Cracow-Warsaw Workshop on LHC, Warsaw, 26 March 2010

WW scattering at the LHC

theory – Jan Kalinowski
simulations – Michał Szleper

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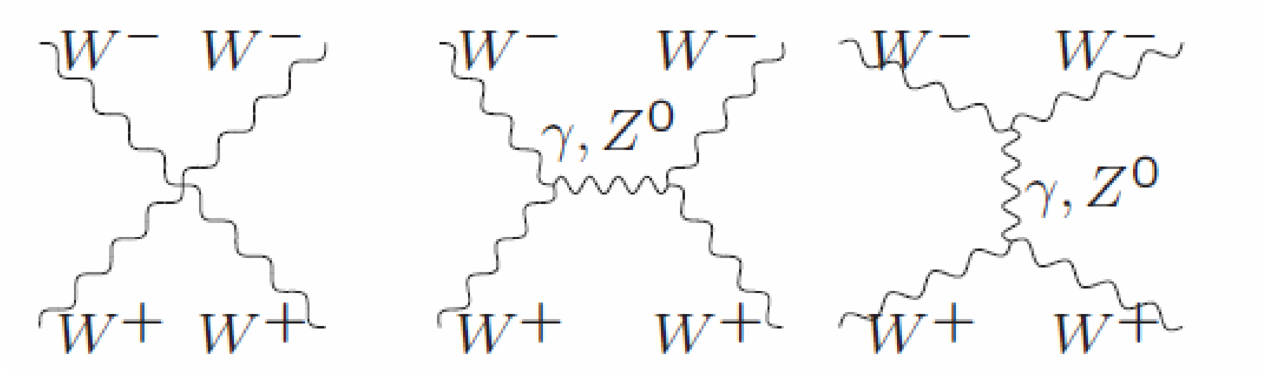
Standard Model of GSW provides a very successful description of fundamental interactions up to the electroweak scale

- the only missing piece is the Higgs boson
- Higgs unitarizes the scattering amplitudes of massive gauge bosons with longitudinal polarizations
- Higgs serves as a means to break the electroweak symmetry
- and is a source of unwanted theoretical features

Processes with longitudinal gauge bosons $V_L V_L \to V_L V_L$

pure gauge sector

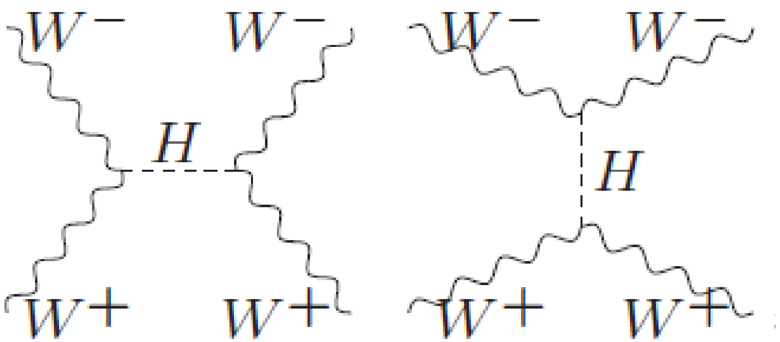


each diagram ~ s^2

summing: $\mathcal{M}_{gauge} = -\frac{g^2}{4M_W^2}(4 - \frac{3}{\rho})u + \mathcal{O}(s^0)$

$\rho = M_W^2/M_Z^2 \cos^2\theta_W$

in the SM the unitarity is restored by adding a scalar H with proper couplins



$\mathcal{M}_H = \frac{g^2}{4M_W^2}u + \mathcal{O}(s^0)$

- SM – the simplest mechanism for the electroweak symmetry breaking
- so far the mechanism of EWSB not tested: Higgs ad hoc
- Higgs mass unstable with respect to radiative corrections
- Goldstone theorem and Higgs mechanism do not require the existence of the elementary scalar

$\Rightarrow$ main motivations to go beyond minimal SM

$V_L V_L \to V_L V_L$ scattering inextricably connected to EWSB mechanism

Unitarity of the WW scattering can be restored by many means:

* resonances, composite objects, multiHiggs models, noHiggs, …

* at the same time the couplings may be modified

Lessons from the SM analysis of $V_L V_L \to V_L V_L$

two limits are of interest

$$\mathcal{A}(W_L W_L \to W_L W_L) = \begin{cases} \dfrac{g^2 s}{4 m_W^2} & \text{for} \quad m_W^2 \ll s \ll m_H^2 \\ \dfrac{g^2 m_H^2}{4 m_W^2} & \text{for} \quad m_W^2 \ll m_H^2 \ll s \end{cases}$$

the heavier the Higgs (unitarity restored later) the more strongly the WW system interacts

in the SM unitarity requires $m_H \leq 800$ GeV

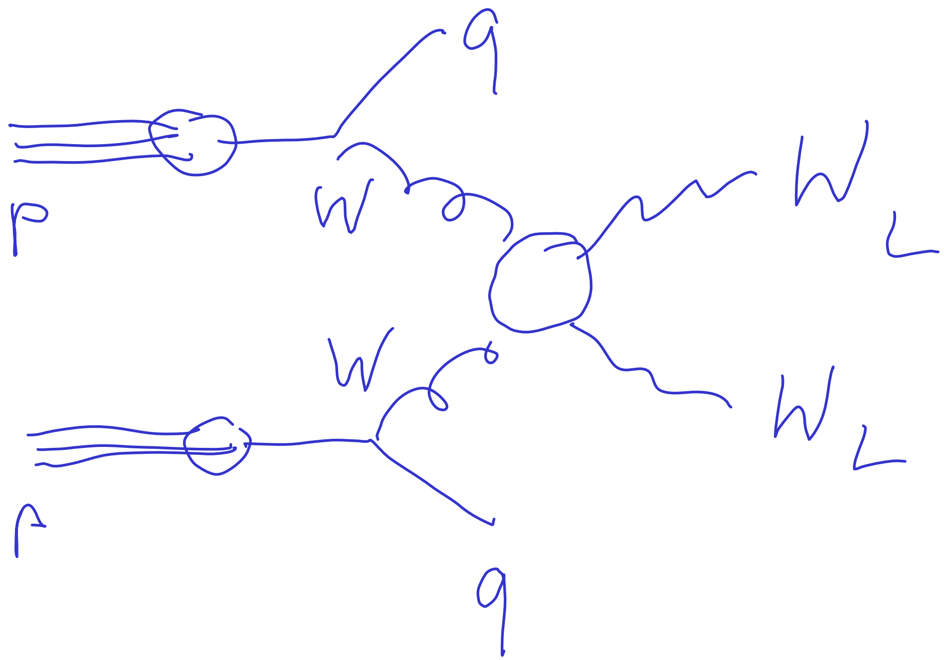
> If the unitarity restoration is delayed to some scale M, the rise of the $\sigma(W_L W_L)$ with energy in the range $m_W \ll \sqrt{s} \ll M$ should be seen

$V_L V_L$ scattering on the shopping list of LHC experiments

Not an easy task:

- we do not have W beams

At the LHC



Not an easy task:

- large irreducible background from $V_L V_T, \; V_T V_T$
- final W decays, no polarisation measurement on event basis
- many sources of reducible background, e.g. $t\bar{t} \to WWb\bar{b}$

Many analyses in past decades:

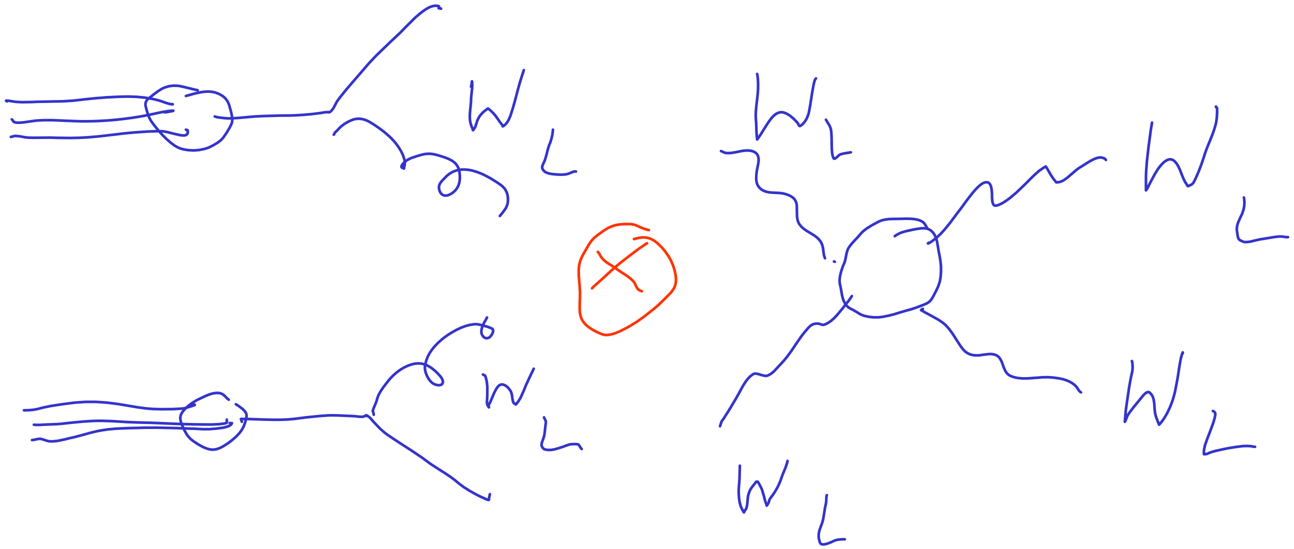
Lee Quigg Thacker '77, Chanowitz, Gaillard 85
Cahn ea, '87, Casalbuoni ea, '85, Gunion ea, '86-89
Dicus, Repko '86, Bagger ea, '93-95, Dobado ea, '95-'99
Butterworth ea, '02-'08, Ballestrero ea, '06-09
Giudice ea, '07, Contino ea, '10,
ATLAS and CMS notes, and many many more

