Vector Boson Scattering in CMS

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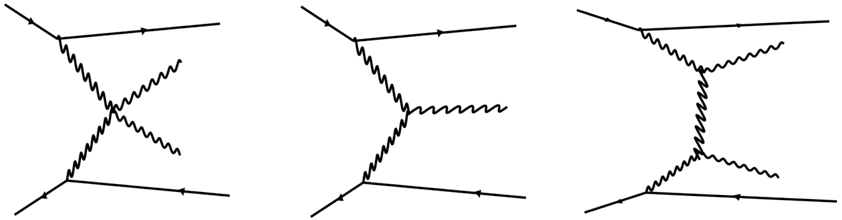
What is VBS? Several definitions

1. The obvious: Scattering of Vector Bosons
2. The Theorist: (not unique) t-channel exchange of two weak bosons (generally W or Z, but also photons) between two quarks (or a quark and an antiquark)
3. The experimentalist: The processes that pass the VBS selection and cuts

None of them is incorrect, but it is important to understand the differences ...

Vector Boson Scattering

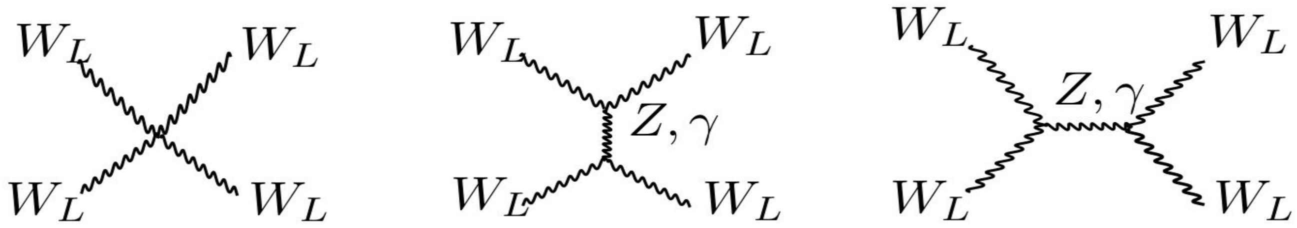


(Weak) Vector Bosons

- At the heart of EWSB (important part of the LHC programme).
- Through the Higgs mechanism the W and Z acquire mass.
- At high enough energies all this "mass" is concentrated in the longitudinal polarization mode. This has two consequences:
    - Transverse/Longitudinal modes behave differently.
    - At high energies longitudinal modes are equivalent to massive goldstone bosons.
- It is an interesting process for Effective Field Theory studies:
    - We think that new physics might be related with or at least *"seen in"* EWSB
    - Triple and Quartic gauge couplings are very unconstrained in the SM

Vector Boson Scattering at high energies

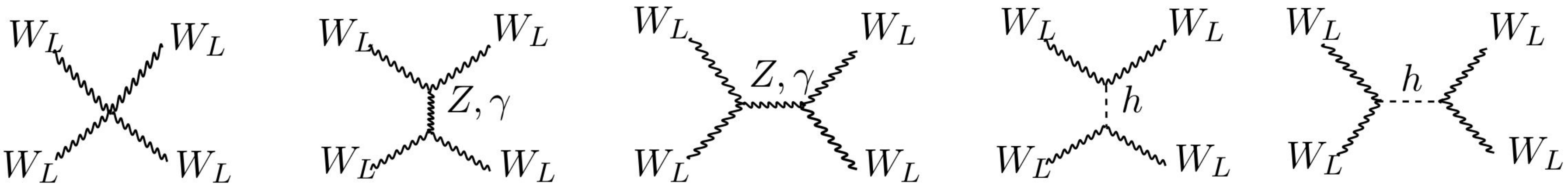
Imagine scattering of same-sign WW long. polarized Vector Bosons, without the Higgs:



$$\epsilon_L^{W^+} \cdot \epsilon_L^{W^-} \approx \frac{k_{W^+} \cdot k_{W^-}}{\mathrm{M}_{\mathrm{W}^2}} = \frac{s}{2\mathrm{M}_{\mathrm{W}}^2} \quad \Rightarrow \quad D_i \sim \frac{k_{W^+} \cdot k_{W^-}}{\mathrm{M}_{\mathrm{W}^2}} \frac{k_{W^+} \cdot k_{W^-}}{\mathrm{M}_{\mathrm{W}^2}} = \frac{s^2}{\mathrm{M}_{\mathrm{W}}^4}$$

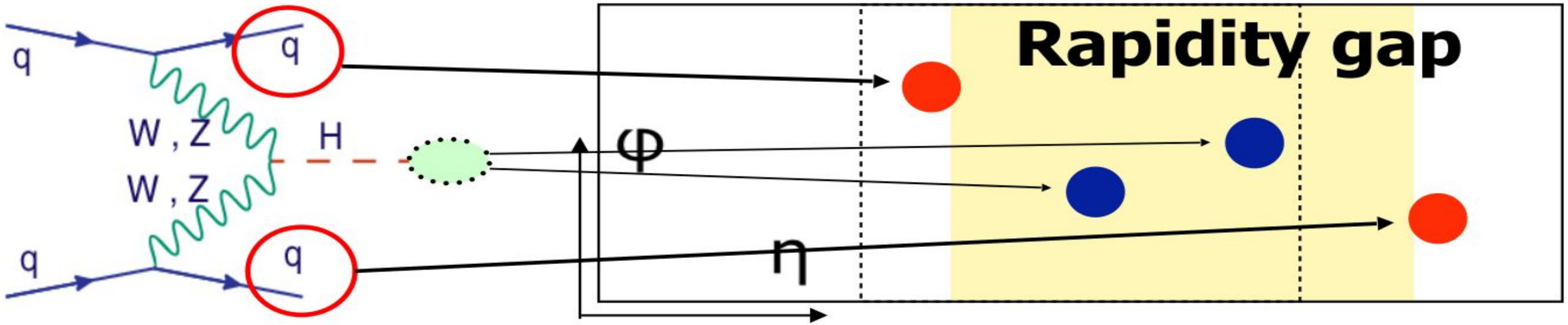
Vector Boson Scattering at high energies

Massive L Modes → Unitarity Violation → Need Higgs



The Higgs stabilizes the otherwise divergent amplitude. In general in all VBS processes, gauge invariance is preserved thanks to a set of precise cancellations. Further, such processes are fundamental to study unitarity.

VBS in experiment. The signature:



- Final state: 4 leptons and 2 jets (leptonic VBS) or 2 leptons and 4 jets (semileptonic)
-
- Very energetic Forward/Backward jets ⇒ Use central jet veto
  Look at tagged-jets variables: rapidity, mjj

- Interesting Variables: All di-jet related: mjj, Delta(eta), Delta(phi), Zeppenfeld Z

First evidence of VBS in LHC: Same sign WW

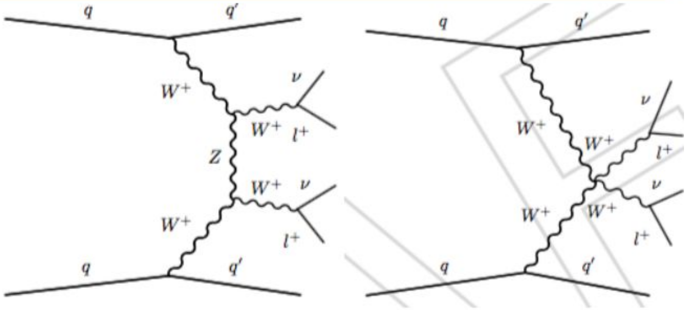
- Large cross-section times BR
- Low irreducible background (B~S)

