RESTORING GOOD HIGH ENERGY BEHAVIOUR IN HIGGS PRODUCTION VIA WW FUSION IN THE LHC

K. PHILIPPIDES and W. J. STIRLING

hep-ph / 9901451

to be published in Eur. J. Phys.

APPROXIMATIONS FOR TREE LEVEL MULTI-LEG CALCULATIONS IN GAUGE THEORIES

WARNING !!!

Do not even think of calculating a subset of graphs which is not gauge-invariant — T. Ohl

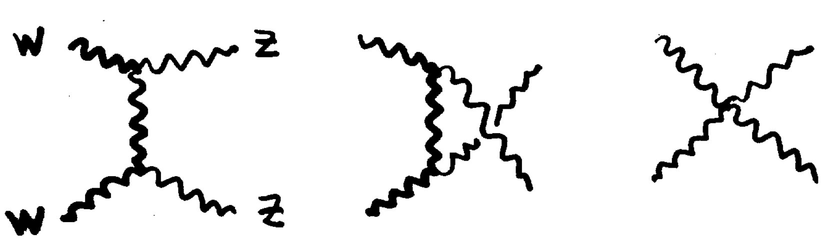
UNLESS

You have a method that controls gauge cancellations — K. Ph., J. Stirling

Approximations are desirable for:

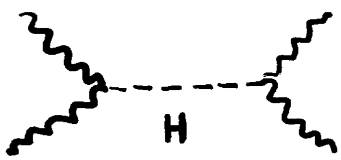
- Fast numerical codes
- Better control on long calculations

WW FUSION (ON SHELL)



$\Big\} \sim s$

$\sim s^2$ $\sim s^2$ $\sim s^2$

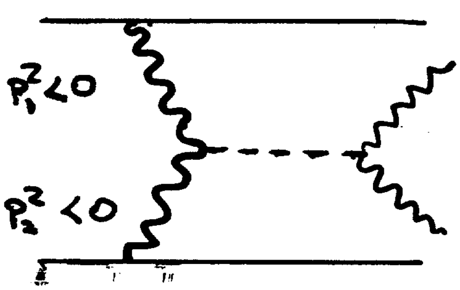


$\sim s$

DOMINANT PRODUCTION MECHANISM
FOR HEAVY HIGGS ($M_H > 2M_Z$)
AND/OR HIGH ENERGIES

REALISTICALLY (OFF SHELL)

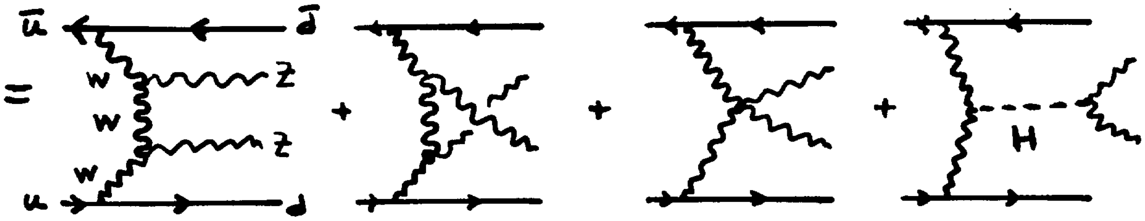
$$q_1\, q_2 \rightarrow q_1'\, q_2'\; W^*\, W^* \longrightarrow q_1'\, q_2'\; Z\, Z$$



Resonant
Higgs

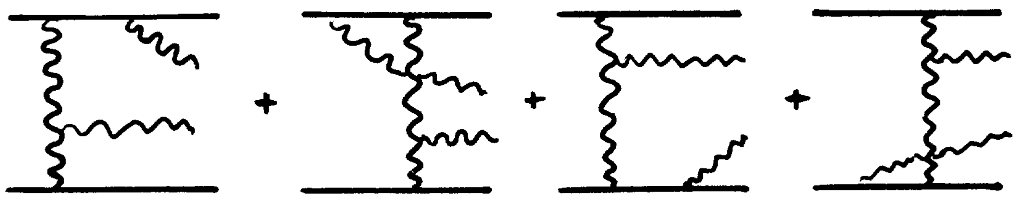
$qq \longrightarrow qq\,ZZ$

$T_{WW} =$



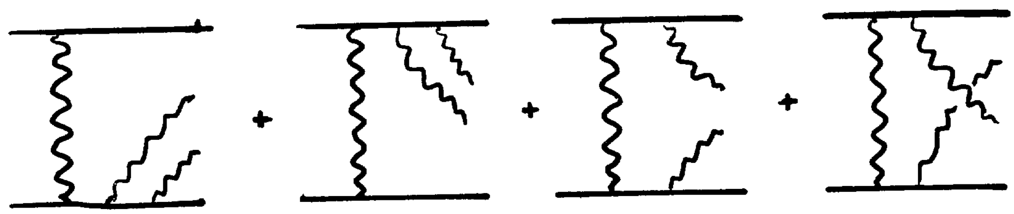
WW fusion (6)

$T_{Wf} =$



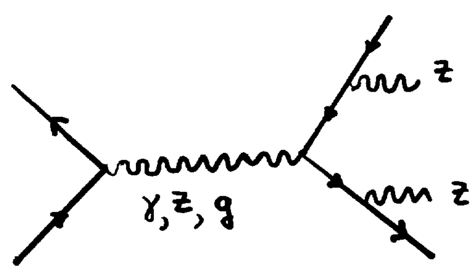
+ crossed (8)

$T_{ff} =$



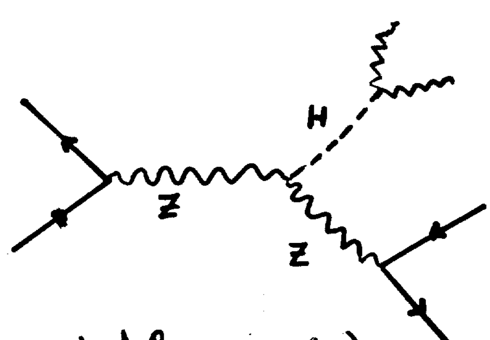
+ permutations (20)

$S_{\gamma,Z,g} =$



(20) + (20) + (20)