- difficult to select $V_L V_L \to V_L V_L$
- analysed mostly in the context of resonances restoring unitarity:
  scalars, vectors, elementary, composite etc.

- other scenarios, like non-resonant mechanisms, received less attention
- possible improvements in theoretical understanding of mechanisms of enhancing the flux of V_L

Effective W-boson Approximation (EWA)

Cahn, Dawson ’84, Dawson ’84,
Kane Repko Golnik ’84, Lindfors ‘85



$$\sigma \sim \int ds \;\; \mathcal{L}_{WW}(s) \;\; \frac{d\sigma(WW \to WW)}{ds}$$

- intrinsically small angle approximation
- for large WW invariant mass
- off-shell effects should become less relevant
- with delayed unitarity restoration, $V_L V_L \to V_L V_L$ should dominate

Anatomy of WW➔ WW: for $m_V^2 \ll s \ll M^2$

★ $$\mathcal{A}_T = \mathcal{A}(V_T V_T \to V_T V_T) \sim \mathcal{O}(1)$$

$$\mathcal{A}_L = \mathcal{A}(V_L V_L \to V_L V_L) \sim \; s/m_V^2$$

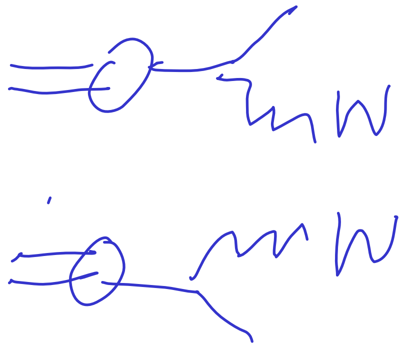
since $\mathcal{A}_T$ has Coulomb poles in forward dirrection, we expect

$$\frac{\sigma_{LL}(Q^2)}{\sigma_{TT}(Q^2)} \sim \frac{s\,Q^2}{m_W^4}$$

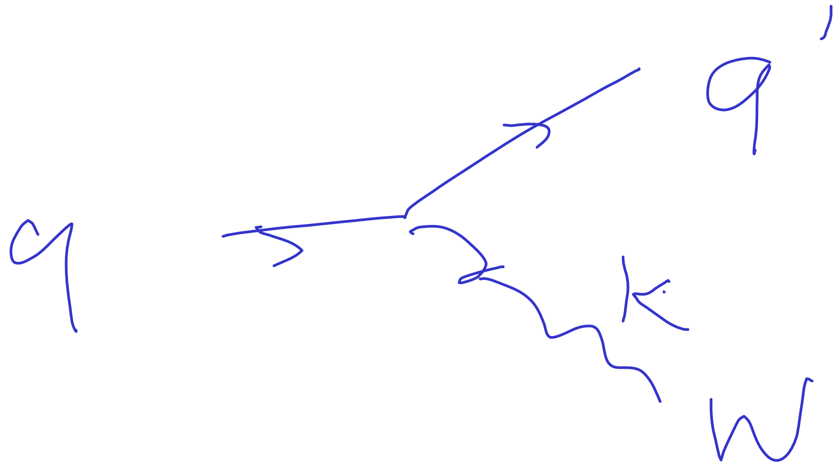
where $m_W^2 \ll Q^2 \ll s$ cuts out forward region

★ cross section weighted with the WW luminosity

$\mathcal{L}_{WW} \sim$



probability of radiating W



$$\mathcal{M}^i \sim \bar{u}(q')\,\gamma^\mu\, u(q)\, \epsilon^i_\mu(k)$$

$i = L, T$

probability

$$P^i \sim \int \frac{dk^2}{(k^2 - m_W^2)^2}\, |\mathcal{M}^i|^2$$

$$k^2 = (q-q')^2 \sim -EE'\theta'^2$$

- for transverse W like in QCD: $\sum_{i=T} |\mathcal{M}^i|^2 \sim \theta'^2$
- for longitudinal W: $|\mathcal{M}^L|^2 \sim 1$

