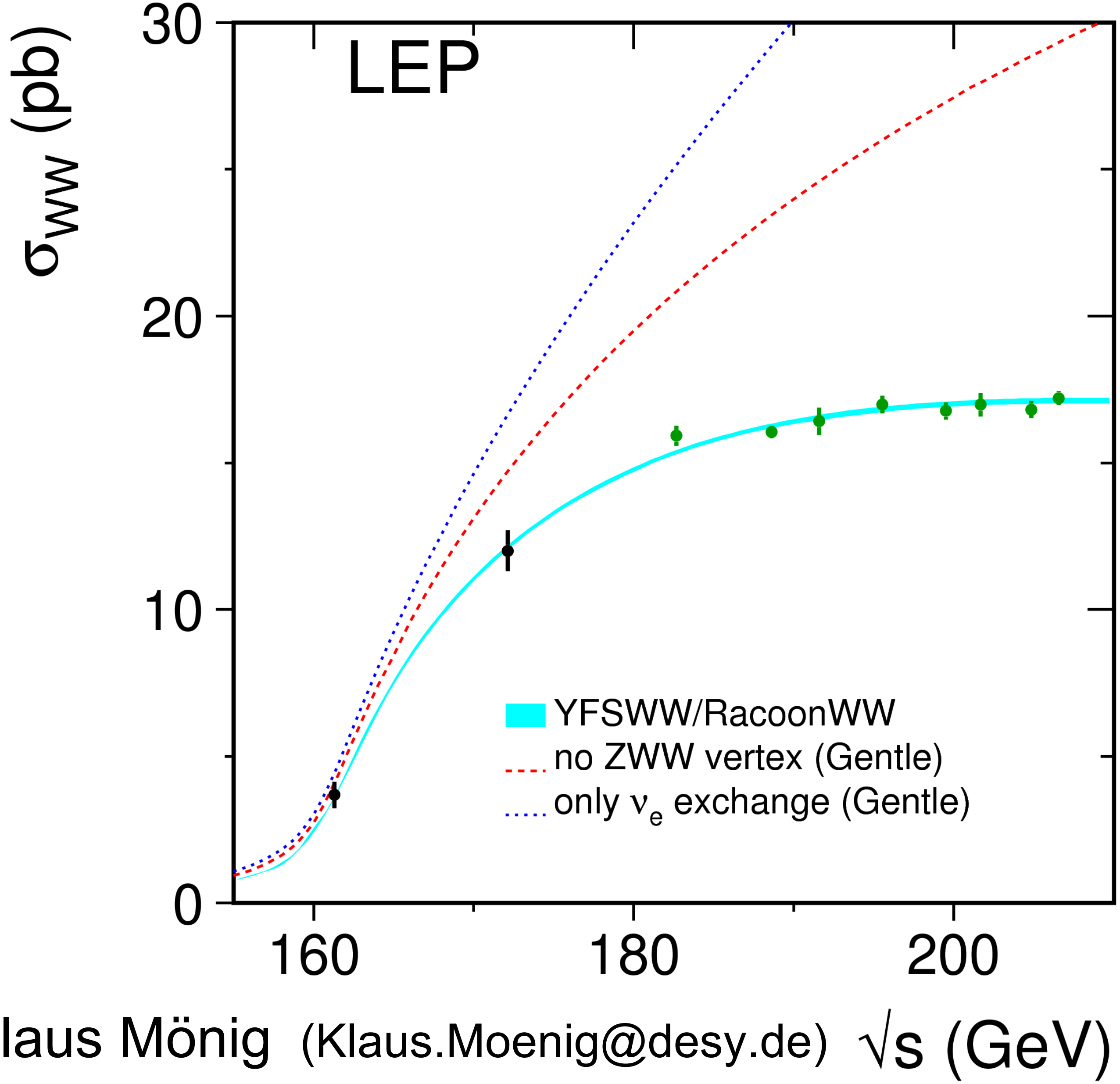
Electroweak Measurements



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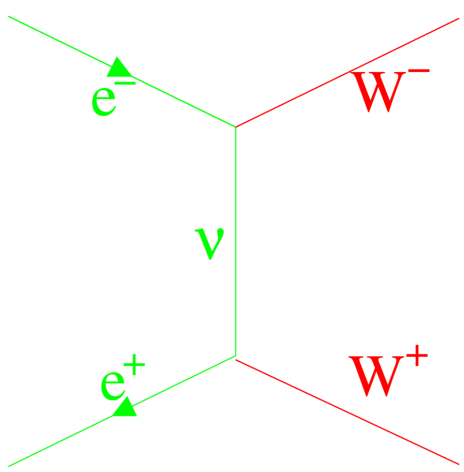
Outline

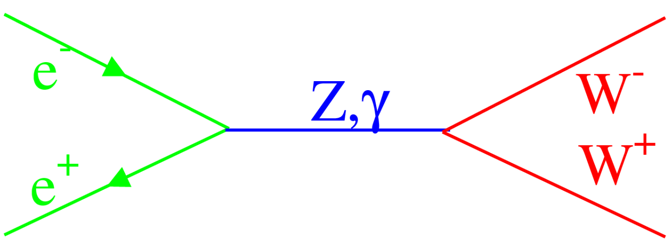
- Introduction
- Accelerators for electroweak physics
- Electroweak measurements at LEP and SLD
- Electroweak measurements at hadron colliders
- Electroweak measurements at HERA
- Electroweak fits
- Higgs boson production
- Gauge boson production and couplings

Gauge boson production and couplings

Gauge boson pair production

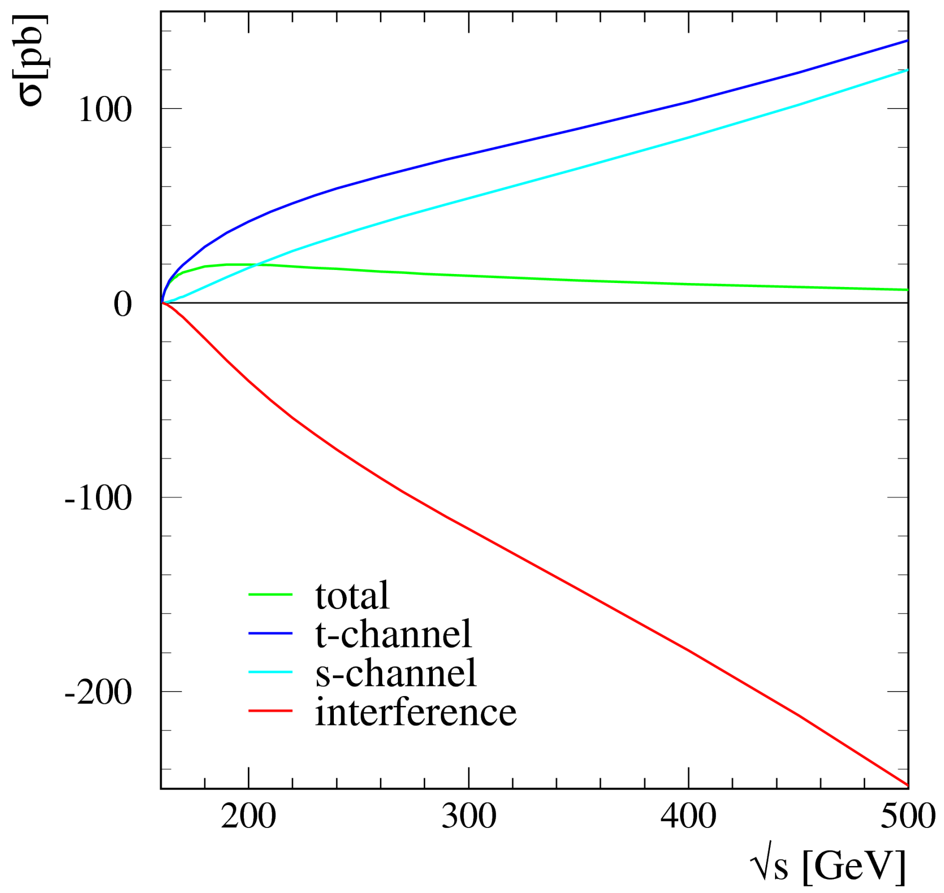
- W-pairs are produced by fermion t-channel and Z/γ s-channel exchange
- The latter involves gauge boson self-couplings predicted by a non-Abelien gauge theory
- Z-boson pairs are only produced via the t-channel and the SM contains no couplings among neutral gauge bosons





