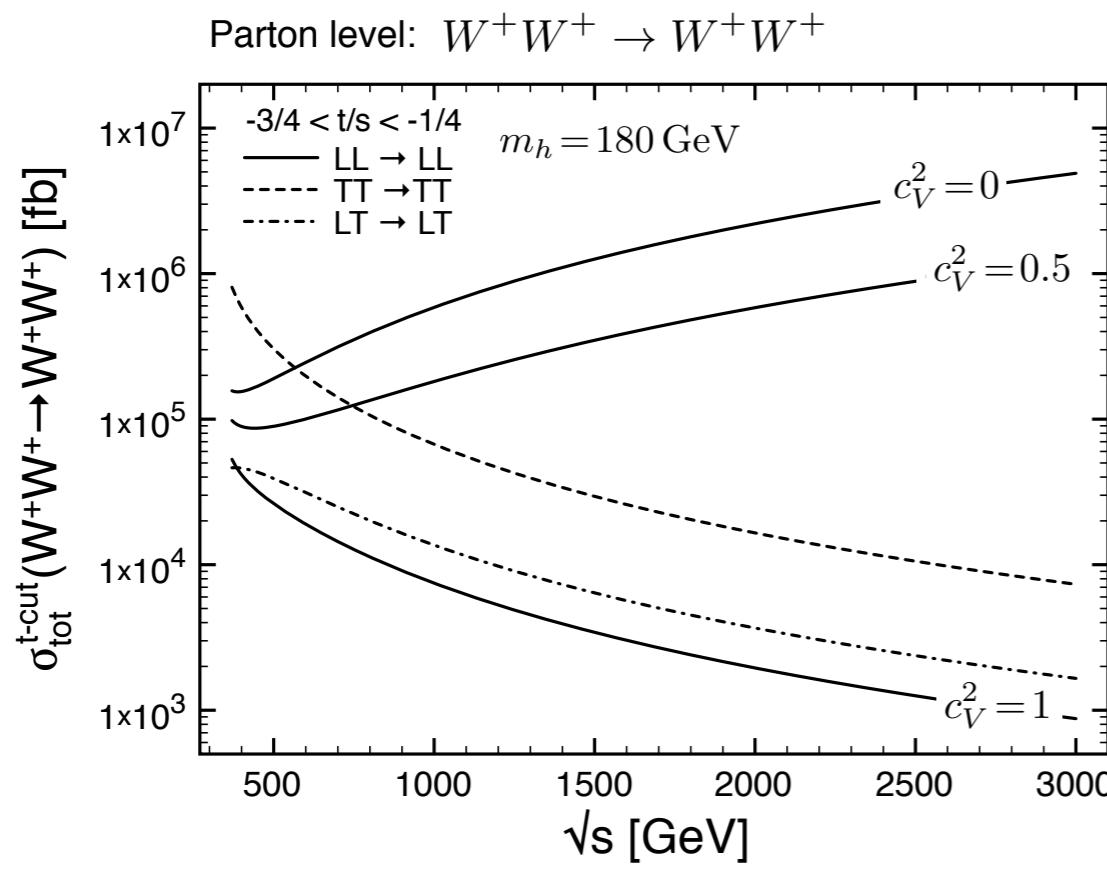
$$\frac{d\sigma_{LL \rightarrow LL}/dt}{d\sigma_{TT \rightarrow TT}/dt} \Big|_{t \sim -s/2} = N_h \frac{s^2}{m_W^4}$$

One naively expects $N_h, N_s \sim O(1)$, but an explicit calculation gives $N_s \simeq 1/500$, $N_h \simeq 1/2000$!

Strong numerical (accidental)
enhancement of the TT channel

RC, C. Grojean, M. Moretti, F. Piccinini, R. Rattazzi JHEP 1005 (2010) 089

Naive estimate of the hard scattering



From: JHEP 1005 (2010) 089

Cuts: $m_{jj} > 500$ GeV, $p_{Tj} < 120$ GeV, $p_{TW} > 300$ GeV

👉 Crossover between TT and LL scattering cross sections occurs at energies much higher than the naively expected scale $E \sim m_W / \sqrt{|1 - c_V^2|}$

What can we learn from WW scattering ?

- Anomalous Higgs couplings (within the EFT framework)
- Production of new states

Effective Lagrangian for a Higgs doublet

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Giudice et al. JHEP 0706 (2007) 045

Grzadkowski et al. JHEP 1010 (2010) 085

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_{(6)} + \Delta\mathcal{L}_{(8)} + \dots$$



$$\sum_i \bar{c}_i O_i(x)$$

Leading effects from dim-6 operators

59 independent operators for 1 SM family

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CP-conserving operators relevant for WW scattering:

$$O_H = \frac{1}{2v^2} [\partial_\mu (H^\dagger H)]^2$$

$$O_W = \frac{ig}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^i$$

$$O_{2W} = \frac{1}{m_W^2} (D^\mu W_{\mu\nu})^i (D^\rho W_{\rho\nu})^i$$

$$O_B = \frac{ig'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) \partial^\nu B_{\mu\nu}$$

$$O_{3W} = \frac{g}{m_W^2} \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

$$O_{HB} = \frac{ig'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$O_{HW} = \frac{ig}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i$$

Constrained by:

$$\bar{c}_W + \bar{c}_B$$

LEP1 (S parameter) at the 10^{-3} level

$$\bar{c}_{2W}$$

LEP2 at the 10^{-3} level

$$(\bar{c}_W - \bar{c}_B), \bar{c}_{HB}, \bar{c}_{3W}$$

TGC (LEP2 and Tevatron) at the level of a few $\times 10^{-2}$

$$\begin{aligned} & \bar{c}_H \text{ and the linear} \\ & \text{combination } H^\dagger H W_{\mu\nu} W^{\mu\nu} \end{aligned}$$

Higgs couplings at the 10^{-1} level

$$O_H = \frac{1}{2v^2} [\partial_\mu (H^\dagger H)]^2$$

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$$O_{3W} = \frac{g}{m_W^2} \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

$$O_{HB} = \frac{ig'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$O_{HW} = \frac{ig}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i$$

Constrained by:

$\bar{c}_W + \bar{c}_B$	<i>LEP1 (S parameter) at the 10^{-3} level</i>
\bar{c}_{2W}	<i>LEP2 at the 10^{-3} level</i>
$(\bar{c}_W - \bar{c}_B), \bar{c}_{HB}, \bar{c}_{3W}$	<i>TGC (LEP2 and Tevatron) at the level of a few $\times 10^{-2}$</i>
\bar{c}_H and the linear combination $H^\dagger H W_{\mu\nu} W^{\mu\nu}$	<i>Higgs couplings at the 10^{-1} level</i>

SILH power counting (1 scale m_* and 1 coupling strength g_*):