$S_{ZH} =$

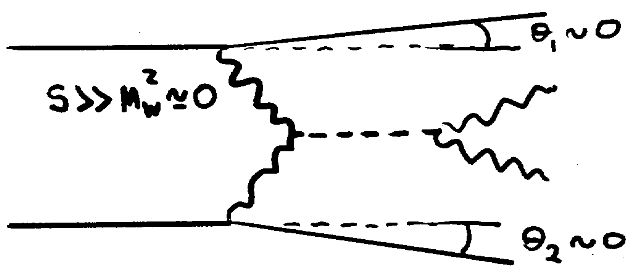


Higgs-strahlung (3)

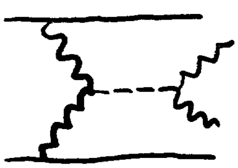
EXISTING APPROXIMATION

- **EFFECTIVE W APPROXIMATION**

  i. Higgs graph only
  ii. Quarks strictly forward
  iii. Ws practically massles and thus closely on-shell : $s \gg M_{WW}^2 \gg M_W^2$



- **FULL HIGGS GRAPH ONLY FAILS**

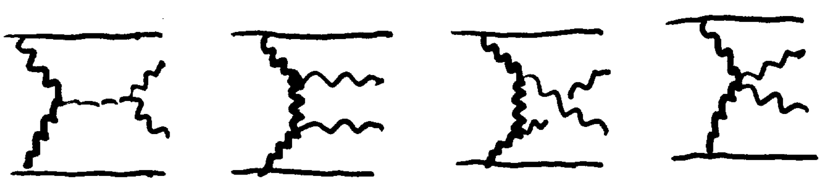


$= T_H$

$$d\sigma = \frac{1}{2s} |T_H|^2 \cdot \frac{1}{2} d\Phi_4$$

$$\sigma \sim s$$

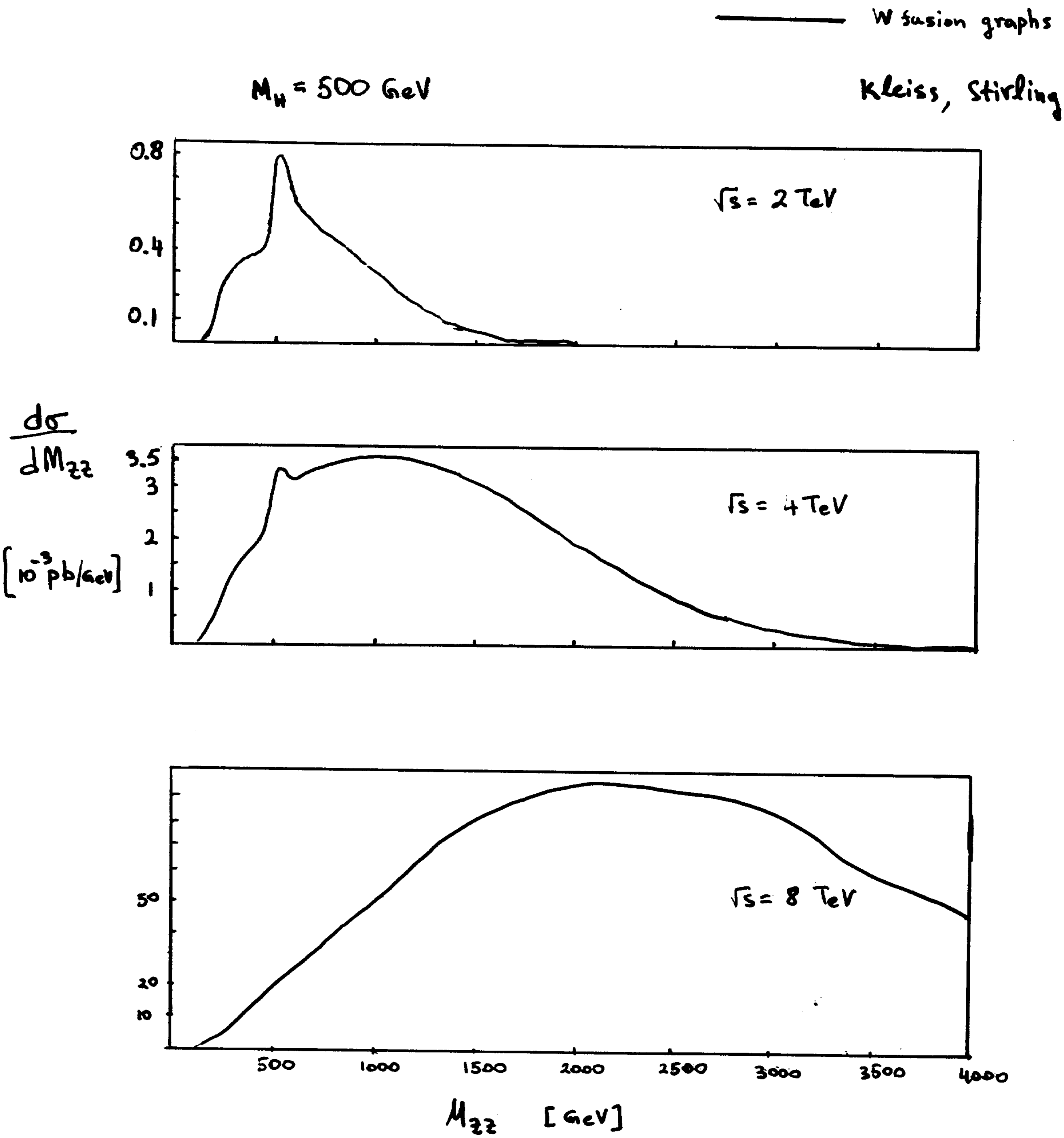
- **W FUSION GRAPHS FAIL OFF SHELL**

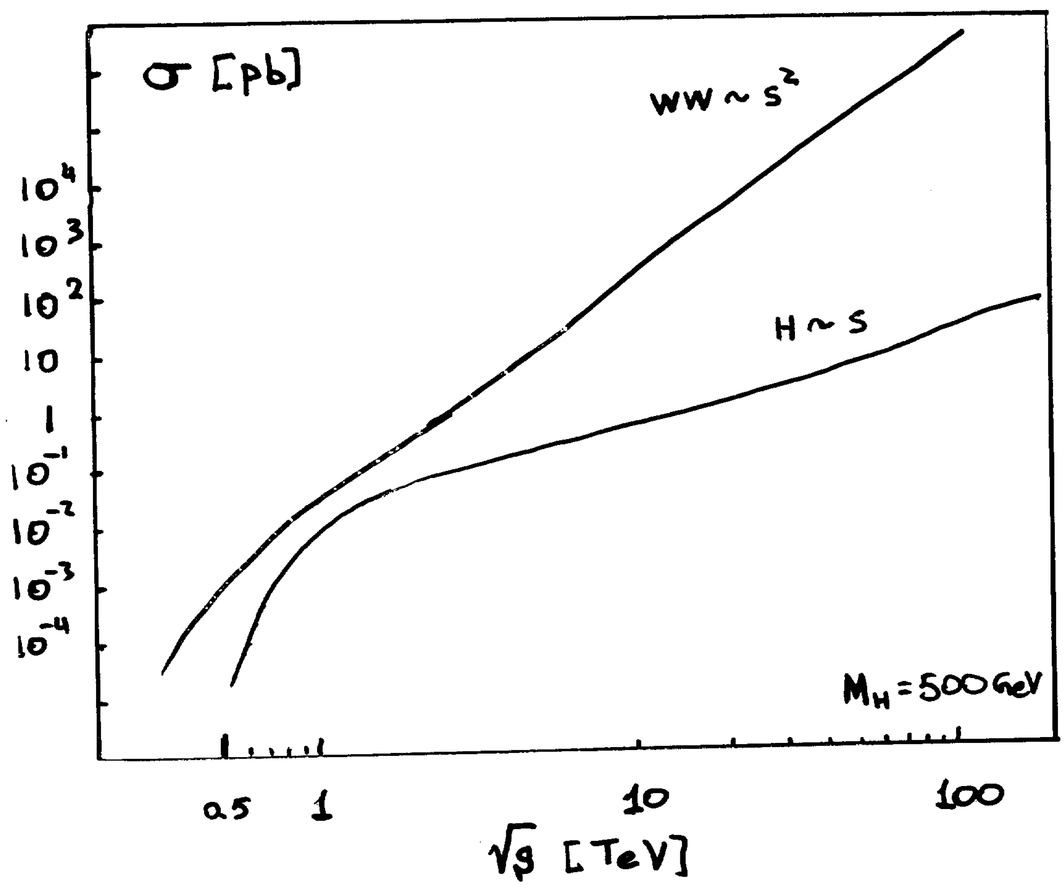


$= T_{WW}$

$$\sigma \sim s^2$$

$qq \to qqZZ$


W fusion graphs
$M_H = 500$ GeV
Kleiss, Stirling
0.8
0.4
0.1
$\sqrt{s} = 2$ TeV
$\frac{d\sigma}{dM_{ZZ}}$
[10^{-3} pb/GeV]
3.5
3
2
1
$\sqrt{s} = 4$ TeV
50
20
10
$\sqrt{s} = 8$ TeV
500
1000
1500
2000
2500
3000
3500
4000
M_{ZZ} [GeV]



σ [pb]
WW ~ s²