Gauge cancellations

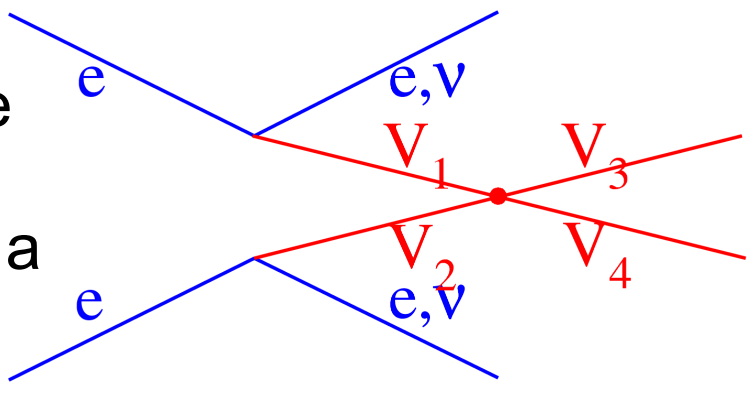
- For W-pair production the t- and s-channel violate unitarity individually
- The unitarity gets only restored by the interference term
- This means that the gauge couplings must asymptotically be exactly as predicted, otherwise the theory doesn't work



Vector boson scattering

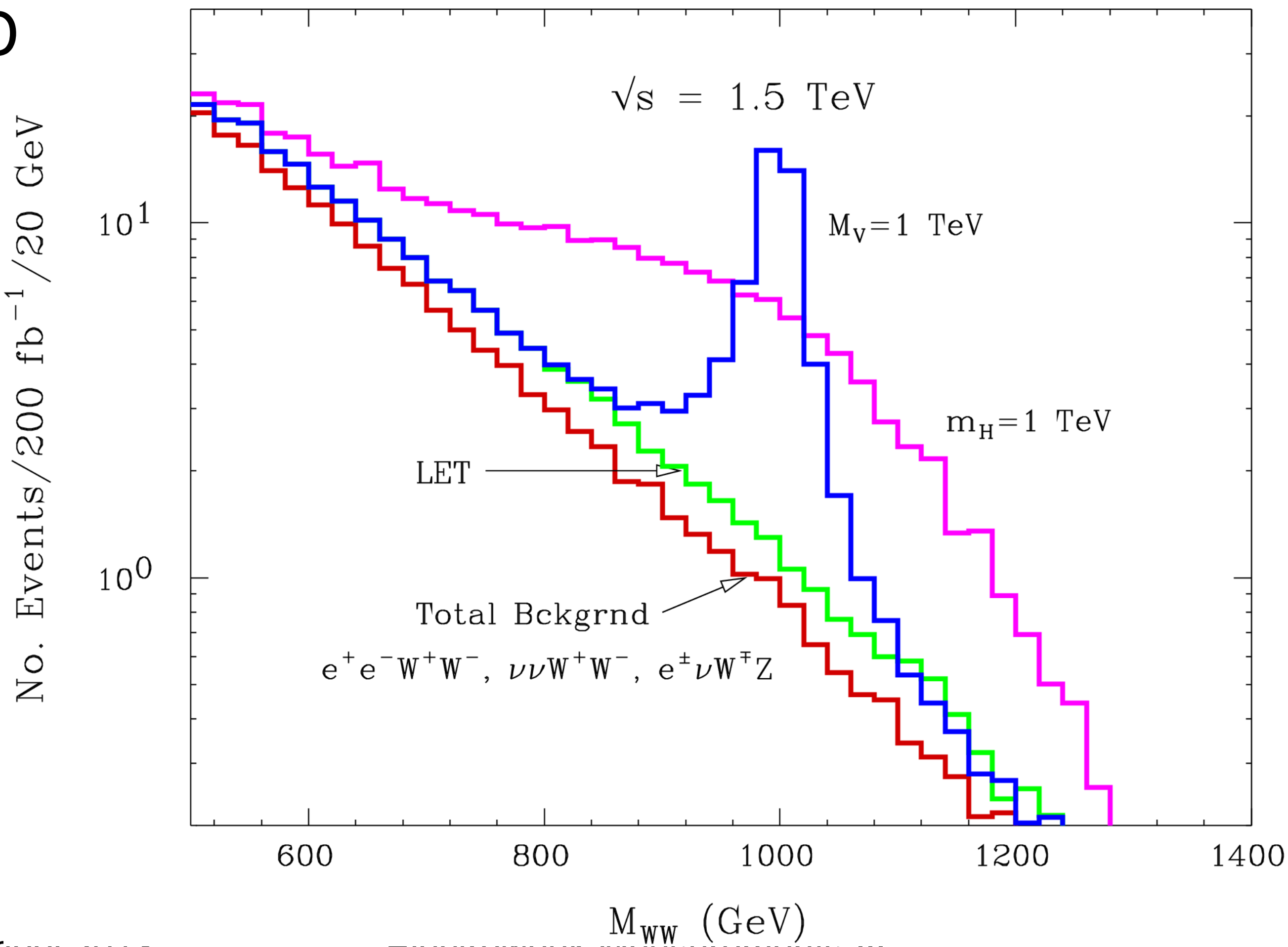
- Something similar happens in vector boson scattering
- This processes is mediated by gauge boson and Higgs s-, t-channel exchange
- Without a Higgs unitarity is violated at 1.2 TeV
- This either constraints VVH couplings or something else must restore unitarity

- This is only relevant for longitudinal gauge bosons, since the SM with massless gauge bosons and without the Higgs is a finite theory



Vector boson scattering (ii)

- If Higgs is non-standard expect deviations in vector boson scattering at high energy, including resonances, like in QCD



Triple gauge couplings

- The triple couplings are usually parametrised as

$$\mathcal{L} = g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu} \right) + \kappa_\upsilon W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}$$

+ more terms violating C,P... $V = \gamma, Z \qquad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

(em gauge invariance requires $\mathrm{g}_1^\gamma = 0$)

- Magnetic dipole moment

$$\mu_W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

- Electric quadrupole moment

$$q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

- SM:

$$g_1^V = \kappa_V = 1,\ \lambda_V = 0 \qquad \Delta x = x - 1$$

Triple gauge couplings (ii)