Giudice et al. JHEP 0706 (2007) 045

$$\bar{c}_H \sim \frac{v^2}{f^2}$$

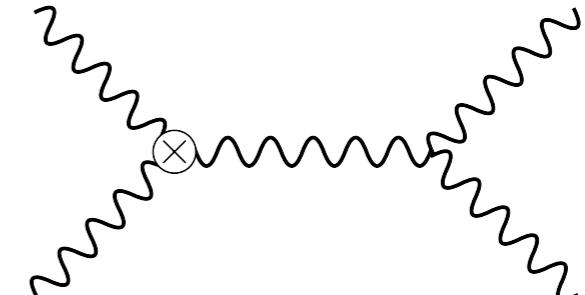
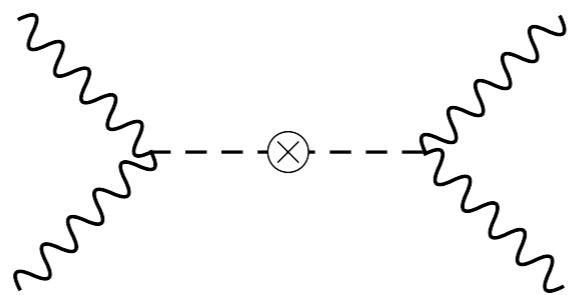
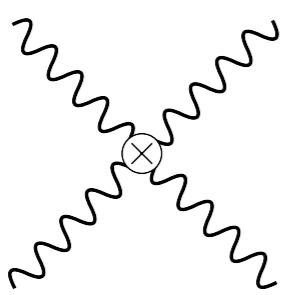
$$\bar{c}_W, \bar{c}_B \sim \frac{m_W^2}{m_*^2}$$

$$\bar{c}_{2W} \sim \frac{g^2}{g_*^2} \frac{m_W^2}{m_*^2}$$

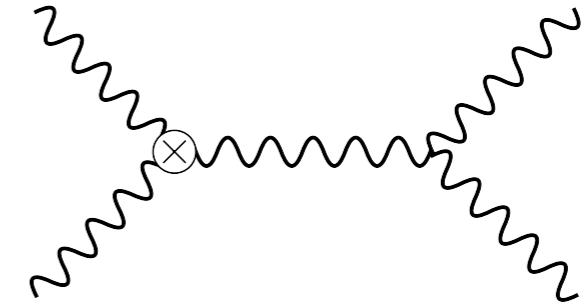
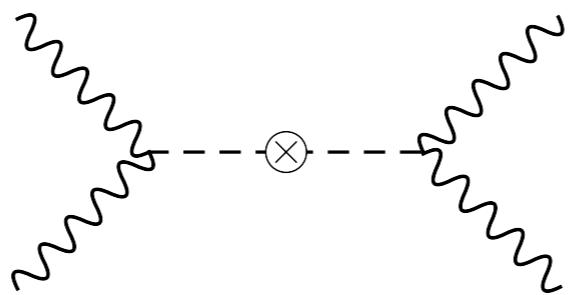
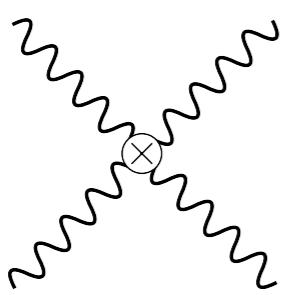
$$f \equiv \frac{m_*}{g_*}$$

$$\bar{c}_{HW}, \bar{c}_{HB} \sim \frac{m_W^2}{16\pi^2 f^2}$$

$$\bar{c}_{3W} \sim \frac{g^2}{16\pi^2} \frac{m_W^2}{m_*^2}$$

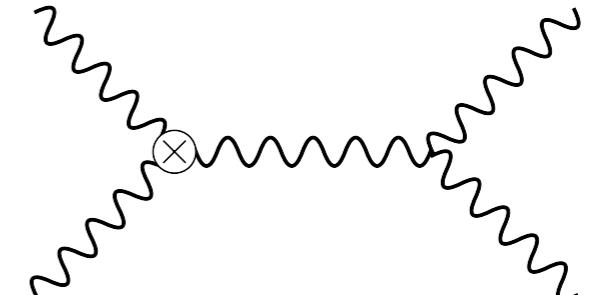
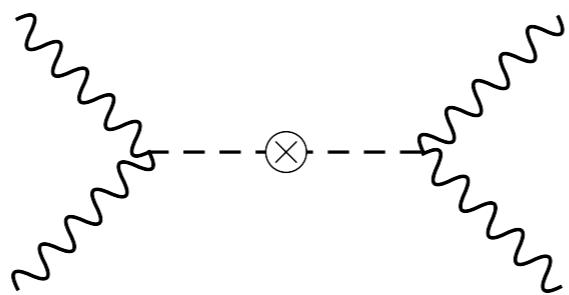
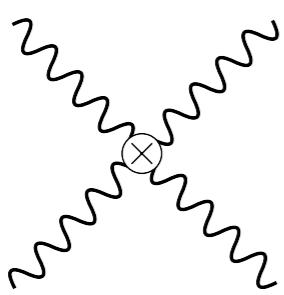


$$\mathcal{A}_{LL \rightarrow LL} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + \bar{c}_H \frac{E^2}{v^2} + \dots$$



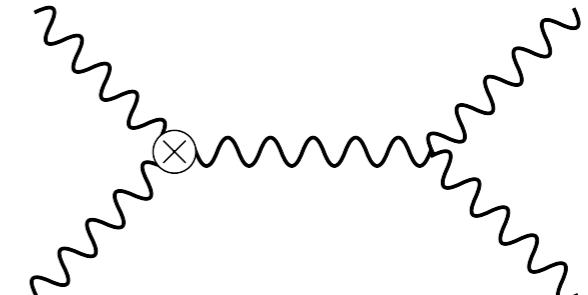
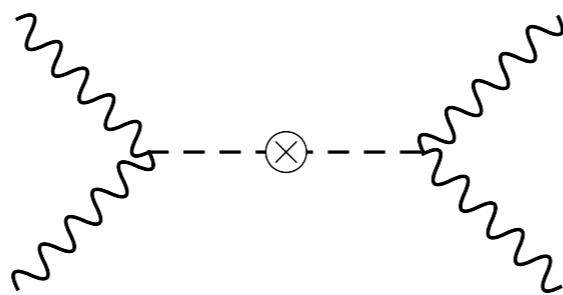
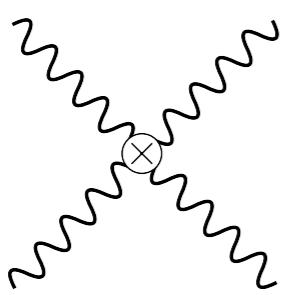
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$\underbrace{}_{\sim g_{SM}^2}$



$$\mathcal{A}_{LL \rightarrow LL} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + \bar{c}_H \frac{E^2}{v^2} + \dots$$

