VV scattering and Higgs-like couplings @LHC as a probe of EWSB

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PhD seminar

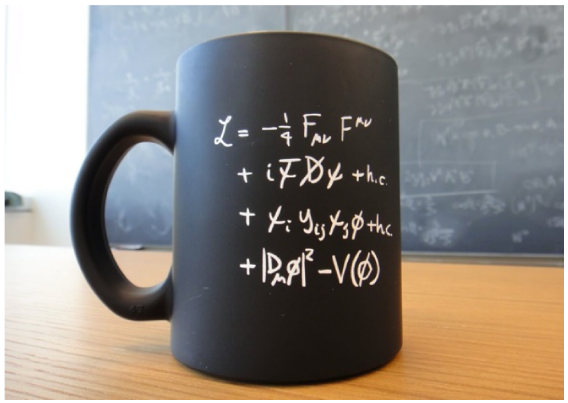
December 6, 2016

[1] Work done in collaboration with G. Passarino and the CMS-Torino group

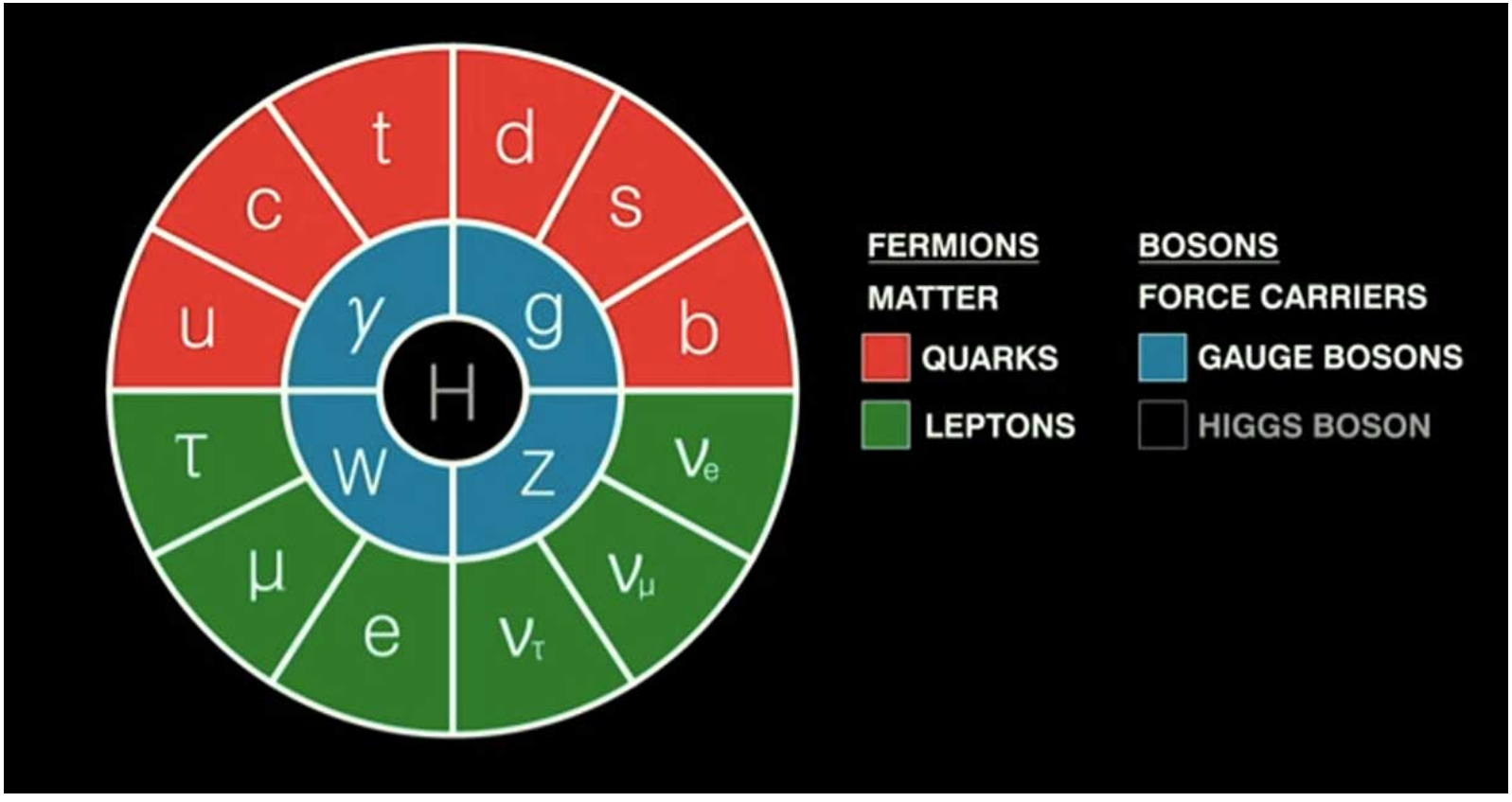
1. Introduction
   - The Standard Model of particle physics
2. Part I: Effective Field Theories
   - Search for new physics: EFT
3. Part II: VBS studies at LHC
   - $ZZ \to 4\ell$ analysis