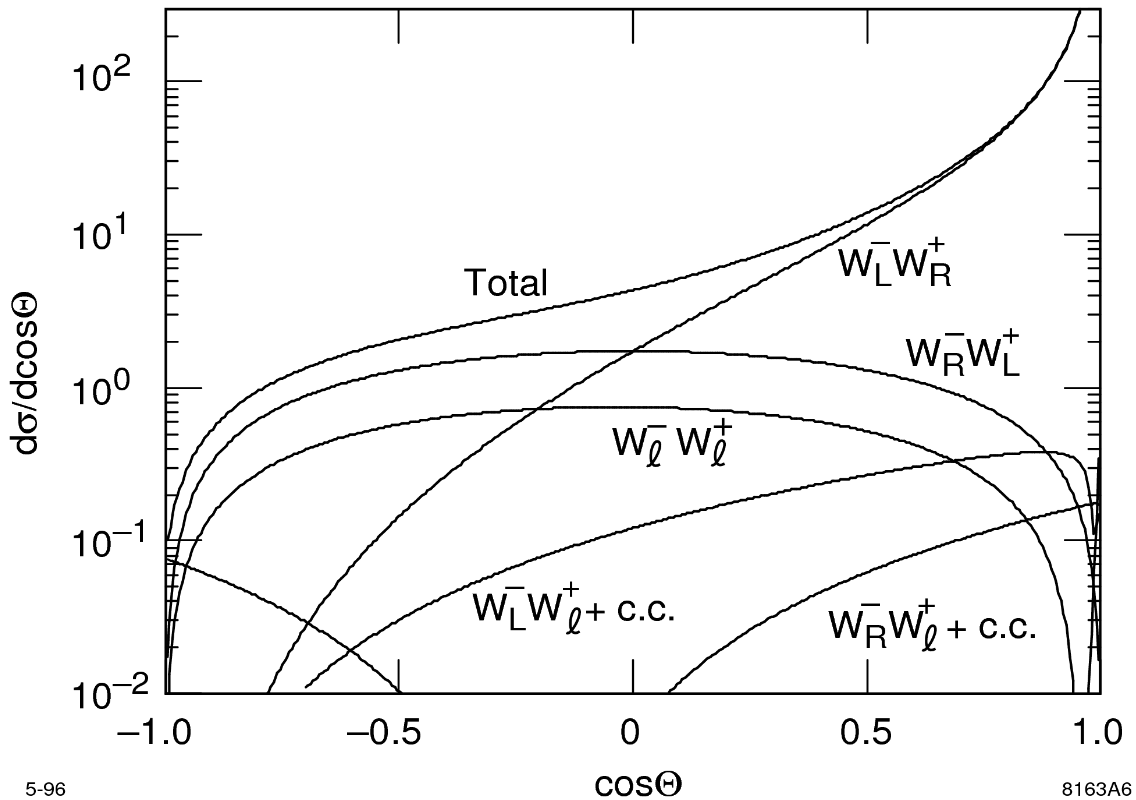
- Dimension 4 operators (g,κ) grow like √s
- Dimension 6 operators (λ) grow like s
- In analyses often regulated by form factor

$$x = \frac{x_{bare}}{\left(1 + \hat{s}/\Lambda^2\right)^n}$$

- In e^+e^- experiments with fixed √s results can be converted a posteriori
- In hadron colliders put Λ around centre of mass energy

Measurement of TGCs

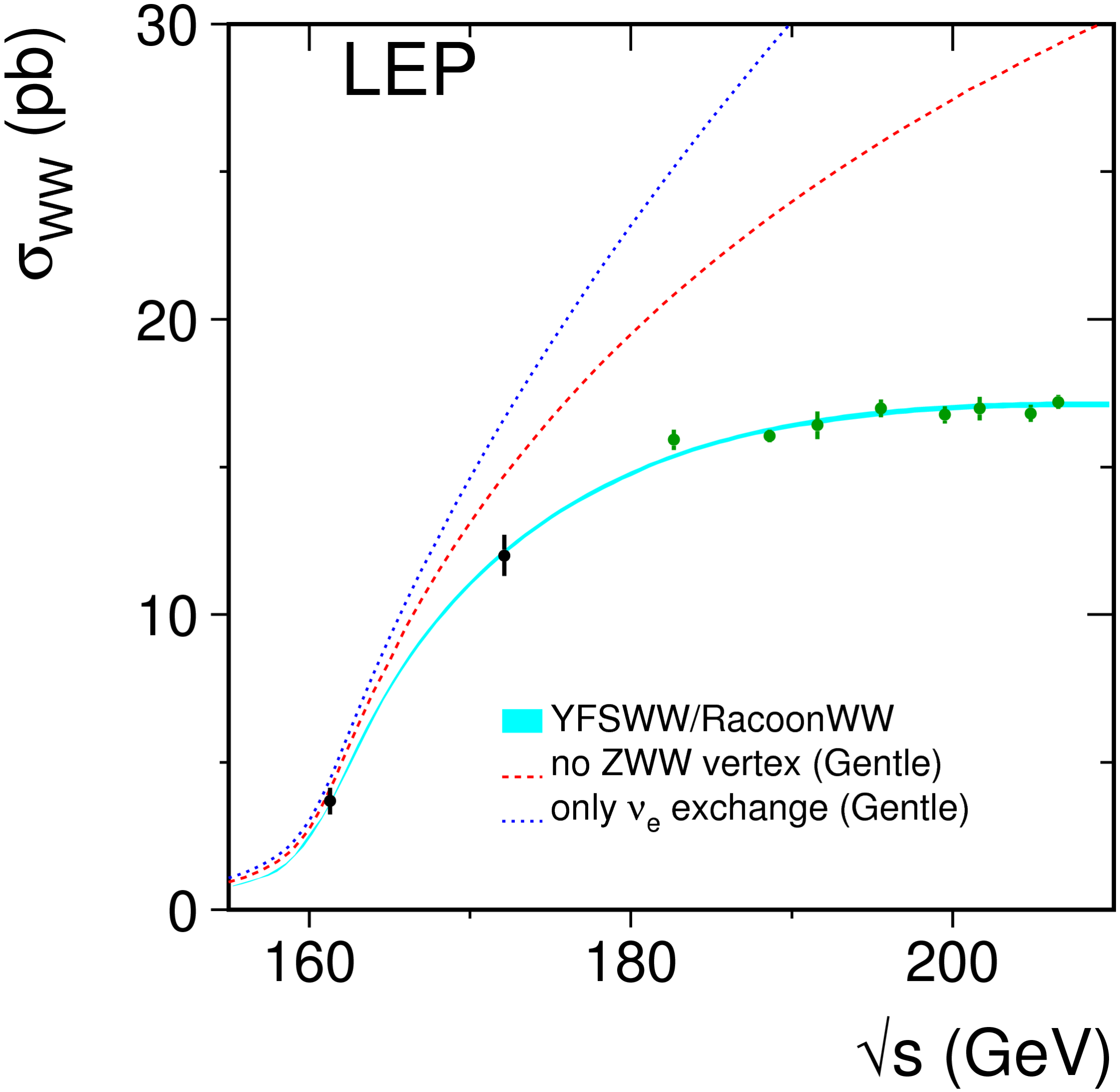
- The cross section is already very sensitive
- The W-production angle separates s- and t-channel
- The W-decay angles separate to the W-polarisation states



arxiv:1302.3415

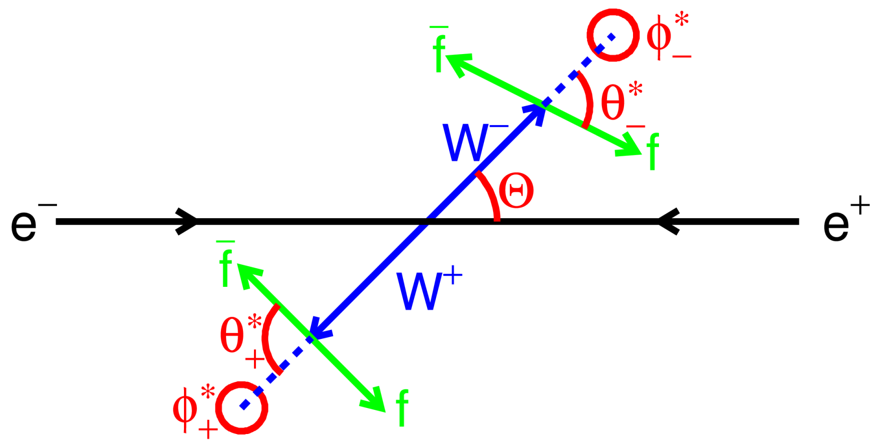
TGCs at LEP

- TGCs are measured in W-pair production
- The cross section proved that TGCs must be present
- Without beam polarisation WWγ and WWZ couplings cannot be separated
- Quantitative analyses add full event information



TGCs at LEP (ii)

