Combination of diboson results (TGC)

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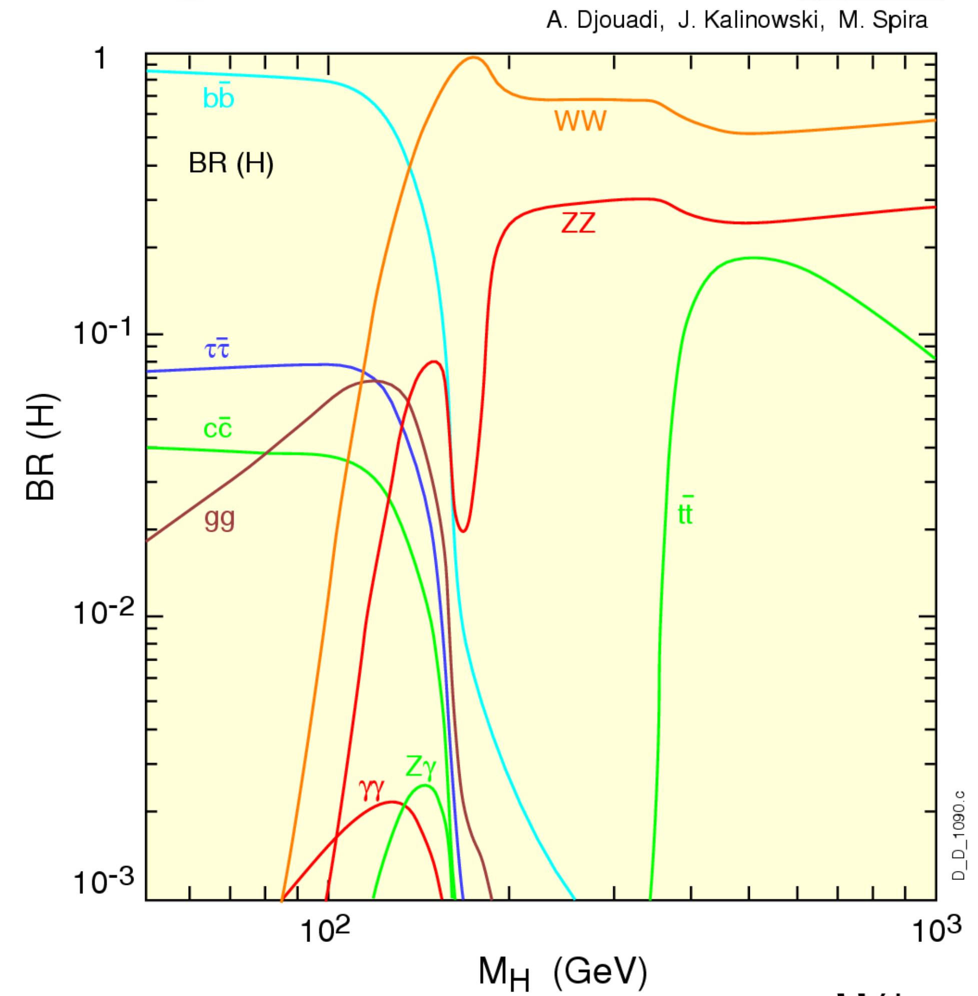
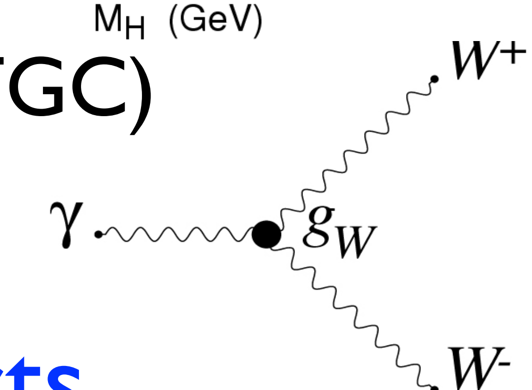
Diboson physics @ LHC

- Physics with multiple bosons in the final state is an important test of the standard model
  - Cross section
  - Search for resonant production
    - Higgs, fermiophobic Higgs, Higgs-less ED-based theories, Technicolor, or whatever…
  - Search for broad excess: trilinear gauge couplings (TGC)
    - QGCs in the future