The Standard Model: Electromagnetic, Electroweak and Strong Force

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

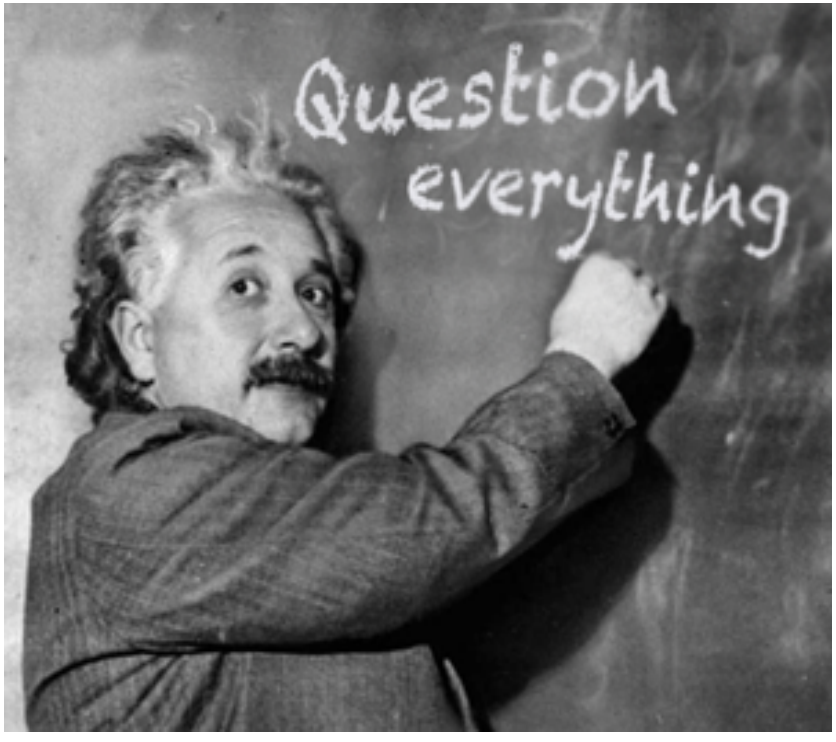


In terms of particles:



Open questions

- Neutrino masses
- Gravity
- Dark Matter
- Hierarchy problem
- Naturalness
- Origin of EWSB

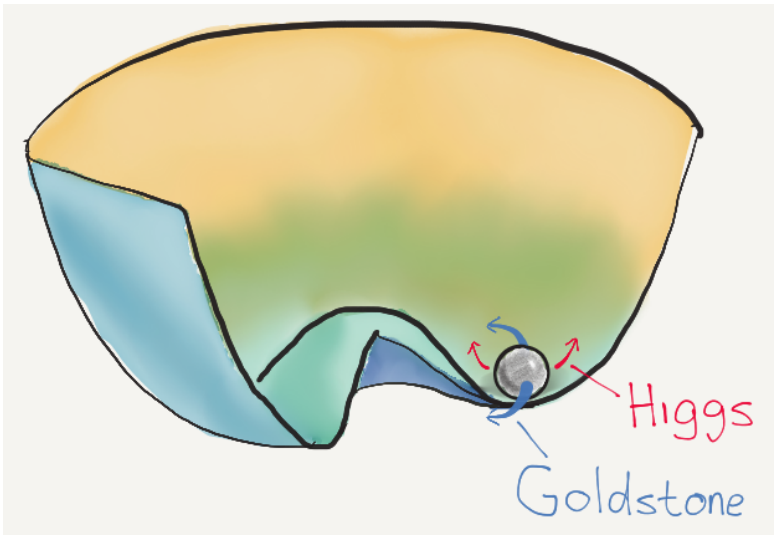


Electroweak Symmetry Breaking (EWSB)

We know that the Gauge Bosons of the $SU(2) \times SU(3)$ theory, are not exactly the same as we observe experimentally: $W^{\pm}$ and Z

There is a mechanism that describes how these bosons acquire masses, breaking the gauge symmetry *spontaneously* ...

This is known as the **"Higgs Mechanism"** or **"EWSB mechanism"**



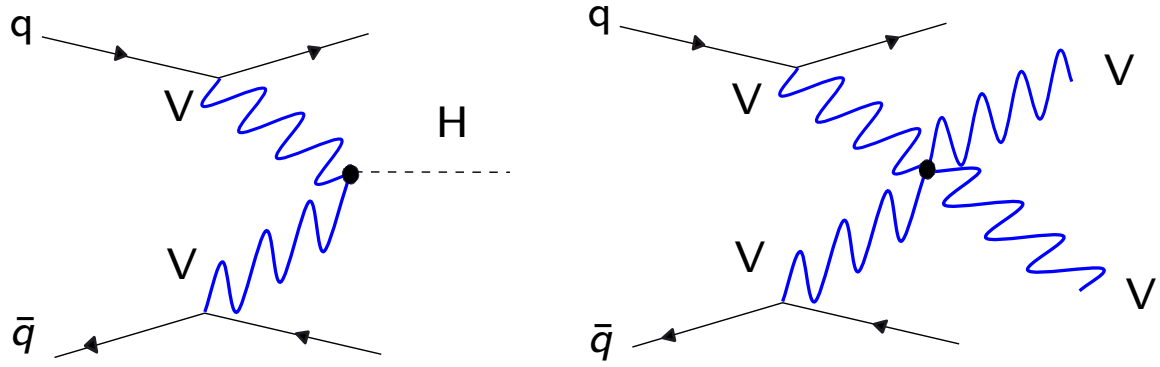
Higgs Mechanism

We say that the Gauge symmetry is broken spontaneously, because we don't really know **why** this happens.

The Higgs boson was discovered in 2012 at LHC, representing a huge success for the Standard Model of particle physics.

But still, all the questions regarding the behaviour of this new particle (couplings, decay widths, ...) and in particular, the **origin of EWSB** remains unknown to us.

Vector Boson Fusion & Vector Boson Scattering



$$V = W^+ , W^-, Z , \gamma$$

Why look at this production channel? Mainly 2 reasons:

- Subleading channel for H production at LHC.
- Most important channel for EWSB and unitarity studies.