H ~ s
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
M_H = 500 GeV
0.5
1
10
100
√s [TeV]

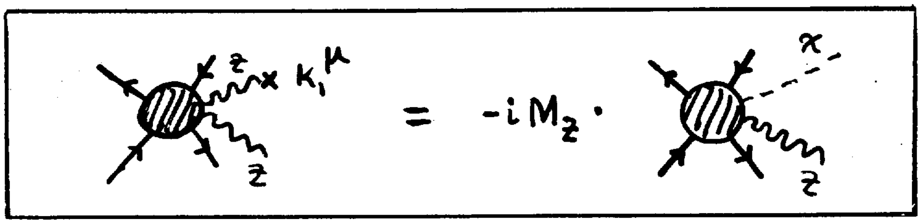
Gauge invariant

subsets of graphs

$$A = \Big[(T_{WW}) + T_{Wf} + T_{ff} \Big] + \big[S_{\gamma} \big] + \big[S_{Z} \big] + \big[S_{g} \big] + \big[S_{ZH} \big]$$

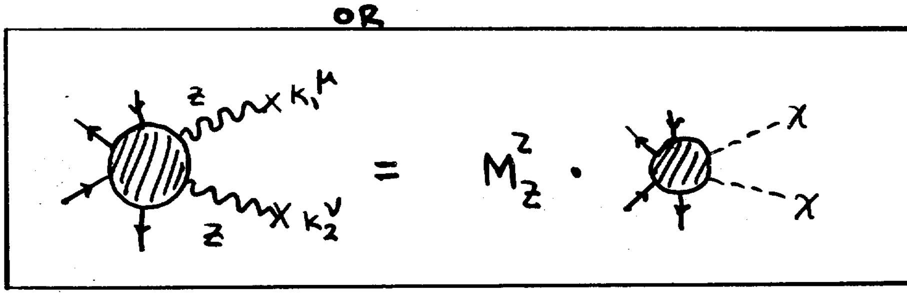
$[\ldots]$: i) gauge parameter independent

ii) satisfy Ward identity



$$k_1^{\mu} \cdot T^{\mu}_{(Z)} = -iM_Z \cdot \mathcal{T}(\chi)$$

OR



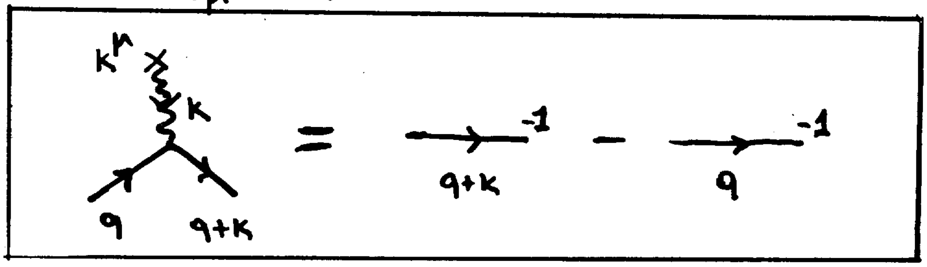
$$k_1^{\mu} k_2^{\nu} T^{\mu\nu}_{(ZZ)} = M_Z^2 \, \mathcal{T}(\chi\chi)$$

BUT

$$k_1^{\mu} T_{WW}^{(Z)} \neq -iM_Z \, \mathcal{T}_{WW}(\chi)$$

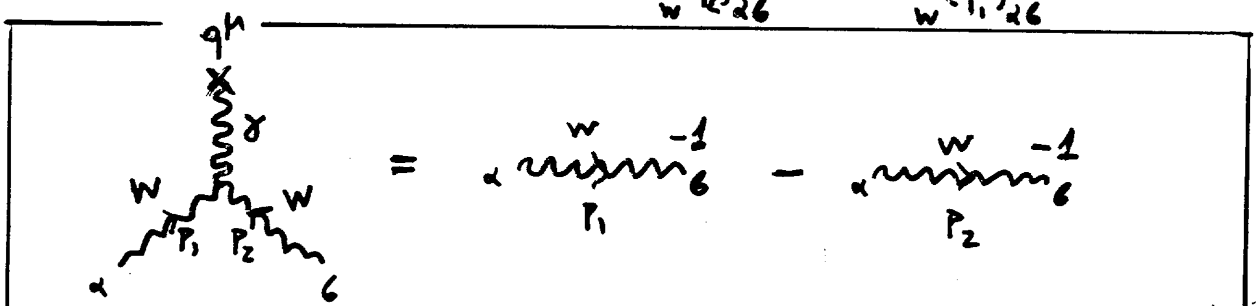
The Ward identity for the physical amplitude (set of graphs) is a direct consequence of the Ward identities satisfied by the tree level vertices of the theory (classical gauge invariance).