- Final state selection:
  - Two (equally) charged leptons (e,mu)
  - Two (leading) jets with pT>30 GeV (tag)

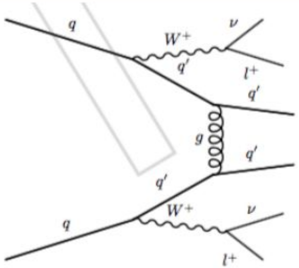
- Further bkg suppression:
  - b-jet veto (ttbar)
  - anti-Zcuts in e channels (DY)

- Observed in CMS run-2 data:
  - 5.5 standard deviations (5.7 expected)

Electroweak signal - α_{EW}^6



QCD background - $\alpha_{EW}^4\alpha^2$

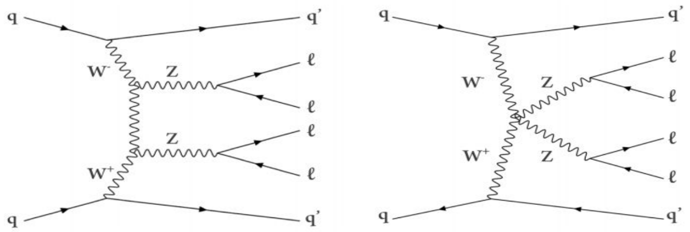


More in Giulia's talk...

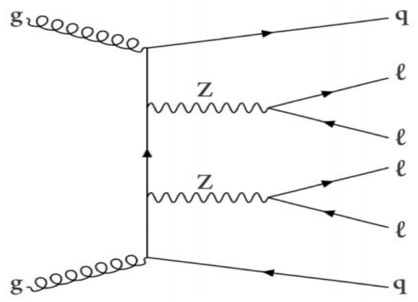
Next? evidence of VBS in LHC: ZZ -> 4l

- Low cross-section times BR
- Big irreducible background (B ~ 20 S)
- Very good final state reconstruction
- Final state selection:
  - Two lepton pairs (4e, 4mu, 2e 2mu)
  - Two (leading) jets with pT>30 GeV (tag)
  - Additionally:
    - mjj > 100
    - ZZ on shell
- Obs: Very similar analysis to H -> ZZ -> 4l
- Observed in CMS run-2 data:
  - 1.6 standard deviations (2.7 expected)

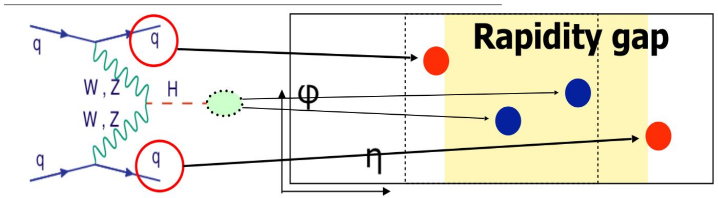
Electroweak signal – α_{EW}^6



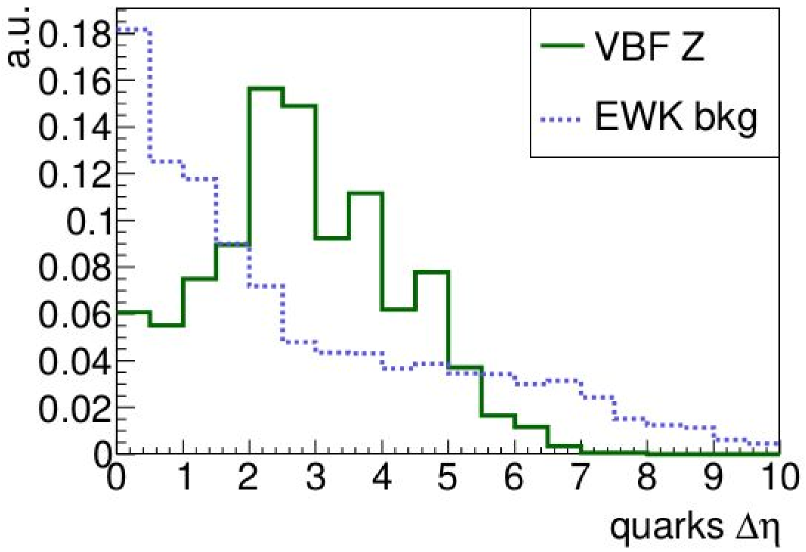
QCD background – $\alpha_{EW}^4\alpha^2$



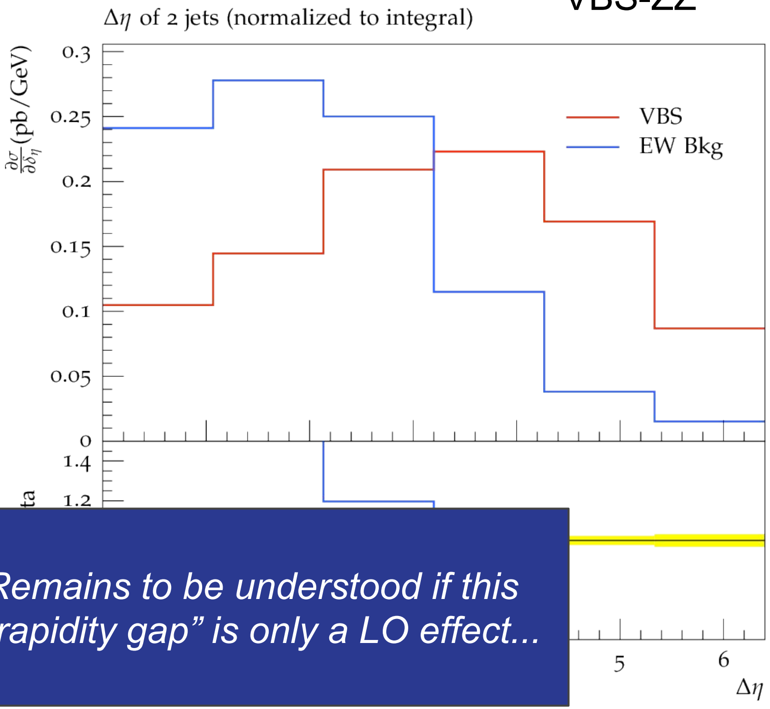
Interesting Variables for VBS: Delta(eta)



VBF-Z



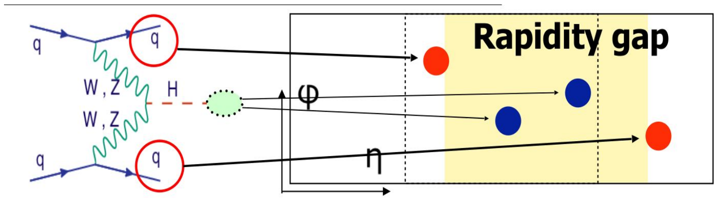
VBS-ZZ



Remains to be understood if this "rapidity gap" is only a LO effect...