- In semileptonic events the full information is available apart from the separation of the quark and the anti-quark
- The full polarisation state can be obtained from the decay angles apart from the polarisation direction of the hadronic W

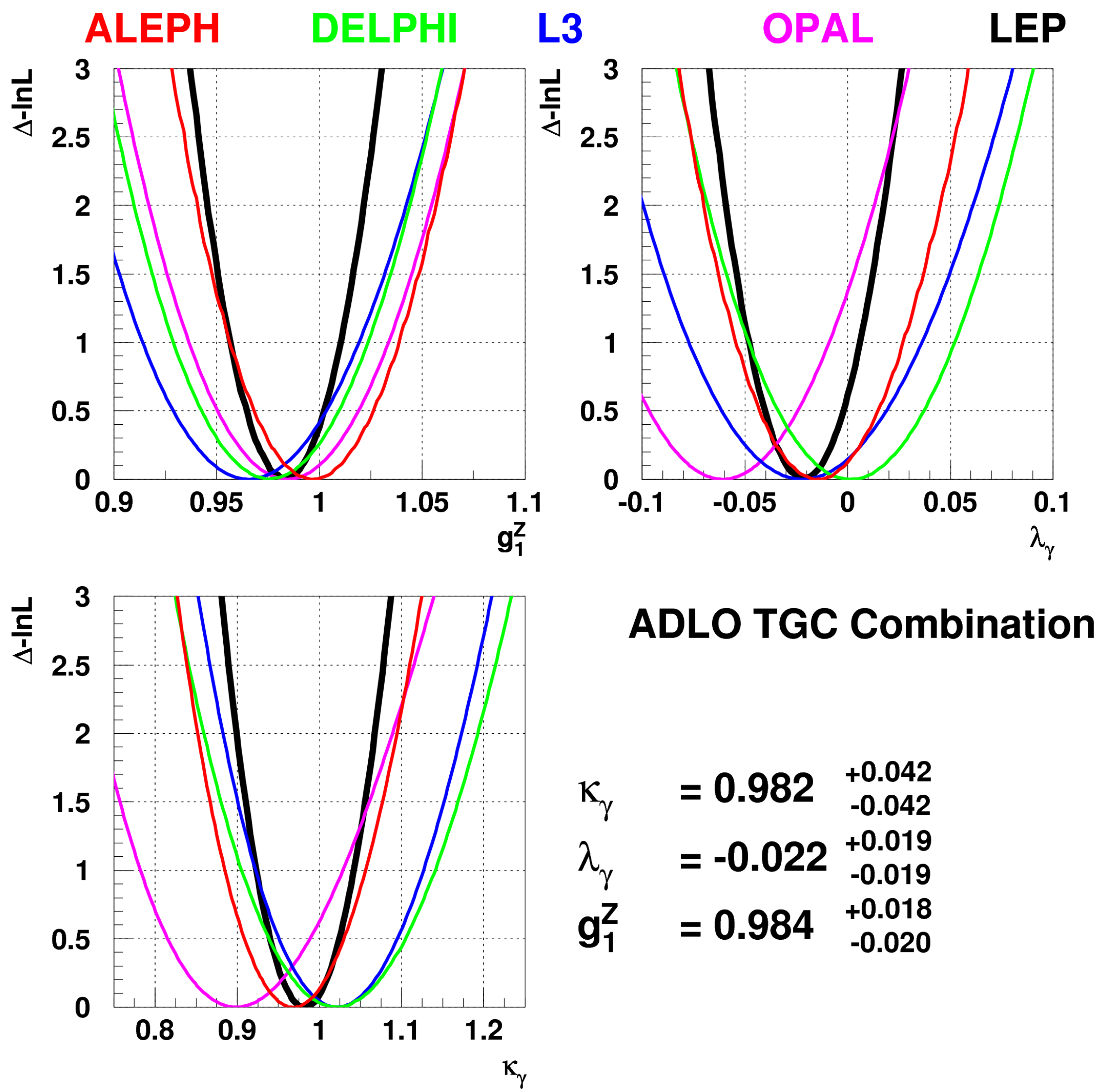


- WWγ and WWZ couplings are related, inspired by gauge invariance

$$\begin{aligned}\kappa_Z &= g_1^Z - (\kappa_\gamma - 1)\tan^2_W \\ \lambda_Z &= \lambda_\gamma\end{aligned}$$

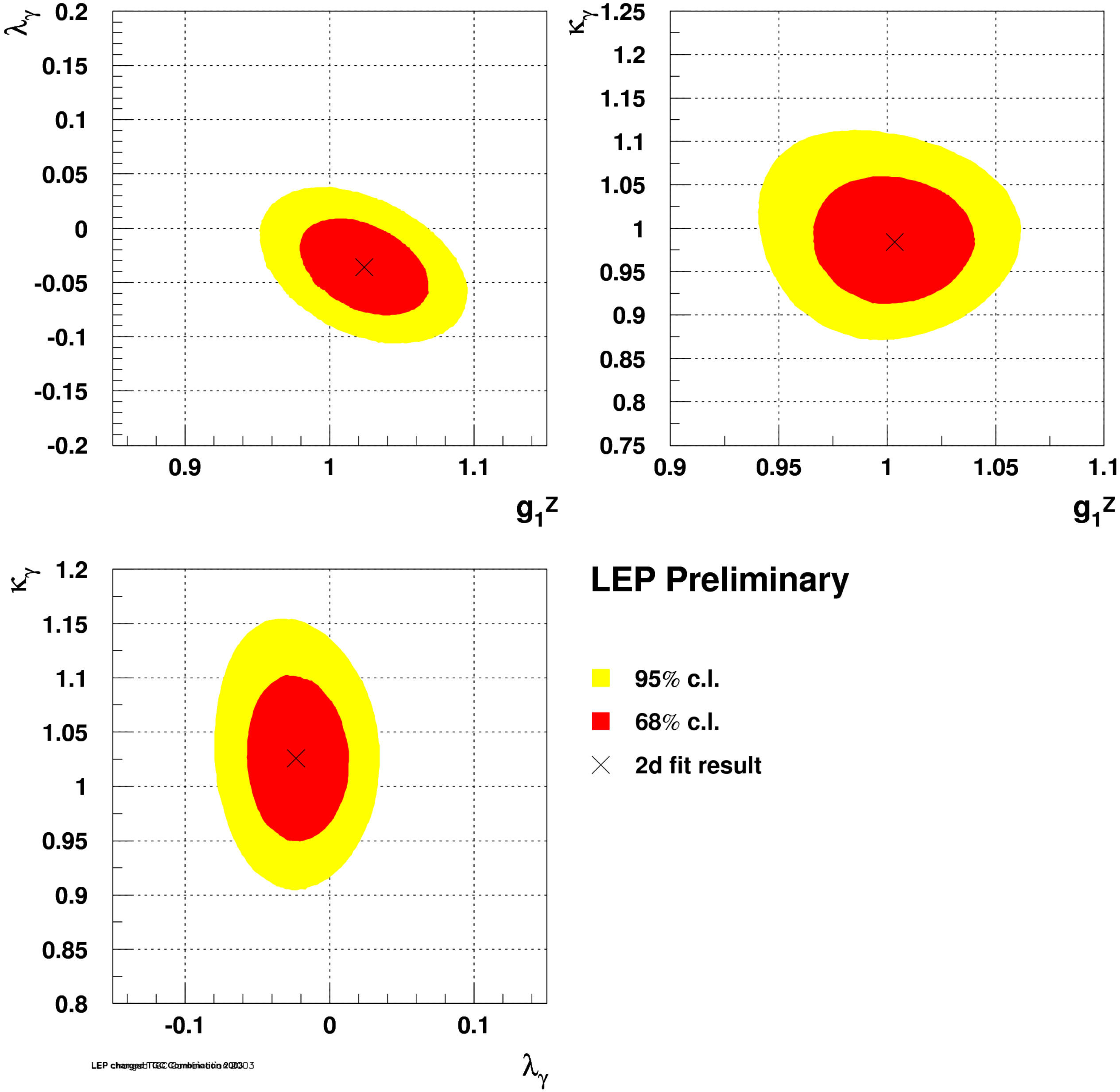
TGCs at LEP (iii)

