Partially Strong WW Scatterings

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GoranFest@Split, June 9 - 12, 2010

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Outline

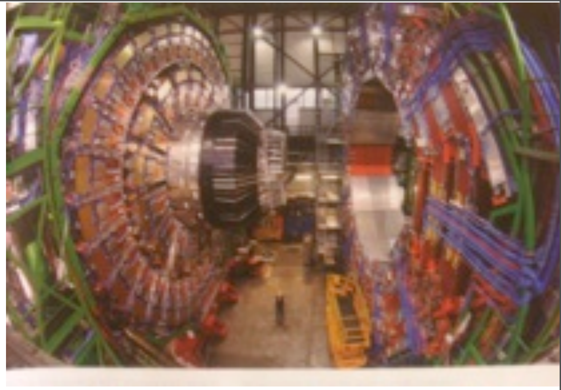
- Introduction
- WW scattering in SM
- WW scattering in extended Higgs Sector
- WW scattering in Stueckelberg Z' model
- Summary

(1) Cheung, Chiang, Hsiao and Yuan, PRD81:053001(2010);
(2) Cheung, Chiang and Yuan, PRD78:051701(2008).

Missing Piece of SM

- One important mission of LHC experiments is to scrutinize and understand the EWSB in elementary particle physics.
- In the SM, EWSB is achieved through the Higgs mechanism, which predicts the existence of a Higgs boson without further information on its mass.
- Finding the Higgs boson will not only provide us more insight into the origin of particle masses, but may also help develop new physics.

Mission of LHC



- Electroweak Symmetry Breaking
  -- SM Higgs
- New Physics Beyond SM
  -- Extended Higgs Sector (2HDM, ...)
  -- Extended Gauge Group (W', Z', ...)
  -- New Flavors

Questions of Interest

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- Can we claim that we understand EWSB then?
- Is it the SM Higgs boson, or does it belong to a larger Higgs sector?
- In the latter case, what would be clear and direct ways to figure it out in experiments (assuming that we cannot probe and detect the other degrees of freedom directly for some reason)?

Possible Answers

- Some theorists suggest to study Higgs decays in high precision in order to pin down its couplings to SM fermions (and find out whether it is SM-like).

Giudice, Grojean, Pomarol, Rattazzi 2007
Mantry, Trott, Wise 2007; Randall 2007

- Another direction is to study its interactions with the weak gauge bosons through gauge boson scatterings at high energies.
- These two approaches are complementary to each other. In fact, the latter is more direct than the former.

Unitarity Constraints

- General consideration of the S-matrix theory
  ⇒ Scattering amplitude (or cross section) cannot grow with energy.
- Violation of the unitarity indicates the breakdown of an effective theory.
  ⇒ A more complete theory must come in to save the situation.
  ⇒ The scale of new physics is around or below the unitarity-violating scale.

Unitarity Problem in Fermi Theory

- Consider the scattering of $\nu_\mu + e^- \longrightarrow \nu_e + \mu^-$. The cross section to the lowest order is given by

$$\sigma_{tot}(\nu_\mu e^- \to \nu_e \mu^-) = \frac{G_F^2}{\pi} s$$

where only the lowest partial wave (l=0) contributes and unitarity in quantum mechanics requires

$$\frac{G_F^2}{\pi} s \leq \frac{\pi}{2E_{\rm cm}^2} \;\Rightarrow\; E_{\rm cm} \leq \left(\frac{\pi\sqrt{2}}{4G_F}\right)^{\frac{1}{2}} \simeq 310\ \text{GeV}$$

where $E_{\rm cm}$ is the scattering energy in the CM frame.

- This signals a breakdown scale for the theory.
⇒ New degrees of freedom (the W bosons in this case) must emerge at or around this scale to save the trouble.

Partial-Wave Expansion

Lee, Quigg, Thacker 1977

- The scattering amplitude can be decomposed into partial waves as

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

where the J-th partial-wave coefficient may be written as

$$a_J = A_4 \left(\frac{E}{M_W}\right)^4 + A_2 \left(\frac{E}{M_W}\right)^2 + A_0 \left(\frac{E}{M_W}\right)^0 \ ;$$

where E is the scattering energy in the CM frame.

- The amplitudes do not grow with E in the SM because:
  - the A_4 terms vanish among purely gauge diagrams; and
  - the cancellations of A_2 terms involve the Higgs boson.
  - A_0 term provides unitarity bound for Higgs mass.
- The situation will become different if the electroweak sector is extended...

Unitarity Violation

- Even within the SM, the tree-unitarity may be violated if the Higgs mass m_h is greater than ~ 1 TeV.

  $\Rightarrow$ large λ and thus quantum corrections;
  i.e., failure of Born approximation

  $\Rightarrow$ strongly interacting Higgs sector

  $\Rightarrow$ expect to see a spectrum of resonances as strong interactions in the GeV regime.
- On the other hand, if a light Higgs boson is discovered, it would indicate that weak interactions remain weak at all energies. $\Leftarrow$ the case we are considering

Partial Unitarity Violation

- In many extensions of the SM, several Higgs bosons participate in the EWSB together.
- We consider the scenario that only one of them is sufficiently light and detectable at colliders, whereas the others are too heavy to probe.
- The tree-unitarity may be violated at energies between the light Higgs boson and the heavy ones, for the scattering cross sections have effectively $(E/M_W)^2$ growth in the intermediate scale [no $(E/M_W)^4$ terms still].

Example: THDM

- Take as one example the two-Higgs doublet model (THDM) where two scalar doublets are simultaneously involved in the EWSB.
- The ΦVV couplings in this case are:

	SM	THDM
g_{hVV}	$g_{hVV}^{\rm SM}$	$g_{hVV}^{\rm SM}\sin(\beta-\alpha)$
g_{HVV}	0	$g_{hVV}^{\rm SM}\cos(\beta-\alpha)$

- In general, we parameterize the suppressed coupling as

$$g_{hVV} = \sqrt{\delta}\, g_{hVV}^{\rm SM}\ , \qquad (\delta < 1)$$

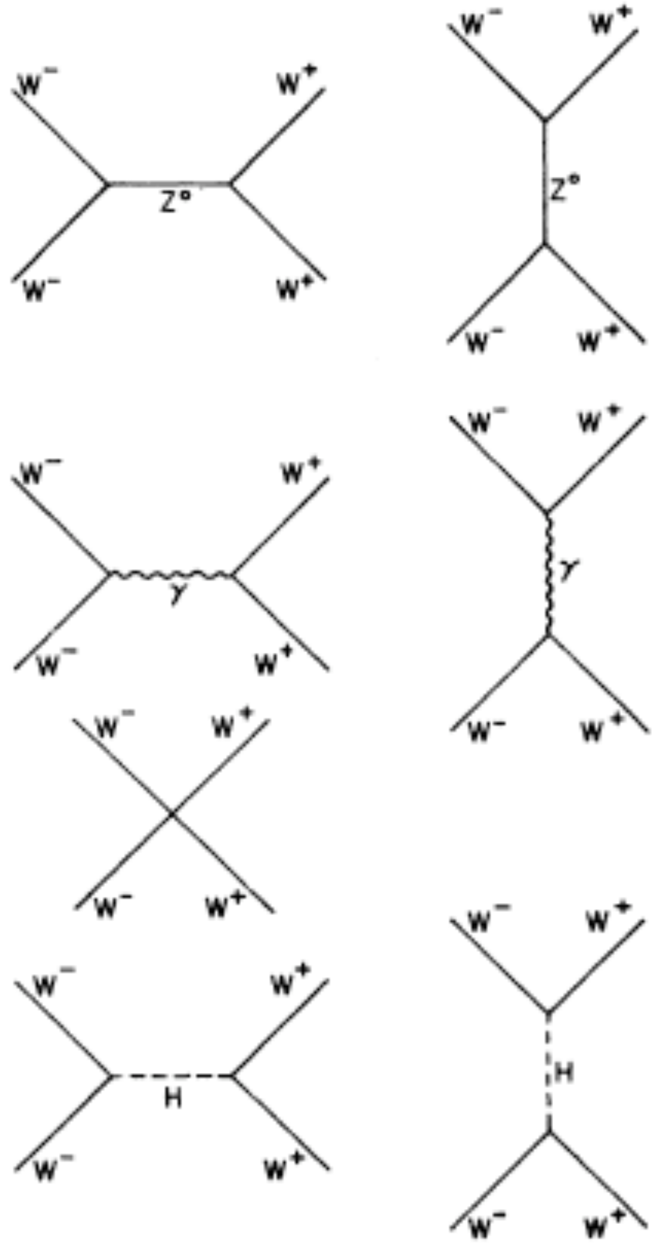
and assume that the other heavy degrees of freedom decouple for the illustration purpose.

Remarks

- Using the conventional $\gamma\gamma$ and $b\underline{b}$ decay modes of the light Higgs boson to hunt for new physics becomes difficult.
- The $\gamma\gamma$ mode is suppressed when g_{hWW} is smaller than its SM value.
- The $b\underline{b}$ mode also suffers from the reduced g_{hWW} coupling because the associate production of $W^{\pm}h$ gets smaller.
- While these modes become less useful, the $W_L W_L$ scattering enjoys its partial growth.

$W_L^+W_L^- \to W_L^+W_L^-$

- As an explicit example, consider this process in the SM in the $s \gg m_h^2, M_W^2$ limit.
- Tree-level Feynman diagrams in the unitarity gauge:
  - 4 four-point interaction;
  - Z and γ in s and t channels; and
  - Higgs boson in s and t channels.
- Other $V_LV_L \to V_LV_L$ scatterings have similar structures.