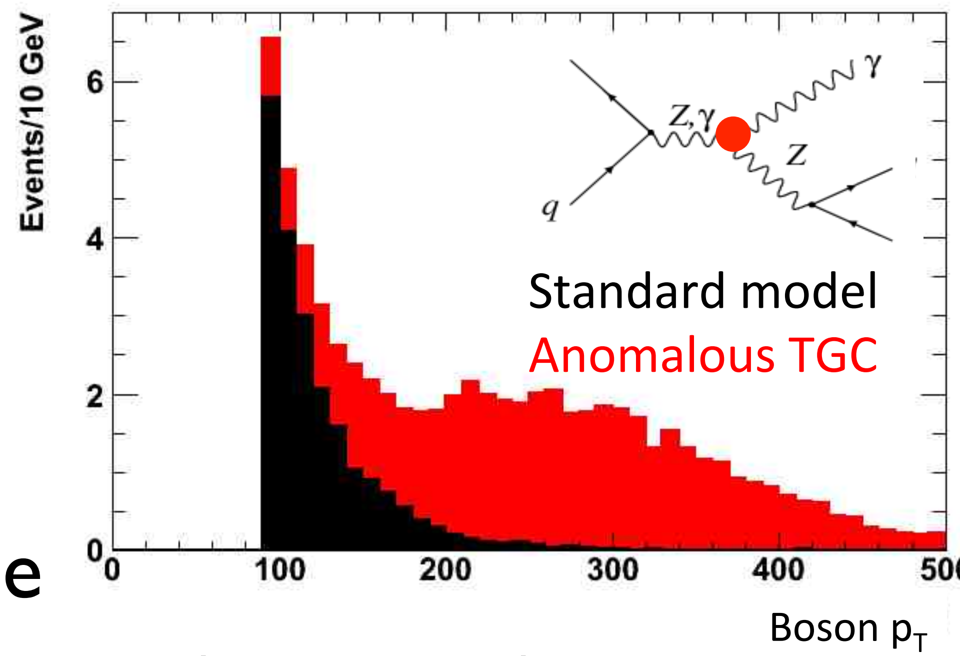
- It would be great to coordinate the efforts to produce ultimate measurements of the multiboson production at LHC

Cross section

- Processes with Z/γ^* boson production have cross section that depends on the dilepton mass cut
- Processes with photons diverge at LO if the photon is too close to either a jet or a charged lepton or is too soft
  - Impose $\Delta R(\ell, \gamma)$, $\Delta R(\text{jet}, \gamma)$, and $E_T(\gamma)$ requirements
- To combine cross sections between experiments, a unified definition of the generator-level requirements with respect to which the cross section is measured is important
- Not important for combination of the TGC results

Measurement of TGCs

- Self-boson interaction is fixed in the SM
- Anomalous TGC strength results in
  - Increase in the cross section
  - Harder p_T of bosons