$\sim g_{SM}^2$ $\sim \frac{E^2}{f^2}$

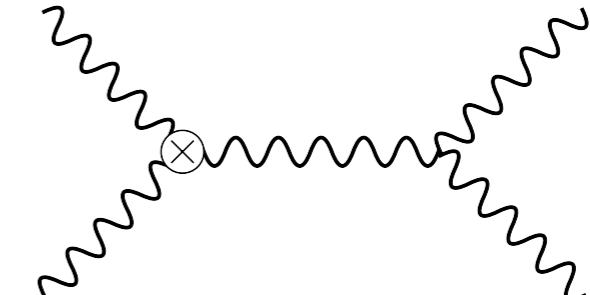
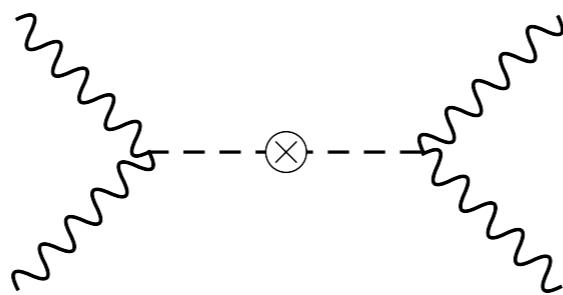
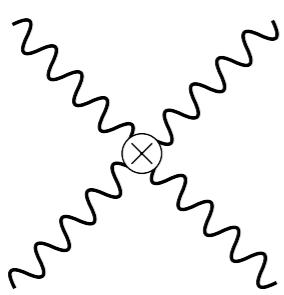


$$\mathcal{A}_{LL \rightarrow LL} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + \bar{c}_H \frac{E^2}{v^2} + \dots$$

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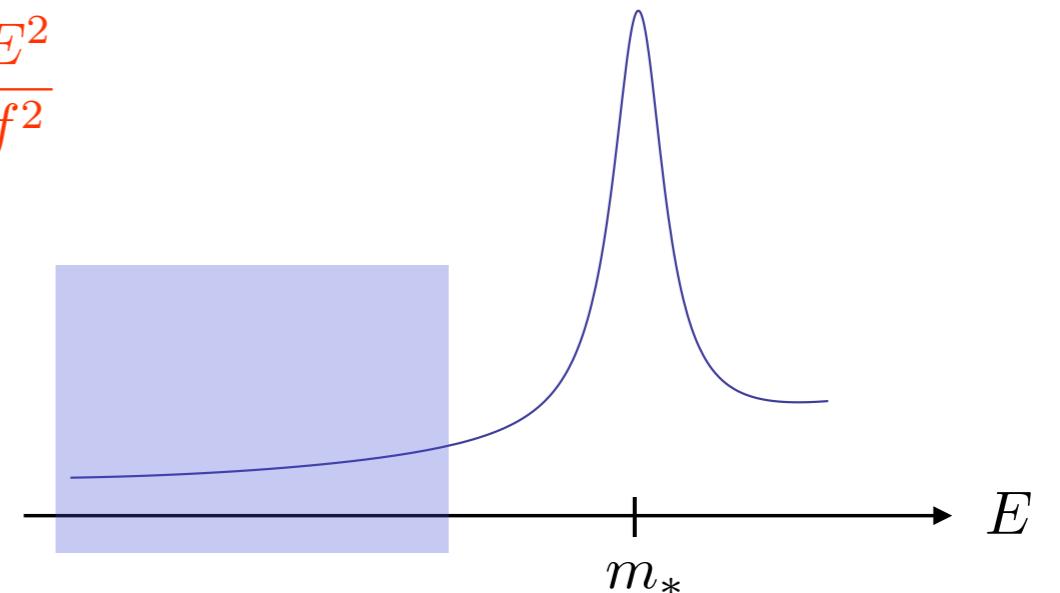
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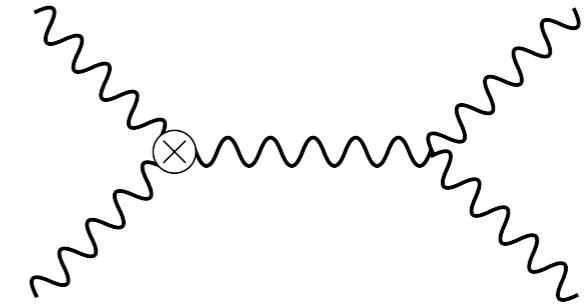
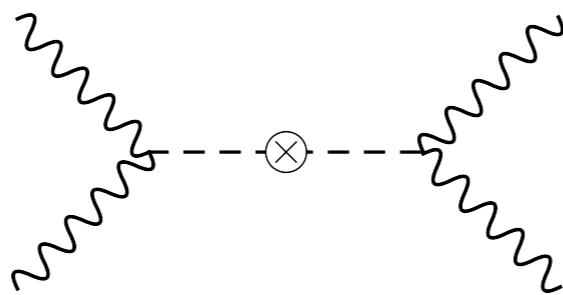
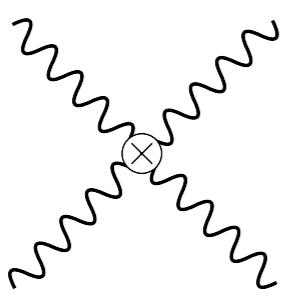
Interesting
energy window:

$$g_{SM} f < E < m_*$$



$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{E^2}{g_{SM}^2 f^2} \lesssim \frac{g_*^2}{g_{SM}^2}$$

can be > 1 if NP dynamics is *strongly coupled* ($g_* > g_{SM}$)



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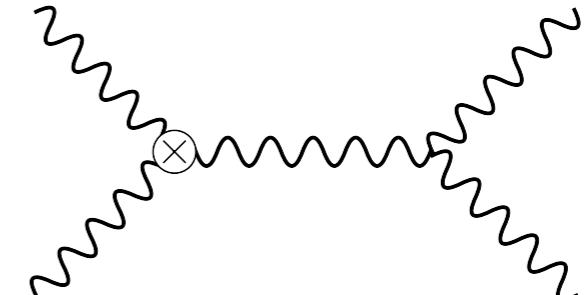
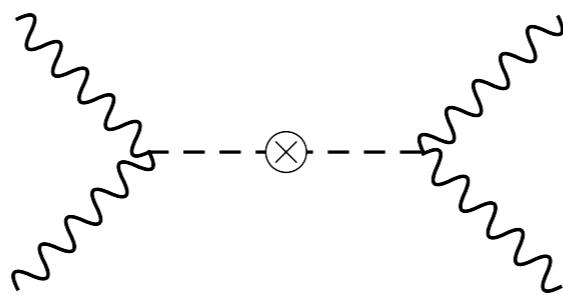
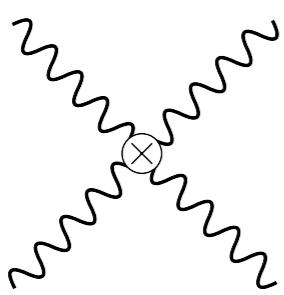
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$$\mathcal{A}_{TT \rightarrow TT} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + O\left(g^2 \bar{c}_{3W} \frac{E^2}{m_W^2}\right) + \dots$$