$W_L^+ W_L^- \to W_L^+ W_L^-$

- Individual amplitudes of gauge diagrams:

$$\begin{aligned} i\mathcal{M}_4 &= i\frac{g^2}{4M_W^4}\left[s^2+4st+t^2-4M_W^2(s+t)-\frac{8M_W^2}{s}ut\right] \\ i\mathcal{M}_t^{\gamma+Z} &= -i\frac{g^2}{4M_W^4}\left[(s-u)t-3M_W^2(s-u)+\frac{8M_W^2}{s}u^2\right] \\ i\mathcal{M}_s^{\gamma+Z} &= -i\frac{g^2}{4M_W^4}\left[s(t-u)-3M_W^2(t-u)\right] \end{aligned}$$

- Individual diagrams grow like $(E/M_W)^4$!
- The sum of them nicely cancel with each other to remove such a divergence.

$W_L^+W_L^- \to W_L^+W_L^-$

- However, there is still an $O((E/M_W)^2)$ divergence in the sum, which needs a sufficiently light Higgs boson to cure:

$$\sim \left(\frac{E}{M_W}\right)^2$$

$$\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) , \\
i\mathcal{M}^{\text{Higgs}} &= -i\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right] \\
&\simeq i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) . \\
\Rightarrow & \quad \text{complete } (E/M_W)^2 \text{ cancellation}
\end{aligned}$$

- The success of SM is thus seen to rely on nice relations among gauge bosons couplings (due to gauge invariance) and a suitable Higgs boson (depending on EWSB structure).

$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$

$$g_{hVV} = \sqrt{\delta}\, g_{hVV}^{\rm SM}$$

- However, the story changes dramatically if as assumed:

$$\begin{aligned} i\mathcal{M}^{\rm gauge} &= -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right)\ , \\ i\mathcal{M}^{\rm Higgs} &= -i\,\delta\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right] \\ &\simeq i\,\delta\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right)\ . \\ \Rightarrow &\qquad \text{only } \textit{partial}\ (E/M_W)^2 \text{ cancellation} \end{aligned}$$

- This gives rise to the “bad” high-energy behavior in the scattering cross section.

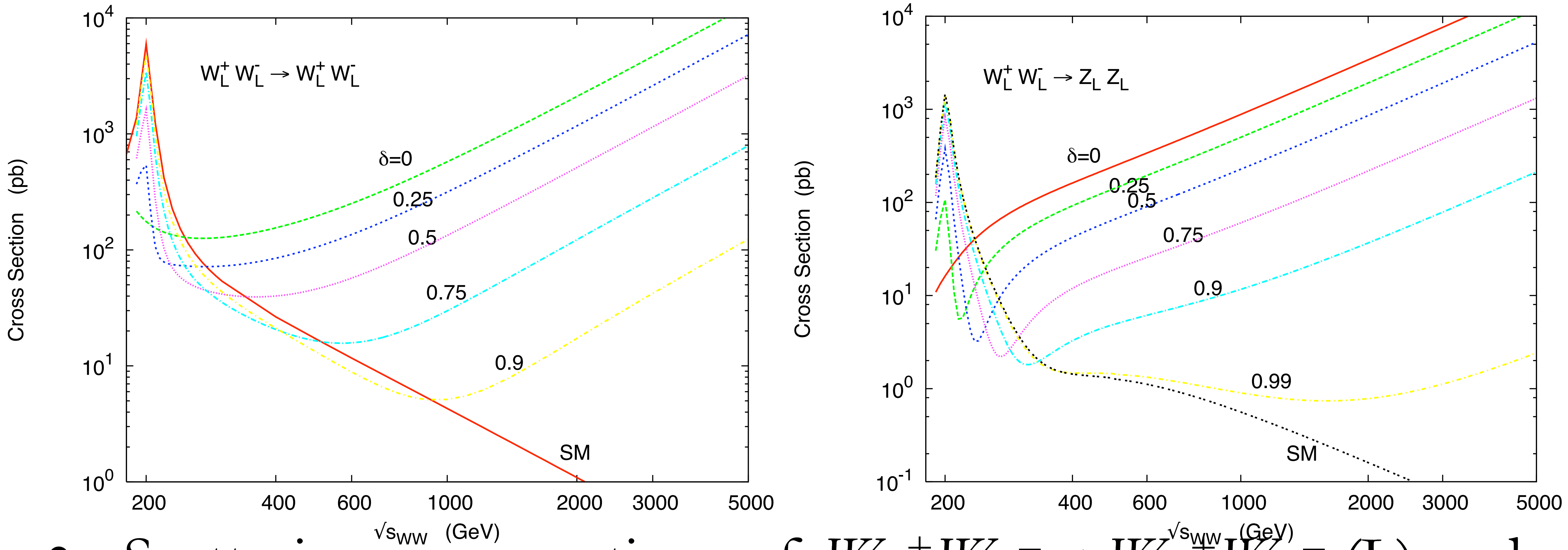
Scattering Channels

- Channels being studied:

Channel	Gauge	Higgs
$W_L^+W_L^- \to W_L^+W_L^-$	x,s,t	s,t
$W_L^+W_L^- \to Z_LZ_L$	x,t,u	s
$Z_LZ_L \to Z_LZ_L$	—	s,t,u
$W_L^\pm Z_L \to W_L^\pm Z_L$	x,s,u	t
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$	x,t,u	t,u

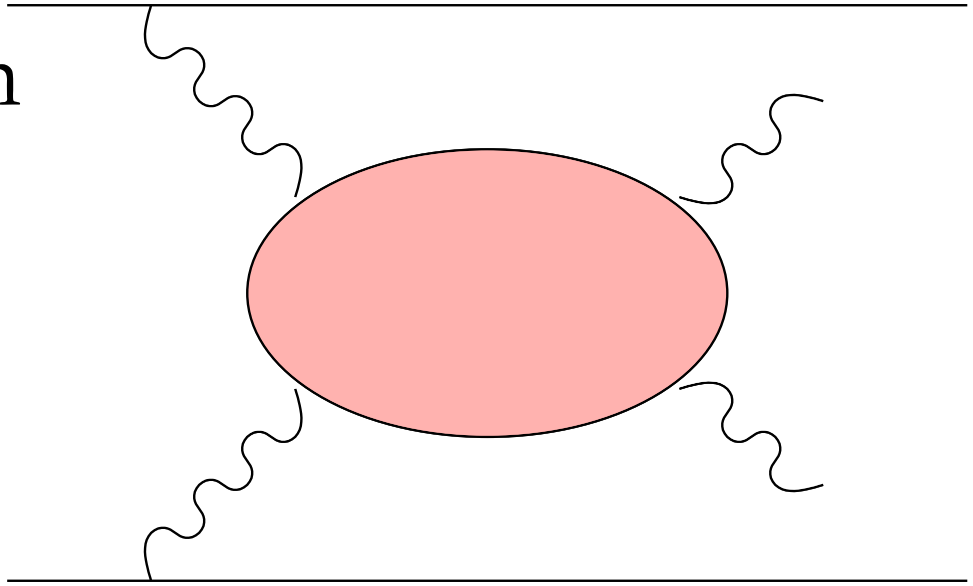
- Cross sections of the first two resonant channels grow with energy as it goes above the light Higgs boson mass.
- Cross sections of the last two non-resonant channels increase in a less dramatic way.
- The $Z_LZ_L \to Z_LZ_L$ channel is suppressed from SM by δ because it is purely Higgs-mediated.

Cross Sections



- Scattering cross sections of $W_L{}^+W_L{}^- \rightarrow W_L{}^+W_L{}^-$ (L) and $W_L{}^+W_L{}^- \rightarrow Z_LZ_L$ (R) as functions of the scattering energy.
- Assume $m_h = 200$ GeV and an angular cut $|\cos\theta| \leq 0.8$.
- The turn-over effect is different from SM both qualitatively and quantitatively, even if effects of heavy Higgs bosons of TeV masses are included.

Effective W Approximation



- At LHC, the weak gauge bosons in the initial state are radiated off the jets from the colliding protons.
- We employ the so-called effective W approximation (EWA)

$$f_{q\to W_L}(x) \sim \frac{1-x}{x}$$

Dawson 1985

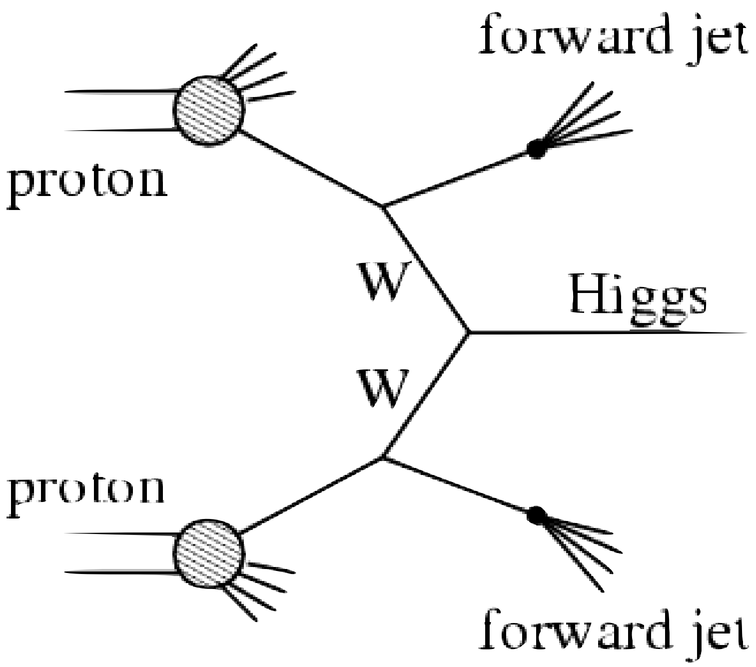
up to some coupling factors depending upon the types of the quark and the gauge boson (x = energy fraction).