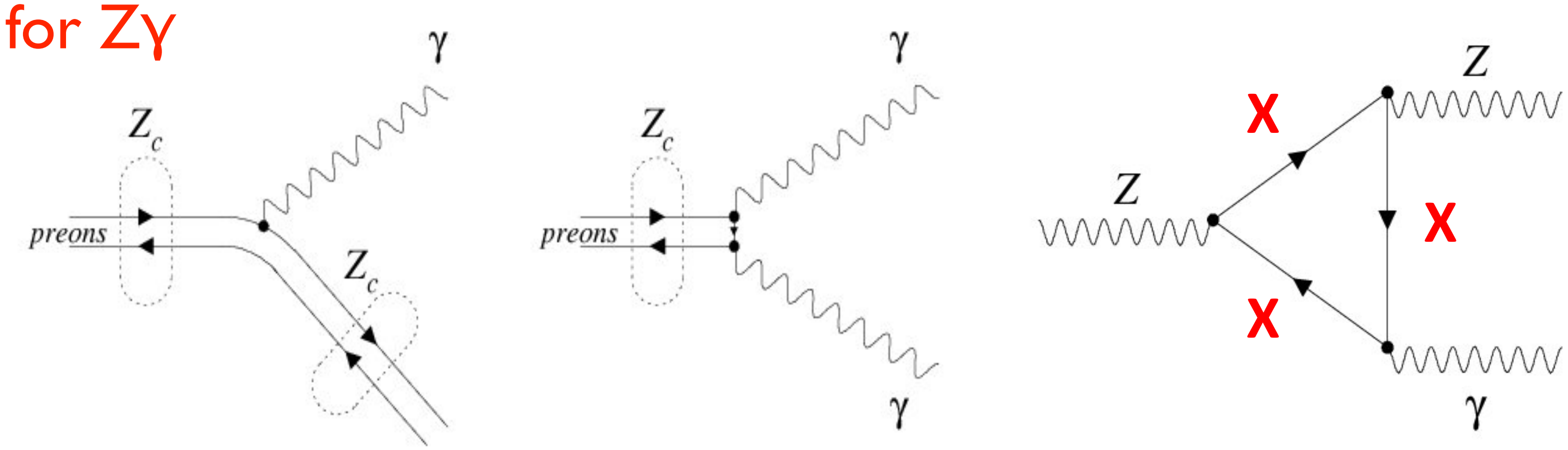


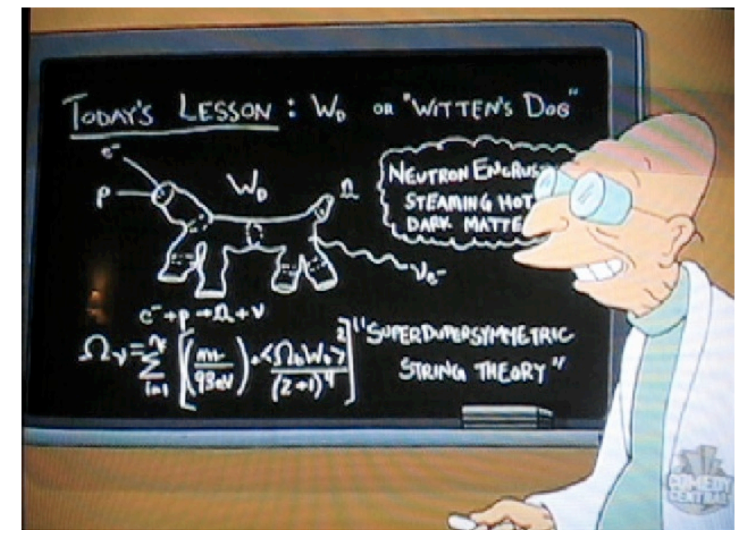
- Methods to measure TGC
  - The simplest approach: compare diboson cross section with measured one
  - More complex: use differential cross sections (boson p_T)
  - Even more complex: add angular distributions
- Define likelihood in TGC space and obtain 95% C.L. contour around measured value
  - Key element: how do we model signal as function of TGCs?

TGCs

- A rich plethora of new phenomena that can produce anomalous TGCs

Example for Zγ





- Produce the most general Lagrangian that describes the triple-boson vertex in terms of TGC couplings
  - WWV (V = γ or Z) is parameterized by 14 TGCs

$$\frac{\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W^*_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^*_\mu W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2}W^*_{\lambda,\mu}W^\mu_\nu V^{\nu\lambda} - g_4^V W^*_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$+ \; g_5^V \epsilon^{\mu\nu\lambda\rho}(W^*_\mu \partial_\lambda W_\nu - \partial_\lambda W^*_\mu W_\nu)V_\rho + i\tilde{\kappa}_V W^*_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2}W^*_{\lambda\mu}W^\mu_\nu \tilde{V}^{\nu\lambda},$$

  - Can be probed in WW, Wγ, and WZ analyses
  - ZVγ vertex is parameterized by 8 TGCs