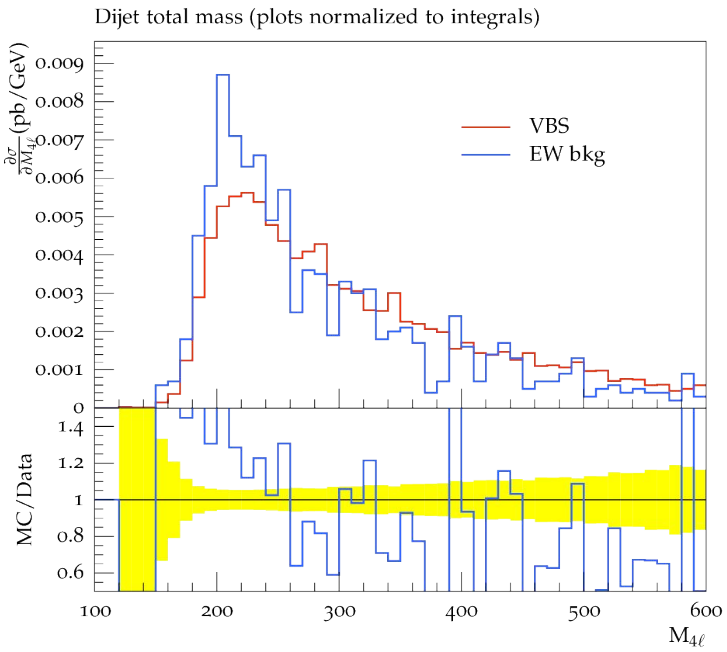
Govoni, Mariotti (hep-ph/1001.4357)

Interesting Variables for VBS: Delta(eta) and mjj

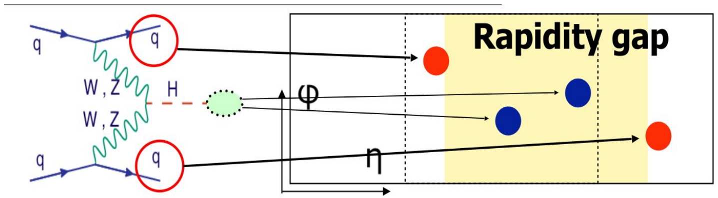


- Mjj is a good discriminator, but only at very high Energies. Starting from ~300 GeV

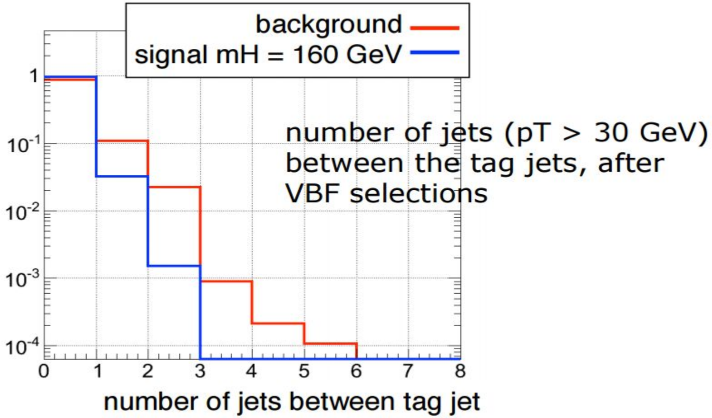
- VBS cut: Mjj > 400 GeV



Interesting Variables for VBS: Zeppenfeld Z and Centrality



- Centrality and Zeppenfeld variable
- Centrality first used in ATLAS H-> tau tau
- Different efficiency for different VBF/VBS channels
    - Di-photon
    - ZZ
    - WW



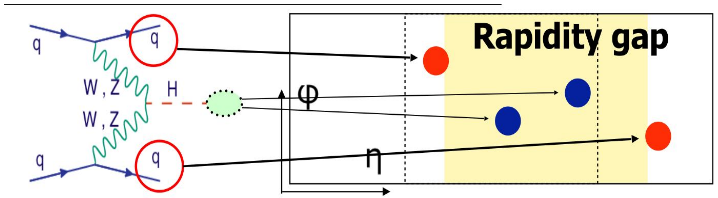
- Centrality:

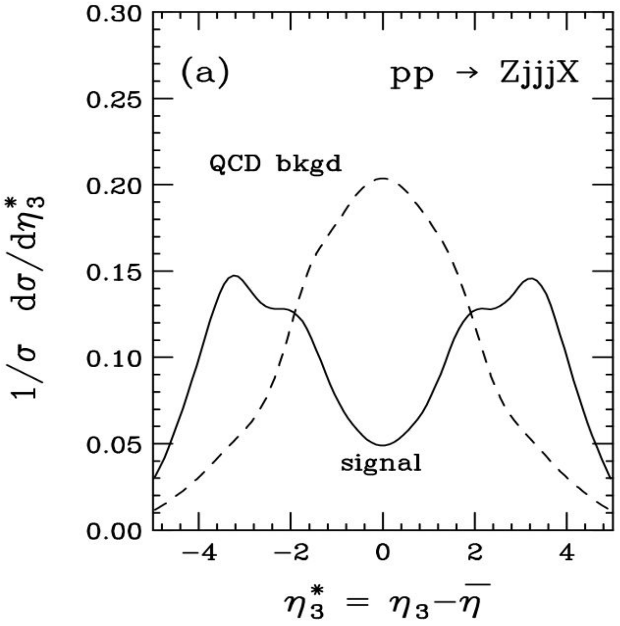
$$C_{\gamma\gamma} = \exp\left(-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_{\gamma\gamma}-\frac{\eta_1+\eta_2}{2}\right)^2\right)$$

$$z_i^* = \frac{z_i}{\Delta\eta} = \frac{\eta_i - \langle\eta\rangle}{\Delta\eta}$$

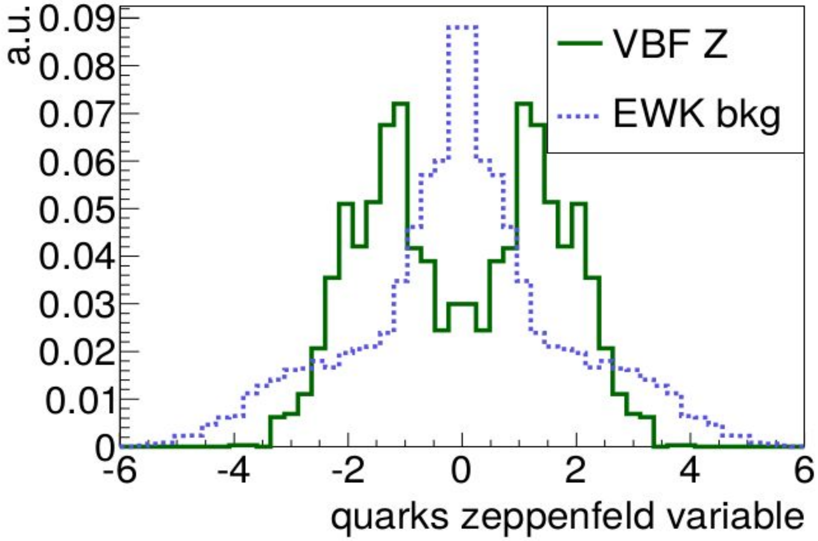
The Zeppenfeld variable: a translation and scaling of the (pseudo)rapidity to the reference given by the tag jets