- The same approximation is used for the Z boson as well.
- The radiation probability peaks when $x\to 0$ and vanishes when $x\to 1$. ⇒ most energy stays with jets

Enhancing S/B

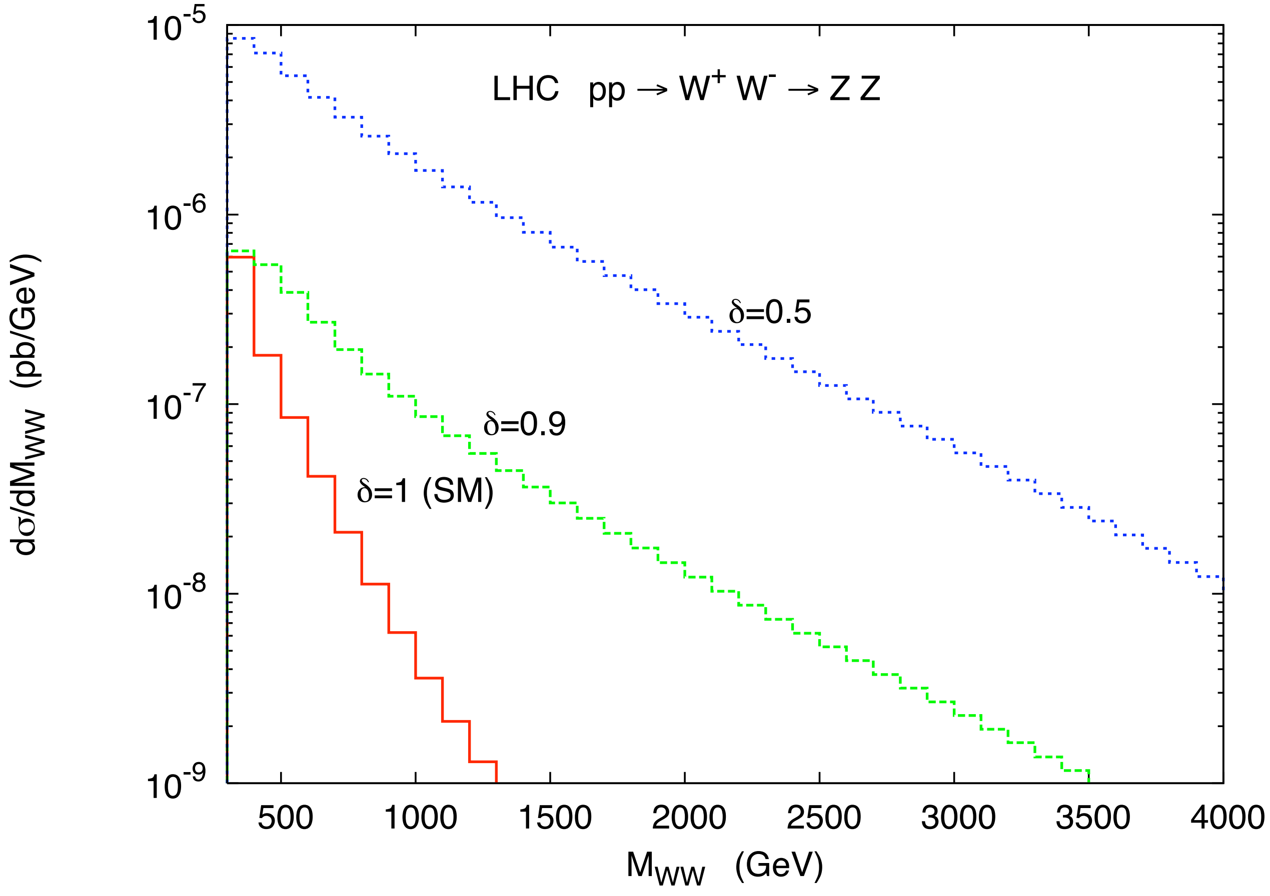
Bagger et al 1994, 1995

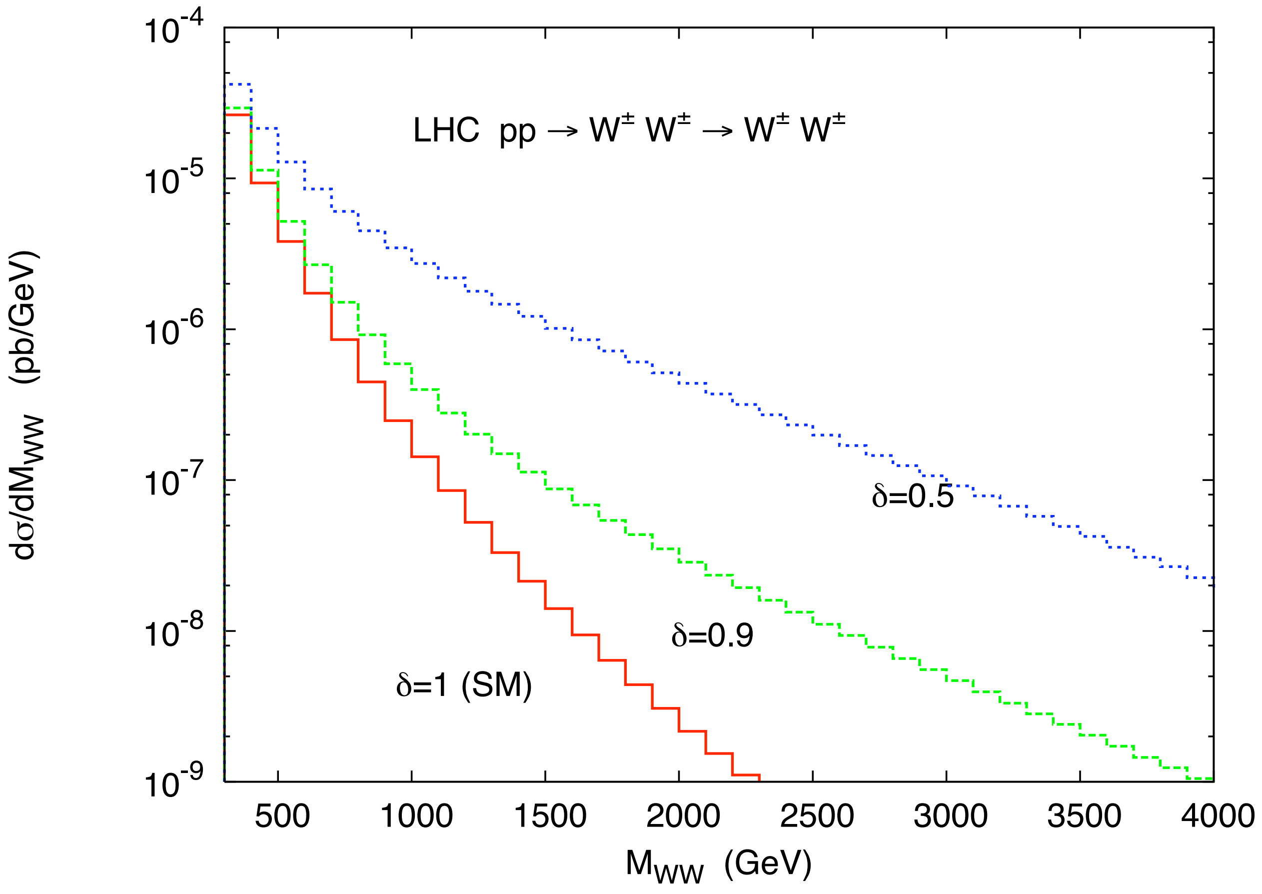
- A good part of initial energy is carried away by the jets.
  $\Rightarrow$ energetic forward jets
  $\Rightarrow$ large rapidity gap ($|\eta|>2$)
  $\Rightarrow$ use central jet veto and forward jet tagging
- A very similar idea had been proposed for Higgs production through VBF.



Diff. cross-section @ LHC

- Invariant mass distribution using naive EWA:





- The difference from the SM can be significant (even for δ as large as 0.9), provided that the UV-completing degrees of freedom are sufficiently heavy.

LHC Signals

- Study leptonic final states to avoid QCD background
- Focus on $WW \to l\nu l\nu$ and $ZZ \to l^+l^-l^+l^-$, $ll\nu\nu$

Table 1: Event rates for longitudinal weak gauge boson scattering at the LHC with a yearly luminosity of 100 fb^{-1} using the EWA for $\delta = 1$ (SM), 0.9, 0.5 and 0 (No Higgs). Branching ratios for the leptonic final states are summed for $\ell = e$ and μ. We set $m_h = 200$ GeV and $M_{WW}^{\min} = 300$ GeV.

Subprocess	Number of Events			
	$\delta = 1$ (SM)	0.9	0.5	0 (No Higgs)
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm \to \ell^\pm \nu \ell^\pm \nu$	21	26	57	118
$W_L^\pm W_L^\mp \to W_L^\pm W_L^\mp \to \ell^\pm \nu \ell^\mp \nu$	8	7	17	67
$W_L^\pm Z_L \to W_L^\pm Z_L \to \ell^\pm \nu \ell^+ \ell^-$	4	5	13	33
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+ \ell^- \ell^+ \ell^-$	0.04	0.12	2	9
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+ \ell^- \nu \bar{\nu}$	0.25	0.74	12	50
$Z_L Z_L \to Z_L Z_L \to \ell^+ \ell^- \ell^+ \ell^-$	0.4	0.32	0.08	0
$Z_L Z_L \to Z_L Z_L \to \ell^+ \ell^- \nu \bar{\nu}$	2.4	2	0.5	0

SM with an hidden $U(1)$ – Stueckelberg extension of SM

Kors and Nath, PLB586, 366 (2004); Feldman, Liu and Nath, PRL97, 021801 (2006)

Cheung and Yuan, JHEP 0703 120 (2007)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{StSM}}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}} = & -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i\bar{f}\gamma^\mu D_\mu f \\ & + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi),\end{aligned}$$

Hidden $U(1)$ Lagrangian

$$\begin{aligned}\mathcal{L}_{\mathrm{StSM}} = & -\frac{1}{4} C_{\mu\nu} C^{\mu\nu} + \frac{1}{2}(\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu)^2 \\ & + \bar{\chi}(i\gamma^\mu D^X_\mu - M_\chi)\chi,\end{aligned}$$