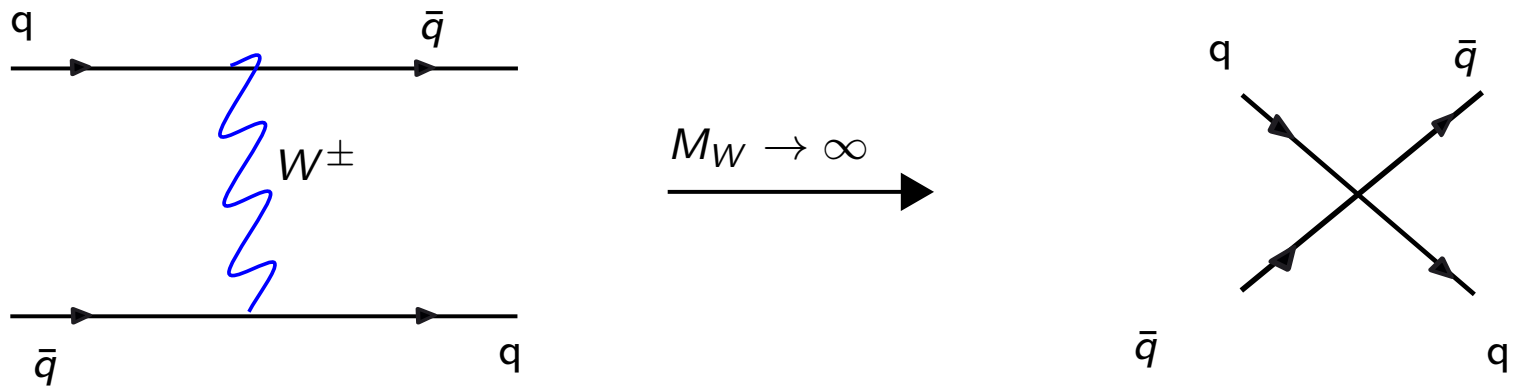
Plus: LHC will reach % accuracy $\rightarrow$ EW corrections challenging but relevant

SEARCHING FOR NEW PHYSICS

Effective Field Theory

Take an *ultraviolet* theory and integrate out the heavy fields to find out its low energy behaviour. In particular, the propagator becomes a point.

Recall Fermi theory for β decay :



Other historical examples of EFTs are Landau-Ginzburg theory for superconductivity and the (non)-linear sigma model for (anti)-ferromagnetism.

Two basic things about EFTs:

1) Top-down Vs. Bottom-up approach

- In the **Top-down** approach,
  - Start from a complete high energy theory
  - Study its behaviour in its infrared regime
  - Assuming heavy modes decouple, calculations become simpler.

- In the **Bottom-up** approach,
  - Start from an low-energy known theory (the SM).
  - Study its high energy behaviour.
  - Add operators consistent with the symmetries.
  - Match the unknown with experimental observations.

Two basic things about EFTs:

2) Relevant, Marginal and Irrelevant operators

- Introduced by K. Wilson, in the context of renormalization
- Check mass dimension Vs. spacetime dimensions $\begin{cases} [\mathcal{O}] < d & \text{relevant} \\ [\mathcal{O}] = d & \text{marginal} \\ [\mathcal{O}] > d & \text{irrelevant} \end{cases}$
- Relevant and marginal operators, like the ones in $\mathcal{L}_{SM}$, become increasingly large at higher energies
- Irrelevant operators, decrease at higher energies, and are not *"influential"*

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{dim=5} + \mathcal{L}_{dim=6} + \cdots = \\ = (\sim \Lambda^0) + (\sim \Lambda^{-1}) + (\sim \Lambda^{-2}) + \ldots$$

Effective Field Theory: Top-Down approach

- Model-dependent, therefore not very efficient ...
- Useful for Dark Matter and SUSY searches

Low energy behaviour of standard model extensions

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INFN, Sezione di Torino, Italy

arXiv: 1603.03660

Effective Field Theory: The bottom-up approach

Augment the SM with operators of dim > 4, suppressed by factors of a new scale Λ^{d-4}

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{dim 4}} + \underbrace{\frac{1}{\Lambda^2}\sum_k \alpha_k \mathcal{O}_k^{(6)}}_{\text{dim 6}} + \underbrace{\frac{1}{\Lambda^4}\sum_k \alpha_k \mathcal{O}_k^{(8)}}_{\text{dim 8}} + \underbrace{\ldots}_{\text{higher dim. operators}}$$

- α_k is the Wilson coefficient of the kth operator. $\rightarrow$ *assume they allow to use PT*
- For the current experimental resolution we can truncate this expansion at $d = 6$
- Choose a basis of dim-6 operators, with $SU(2) \times SU(3) \times U(1)$ and lepton/baryon conservation, **and** assuming flavor universality.
- We chose the "Warsaw Basis" $\rightarrow$ arXiv: 1008.4884 $\rightarrow$ containing 59 operators.

A word on renormalization of the EFT

- The EFT is renormalizable order by order. We have to calculate the new CTs though: $\Phi = Z_\Phi \cdot \Phi_{ren}, \quad p = Z_p \cdot p_{ren}$

$$Z_i = 1 + \frac{g^2}{16\pi^2}\left(dZ_i^{(4)} + g_6\, dZ_i^{(6)}\right)$$

- This is what we studied in: see [arXiv: 1505.03706]

NLO Higgs Effective Field Theory and κ-framework*

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Amplitudes

EFT Amplitudes

$$\mathcal{A} = \sum_{n=N}^{\infty} g^n \mathcal{A}_n^{(4)} + \sum_{n=N_6}^{\infty} \sum_{\ell=0}^{n} \sum_{k=\ell}^{\infty} g^n g_{4+2k}^{\ell} \mathcal{A}_{n\ell k}^{(4+2k)}, \qquad g_{4+2k} = \frac{1}{(\sqrt{2} G_F \Lambda^2)^k}$$

More concretely:

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(6)}|}_{\mathcal{O}(\frac{1}{\Lambda^2})} + \underbrace{|\mathcal{A}^{(6)}|^2}_{\mathcal{O}(\frac{1}{\Lambda^4})} + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(8)}|}_{\mathcal{O}(\frac{1}{\Lambda^4})} + \ldots$$

Where do we truncate the amplitude expansion?
How do we estimate theoretical uncertainties?