- Single parameter fits give errors of 2-4%
- Confirms gauge structure of SM
- However not precise enough to see deviations from new physics



TGCs at LEP (iv)

- Correlations in 2d fits are modest

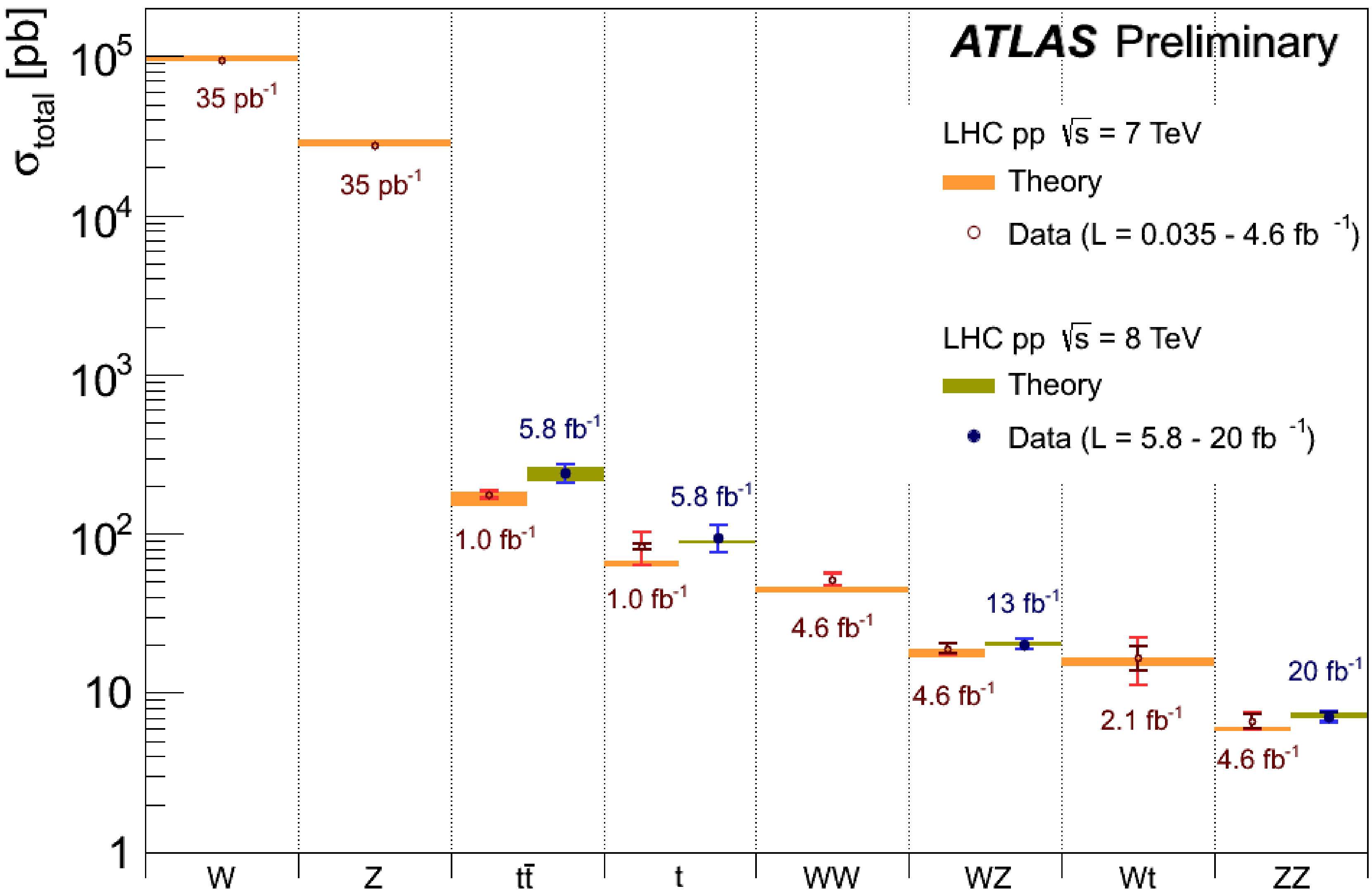


TGCs at the LHC

- At the LHC WW, Wγ and WZ production is accessible
  → WWγ and WWZ couplings can be separated
- Decay angles only partially accessible:
  - γ is stable → only production angle can be measured
  - Z not maximally parity violating → Z polarisation sensitivity is weaker
  - In WW events two neutrinos are missing → events not fully reconstructible
- Up to now only cross sections as function of $\sqrt{\hat{s}}$ or a typical p_T measured
- Only 2011 data (7 TeV) used for TGCs up to now
- n-dimensional limits are possible because at the current sensitivity TGCs always increase the cross section

2-Boson cross sections

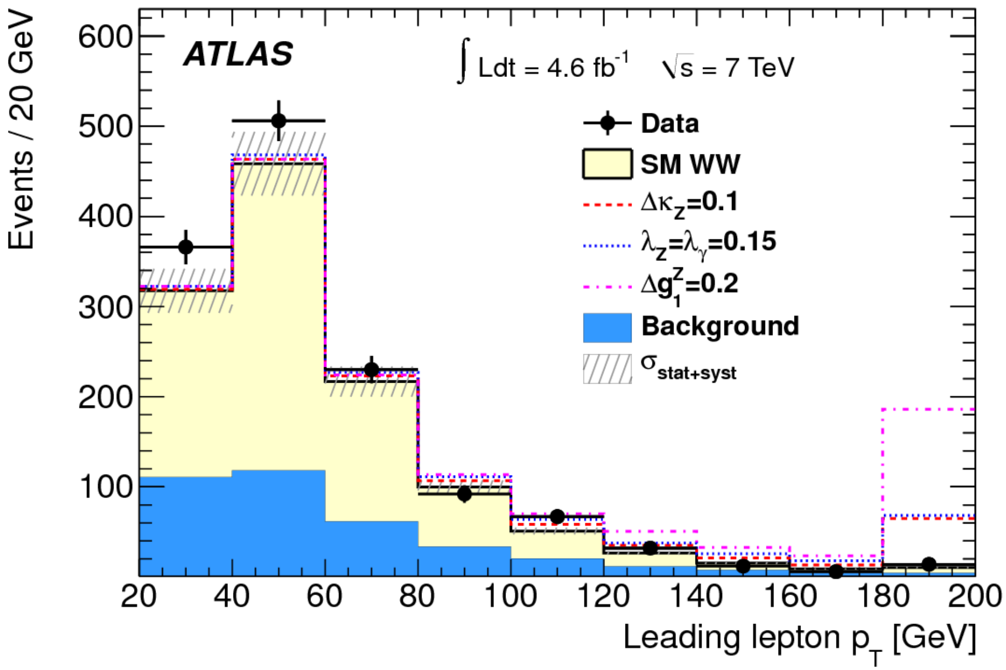
- All cross sections agree with SM prediction