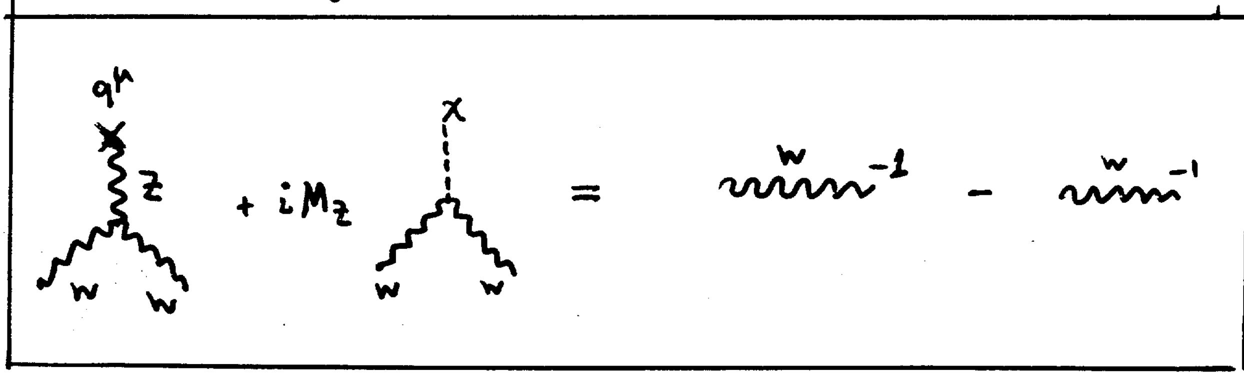
$$K^\mu \gamma_\mu = \not{K} = (\not{K} + \not{q}) - \not{q} = S^{-1}(K+q) - S^{-1}(q)$$



$$q^\mu \Gamma_{\mu\alpha\beta}(q, P_1, P_2) = \left[P_2^2 g_{\alpha\beta} - P_{2\alpha} P_{2\beta}\right] - \left[P_1^2 g_{\alpha\beta} - P_{1\alpha} P_{2\beta}\right]$$

$$= U_W^{-1}(P_2)_{\alpha\beta} - U_W^{-1}(P_1)_{\alpha\beta}$$





$$\overline{|A|^2} = \overline{|T_{ww}|^2} + \overline{|T_{wf}+T_{ff}|^2} + 2\overline{Re}\left[T_{ww}(T_{wf}+T_{ff})\right] + \dots$$

$$= \overline{|T|^2_{ww}} - \not{O}_1 + \overline{|T_{wf}+T_{ff}|^2} + \not{O}_2 + 2Re[\dots] + \not{O}_3 + \dots$$

$$= (T_{ww}+T_{wf}+T_{ff})^{\mu\nu}\left[-g^{\mu\mu'} + \frac{k_1^{\mu}k_1^{\mu'}}{\underline{M_Z^2}}\right]\left[-g^{\nu\nu'} + \frac{k_2^{\nu}k_2^{\nu'}}{\underline{M_Z^2}}\right](T_{ww}+T_{wf}+T_{ff})^{*}_{\mu'\nu'} + \dots$$

Communication between seemingly different graphs is made possible because of the presence of momentum factors on the numerators due to :

i) trilinear gauge boson vertices

ii) longitudinal Z bosons

$$\varepsilon_Z^{\mu}(k_1) = \frac{k_1^{\mu}}{M_Z} + O(M_Z/E_Z)$$

The off-shell unitarity violating terms O_i are identified, in a well defined way, and are shown to cancell,

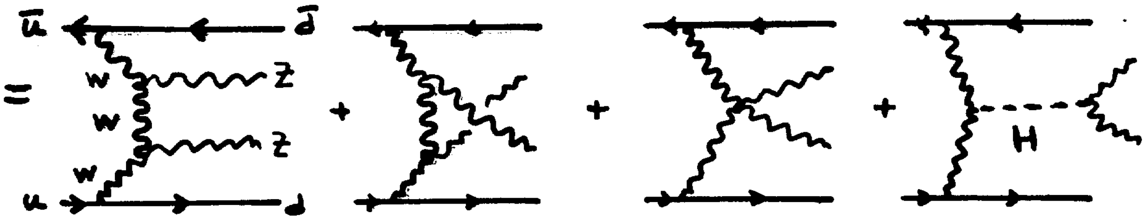
by using the tree level Ward identities

triggered by the momenta in i) and ii)

TREE LEVEL PINCH TECHNIQUE : de Rafael
Papavassiliou
Watson
...

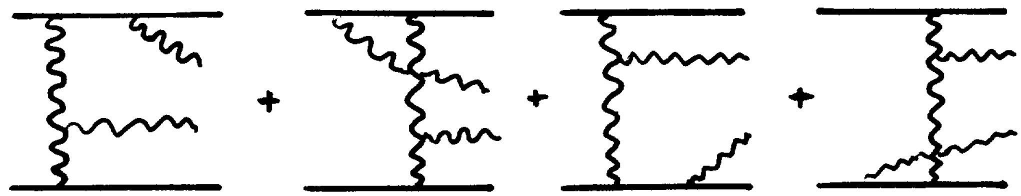
$qq \longrightarrow qq\,ZZ$

$T_{WW} =$



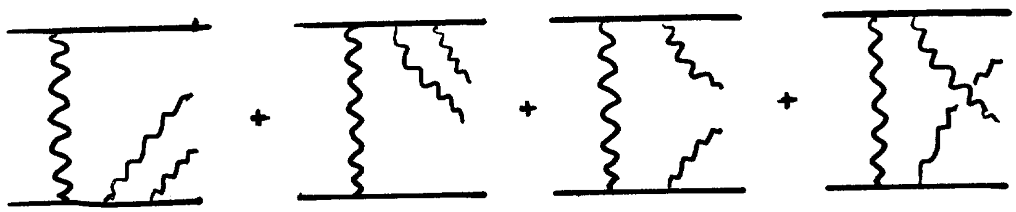
WW fusion (6) SIGNAL

$T_{Wf} =$



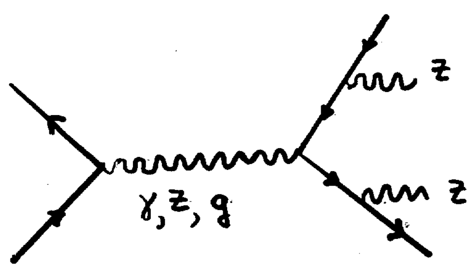
+ crossed (8)