Interesting Variables for VBS: Zeppenfeld Z





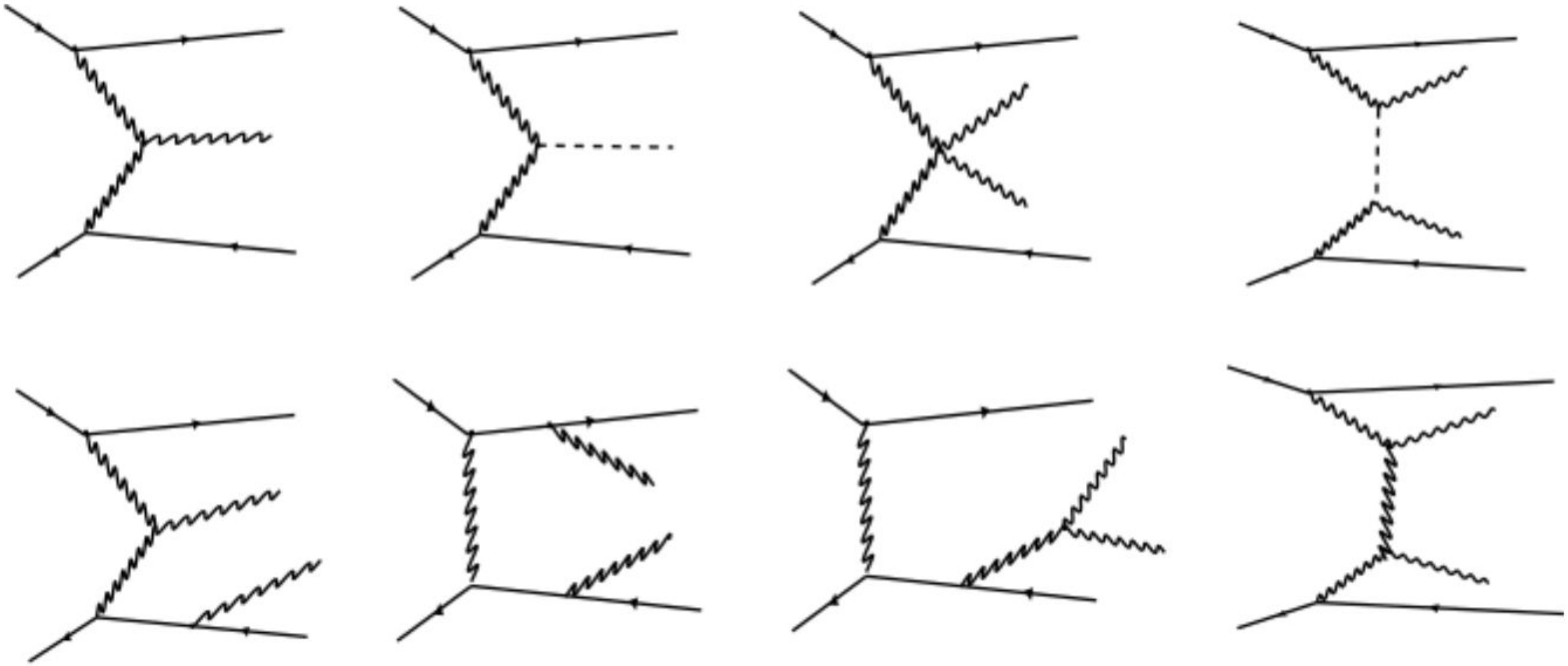
Rainwater,Szalapski,Zeppenfeld (hep-ph/9605444)



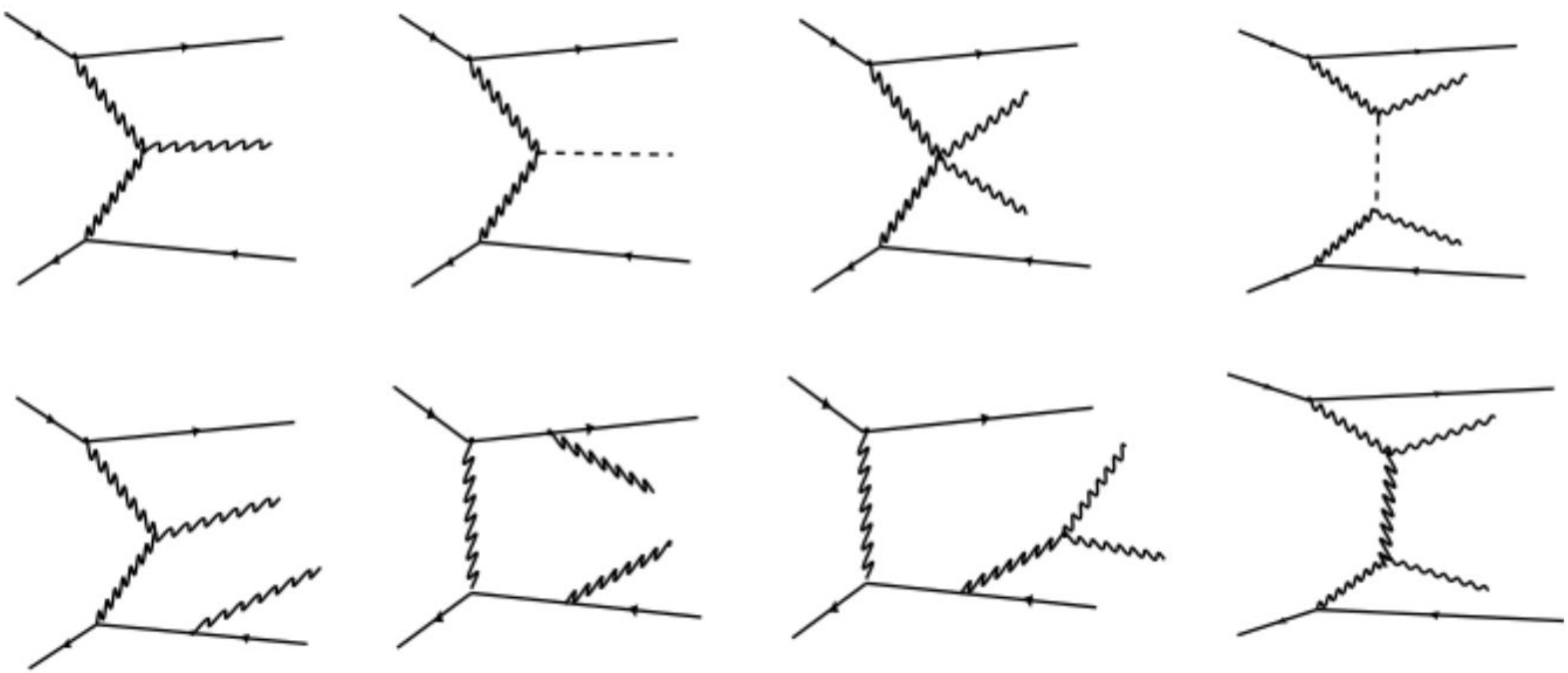
Govoni, Mariotti (hep-ph/1001.4357)

In general, dijet variables are the most interesting for VBF/VBS studies, still the cross section is very small and hence it is difficult to measure results from individual variables. → Need to use multivariate analysis

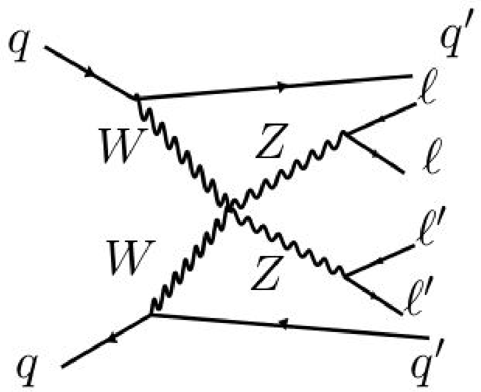
Quiz: Which of these diagrams are VBS (or VBF)?

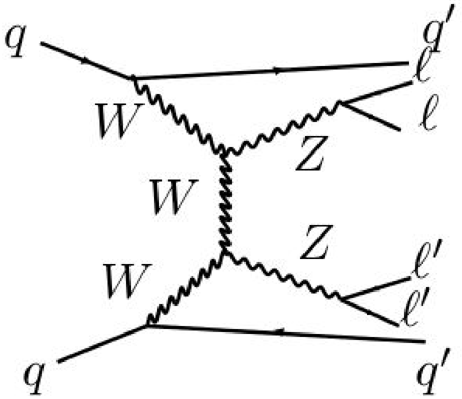


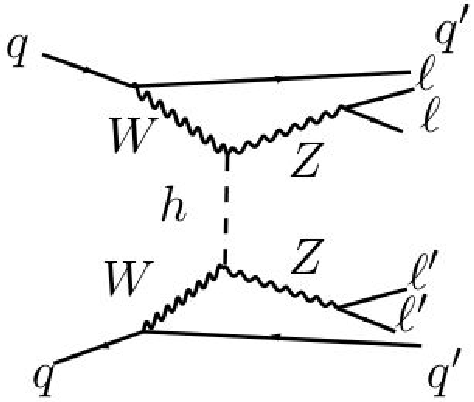
Quiz: Which of these diagrams are *VBS-signal*?