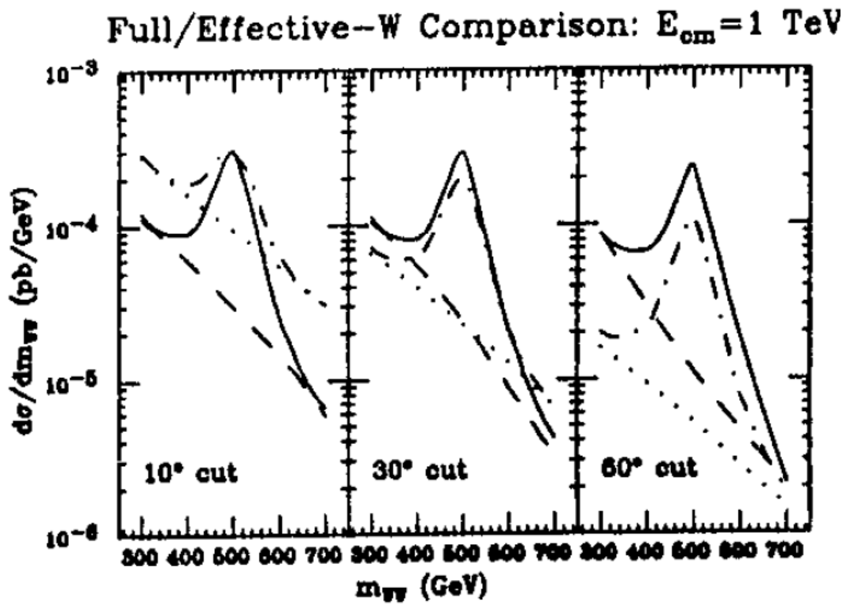
in the small angle approximation:

$$P^i = \int_0^{\theta_M} \frac{d\theta'^2}{\left(\theta'^2 + \frac{m_W^2}{EE'}\right)^2} \times \begin{cases} \theta'^2 ; & T \\ 1 ; & L \end{cases}$$

➔ longitudinal W collimated into a smaller forward angle than transverse

so tagging forward jets with relatively small p_T should enhance the content of W_L in data sample

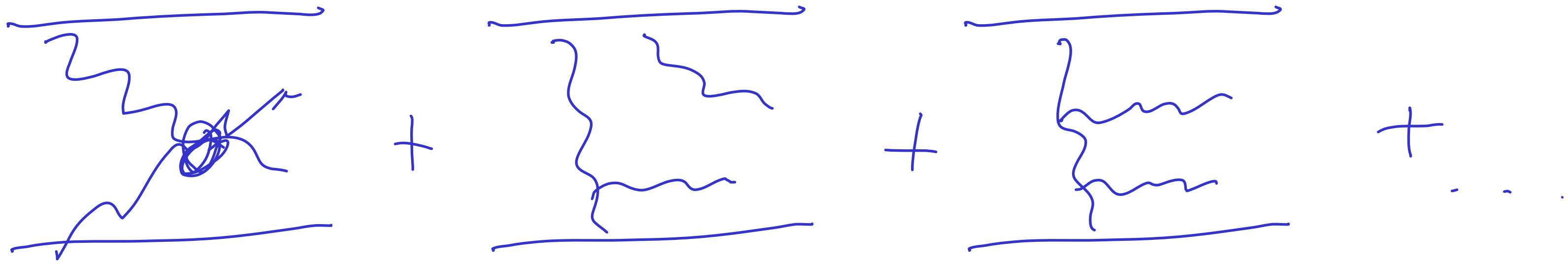
How good is EWA?



Gunion, Tofighi-Niaki, JK: 1986

- OK for Higgs resonance
- bad outside

Need to include full set of diagrams qq→ qqWW



separately diagrams are not gauge invariant

Diagrams	MadGraph	CompHEP Feynman gauge	CompHEP Unitary gauge
With WW scattering	12.29 +- 0.014 pb	0.0282 +- 0.7% pb	10.98 +- 0.2% pb
Non-scattering	12.36 +- 0.02 pb	0.132 +- 0.8% pb	11.01 +- 0.3% pb
Total	0.170 +- 0.001 pb	0.170 +- 0.4% pb	0.169 +- 1.1% pb

Conclusions and open questions:

- full set of diagrams is needed
- experimental analysis very difficult
- with the start up of LHC renewed interest

- to what extend the early LHC phase can provide answers
- concentrate on non-resonant scenarios
- investigate means of improving the flux of longitudinal V

Work started, preliminary results encouraging

as will be demonstared with simulations in the following