$T_{ff} =$



+ permutations (20)

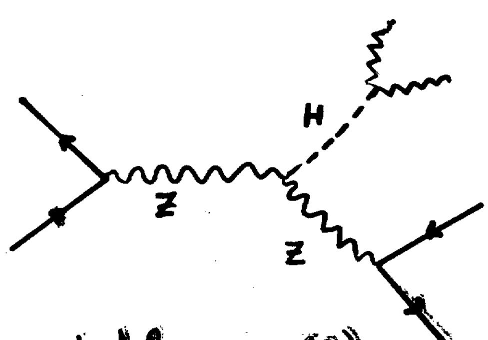
$S_{\gamma,Z,g} =$



(20) + (20) + (20)

BACKGROUND

$S_{ZH} =$



Higgs-strahlung (3)

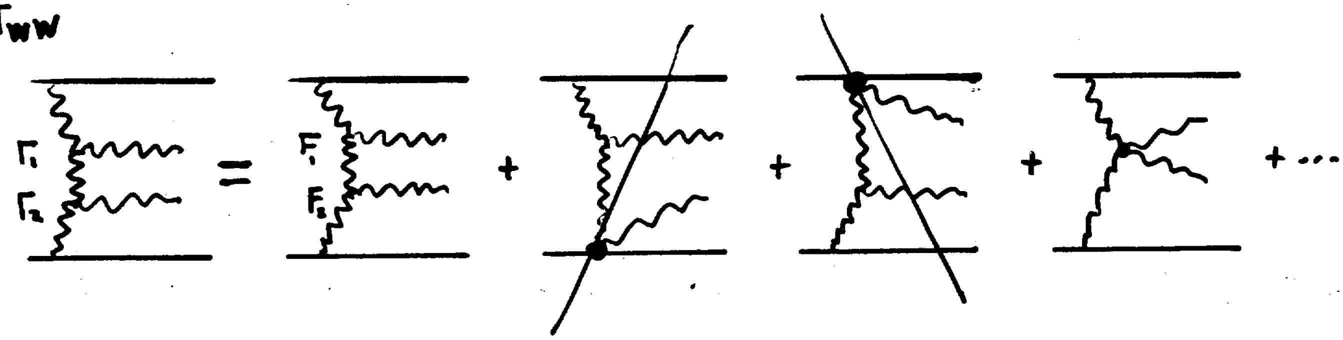
The 1st Cancelation

Trilinear Vertices

$$\varepsilon_2^\mu \varepsilon_1^\nu T^{\mu\nu} = \left(T_{ww} + T_{wf} + T_{ff} \right)^{\mu\nu} \varepsilon_1^\mu \varepsilon_2^\nu$$

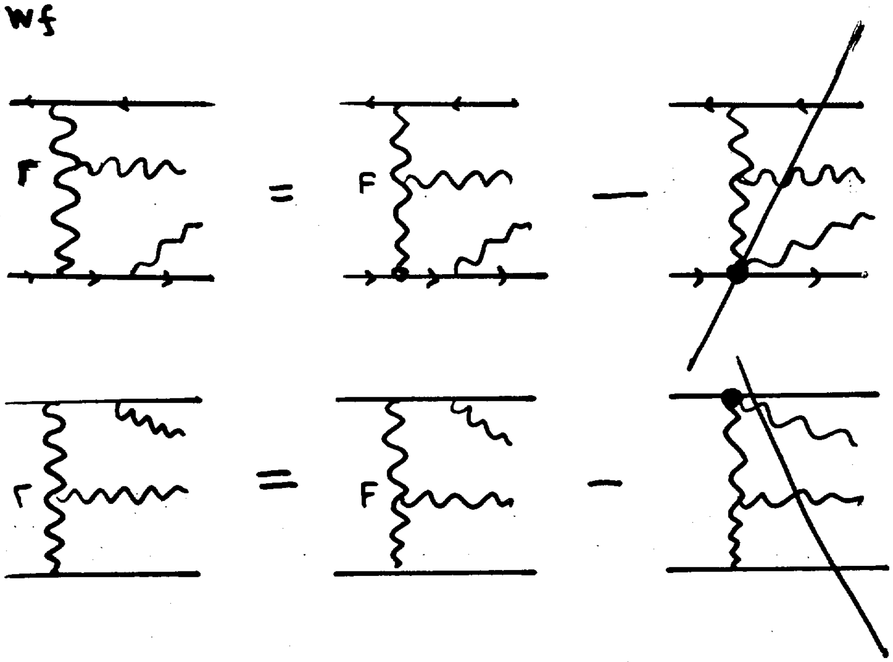
$$= \left(T^F_{ww} + \cancel{T^P_{ww}} + T^F_{wf} + \cancel{T^P_{wf}} + T_{ff} \right)^{\mu\nu} \varepsilon_1^\mu \varepsilon_2^\nu$$

T_{ww}



$$\Gamma_1 \;\Gamma_2 = \Gamma_1^F \Gamma_1^F + \Gamma_1^P \Gamma_2 + \Gamma_1 \Gamma_2^P - \Gamma_1^P \Gamma_2^P$$