$\sim g^2$

$\sim g^2 \frac{g^2}{16\pi^2} \frac{E^2}{m_*^2}$



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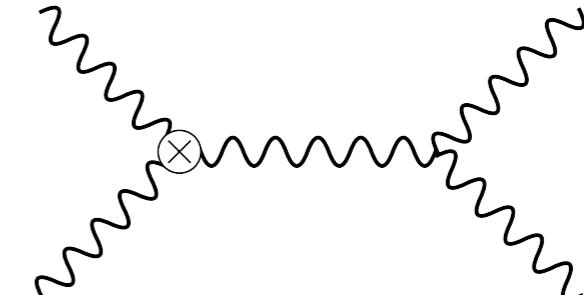
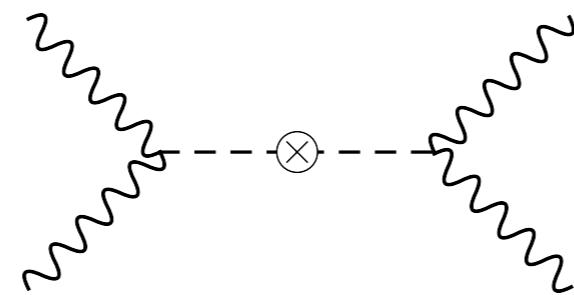
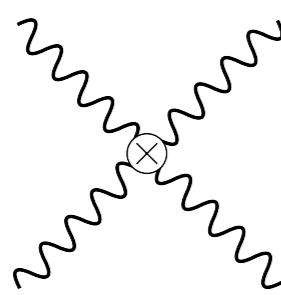
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$$\sim g^2$$

$$\sim g^2 \frac{g^2}{16\pi^2} \frac{E^2}{m_*^2}$$

← smaller than SM



$$\mathcal{A}_{LL \rightarrow TT} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + O\left(g^2 \bar{c}_{HB,HW} \frac{E^2}{m_W^2}\right) + \dots$$

$\sim g^2$

$\sim g^2 \frac{E^2}{16\pi^2 f^2}$

$$\mathcal{A}_{LT \rightarrow TT} = \mathcal{A}_{SM} (1 + O(\bar{c}_H)) + O\left(g^2 \bar{c}_W \frac{E}{m_W}\right) + \dots$$

$\sim g^2$

$\sim g^2 \frac{m_W E}{m_*^2}$

- Montecarlo implementations of the Higgs EFT exist and can be used for WW scattering:

- FEYNRULES models implementing the Higgs Effective Lagrangian

Alloul, Fuks, Sanz arXiv:1310.5150

<http://feynrules.irmp.ucl.ac.be/wiki/HEL>

P. Artoisenet et al. JHEP 1311 (2013) 043

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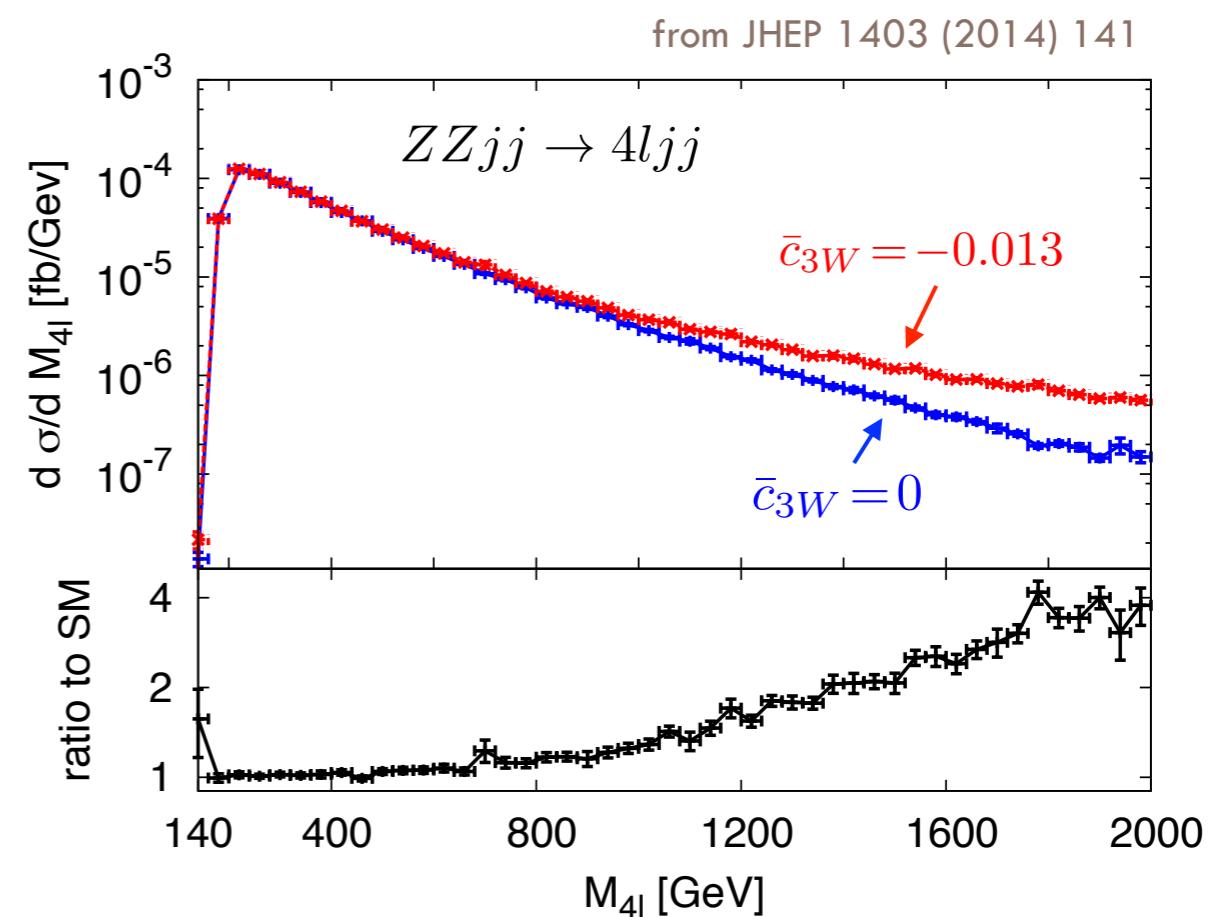
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Limits from TGC (LEP) at 95% CL:

$$-3.5 \times 10^{-2} < \bar{c}_{3W} < +5 \times 10^{-3}$$

Large enhancements on tails of distributions from derivative operators are possible and compatible with current constraints

... but what about validity of EFT ?



On the Validity of the EFT description

- Problem: Setting limits within the validity of the EFT ($E = m_{WW} < m_*$) without knowing the value of m_*

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2. Scan over M_{cut} and report (model-independent) bounds as functions of M_{cut}
3. Specify a power counting to express $\bar{c}_i = \bar{c}_i(m_*, g_*)$ and set $M_{cut} = m_*$ (optimal value compatible with EFT)