Hidden Dark Matter

Stueckelberg mass term

- After the EWSB $\langle\Phi\rangle = v/\sqrt{2}$ with $v \simeq 246$ GeV

$$-\frac{1}{2}V^{\mathrm{T}}M^2_{\mathrm{Stu}}V \equiv$$

$$-\frac{1}{2}\left(C_\mu,\, B_\mu,\, W^3_\mu\right)\begin{pmatrix} M_1^2 & M_1M_2 & 0 \\ M_1M_2 & M_2^2+\frac{1}{4}g_Y^2v^2 & -\frac{1}{4}g_2g_Yv^2 \\ 0 & -\frac{1}{4}g_2g_Yv^2 & \frac{1}{4}g_2^2v^2 \end{pmatrix}\begin{pmatrix} C_\mu \\ B_\mu \\ W^3_\mu \end{pmatrix}$$

$Det(M^2_{\mathrm{Stu}}) = 0 \Rightarrow$ at least one zero eigenvalue

- $O^{\mathrm{T}}M^2_{\mathrm{Stu}}O = \mathrm{Diag}\left[M^2_{Z'},\, M^2_Z,\, 0\right]$

$$O = \begin{pmatrix} c_\psi c_\phi - s_\theta s_\phi s_\psi & s_\psi c_\phi + s_\theta s_\phi c_\psi & -c_\theta s_\phi \\ c_\psi s_\phi + s_\theta c_\phi s_\psi & s_\psi s_\phi - s_\theta c_\phi c_\psi & c_\theta c_\phi \\ -c_\theta s_\psi & c_\theta c_\psi & s_\theta \end{pmatrix}$$

- Relations for the three angles:

$$
\begin{aligned}
&\boxed{\epsilon \equiv \tan\phi = \frac{M_2}{M_1}\ ,}\\
\tan\theta &= \frac{g_Y}{g_2}\cos\phi\ ,\\
\tan\psi &= \frac{M_W^2\tan\theta\ \tan\phi}{\cos\theta[M_{Z'}^2 - M_W^2(1+\tan^2\theta)]}\ .
\end{aligned}
$$

- The masses of W, Z and Z':

$$
\begin{aligned}
M_W^2 &= \frac{g_2^2 v^2}{4}\ ,\\
M_{Z',Z}^2 &= \frac{1}{2}\Big[M_1^2 + M_2^2 + M_W^2 + M_Y^2 \pm \mathbf{M^2}\Big]\ ,\\
M_Y^2 &= \frac{g_Y^2 v^2}{4}\ ,\\
\mathbf{M^2} &= \sqrt{(M_1^2 + M_2^2 + M_W^2 + M_Y^2)^2 - 4(M_1^2 + M_2^2)M_W^2 - 4M_1^2 M_Y^2}\ .
\end{aligned}
$$

- The ρ parameter:

SM: $\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$

StSM: $\rho = \frac{M_W^2}{\cos^2 \theta \left(M_Z^2 \cos^2 \psi + M_{Z'}^2 \sin^2 \psi \right)} = 1$

- In the limit of the custodial symmetry:

$g_Y \longrightarrow 0$

$M_Z = M_W$

$M_{Z'} = \left(M_1^2 + M_2^2 \right)^{1/2}$

W^+, W^-, Z form a triplet

Z' transforms as a singlet

Large $\tan\phi$ Scenario

$$M_Z = M_Z(M_{Z'}, \tan\phi)$$

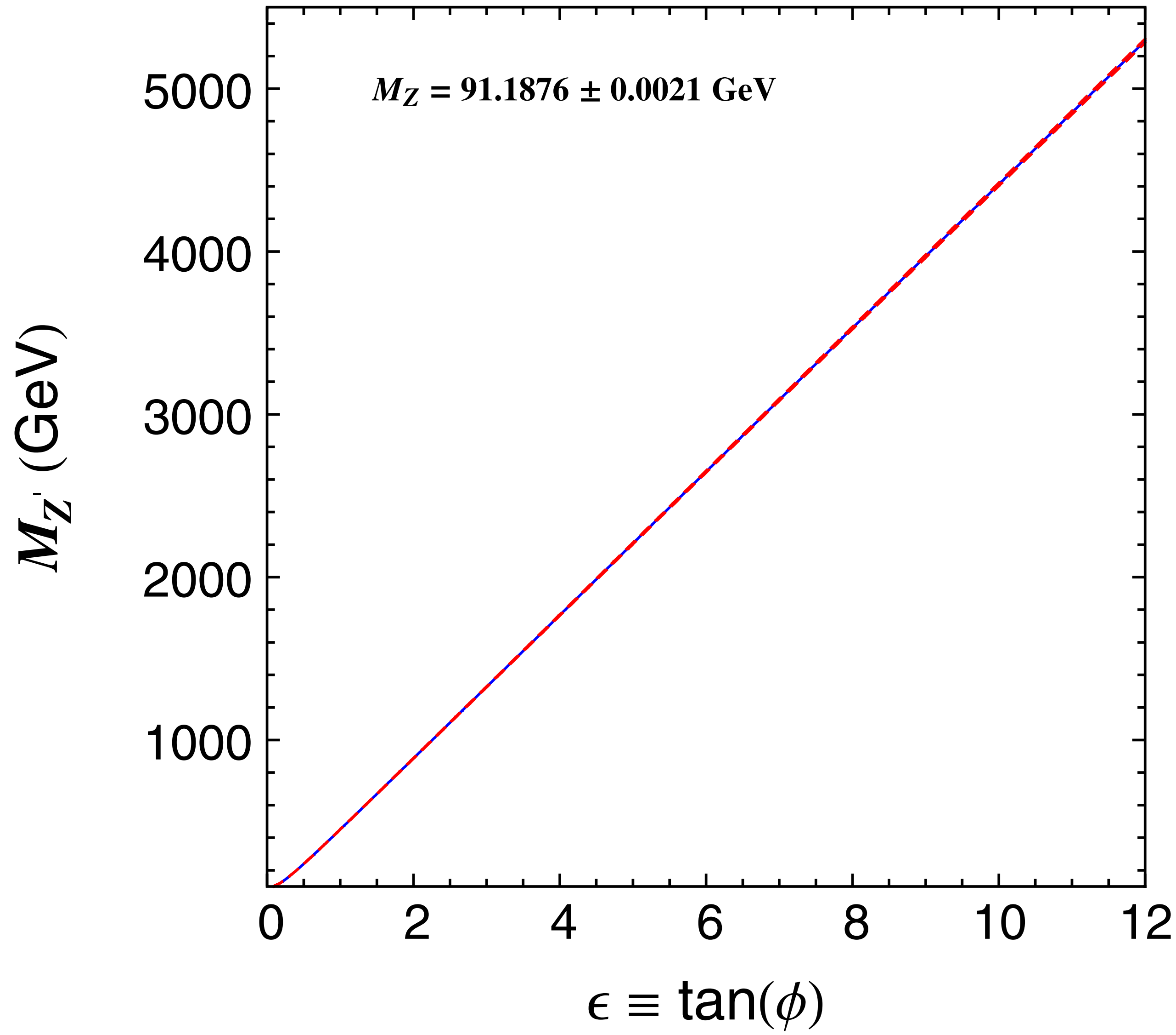


FIG. 1 (color online). Contour of the Z mass as a function of $\tan(\phi)$ and $M_{Z'}$. The solid blue line corresponds to the central value of measured M_Z and the red dashed lines correspond to its 1σ deviation.

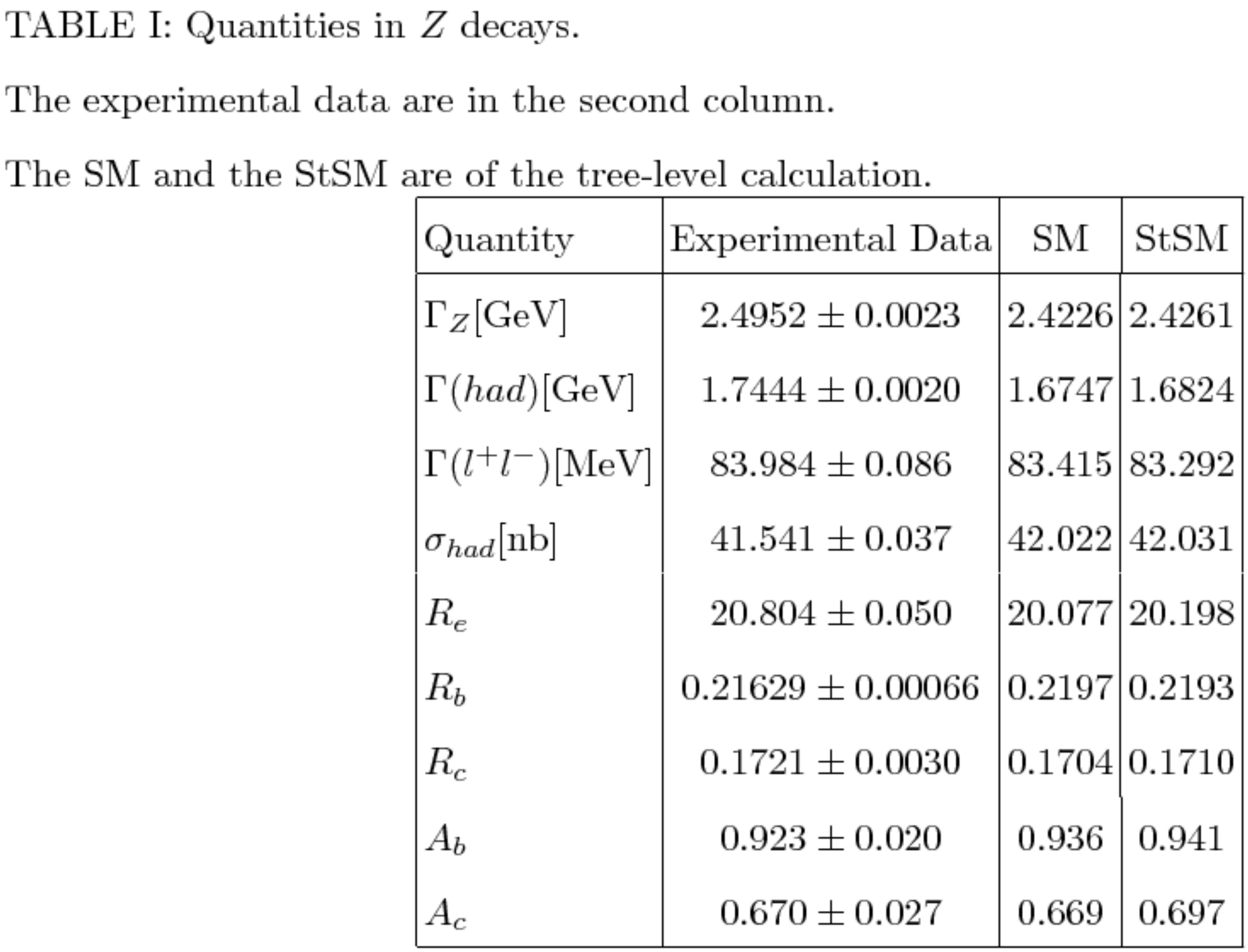


TABLE I: Quantities in Z decays.