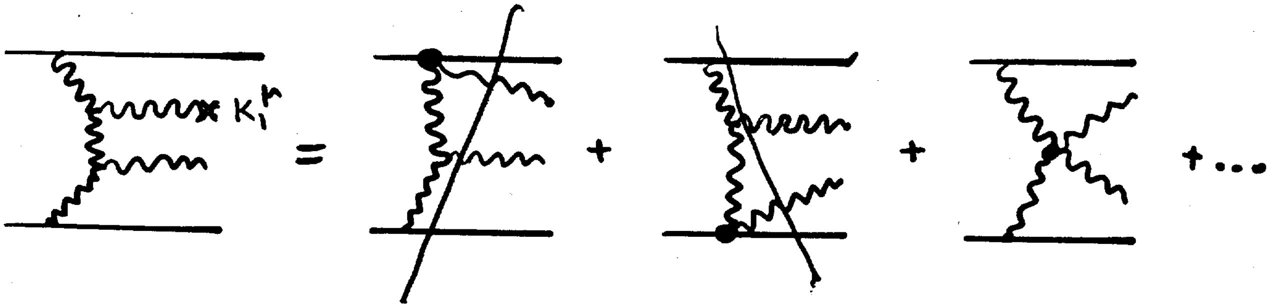
T_{wf}



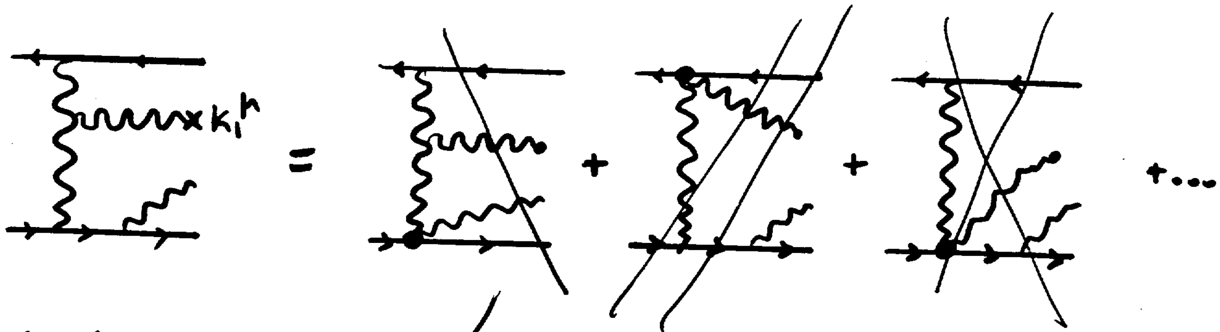
$$\Gamma = \Gamma^F + \Gamma^P$$

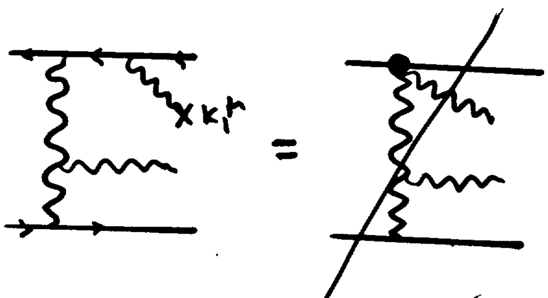
THE 2nd CANCELATION

T_{ww} :

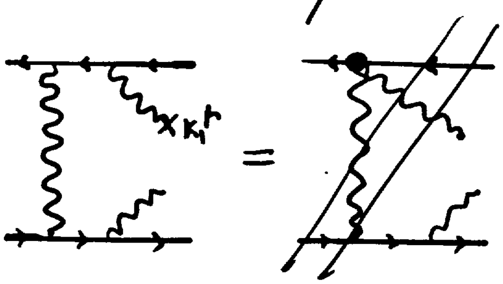


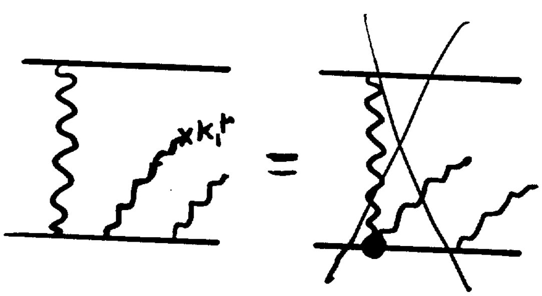
T_{wf} :





T_{ff} :





2nd Cancellation

$$\overline{|T|^2} = \left(T^F_{WW} + T^F_{Wf} + T_{ff}\right)^{\mu\nu}\left[-g^{\mu\mu'} + \frac{k_1^\mu k_1^{\mu'}}{M_Z^2}\right]\left[-g^{\nu\nu'} + \frac{k_2^\nu k_2^{\nu'}}{M_Z^2}\right]\left(T^{*F}_{WW} + T^{*F}_{Wf} + T^*_{ff}\right)^{\mu'\nu'}$$

$$k_1^\mu \cdot T^{\mu\nu}_{WW} = M_Z^2 \cdot A_1^\nu - 2c_W^2 F_1 \cdot k_2^\nu + M_Z^2 H \cdot k_1^\nu + c_W^2 \phi_1^\nu$$