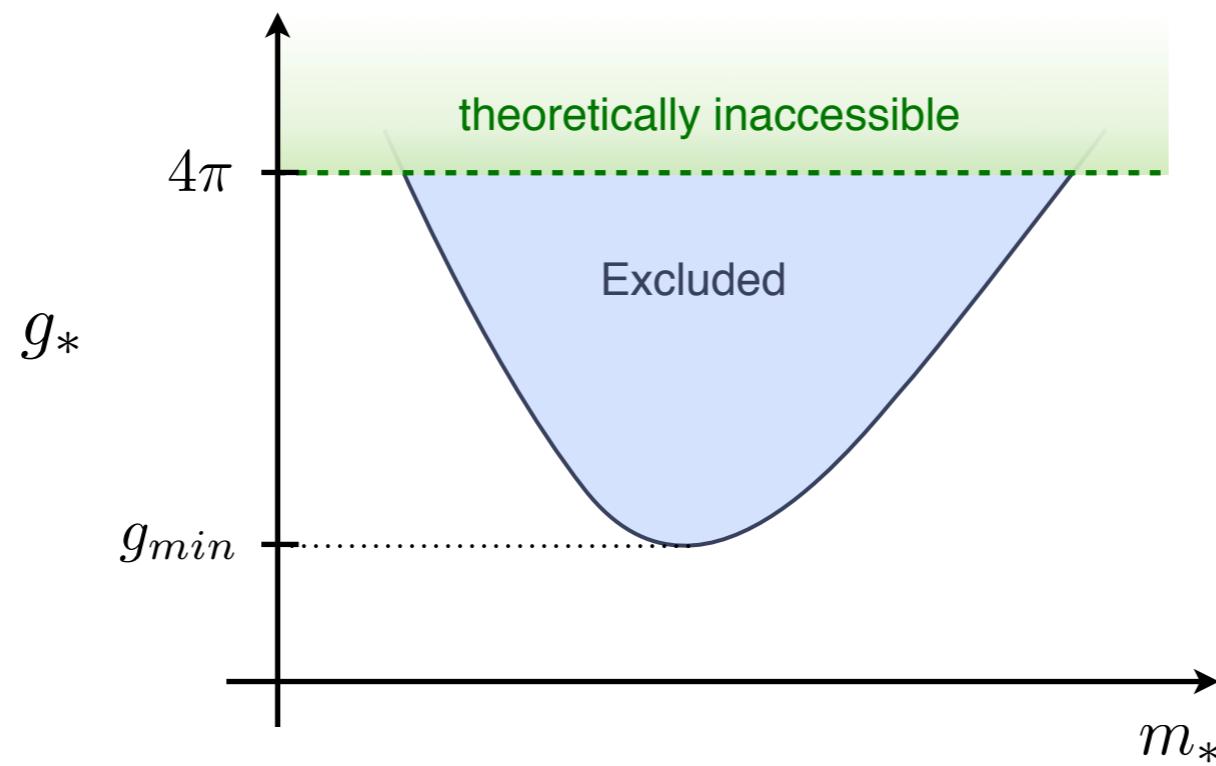
Bounds in the plane (m_*, g_*) follow from the inequalities

$$\bar{c}_i(m_*, g_*) \leq \delta_i(m_*)$$

Example:

$$\bar{c}_H = \frac{v^2 g_*^2}{m_*^2} \leq \delta_H(m_*) \quad \Rightarrow$$

$$g_* \leq \frac{m_*}{v} \sqrt{\delta_H(m_*)}$$



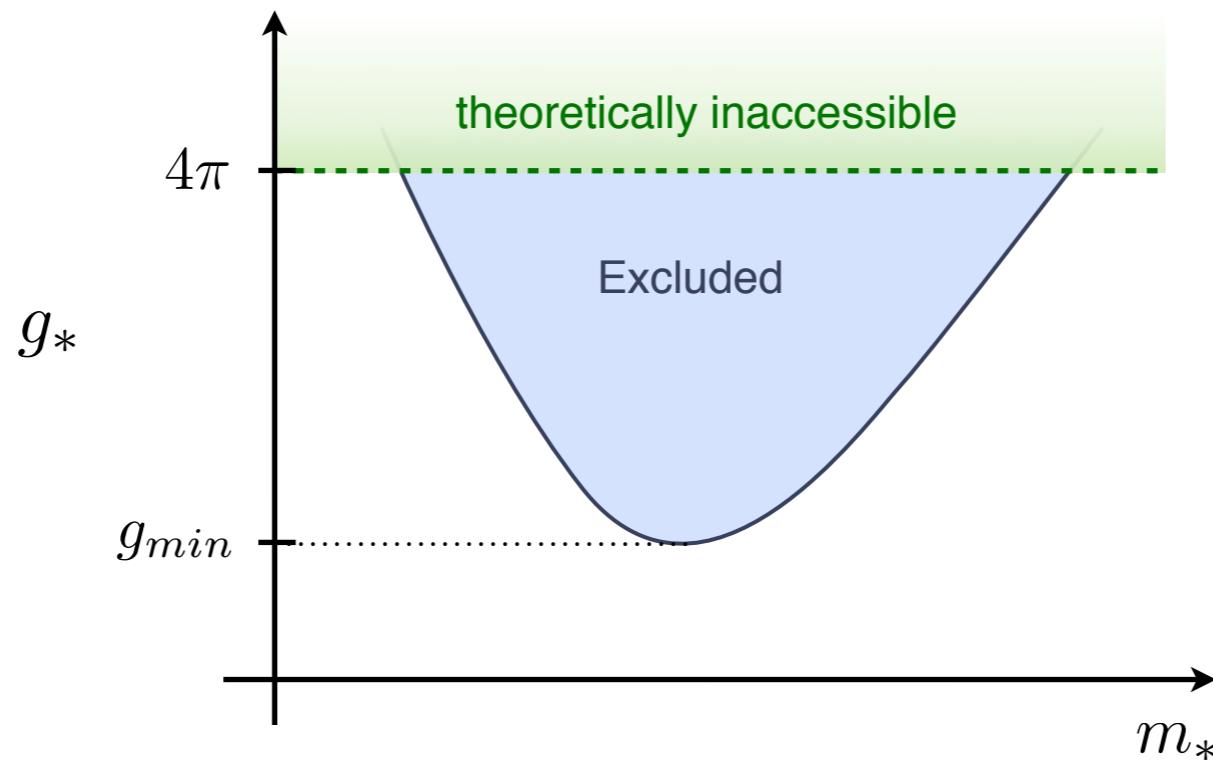
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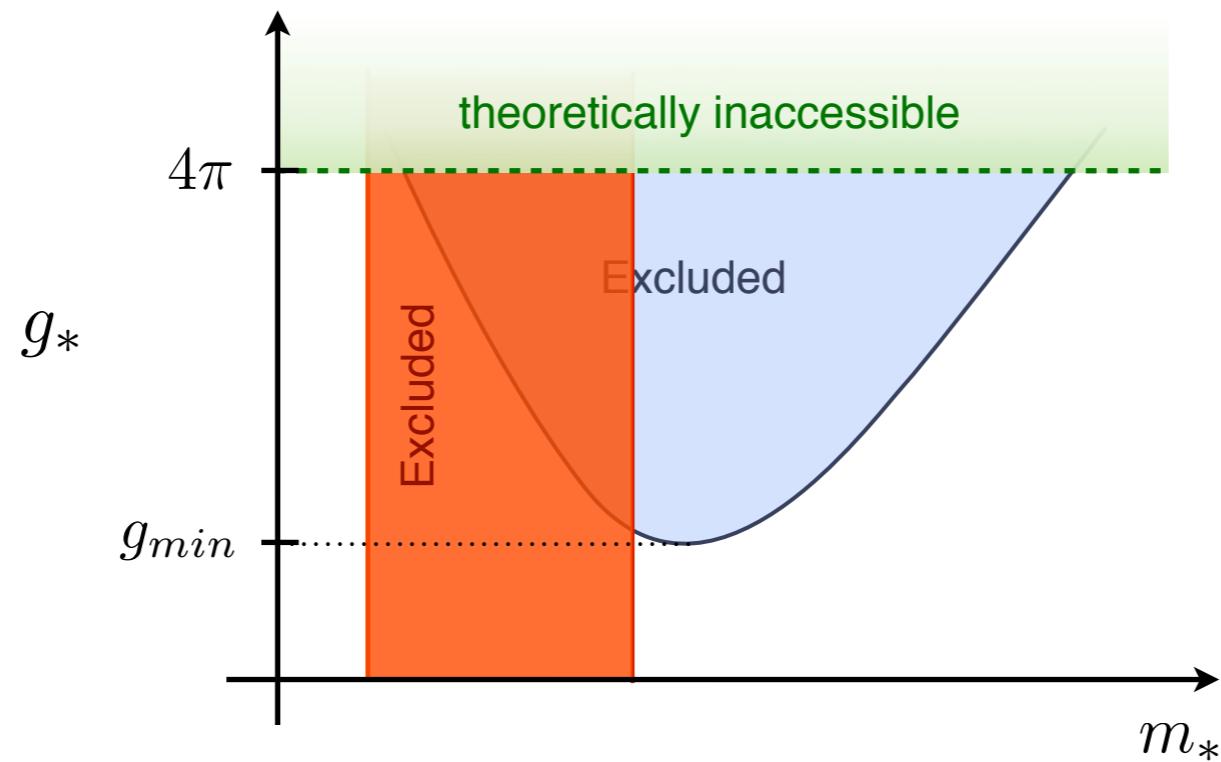
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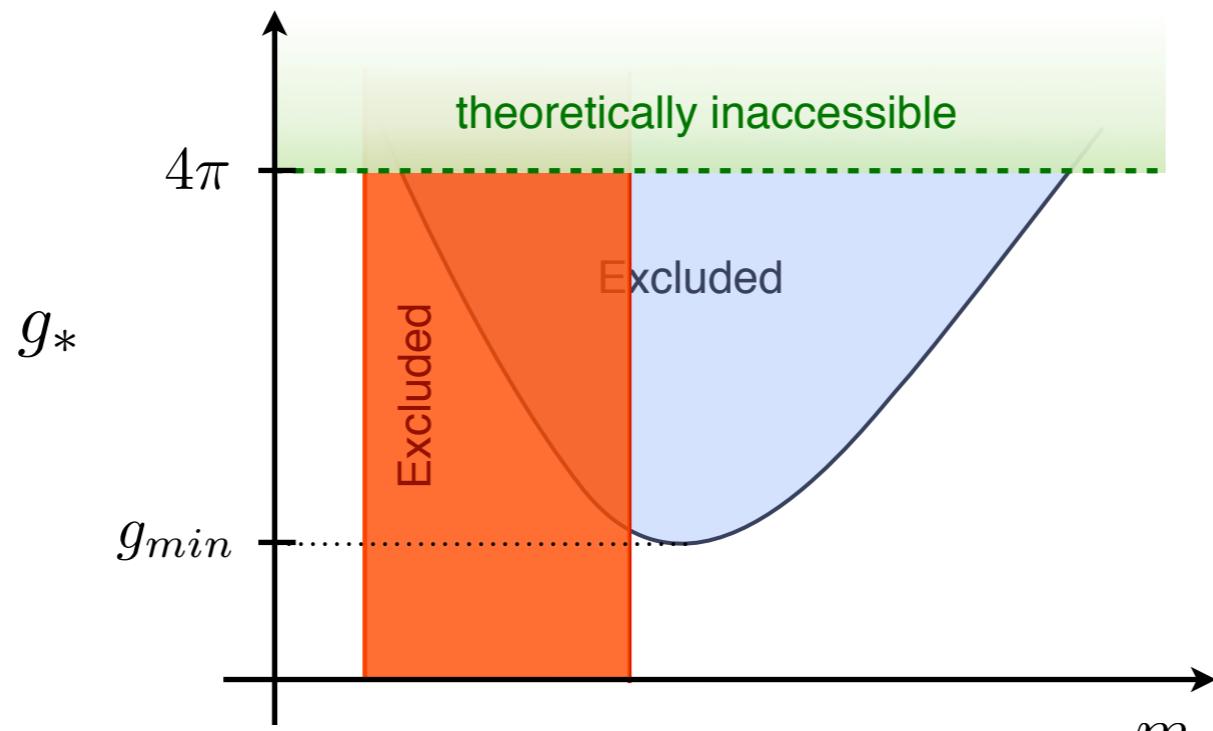
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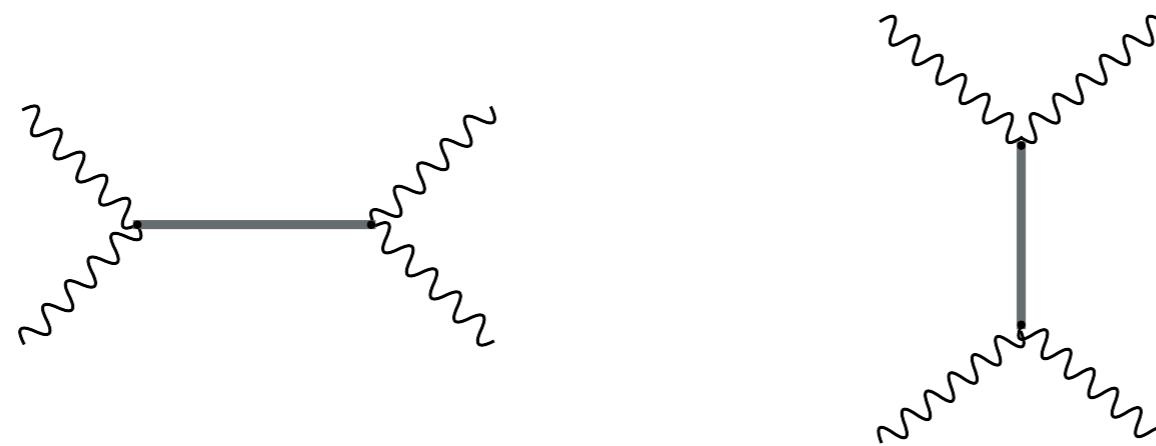
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Excluded region is non-vanishing
only if analysis is sensitive to SM

Production of new states

- At energies $E \sim m_*$ the exchange of new states cannot be described by local operators: a full description of the resonances is required



- Simplified models give an economical description of resonances and allow comparison between limits from precision observables and direct searches