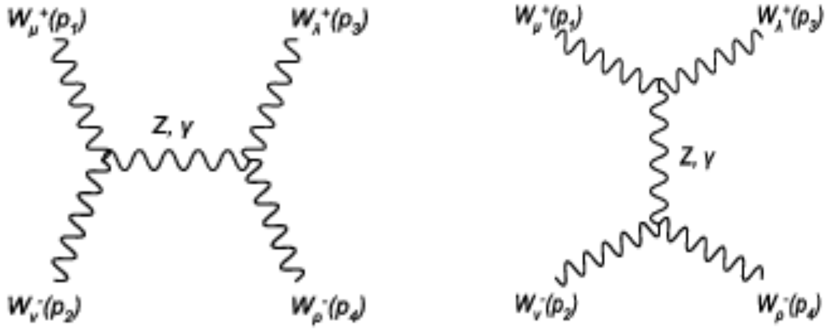
The experimental data are in the second column.

The SM and the StSM are of the tree-level calculation.

Quantity	Experimental Data	SM	StSM
Γ_Z[GeV]	2.4952 ± 0.0023	2.4226	2.4261
$\Gamma(had)$[GeV]	1.7444 ± 0.0020	1.6747	1.6824
$\Gamma(l^+l^-)$[MeV]	83.984 ± 0.086	83.415	83.292
σ_{had}[nb]	41.541 ± 0.037	42.022	42.031
R_e	20.804 ± 0.050	20.077	20.198
R_b	0.21629 ± 0.00066	0.2197	0.2193
R_c	0.1721 ± 0.0030	0.1704	0.1710
A_b	0.923 ± 0.020	0.936	0.941
A_c	0.670 ± 0.027	0.669	0.697

$$\tan\phi = 2 \;\;,\;\; M_{Z'} = 1\ \text{TeV}$$

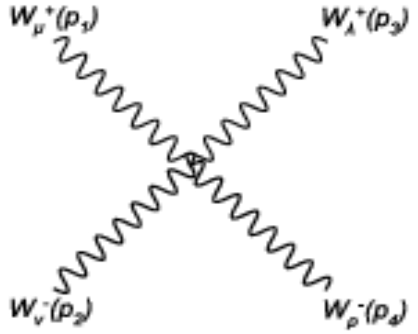
- The modified pure gauge couplings:



$$W(k_1,\mu)W(k_2,\nu)V_i(k_3,\lambda)$$

$$-ig_2 O_{3i}[(k_1-k_2)_\lambda g_{\mu\nu}+(k_2-k_3)_\mu g_{\nu\lambda}+(k_3-k_1)_\nu g_{\lambda\mu}]$$

$$W(k_1,\mu)W(k_2,\nu)V_i(k_3,\lambda)V_j(k_4,\rho)$$

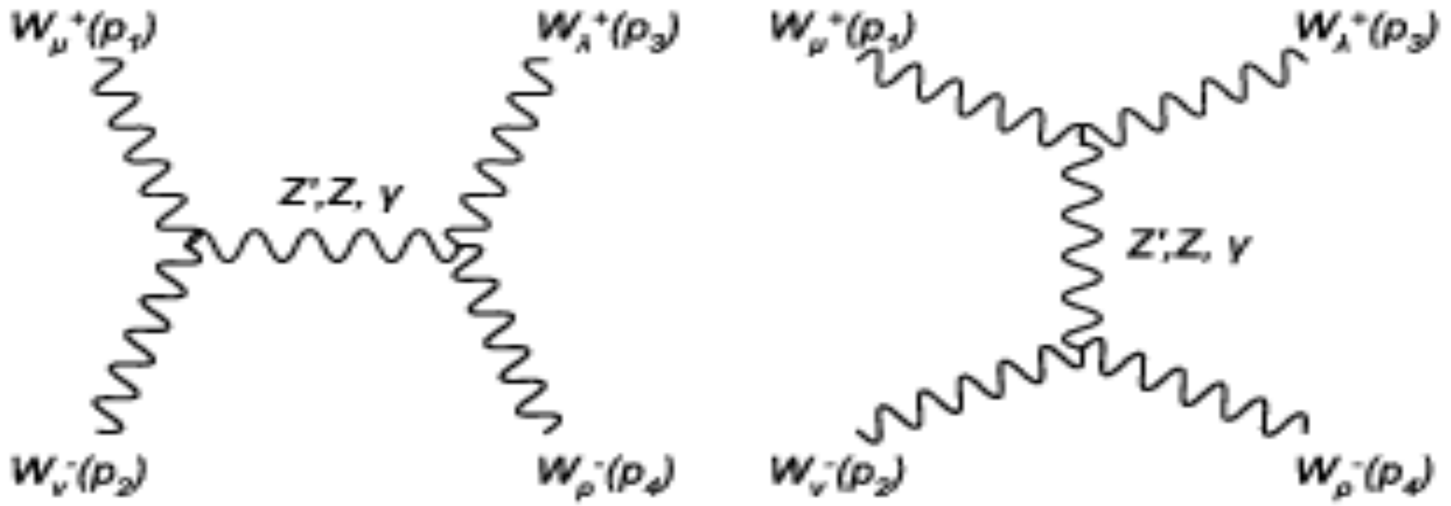


$$-ig_2^2 O_{3i}O_{3j}[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$$

where $V_i = Z', Z, A$ for $i = 1, 2, 3$ respectively.

$O_{31} = -c_\theta s_\psi$, $O_{32} = c_\theta c_\psi$, and $O_{33} = s_\theta$.

$W_L^{\pm}W_L^{\mp} \to W_L^{\pm}W_L^{\mp}$ in the StSM



Propagators

$x = s$ or t

$$A_x^{SM} = \frac{\sin^2\theta_W}{x} + \frac{\cos^2\theta_W}{x - M_Z^2}$$

$$A_x^{\mathrm{StSM}} = \frac{s_\theta^2}{x} + \frac{c_\theta^2 c_\psi^2}{x - M_Z^2} + \frac{c_\theta^2 s_\psi^2}{x - M_{Z'}^2}$$

- In the limit of $x \gg M_{Z'}^2, M_Z^2$:

$$A_x^{SM} \simeq \frac{1}{x}\left(1+\frac{M_Z^2 \cos^2\theta_W}{x}\right)$$

$$A_x^{\mathrm{StSM}} \simeq \frac{1}{x}\left[1+\frac{c_\theta^2(M_Z^2 c_\psi^2+M_{Z'}^2 s_\psi^2)}{x}\right]$$

- sum up the pure gauge diagrams

$$\begin{aligned} i\mathcal{M}^{\text{gauge}} &\simeq -i\frac{g_2^2}{4M_W^4}\left[4M_W^2-3c_\theta^2(M_Z^2 c_\psi^2+M_{Z'}^2 s_\psi^2)\right]u \\ &\simeq -i\frac{g_2^2}{4M_W^2}u, \end{aligned}$$

with $\boxed{M_W^2=\cos^2\theta\left(M_Z^2\cos^2\psi+M_{Z'}^2\sin^2\psi\right)}$

$$\boxed{\Rightarrow i\mathcal{M}^{\text{gauge}}+i\mathcal{M}^{\text{Higgs}}=O\left((E/M_W)^0\right)}$$

- In the intermediate range of $M_Z^2 < x \ll M_{Z'}^2$:

$$A_x^{\mathrm{StSM}} \simeq \frac{1}{x}\left[1 - c_\theta^2 s_\psi^2 \left(1 - \frac{M_Z^2}{x}\right)^{-1} + \frac{M_Z^2 c_\theta^2}{x - M_Z^2}\right],$$

$$i\mathcal{M}^{\mathrm{gauge}} \simeq i\frac{g_2^2}{4M_W^4} c_\theta^2 s_\psi^2 \boxed{(s^2 + 4st + t^2)}\,.$$

$(E/M_W)^4$

$\Rightarrow O((E/M_W)^4)$ enhancement

- Unitarity constraints on the StSM:

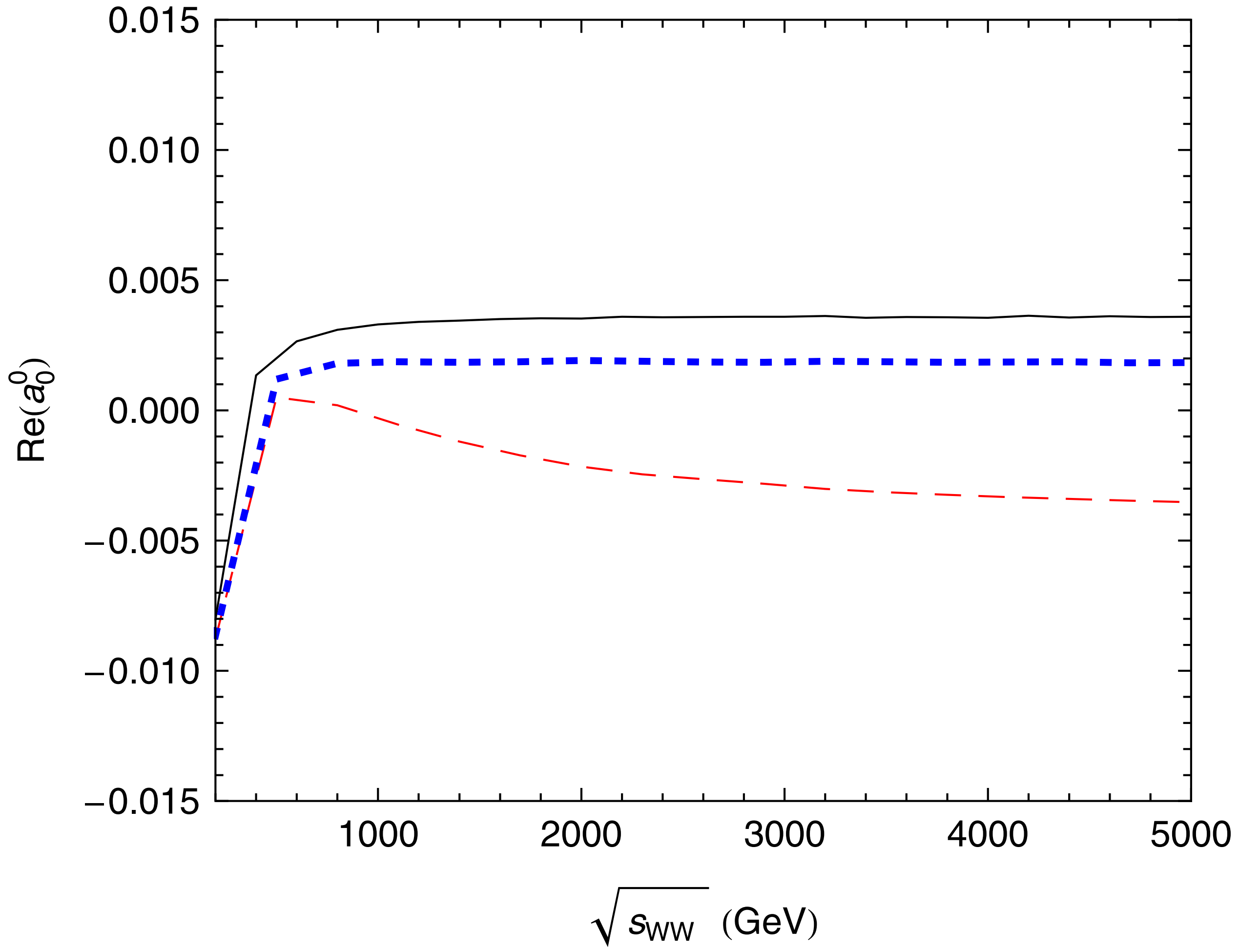
$$a_0^0 = \frac{1}{64\pi}\int_{-1}^{1} d\cos\theta\,\left[3\,\mathcal{M}\left(W_L^+W_L^- \to Z_LZ_L\right) + \mathcal{M}\left(W_L^+W_L^+ \to W_L^+W_L^+\right)\right]\ ,$$

$$\begin{aligned} a_1^1 = \frac{1}{64\pi}\int_{-1}^{1} d\cos\theta\,&\left[2\left(\mathcal{M}\left(W_L^+W_L^- \to W_L^+W_L^-\right) - \mathcal{M}\left(W_L^+W_L^- \to Z_LZ_L\right)\right)\right.\\ &\left.-\mathcal{M}\left(W_L^+W_L^+ \to W_L^+W_L^+\right)\right]\cos\theta\ , \end{aligned}$$

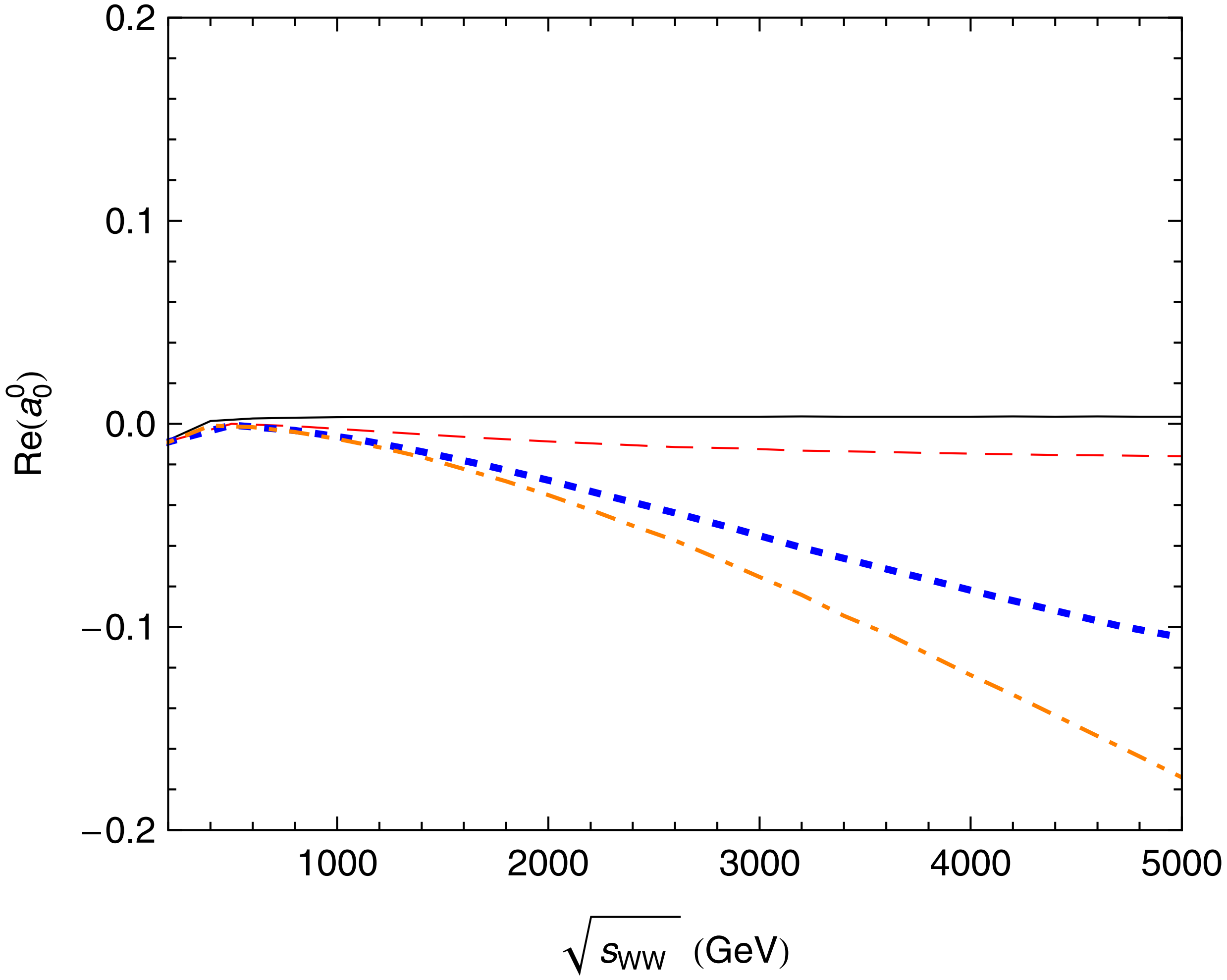
$$a_0^2 = \frac{1}{64\pi}\int_{-1}^{1} d\cos\theta\,\mathcal{M}\left(W_L^+W_L^+ \to W_L^+W_L^+\right)$$