Amplitudes

EFT Amplitudes

$$\mathcal{A} = \sum_{n=N}^{\infty} g^n \mathcal{A}_n^{(4)} + \sum_{n=N_6}^{\infty} \sum_{\ell=0}^{n} \sum_{k=\ell}^{\infty} g^n g_{4+2k}^{\ell} \mathcal{A}_{n\ell k}^{(4+2k)}, \qquad g_{4+2k} = \frac{1}{(\sqrt{2} G_F \Lambda^2)^k}$$

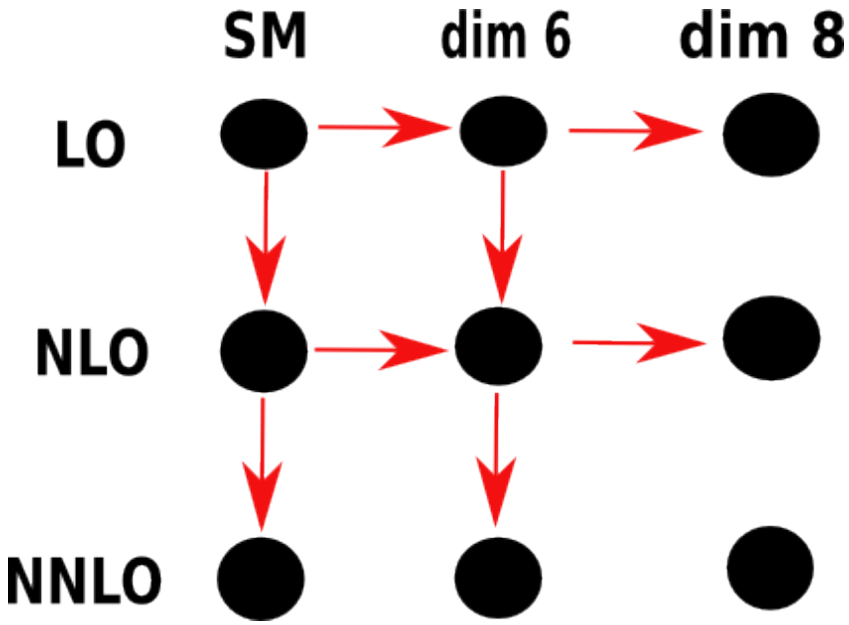
More concretely:

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(6)}|}_{\text{“linear EFT”}} + \underbrace{|\mathcal{A}^{(6)}|^2}_{\text{“quadratic EFT”}} + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(8)}|}_{\text{not available (th.uncertainty)}} + \ldots$$

Where do we truncate the amplitude expansion?
How do we estimate theoretical uncertainties?

Higher order corrections: Power counting

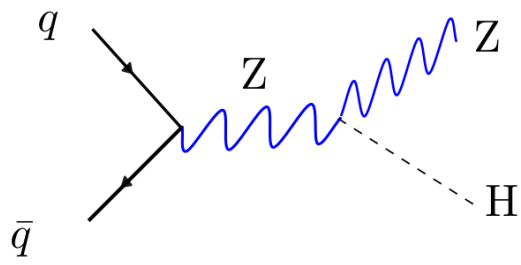
The hierarchy of corrections is driven by the value of Λ. Without knowing Λ we can not know if NLO dim 6 corrections are bigger or smaller than LO dim 8 ones.



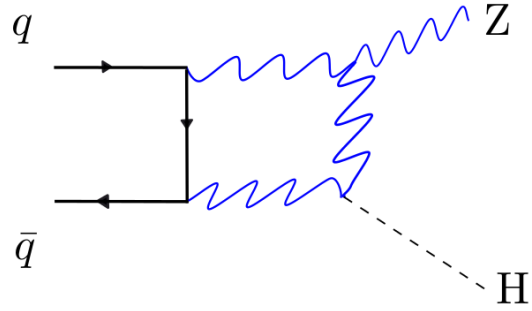
NLO EFT Example:

some diagrams for $pp \to ZH$, contributing up to $\mathcal{O}(\frac{1}{\Lambda^2})$