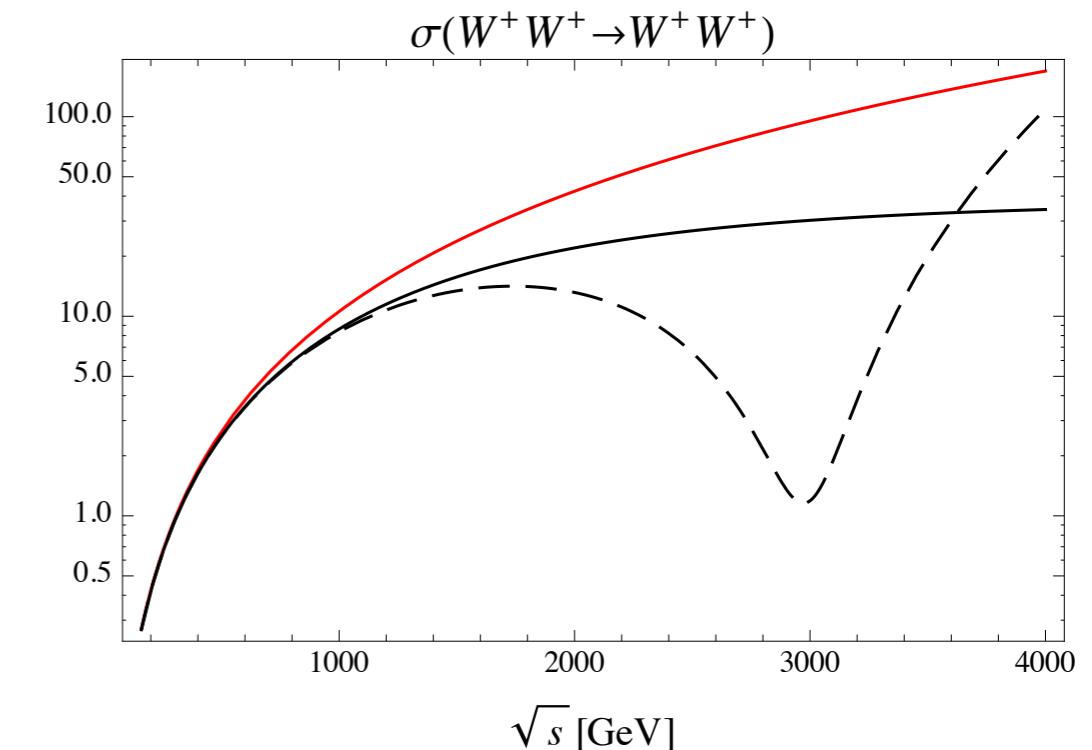
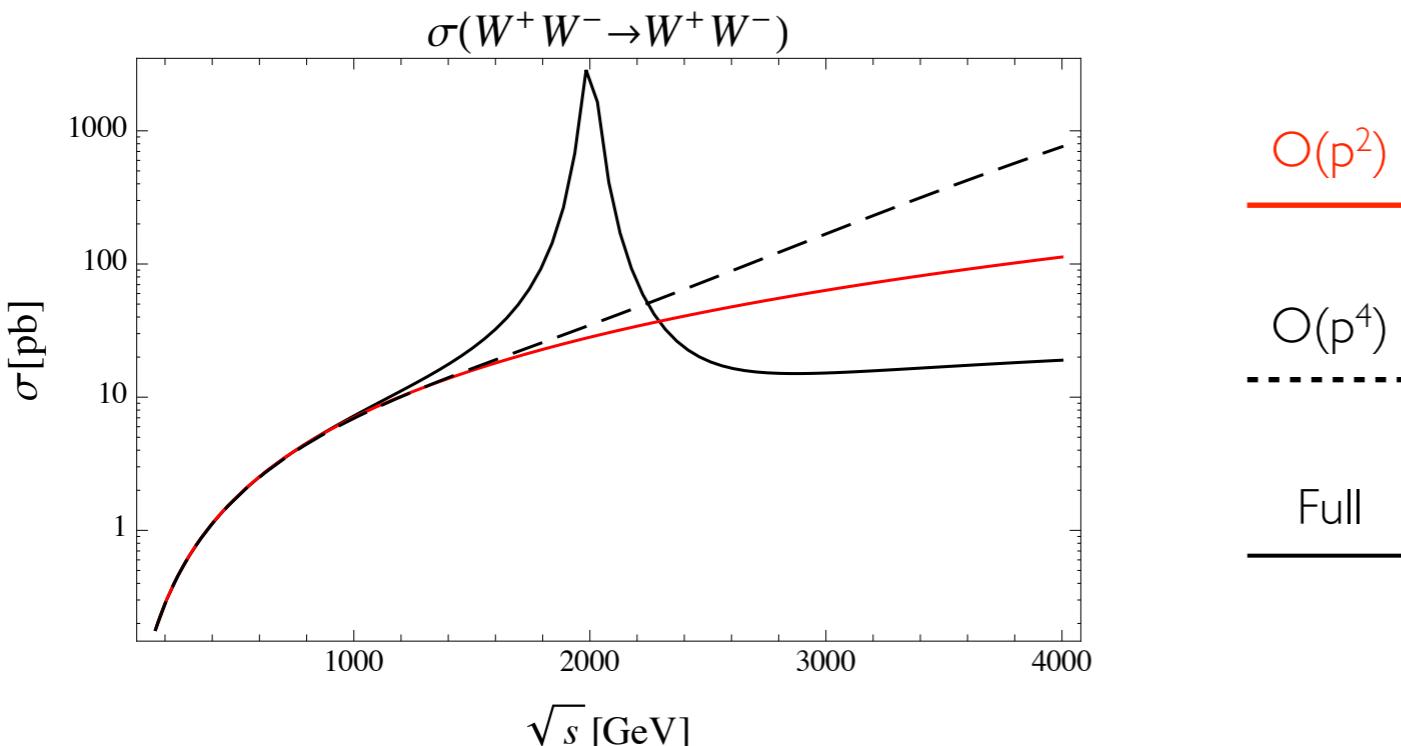
for spin-1 resonances
see for example:

Pappadopulo, Thamm, Torre and Wulzer JHEP 1409 (2014) 060
Greco and Liu JHEP 1412 (2014) 126

- Exchange of resonance enhances (suppresses) the WW cross section if it occurs in s-channel (t-channel)