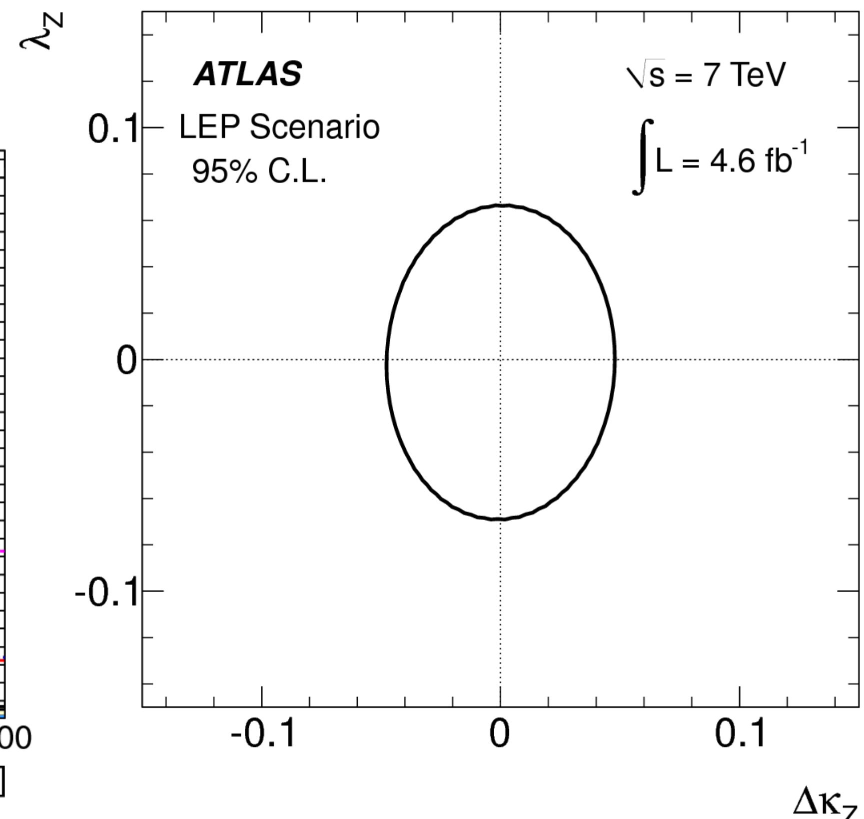


WW cross sections

- m(WW) not reconstructible, use leading $p_{T,l}$ instead
- TGC sensitivity at high $p_{T,l}$
- Data consistent with SM

arxiv:1210.2979

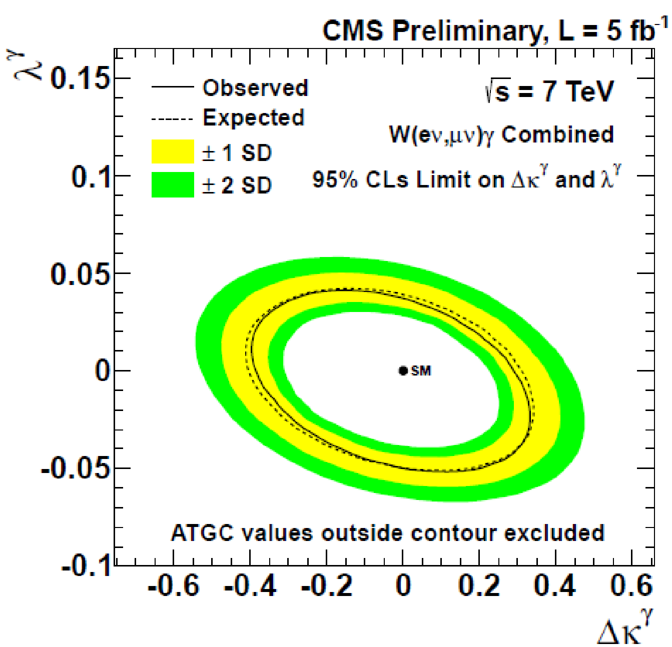


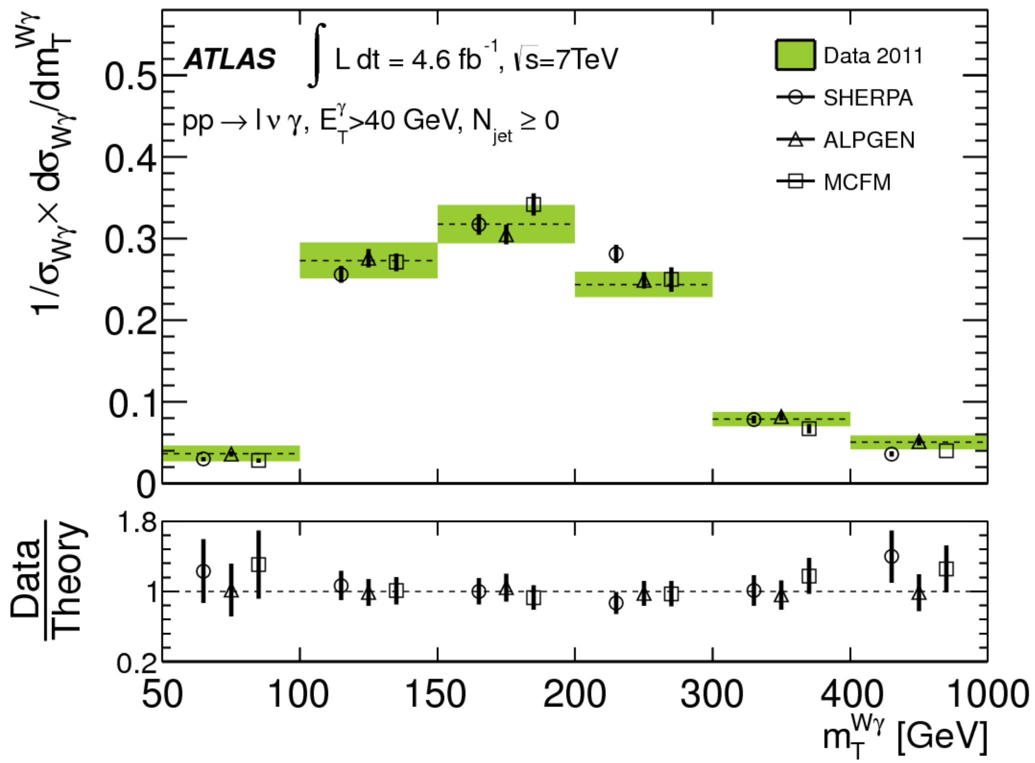


Wγ cross section

- transverse mass $m_T(W\gamma)$ is accessible to experiment
- especially κ limit much worse than LEP