Som representatives of VBS-signal:

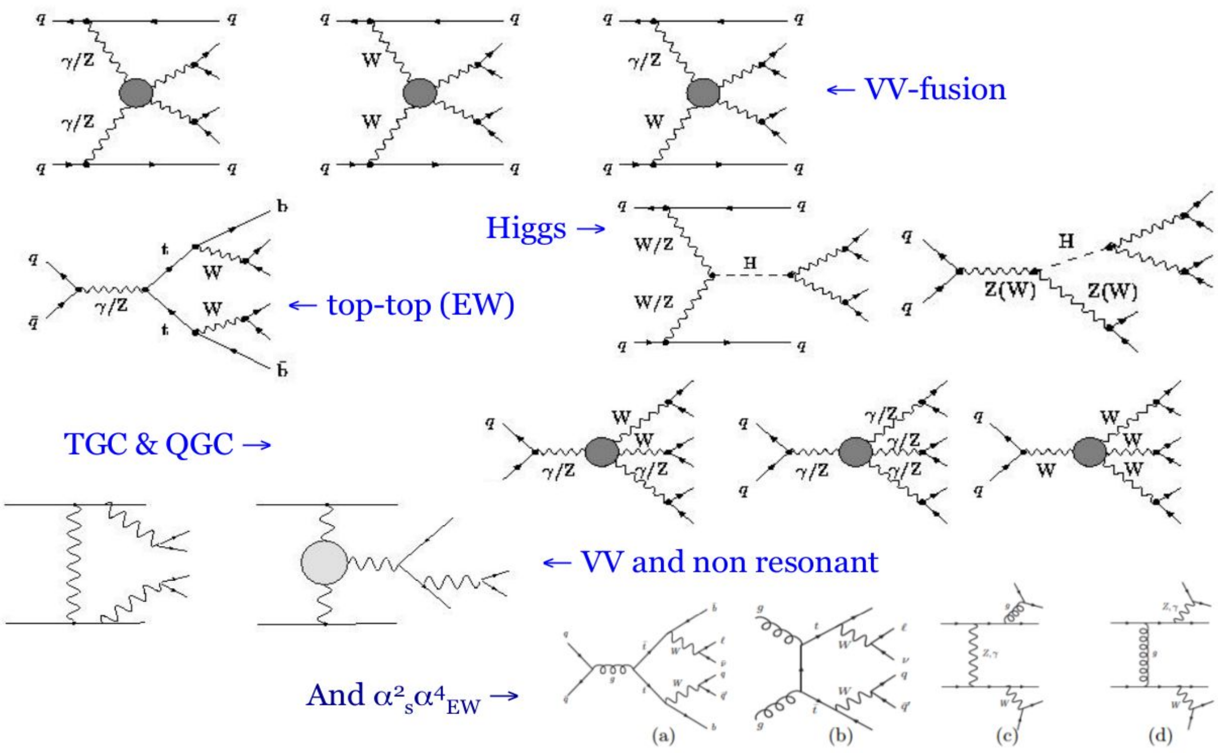






OBS: the background diagrams and the diagrams removed with cuts still interfere with these!

Many diagrams are VBS, not all of them are signal...



VBS at LHC: State of the art

Process	Studied	Observed Significance	Expected Significance
$Z\gamma$ ATLAS	8 TeV	2.0	1.8
$Z\gamma$ CMS	8 TeV	3.0	2.1
$W^{\pm}W^{\pm}$ ATLAS	8 TeV	3.6	2.3
$W^{\pm}W^{\pm}$ CMS	8 & 13 TeV	2.0 & 5.5	3.1 & 5.7
$W^{\pm}\gamma$ CMS	8 TeV	2.7	1.5
ZZ CMS	13 TeV	2.7	1.6

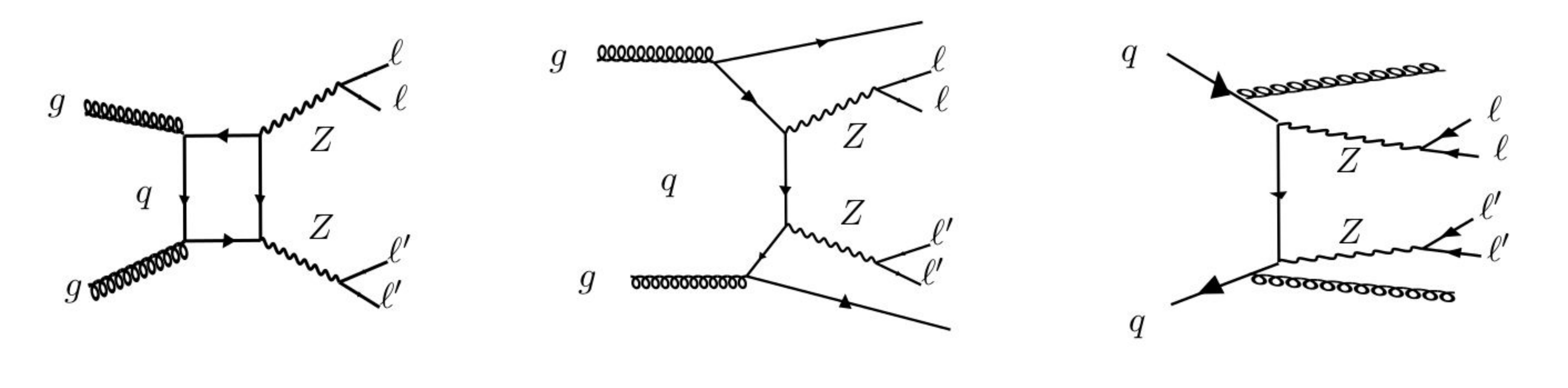
-The only channel observed so far is the same-sign WW (See Giulia’s talk on this search).
- The pronostics for the observation of the other channels in the Run-2 dataset are very good.

The Analysis:

ZZjj production in CMS at 13 TeV

Main Backgrounds

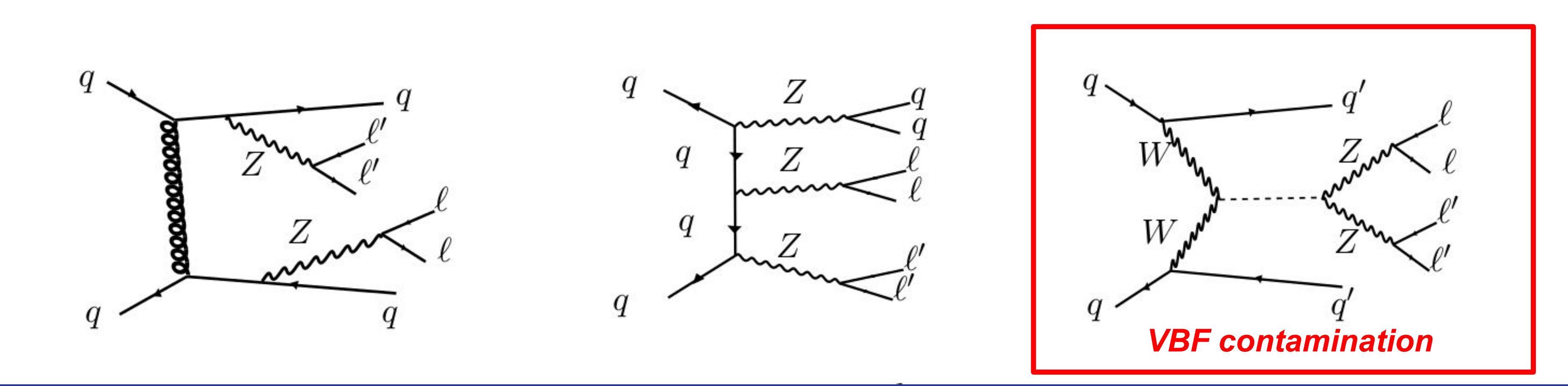
The QCD bkgs are much larger than the signal ⟶ **Need to use multivariate analysis**
In particular we used BDT and MELA