TGCs

- In reality only a few of these parameters are measured in experiments
  - Example: $WV\gamma$ vertex, 14 independent parameters

$$\frac{\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = ig_1^V\left(W_{\mu\nu}^* W^\mu V^\nu - W_\mu^* V_\nu W^{\mu\nu}\right) + i\kappa_V W_\mu^* W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda,\mu}^* W_\nu^\mu V^{\nu\lambda} - g_4^V W_\mu^* W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right)$$
$$+ \; g_5^V \epsilon^{\mu\nu\lambda\rho}\left(W_\mu^* \partial_\lambda W_\nu - \partial_\lambda W_\mu^* W_\nu\right) V_\rho + i\tilde{\kappa}_V W_\mu^* W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^* W_\nu^\mu \tilde{V}^{\nu\lambda},$$

    - Impose EM invariance $g_1^\gamma = 1$
    - Need CP-odd quantity to measure CP-odd effects: set all tilde-marked and g_4^V to zero (SM values)
    - Assume C- and P-conservation: $g_5^V = 0$
  - After all these assumption we have five independent complex couplings: g_1^Z, κ_γ, κ_Z, λ_γ and λ_Z

- Difficult to present results in 5D space in paper: reduce the number using different schemes

Different TGC relations

- LEP parameterization (Δ is defined as a difference from the SM prediction)
  - light Higgs boson scenario

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot tan^2\theta_w \quad \text{and} \quad \lambda_Z = \lambda_\gamma = \lambda$$

  - Effectively reduces number of unknown variables to three
    - For Wγ this reduces the number of free parameters to two

- Hagiwara-Ishihara-Szalapski-Zeppenfeld (HISZ)
  - Assumes the coupling between SU(2) × U(1) fields and Higgs double are the same

$$\Delta\kappa_Z = \frac{1}{2}\Delta\kappa_\gamma(1 - tan^2\theta_w), \Delta g_1^Z = \frac{\Delta\kappa_\gamma}{2cos^2\theta_w} \quad \text{and} \quad \lambda_Z = \lambda_\gamma = \lambda$$

  - Reduces number of free parameters to two

- Equal coupling relation
  - Two free parameters

$$\Delta g_1^Z = \Delta g_1^\gamma = 0$$

$$\Delta\kappa_Z = \Delta\kappa_\gamma \quad \text{and} \quad \lambda_Z = \lambda_\gamma = \lambda$$