$$k_1^\mu \cdot T^{\mu\nu}_{Wf} = M_Z^2 R_1^\nu - c_W^2 \phi_1^\nu + X^\nu$$

$$k_1^\mu \cdot T^{\mu\nu}_{ff} = -X^\nu$$

similarly with $k_2^\nu T^{\mu\nu}$ $\quad k_2^\nu k_1^\mu T^{\mu\nu}$

3rd Cancelation

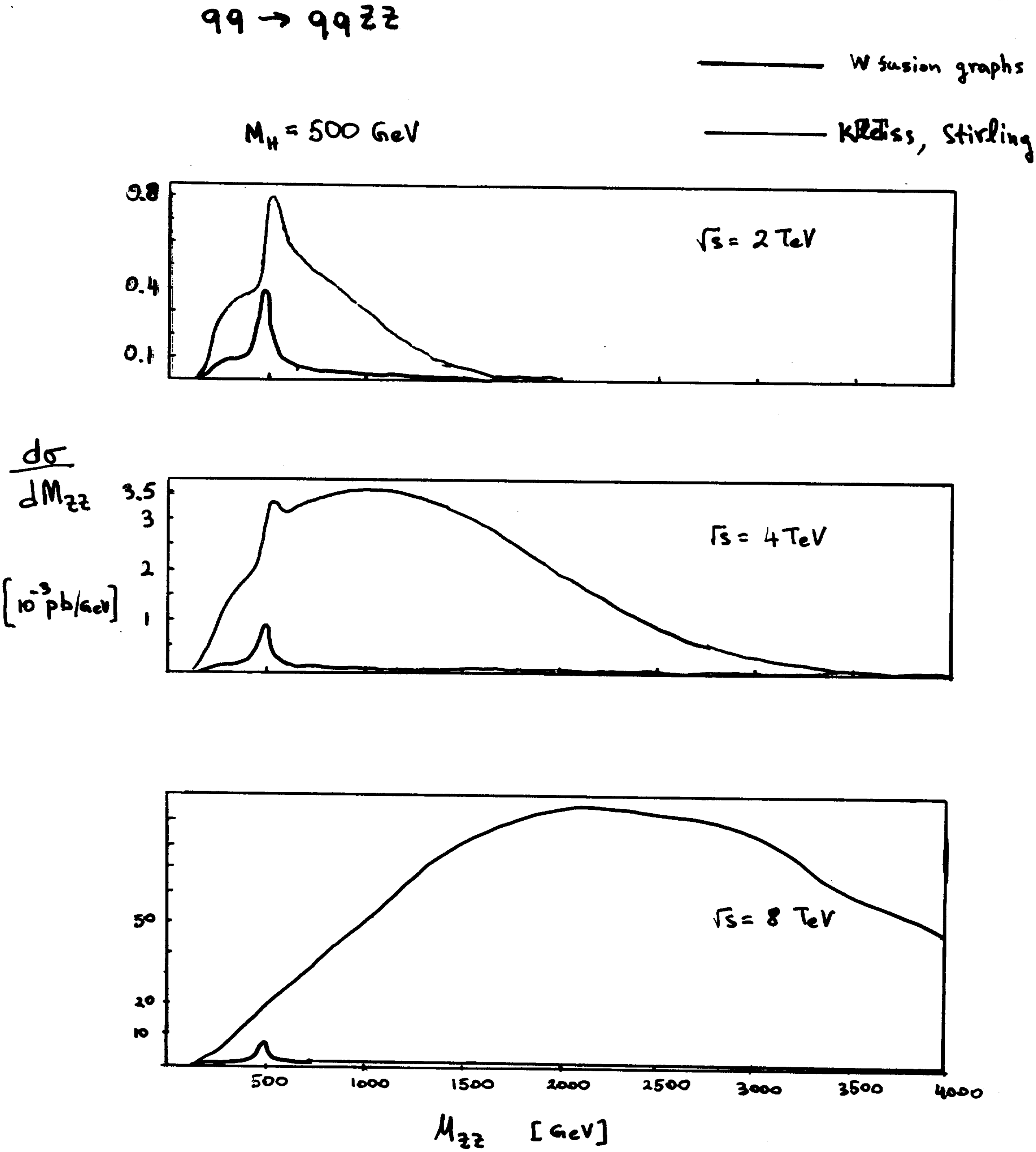
$$\overline{|T|^2} = \left(T^F_{WW}\right)^{\mu\nu}\left(T^{*F}_{WW}\right)_{\mu\nu}$$

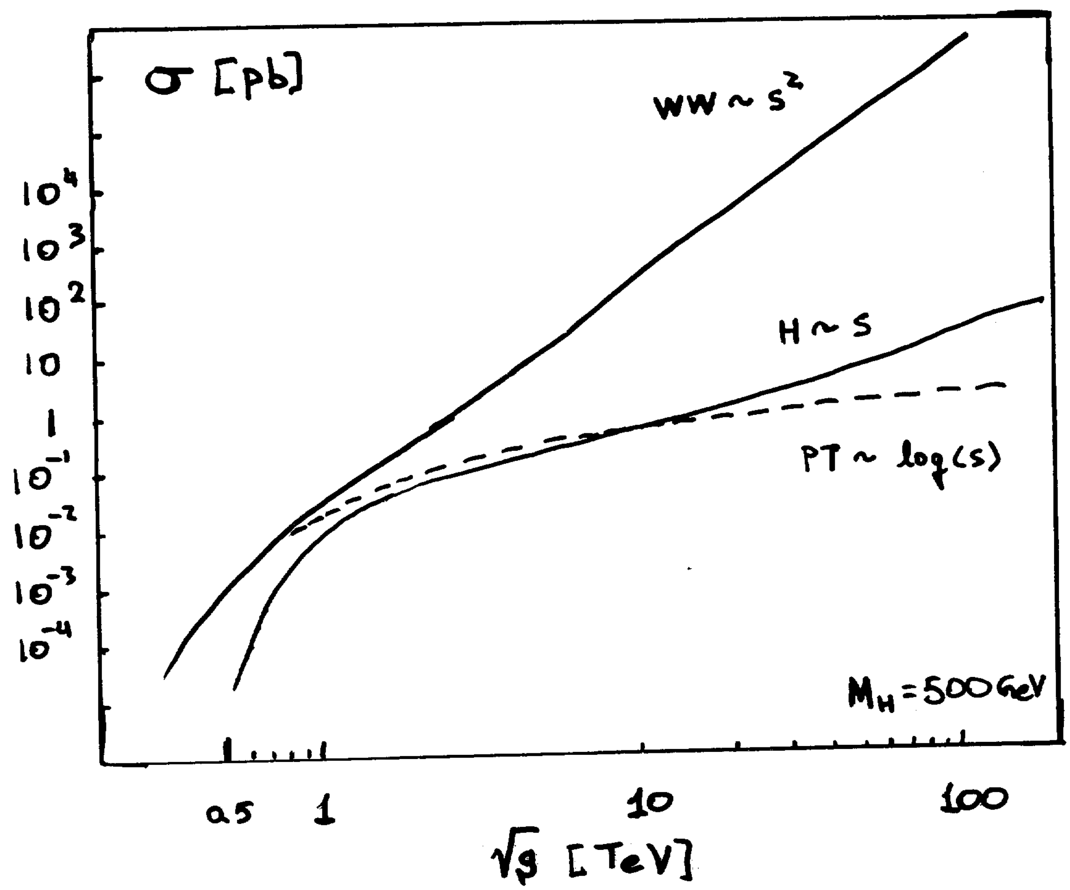
$$-\frac{1}{M_Z^2}\left[M_Z^2 A_1^\nu - 2c_W^2 F_1 \cdot k_2^\nu + M_Z^2 H \cdot k_1^\nu + M_Z^2 R_1^\nu\right]\left[M_Z^2 \cdot A_1^\nu - 2c_W^2 F_1 \cdot k_2^\nu + M_Z^2 H \cdot k_1^\nu + M_Z^2 R_1^\nu\right]$$

$$-\frac{1}{M_Z^2}\left[\;\cdots\;\right]^\mu\left[\;\right]_\mu + \frac{1}{M_Z^4}\left[\;\right]\left[\;\right]$$

$$\Rightarrow \overline{|T|^2} = \overline{|T|^2_{WW}} + \cdots$$

↑ No fermion propagators


qq → qqZZ
W fusion graphs
Kleiss, Stirling
M_H = 500 GeV
0.8
0.4
0.1
√s = 2 TeV
dσ/dM_ZZ
[10^-3 pb/GeV]
3.5
3
2
1
√s = 4 TeV
50
20
10
√s = 8 TeV
500
1000
1500
2000
2500
3000
3500
4000
M_ZZ [GeV]