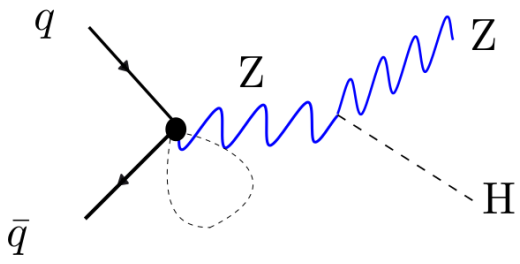
SM LO



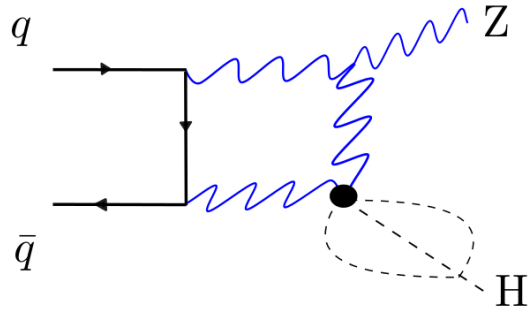
SM NLO



EFT Contact terms



EFT NLO



Applicability of the EFT

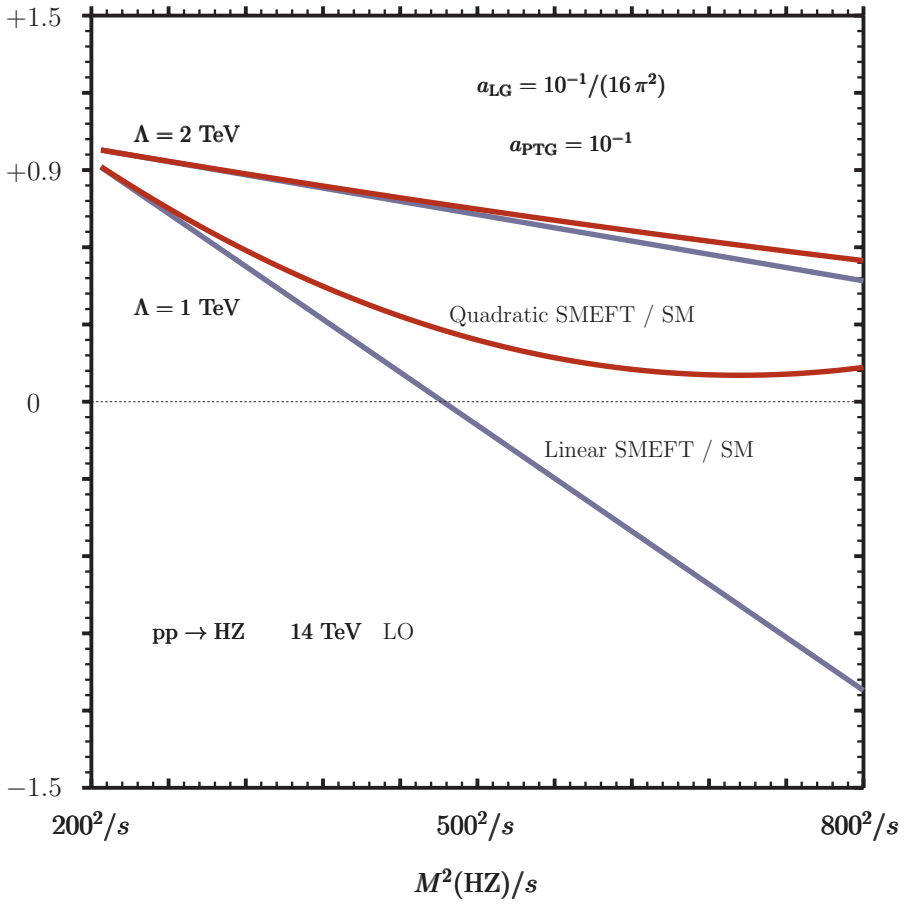
The EFT introduces a new scale on the theory, Λ, or possibly more:

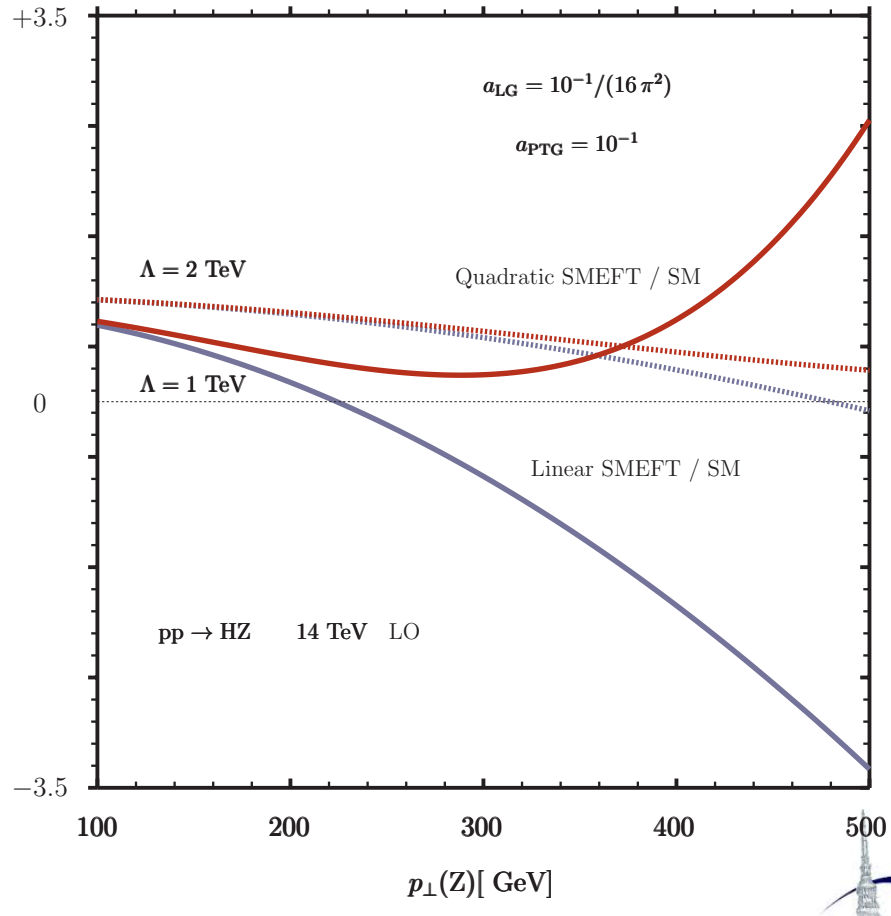
- We assume the new heavy particles are well separated from the SM ones
- Λ is *related* to the mass of the heavy particles in the UV completion.
- But we don't know how they mix with the Higgs: $\Lambda \pm g\nu$, $\sin(\theta)$