Unitarity

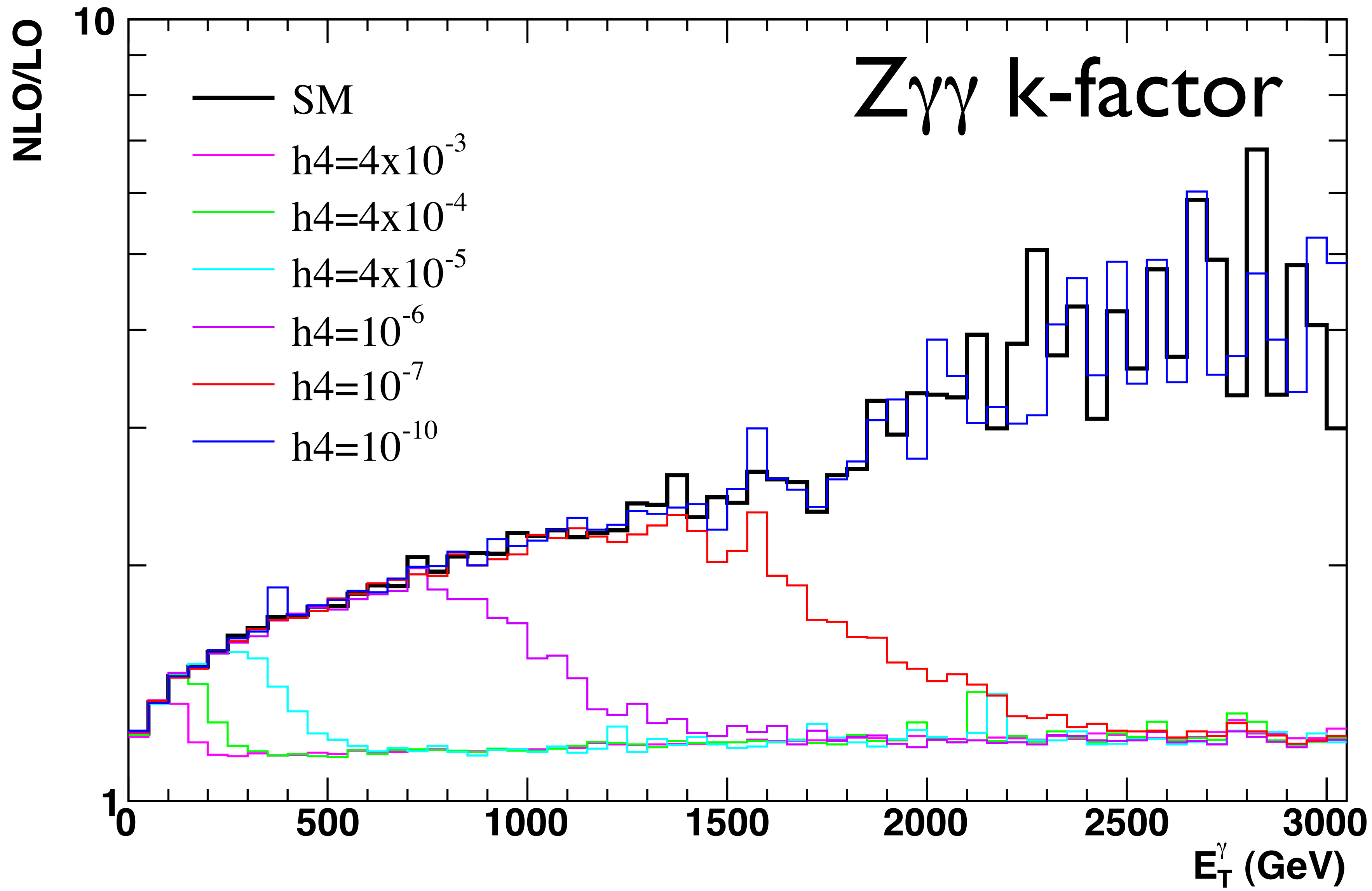
- Any anomalous TGC results in violation of unitarity at sufficiently large energies
  - Theorists prefer to scale the couplings with energy $\alpha(\hat{s}) \rightarrow \frac{\alpha_0}{(1+\hat{s}/\Lambda_{NP}^2)^2}$
  - Tevatron results followed this approach and set limits on α_0
    - Several ways to choose Λ (increasing its value makes α_0 limit smaller but at some point unitarity constraint becomes more restrictive than the limit in data itself)
    - Note DØ results have Λ = 500 GeV for early data set, then 750 GeV, with recent results 1.5 TeV
  - LEP did not assume any energy dependence and set limits on $\alpha(\hat{s})$
  - CMS prefers this approach as well
    - For combination of results it makes things easier as less signal parameters need to be synched (power of the form-factor and the value of new physics scale Λ)
    - Makes comparison of the results with Tevatron difficult

Modeling of signal

- Several generators exist on the market that simulate diboson production with anomalous TGCs
  - For Vγ
    - Sherpa (LO + n partons, unconventional parameterization of form-factors for Zγ production)
    - Baur LO (ISR and FSR)
    - Baur NLO (ISR only)
  - For VV
    - MCFM (NLO) (do not use for Wγ and Zγ!)
    - Hagiwara, Zeppenfeld, Woodside (HZW) generator (LO)
- Comparing results of these generators together with some SM ones (PYTHIA, MadGraph) indicates consistent modeling of processes
  - Probably not a problem with combination with early data

NLO modeling

- NLO signal can be modeled using LO + k-factor or with NLO directly
  - Strong dependence on the choice of the k-factor



  - We need to be consistent in how the signal is modeled

Summary

- A number of items that needs to be coordinated
- TGC definitions: Reduction of couplings
  - Making "sane" assumption, such as EM gauge invariance *etc* reduces the number of WVγ couplings to three. As it is difficult to illustrate 3D limit contour on paper one can reduce the number to two using further assumptions
    - LEP/HISZ/Equal parameterization?
    - Set the third coupling to SM value at a time
    - The best: use 3D limit and produce projections?
  - All these couplings are complex, extra degree of freedom?
- TGC definitions: no form factor?
- NLO signal modeling