Example: ρ_L (spin-1, triplet of $SU(2)_L$) in Composite Higgs models

from: R.C., Marzocca, Pappadopulo, Rattazzi JHEP 1110 (2011) 081



$$m_{\rho} = 2 \text{ TeV}$$

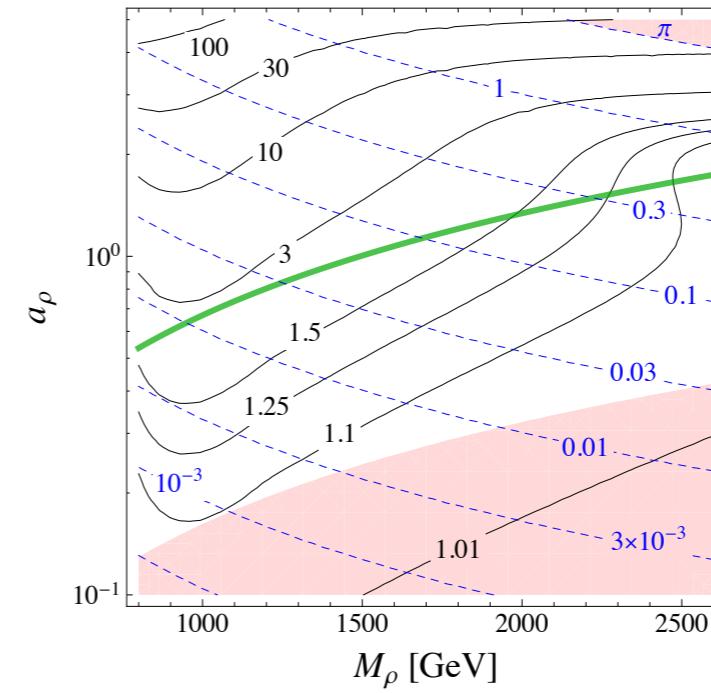
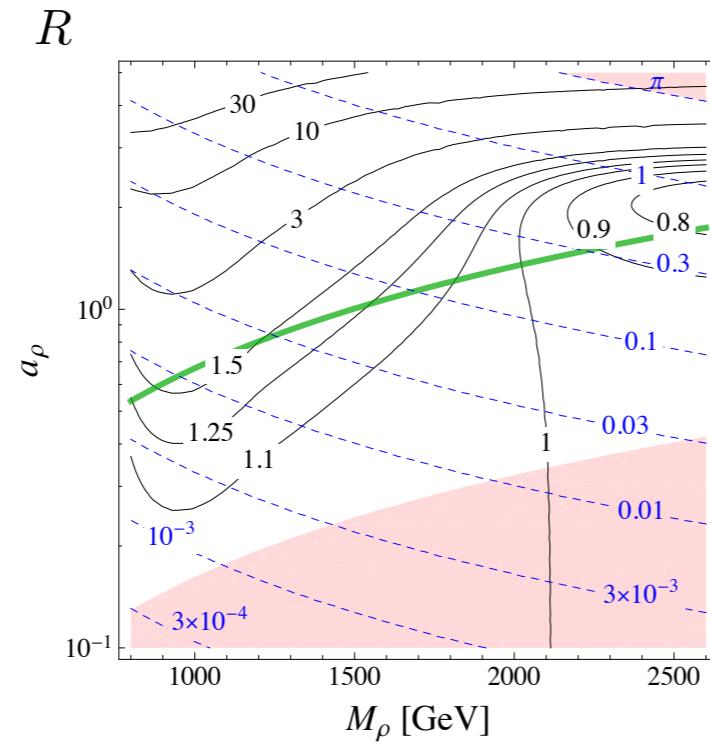
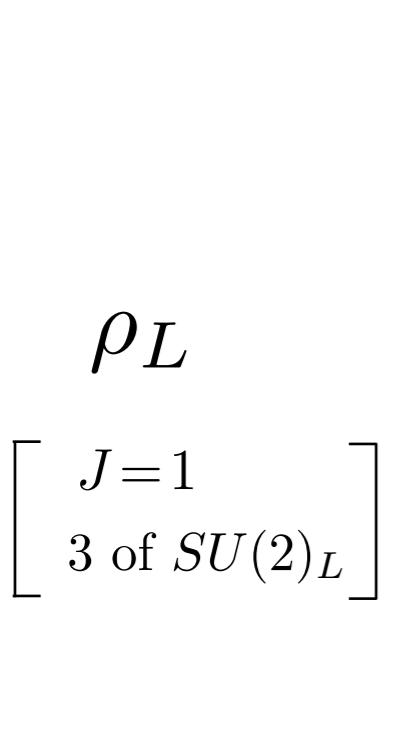
$$\frac{v^2}{f^2} = 0.1$$

- Complementarity: a given resonance enhances some channels and suppresses others

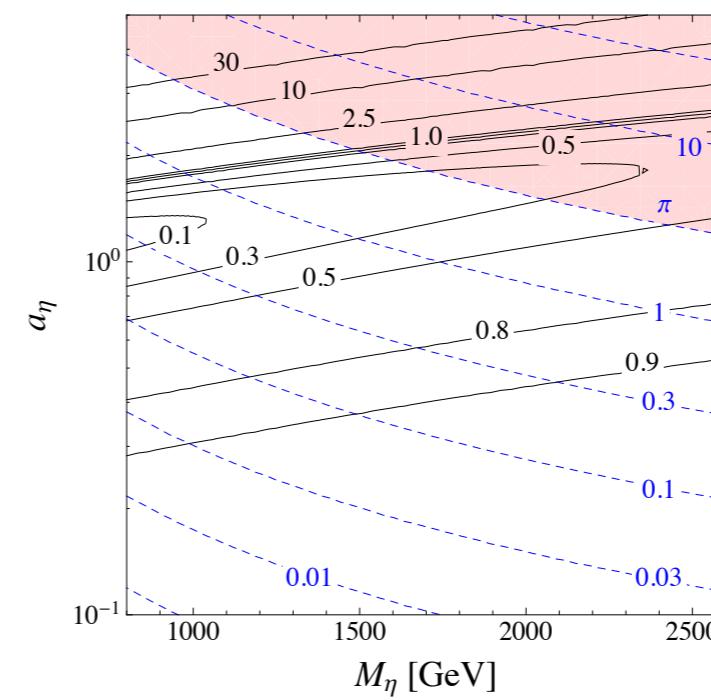
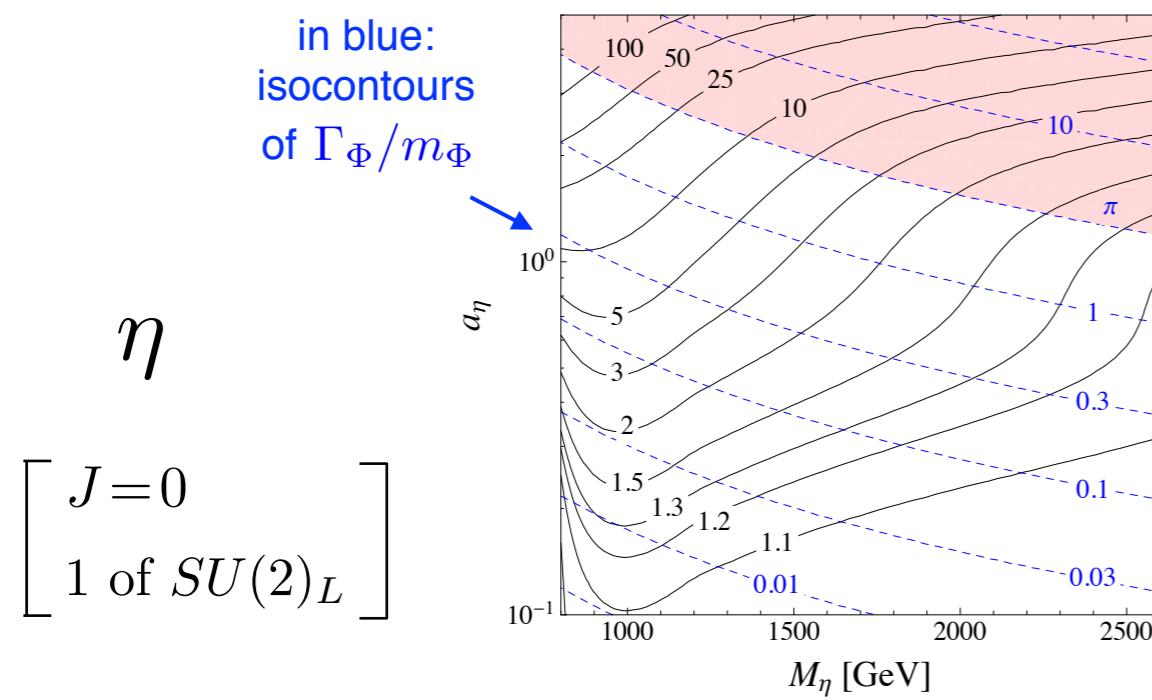
Measuring all channels can determine the quantum numbers of the resonances

$$pp \rightarrow W^+W^-jj$$

$$pp \rightarrow W^\pm Z jj$$



← in black: isocontours
of $R = \sigma/\sigma_{LET}$



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- Complementarity of different channels: quantum numbers of resonances can be deduced by a combined study of all final states