σ [pb]
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
WW ~ s^2
H ~ s
PT ~ log(s)
M_H = 500 GeV
0.5
1
10
100
√s [TeV]

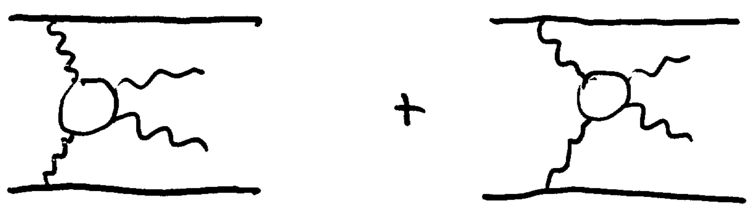
$pp \rightarrow ZZ + 2\text{jets} + X$

Baur
Glover

$$\sigma = \sum \int dx_1 dx_2 \, f_{q_1/p}(x_1, Q^2) \, f_{q_2/p}(x_2, Q^2) \, \hat{\sigma}(q_1 q_2 \rightarrow q_1' q_2' ZZ)$$

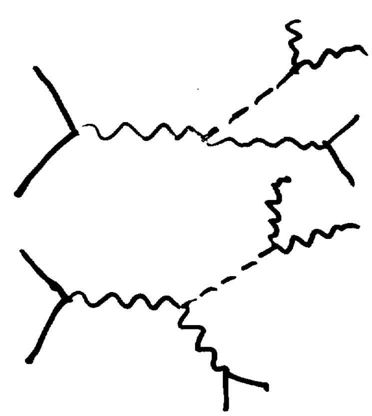
Observe Higgs as a resonance in LHC

To eliminate QCD background you must impose cuts on the jet activity so you must go beyond the effective W approx.



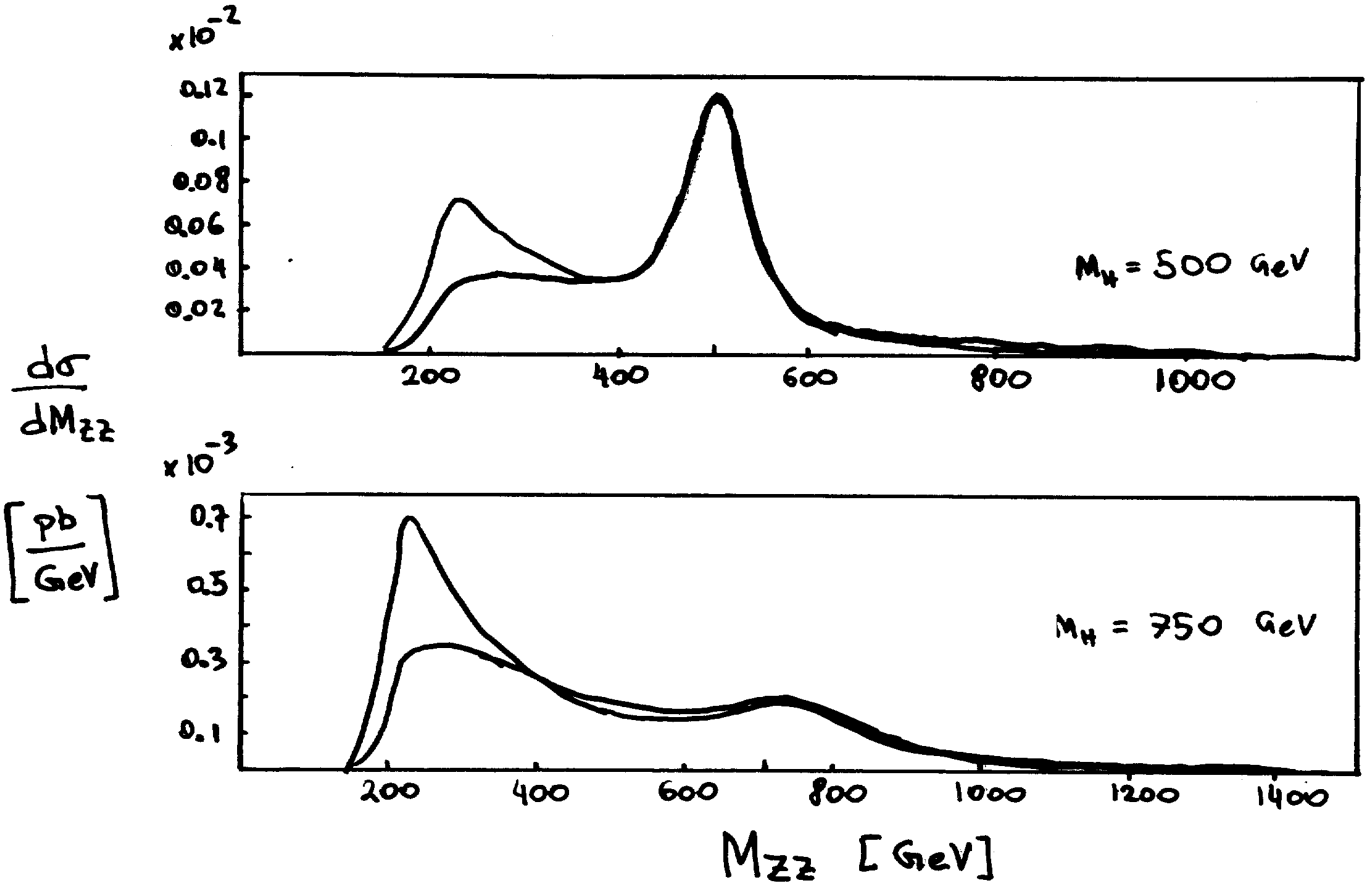
W-fusion   Z-fusion

Neglect even



$PP \longrightarrow ZZ + 2jets + X$

$\sqrt{s} = 14$ TeV (LHC)



——— Full set of EW graphs

——— PT approximation with W-fusion graphs only

$pp \to ZZ + 2\text{jets} + X$