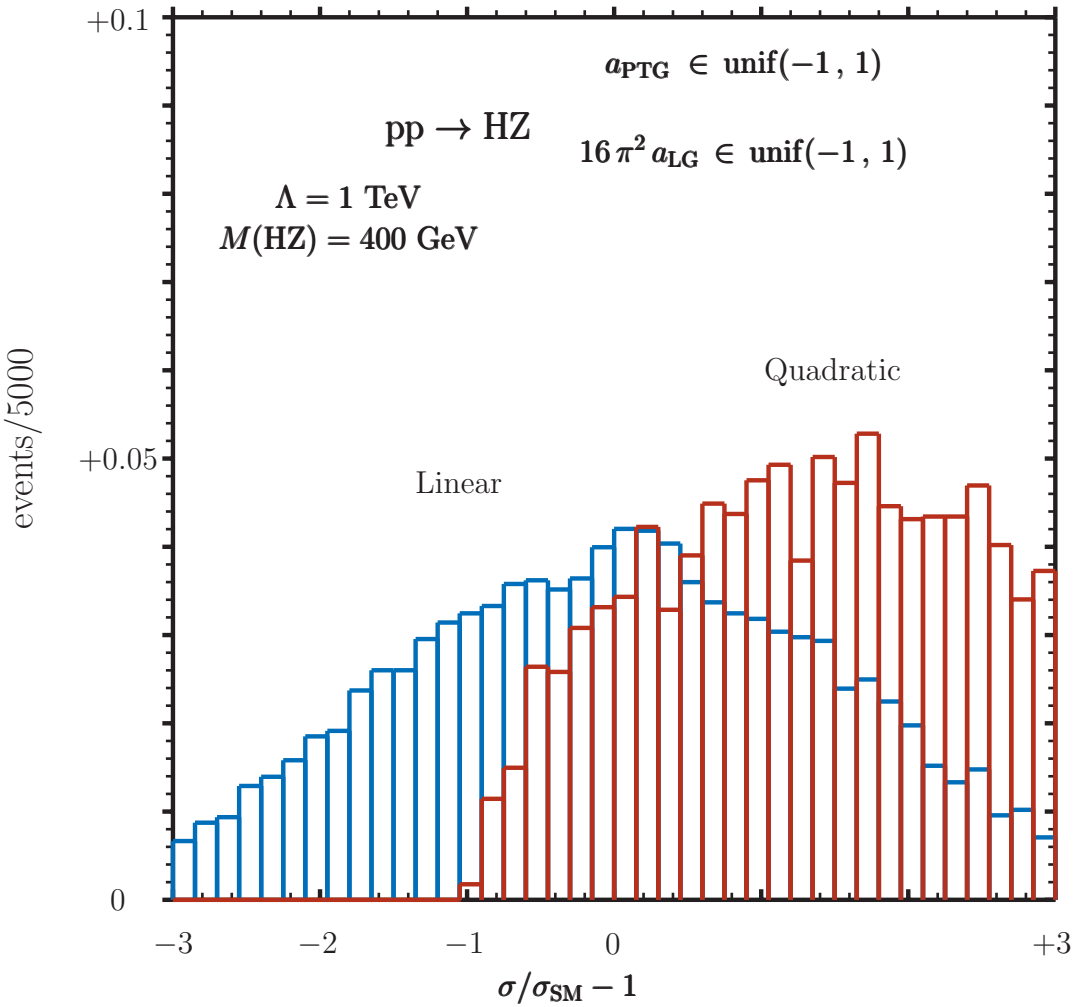
The cut-off of the effective theory at LHC:

- $|\frac{\sigma \times BR}{(\sigma \times BR)_{SM}} - 1| = \frac{g^2 m_h^2}{\Lambda^2} \simeq 0.1 \quad \rightarrow \quad \Lambda < \sqrt{10} g m_h \approx \underbrace{400\,GeV \ldots 1.4\,TeV}_{(\text{for } g = 1 \ldots \sqrt{4\pi})}$

Some results: Tails of kinematic distributions





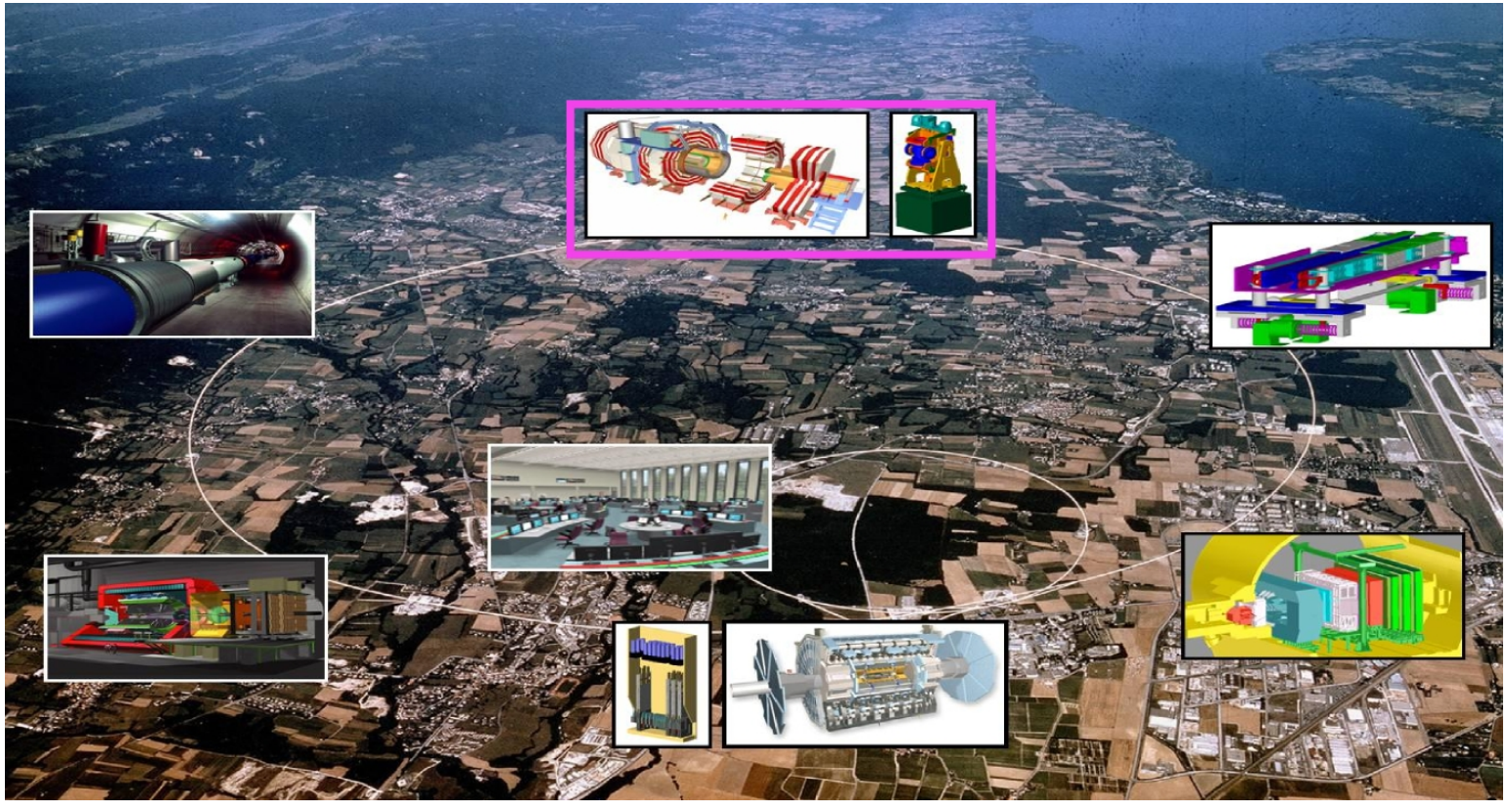


- Sigma goes negative if we only include linear
- The quadratic corrections are apparently bigger than the linear
- A study of partial waves (perturbative unitarity) can help us understand the validity of the theory.