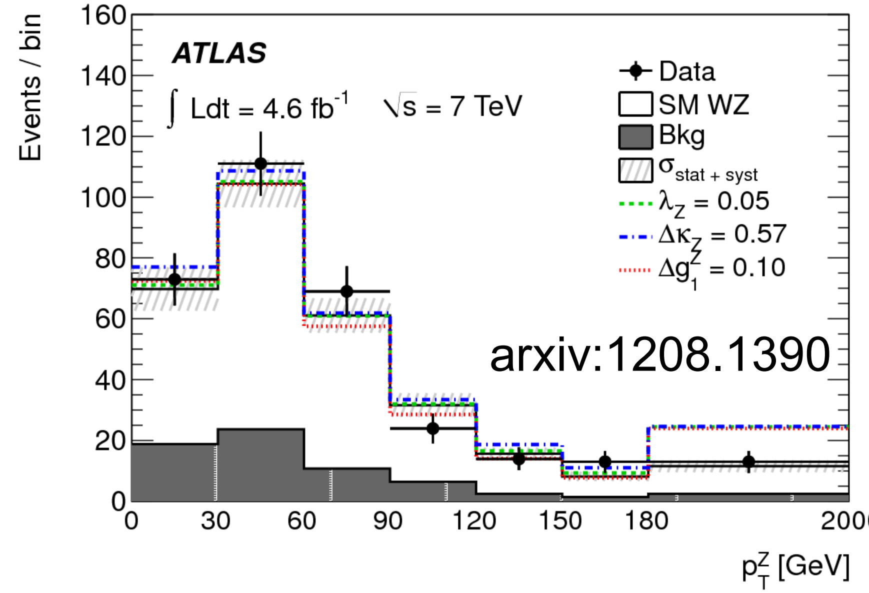
arxiv:1302.1283

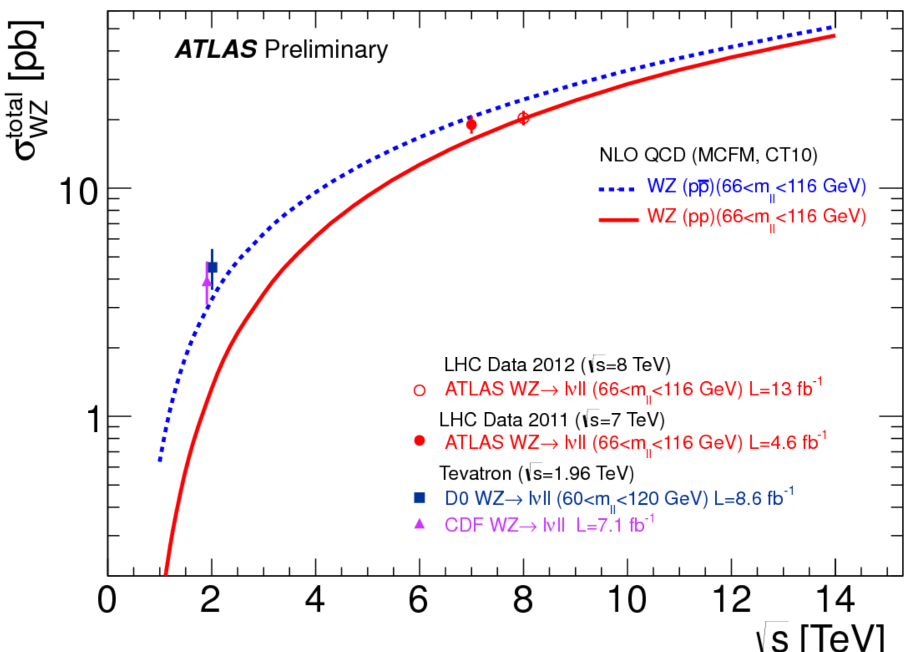


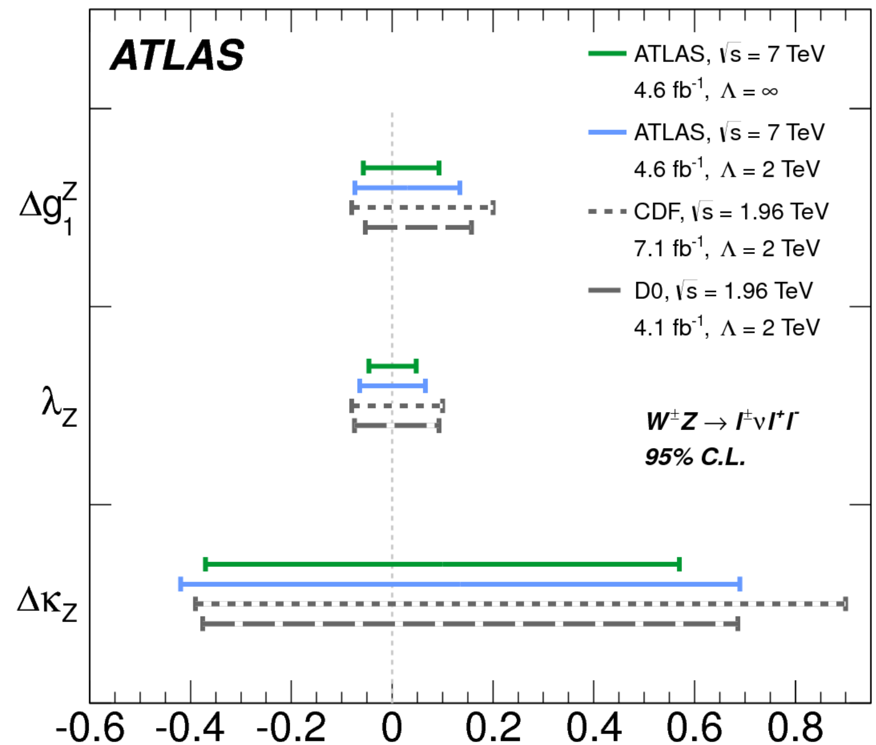


WZ cross section

- Total cross section and as a function of $p_{T,Z}$
- Good TGC limits for g and λ, κ much worse







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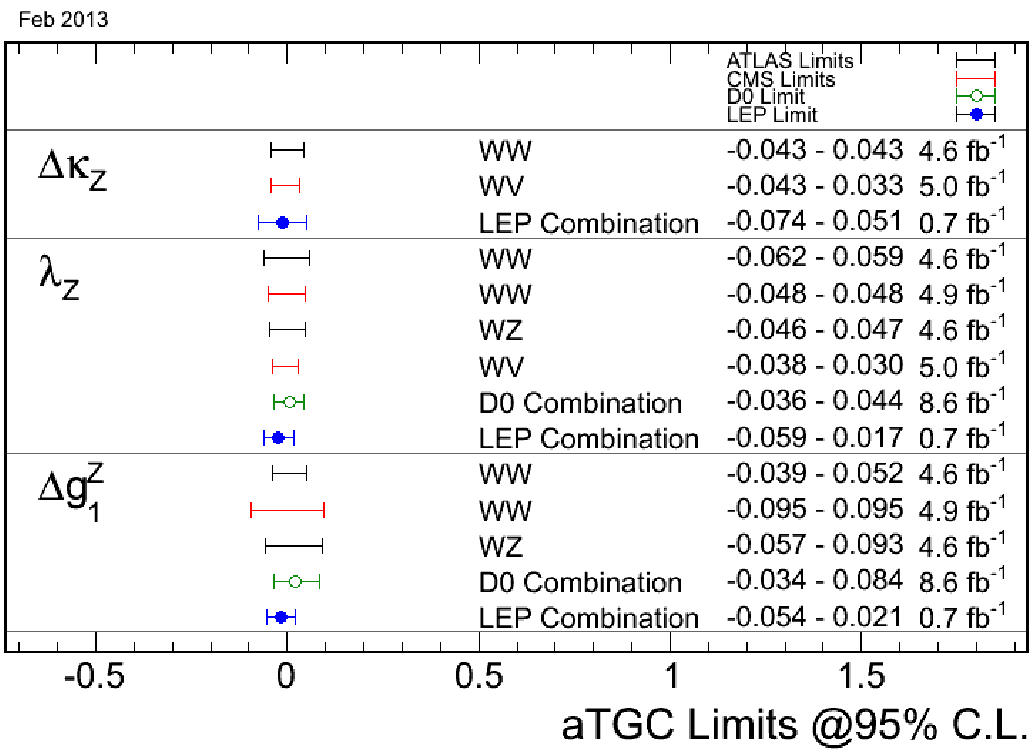
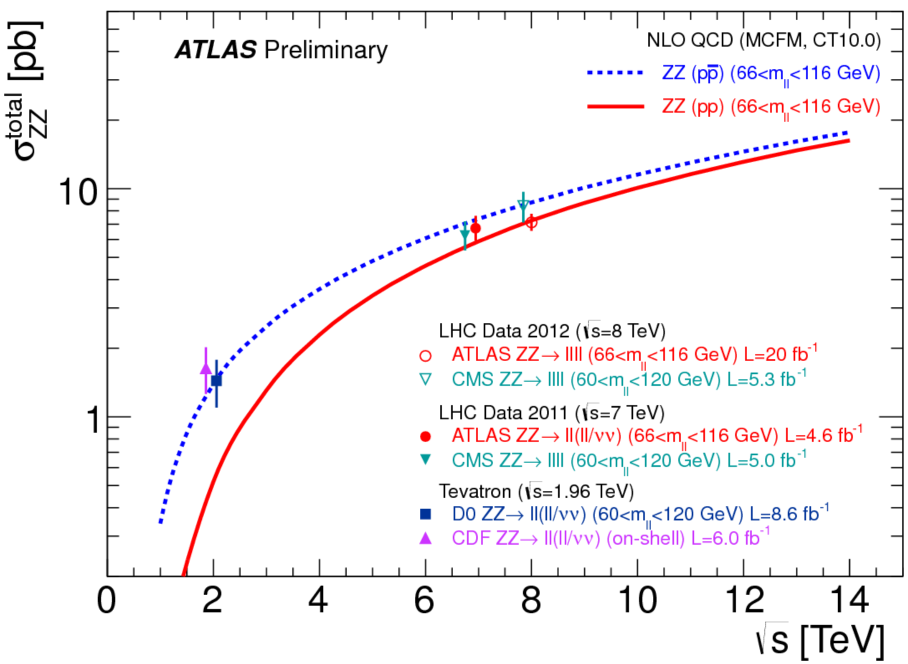
TGC summary