$$|\Re e\ a_J^I| \leq 1/2$$

Unitarity Constraints

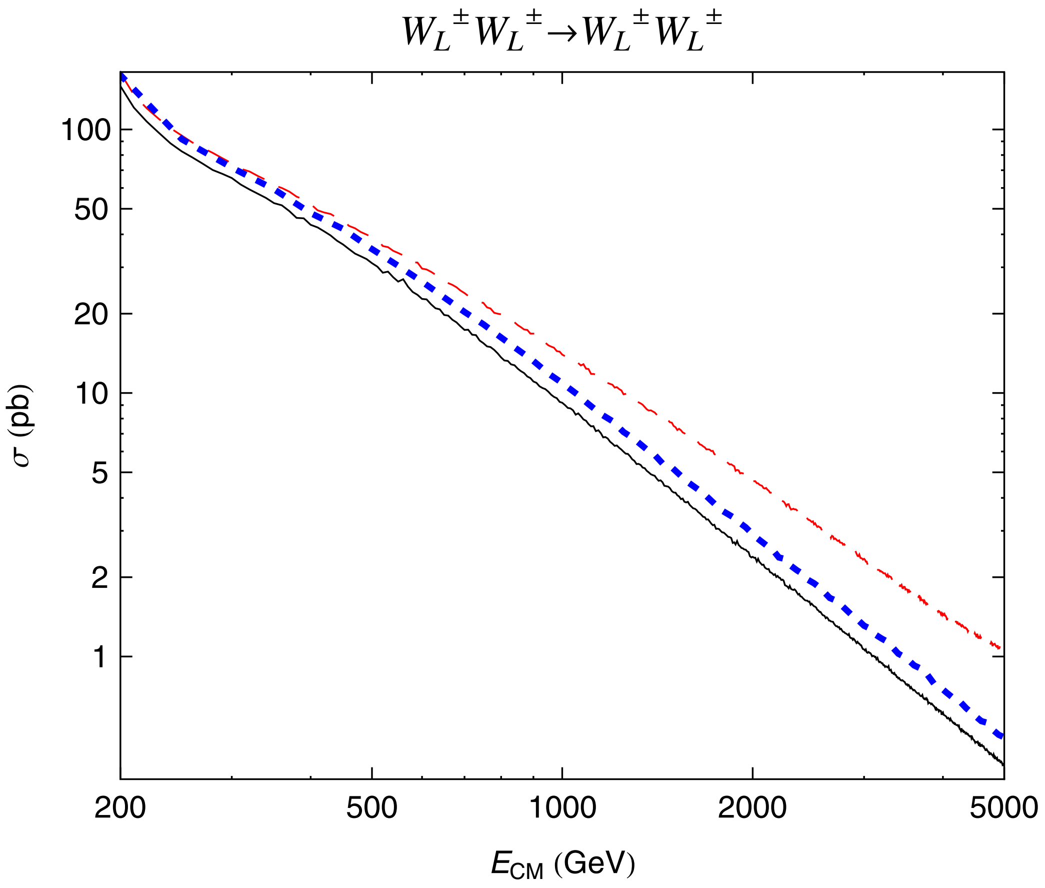


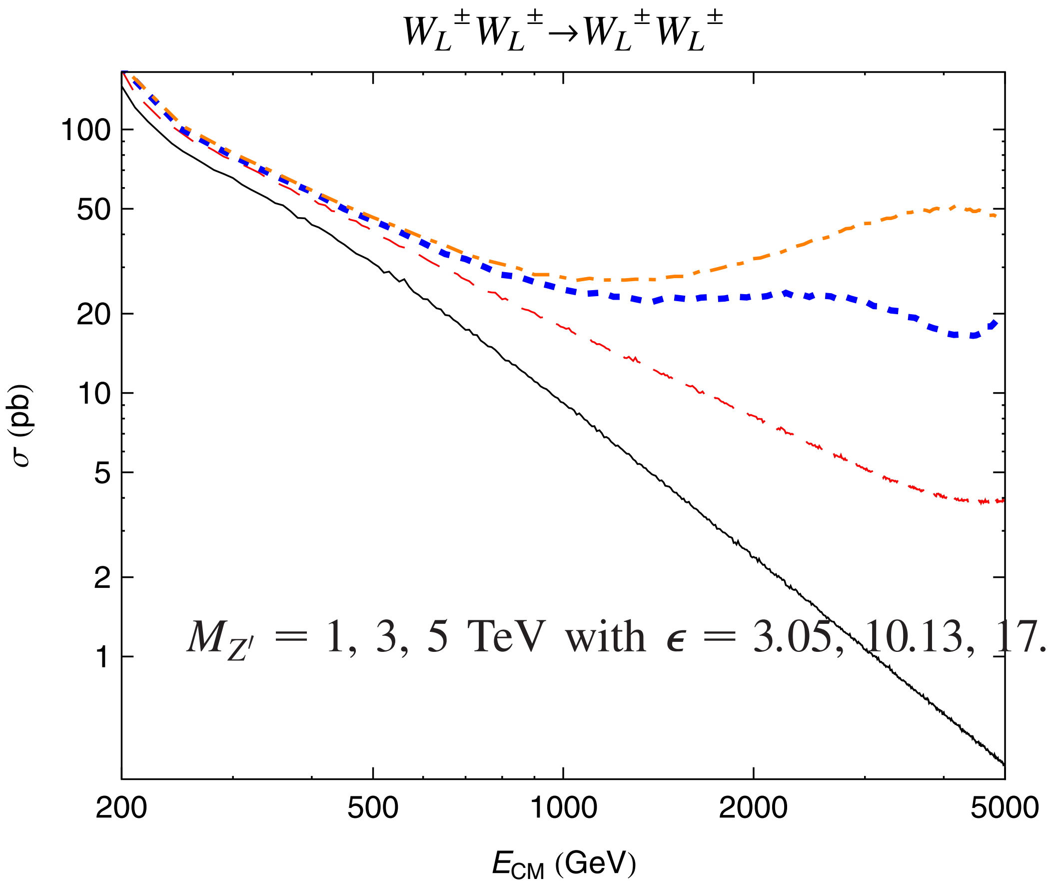
$M_{Z'} = 600\ (300)$ GeV with $\epsilon = 1.73\ (0.77)$



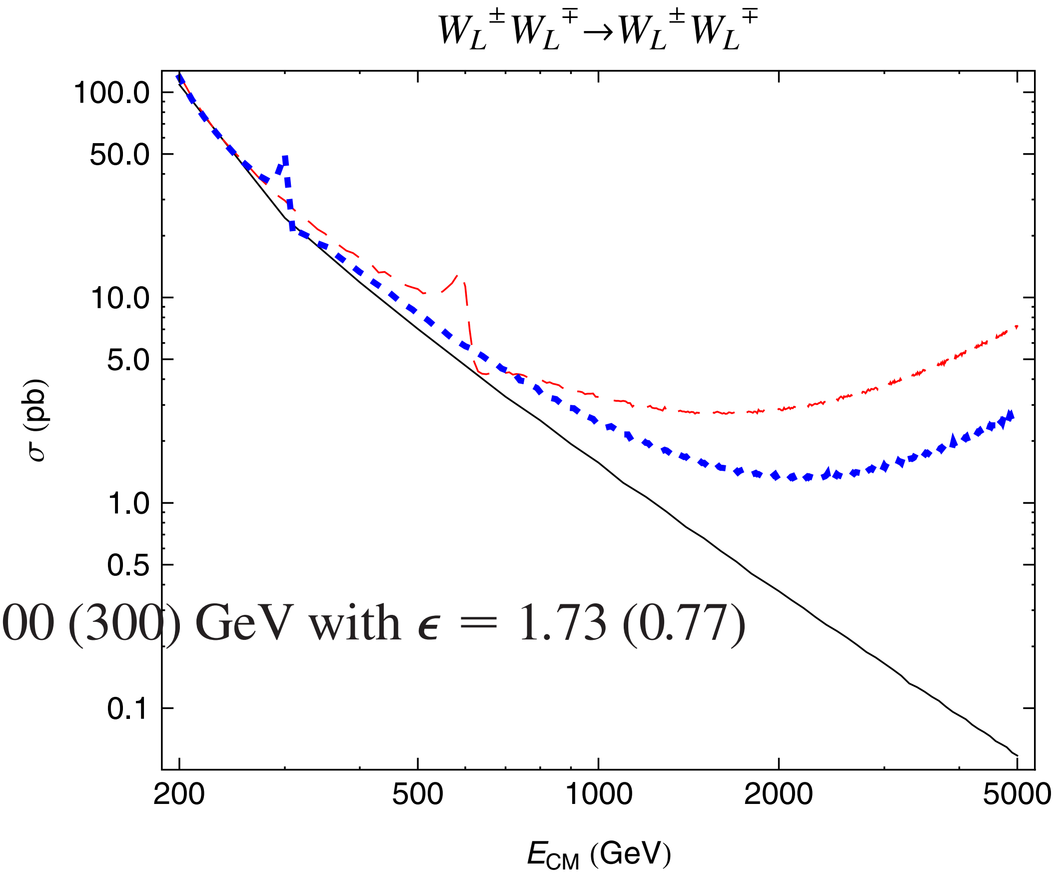
$M_{Z'} = 1,\ 3,\ 5$ TeV with $\epsilon = 3.05,\ 10.13,\ 17.59,$