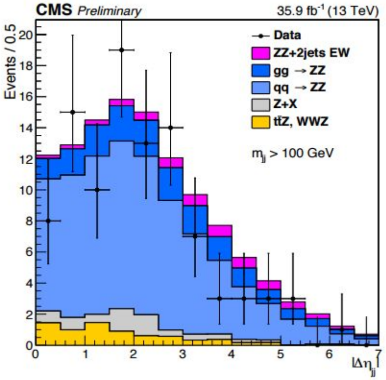


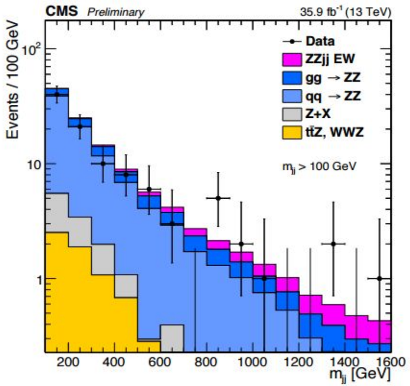
Signal, bkg. and interferences were generated with Madgraph5_aMC@NLO, signal was also studied with PHANTOM

Topologies that don’t enter the signal (cut)

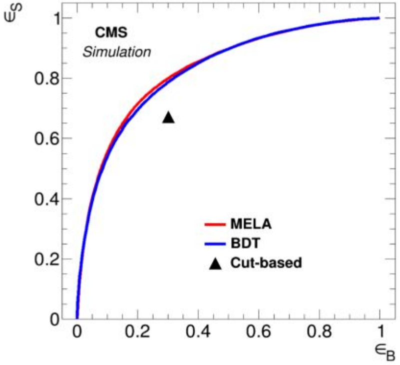
Further, need a smart set of cuts: Mjj> 100 and Mjj > 400 (VBS enriched) , 60 < Mz < 120



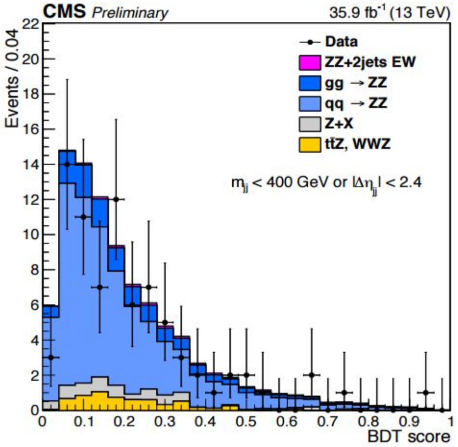




- Little discrimination power on individual variables
- Low statistics, don't want to throw away events
- ⇒ Use multi-variate classifier

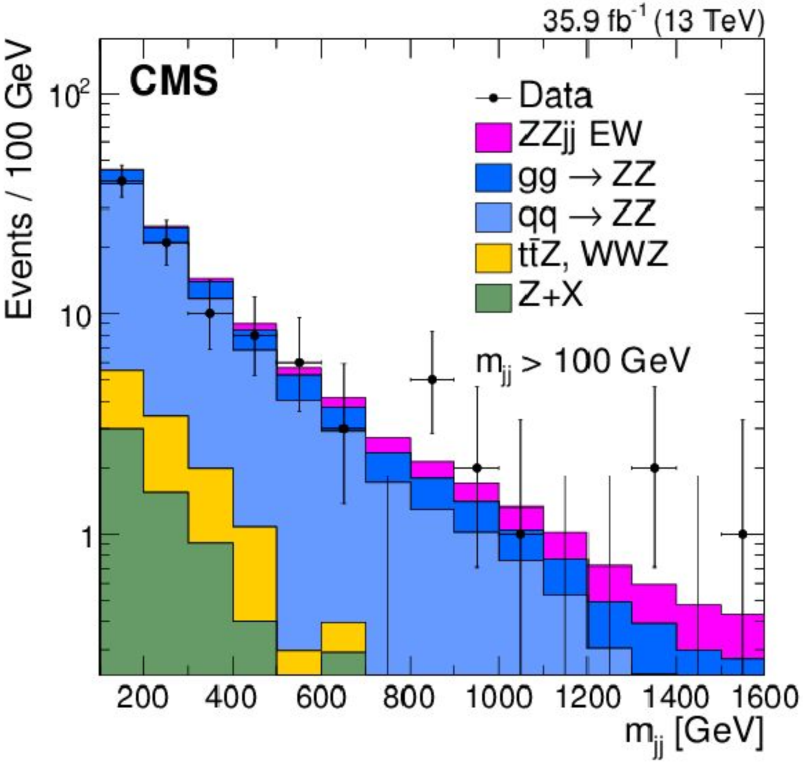


- **BDT optimized** to separate EW signal from QCD-induced production
  - 7 Inputs: m_{jj}, $\Delta\eta_{jj}$, z_1*, z_2*, $R(p_T)$, dijet p_T balance, m_{4l}
  - Identical performance to **M**atrix **E**lement **L**ikelihood **A**pproach