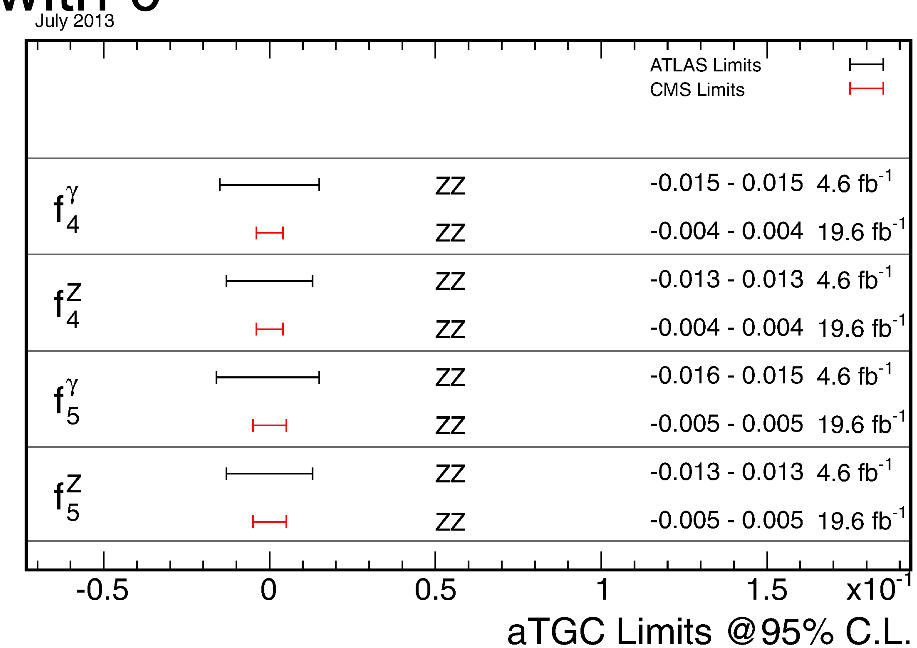
- At the moment LHC, Tevatron and LEP are at the same level
- However much more to come from the LHC (more energy, more luminosity)



Neutral TGCs

- Neutral TGCs can be parametrised in terms of 4 coupling constants $h_{4,5}^{\gamma,Z}$ (Zγγ, ZZγ) and $f_{4,5}^{\gamma,Z}$ (Zzγ, ZZZ)
- They can be measured from Zγ, ZZ production
- Dimension is higher than for neutral TGCs (6,8) → energy helps more
- All neutral TGCs consistent with 0





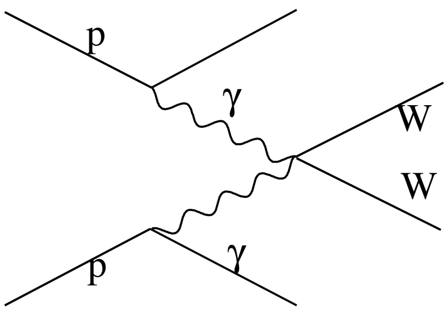
Quartic couplings

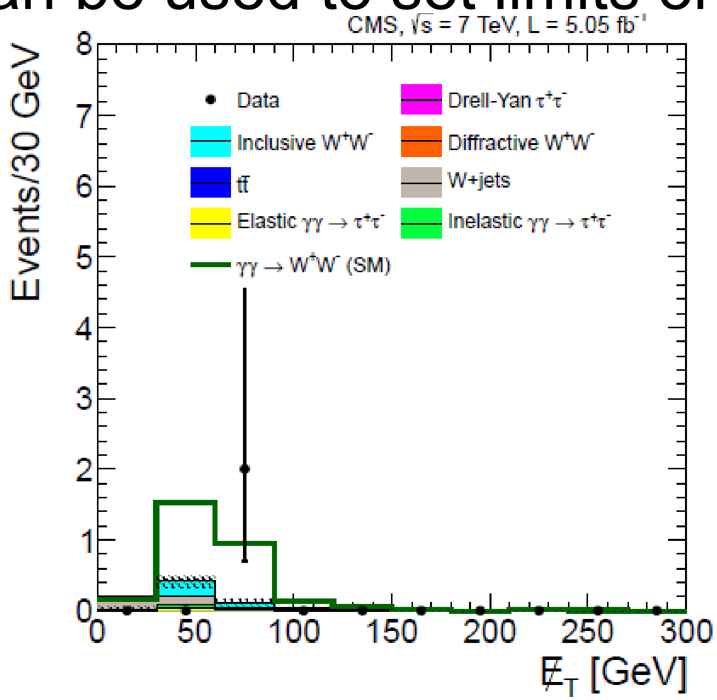
- The quartic couplings are regulated by the Higgs
- If the Higgs is non-standard one can still expect deviations
- The interesting couplings are between longitudinal (i.e. massive) gauge bosons
- To measure them need high energy and very high luminosity

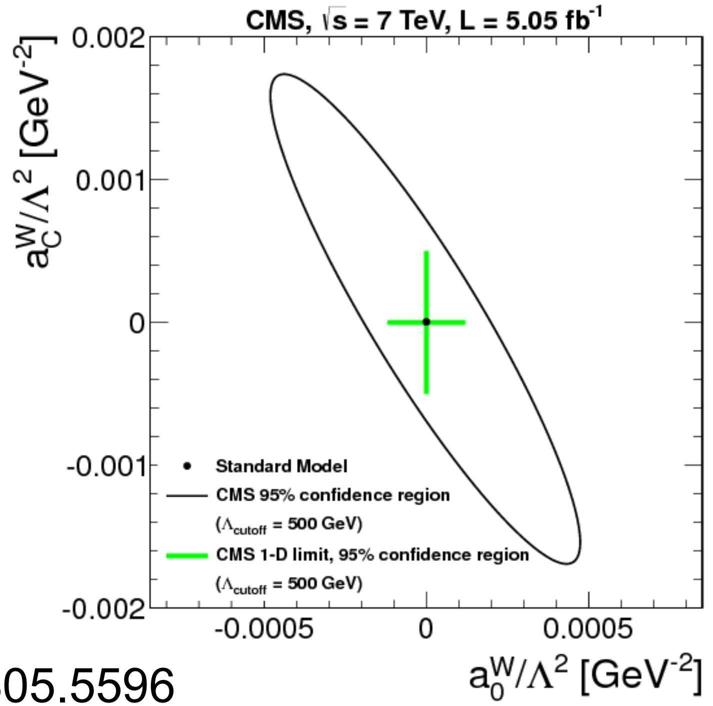
  → may show final results at BND school 2033

γγWW quartic couplings

- CMS idea to measure γγWW: look at pp→ppWW where each proton radiated a photon
- Mostly empty detector with 2 leptons
- 2.2 expected signal events in 2011 data and see 2
- Can be used to set limits on QGCs







arxiv:1305.5596

Conclusions on gauge boson production

- Gauge boson pair production clearly observed at LEP, Tevatron, LHC
- The gauge structure of the Standard Model is established from the measurements of the TGCs
- However there is no sensitivity to loop corrections yet
- Limits on quartic couplings exist only for $\gamma\gamma WW$
- For massive gauge bosons there is a long way to get sensible limits