Total Cross Sections

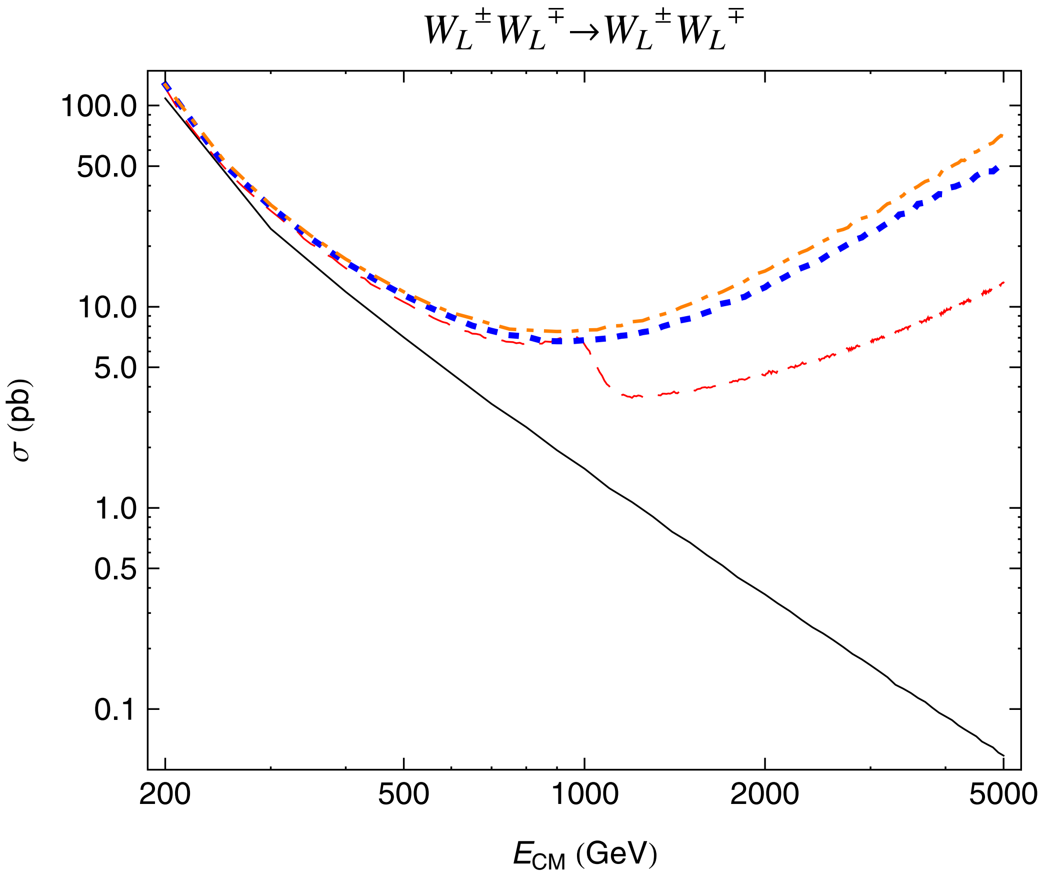

$W_L^{\pm}W_L^{\pm} \to W_L^{\pm}W_L^{\pm}$


$W_L^{\pm}W_L^{\pm} \to W_L^{\pm}W_L^{\pm}$

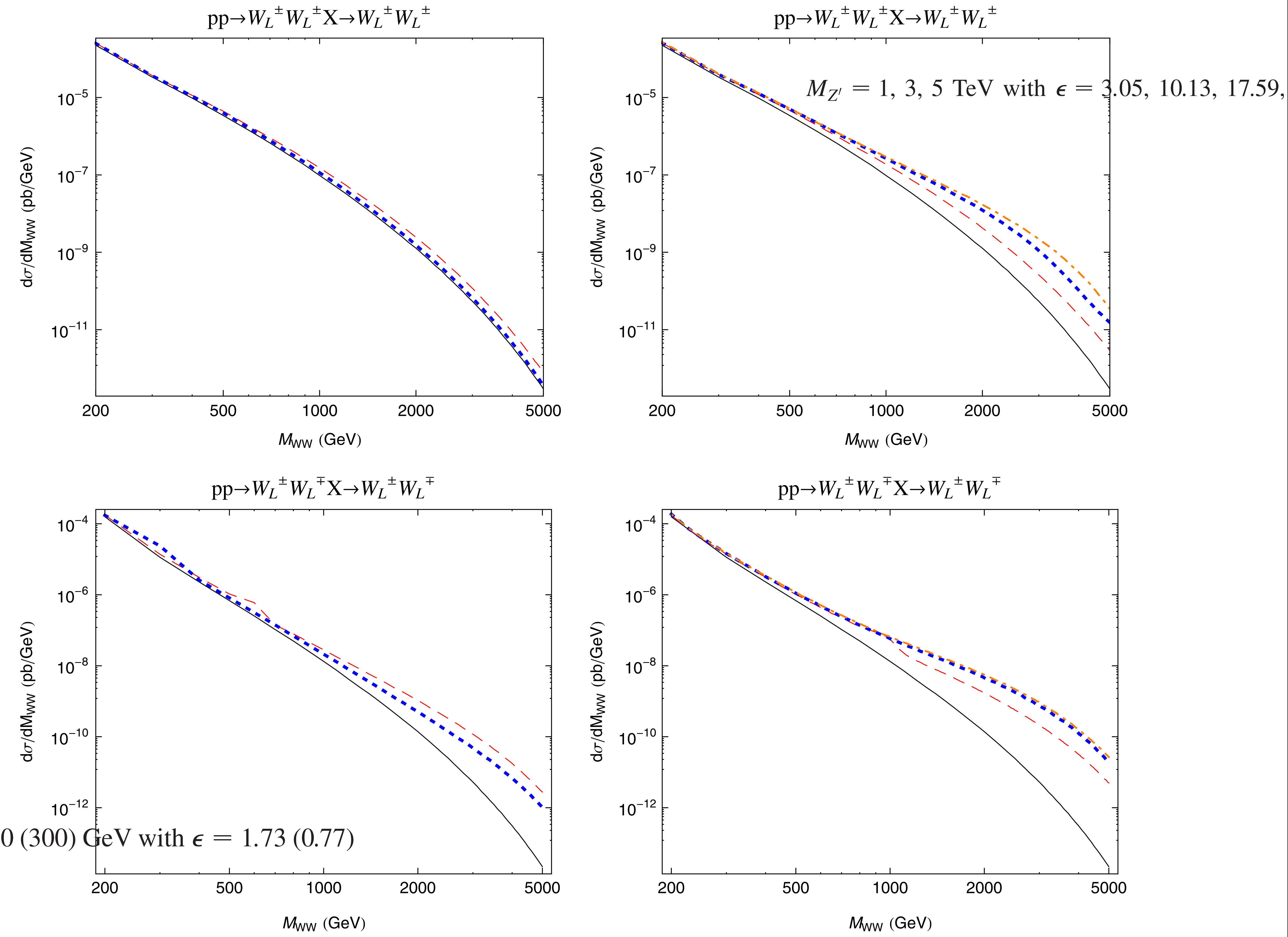
$M_{Z'} = 1,\ 3,\ 5$ TeV with $\epsilon = 3.05,\ 10.13,\ 17.59,$


$W_L^{\pm}W_L^{\mp} \to W_L^{\pm}W_L^{\mp}$

$M_{Z'} = 600\ (300)$ GeV with $\epsilon = 1.73\ (0.77)$


$W_L^{\pm}W_L^{\mp} \to W_L^{\pm}W_L^{\mp}$

Invariant Mass Distribution at LHC



$M_{Z'} = 1, 3, 5$ TeV with $\epsilon = 3.05, 10.13, 17.59,$

$M_{Z'} = 600\ (300)$ GeV with $\epsilon = 1.73\ (0.77)$

Event rates at the LHC

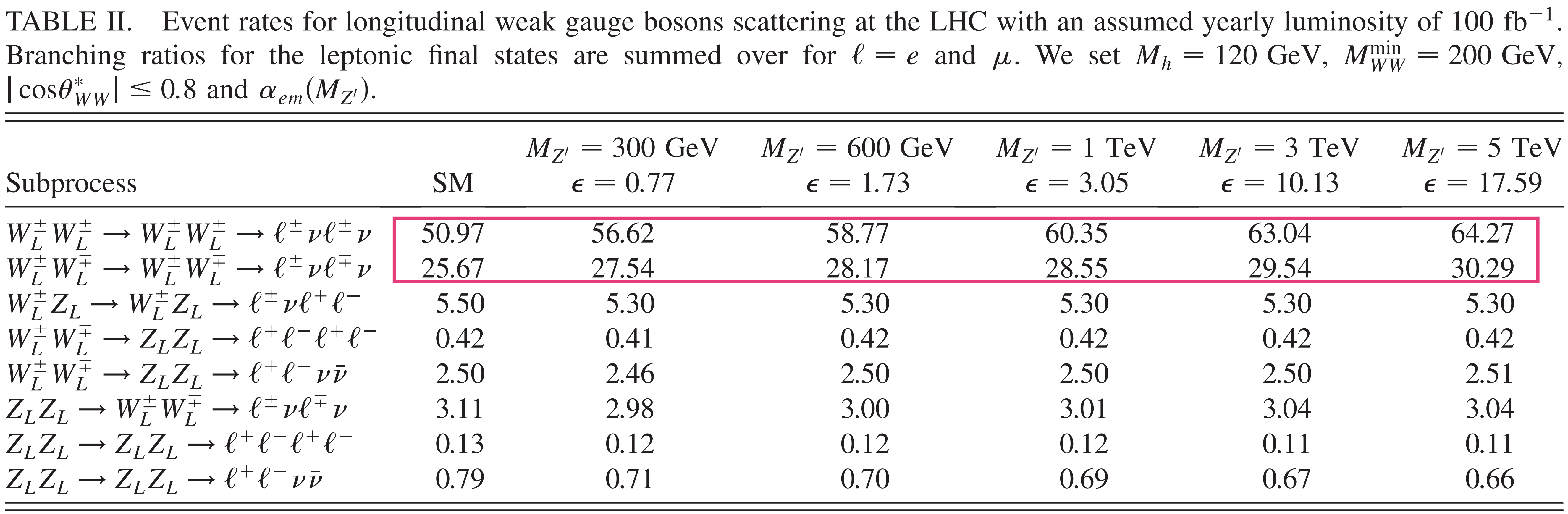


TABLE II. Event rates for longitudinal weak gauge bosons scattering at the LHC with an assumed yearly luminosity of 100 fb^{-1}. Branching ratios for the leptonic final states are summed over for $\ell = e$ and μ. We set $M_h = 120$ GeV, $M_{WW}^{\min} = 200$ GeV, $|\cos\theta^*_{WW}| \leq 0.8$ and $\alpha_{em}(M_{Z'})$.

Subprocess	SM	$M_{Z'} = 300$ GeV $\epsilon = 0.77$	$M_{Z'} = 600$ GeV $\epsilon = 1.73$	$M_{Z'} = 1$ TeV $\epsilon = 3.05$	$M_{Z'} = 3$ TeV $\epsilon = 10.13$	$M_{Z'} = 5$ TeV $\epsilon = 17.59$
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm \to \ell^\pm \nu \ell^\pm \nu$	50.97	56.62	58.77	60.35	63.04	64.27
$W_L^\pm W_L^\mp \to W_L^\pm W_L^\mp \to \ell^\pm \nu \ell^\mp \nu$	25.67	27.54	28.17	28.55	29.54	30.29
$W_L^\pm Z_L \to W_L^\pm Z_L \to \ell^\pm \nu \ell^+ \ell^-$	5.50	5.30	5.30	5.30	5.30	5.30
$W_L^\pm W_L^\mp \to Z_L Z_L \to \ell^+ \ell^- \ell^+ \ell^-$	0.42	0.41	0.42	0.42	0.42	0.42
$W_L^\pm W_L^\mp \to Z_L Z_L \to \ell^+ \ell^- \nu \bar{\nu}$	2.50	2.46	2.50	2.50	2.50	2.51
$Z_L Z_L \to W_L^\pm W_L^\mp \to \ell^\pm \nu \ell^\mp \nu$	3.11	2.98	3.00	3.01	3.04	3.04
$Z_L Z_L \to Z_L Z_L \to \ell^+ \ell^- \ell^+ \ell^-$	0.13	0.12	0.12	0.12	0.11	0.11
$Z_L Z_L \to Z_L Z_L \to \ell^+ \ell^- \nu \bar{\nu}$	0.79	0.71	0.70	0.69	0.67	0.66

$$M_h = 120 \text{ GeV}$$

$$M_{WW}^{\min} = 200 \text{ GeV}$$

Conclusions

- $W_L W_L$ scattering can be used as sensitive probes for modified gauge-Higgs and/or pure gauge couplings which can lead to partially strong scattering amplitudes.

- Using a 2HDM and a StSM as illustrations, we show that these may lead to discernible effects at the LHC.

Happy Birthday, Goran!