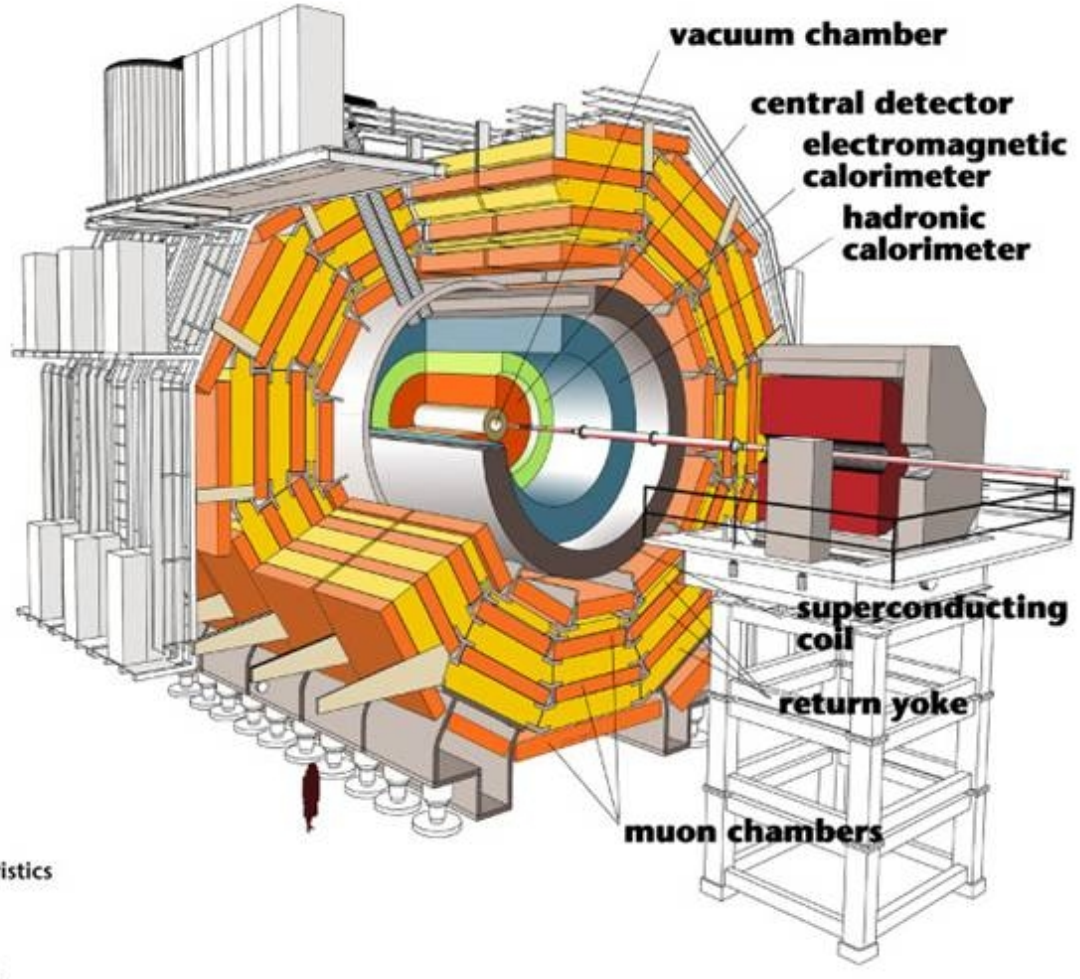
Part II: VBS studies at LHC

Work done in collaboration with part of CMS-Torino:
R. Bellan, R. Covarelli, L. Finco, C. Mariotti, G.L. Pinna

Main Experiements at LHC: ATLAS, CMS, LHCb, ALICE



CMS Detector, the Compact Muon Solenoid



Available on the CERN CDS information server **CMS PAS SMP-15-012**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2016/08/21

Measurement of the differential cross sections for pairs of Z bosons produced in association with jets in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

CMS-PAS-SMP-15-012

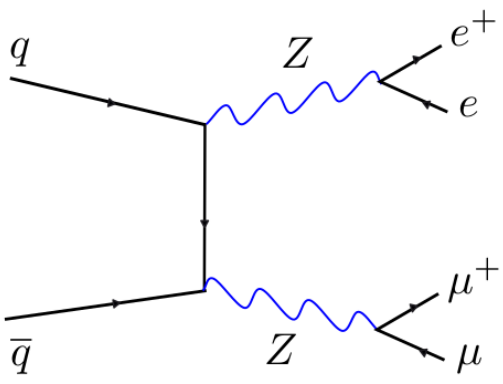
We look at signal and background for VBS processes at the generator level. We confront different generators using Rivet. In particular: Madgraph5_aMC@NLO Vs. POWHEG for the background and Madgraph5_aMC@NLO (at LO) Vs PHANTOM for the signal.

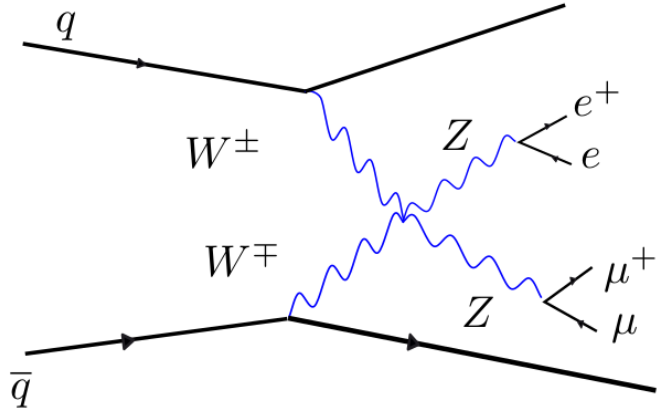
Goal:

Our goal is mainly to figure out which are the most relevant variables to study in order to isolate the VBS signal from its background.