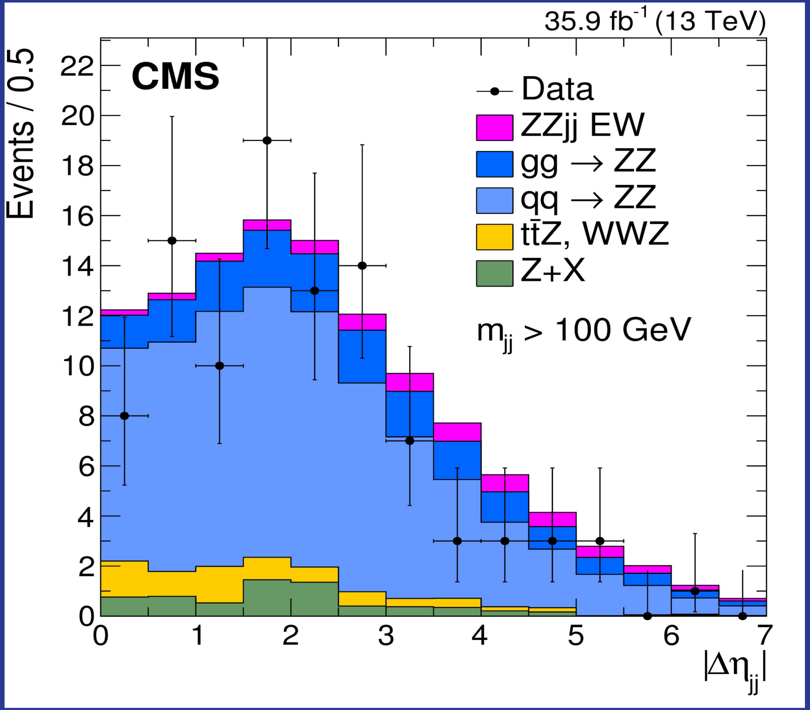


Validation of background model in QCD-enriched side-band finds good agreement

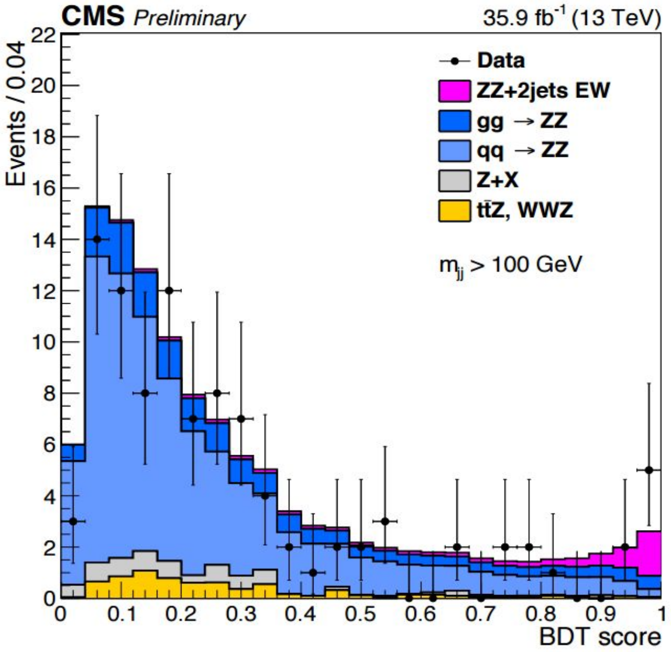
Dijet Mass



Dijet pseudorapidity



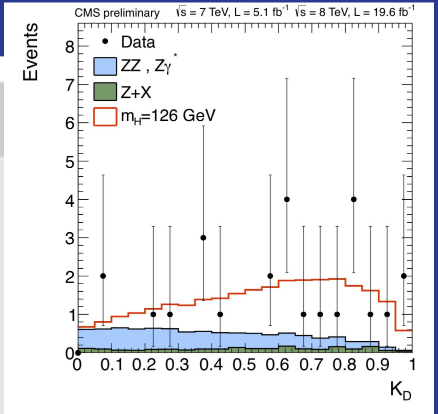
- Signal extracted via template fit, uses full BDT spectrum $\Rightarrow$ constrains the QCD normalization from the data



- Signal strength measured to be $\mu = 1.39^{+0.72}_{-0.57}(\text{stat})^{+0.46}_{-0.31}(\text{syst})$
- Observed significance 2.7σ (expected 1.6σ)
- Fiducial cross section measured as

$$\sigma_{\text{fid.}}(\text{EW pp} \rightarrow \text{ZZ}jj \rightarrow \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb},$$

Alternative to BDT: Matrix element analysis



Method:

- For a given event (i.e. 4ℓ four-momenta) construct probabilities P for it to come from a given process (i.e production + decay)
- These probabilities P are calculated using matrix elements from MC generators (JHUGen, MCFM, ...) or analytical parametrizations
- Already used in the H$\rightarrow$Z$\rightarrow$ 4ℓ analysis

Alternatively:

Matrix element analysis

Use a signal-background kinematic discriminant

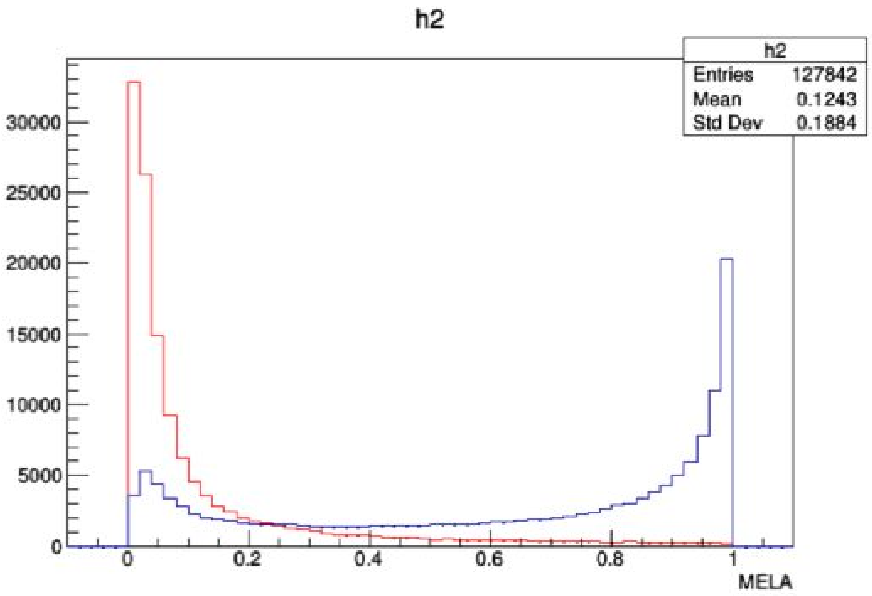
$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, M_{Z_1}, M_{Z_2} | M_{4\ell}) = \frac{P_{sig}}{P_{sig} + P_{bkg}}$$

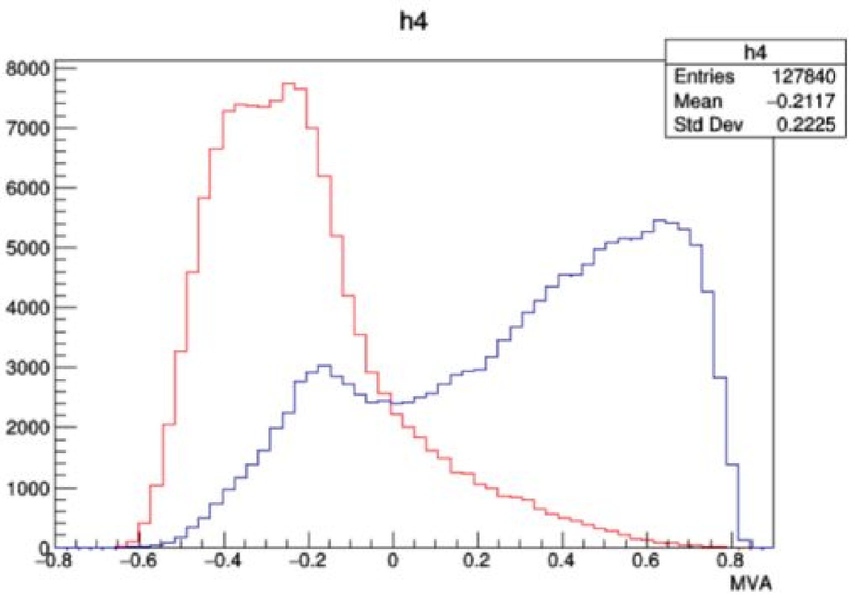
- "sig" and "bkg" are the two processes we want to separate
- P are assumed to be normalized to 1 (else there is one additional dof: "C-Constant", see next slides)
- For a given 4ℓ total mass, there are 7 independent variables for which P are aggregated probabilities, taken correlations into account

Alternatively:

Matrix element analysis

Discriminants for signal and background probabilities (red bkg, blue signal)





Alternatively:

Matrix element analysis

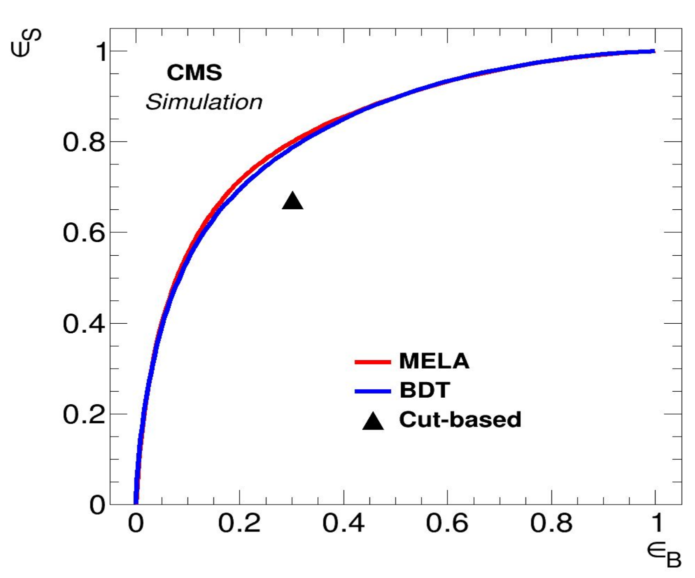
Advantages and Disadvantages of MELA

- (+) Solid theoretical background (wrt MVA)
- (−) Depends on the MELA authors, not autonomous (yet)
- (−) Only useful to discriminate 2 processes, not ≥ 2

(+) Very good results with "minimum effort"

Results for the Expected significance

- $\sigma_{\text{no syst}} = 1.43751$
- $\sigma_{\text{incl.syst}} = 1.23922$



Alternatively:

MELA, systematic errors

Matrix element analysis

Monte Carlo	0.47 - 2.67 %	
PDF Variation	1 - 9.27 %	*OBS. 1 is a "dummy value"*
Scale Variation	1 - 31 %	*31 % due to LO samples*
Jet energy scale	1.12 - 7.24 %	

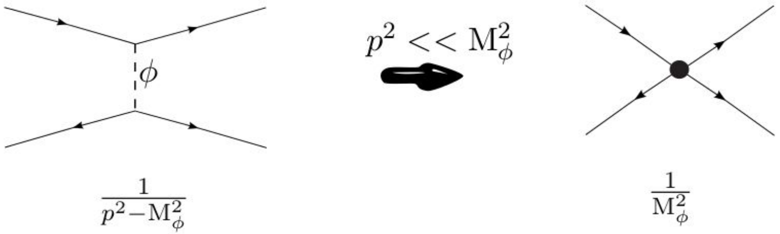
A question for the experts is:
How does the MVA affect the measured cross-section?
i.e. the MVA helps us to extract the signal thanks to an “optimized” fiducial region, then can you really compare the BDT measurement with the theory prediction for the original fiducial region?

(Pseudo-)EFT in VBS:
Searches for aQGCs

**anomalous Quartic Gauge Couplings*

aQGCs:

- Historically: Search for non-SM couplings: ZZZZ, ZZZA, WWAA
- Such couplings must come from some higher energy theory
- EFT interpretation:



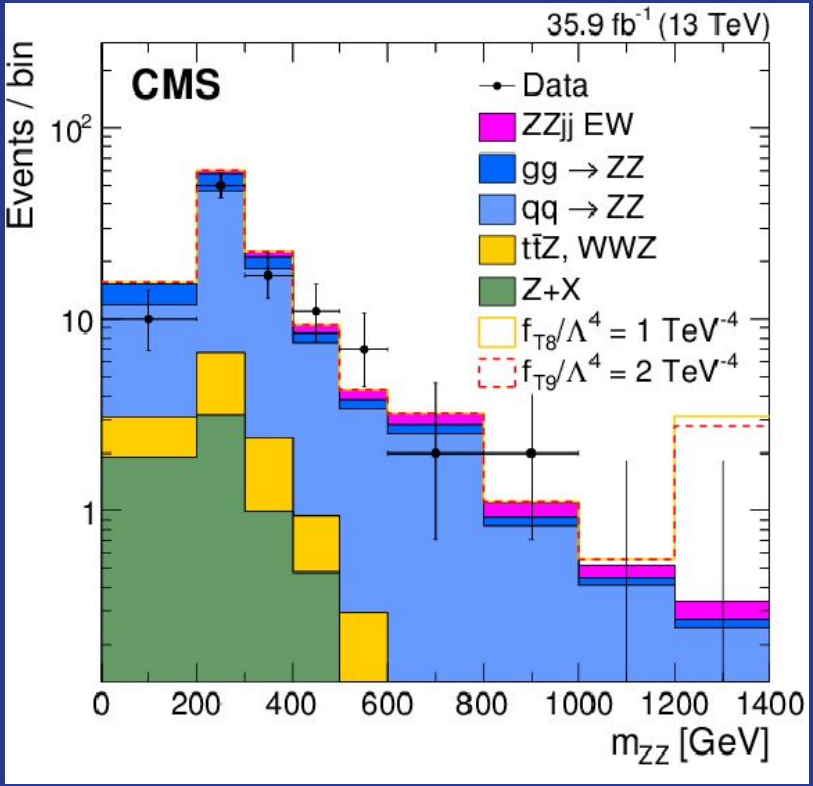
- In triple and quartic gauge couplings, EFT operators enter only from dimension 8 (not at dimension 6)

<u>Modern approach:</u> reinterpret aQCGs as EFT operators.

Scalar operators only involve Higgs doublet	$L_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]$ $L_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D_\nu\Phi\right]$
Mixed operators *mix scalar and tensor*	$L_{M,0} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$ $L_{M,1} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$ $L_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$ $L_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$
Tensor operators *only field strength tensors*	$L_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$ $L_{T,1} = Tr\left[W_{\alpha\nu}W^{\mu\beta}\right] \times Tr\left[W_{\mu\beta}W^{\alpha\nu}\right]$ $L_{T,2} = Tr\left[W_{\alpha\mu}W^{\mu\beta}\right] \times Tr\left[W_{\beta\nu}W^{\nu\alpha}\right]$

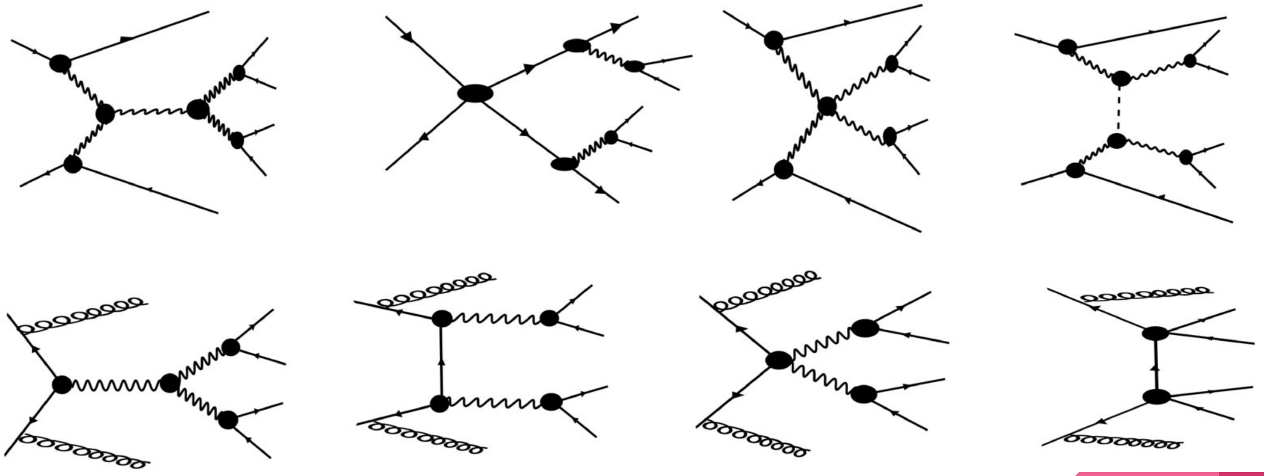
Set limits on aQGCs:

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Run-I limits (TeV^{-4})
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [27]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [27]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [28]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]



Unfortunately EFT is not so simple...

A consistent EFT study needs to include also the dimension 6 contributions, and further, allow modifications in all vertices, not only one.



Thanks

For your attention