Monte Carlo Samples

- First we looked at the process $q\bar{q} \to ZZ \to 4\ell$ (background for VBS and VBF)
- We produced different samples using Madgraph5_aMC@NLO and Powheg with similar settings as the CMS official production.
- Then we looked at the VBS induced process: $pp \to ZZ \to 4\ell$





Samples Generated

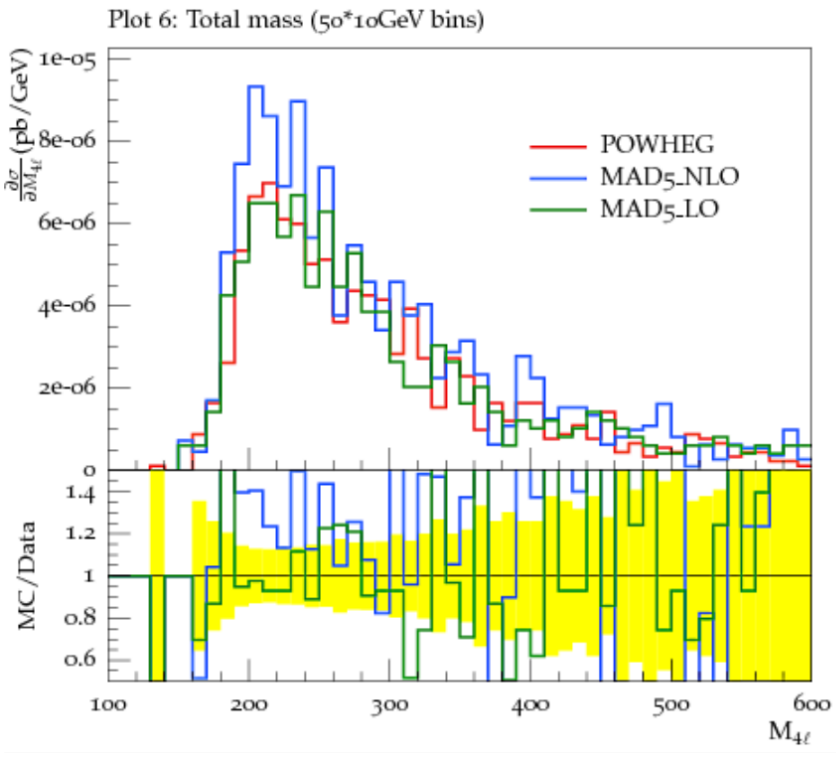
ZZ + jets (3 generators

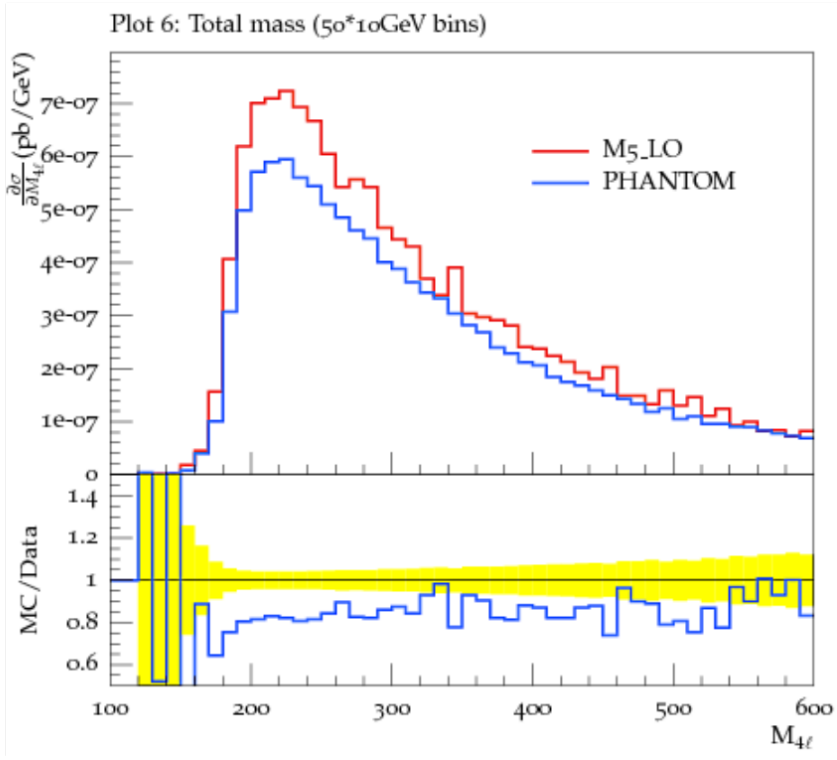
- Madgraph5_aMC@NLO at Leading Order: up to 2 jets in ME, MLM merging
  pp $\to \ell^+\ell^-\ell^+\ell^-$ j j QCD = 0 , QED = 4
  Cross-section $= 1.003 \pm 4.343 \cdot 10^{-03}$ pb
- Powheg, NLO process:
  pp $\to \ell^+\ell^-\ell^+\ell^-$ j j QCD = 2, QED = 4
  Cross-section $= 1.257 \pm 1.921 \cdot 10^{-03}$ pb
- Madgraph5_aMC@NLO, NLO up to 1 jet in ME, FxFx merging.
  pp $\to \ell^+\ell^-\ell^+\ell^-$ j j QCD = 2, QED = 4
  Cross-section $= 1.218 \pm 2.073 \cdot 10^{-03}$pb

VBS (ZZ)

- Madgraph5_aMC@NLO at LO:
  pp $\to \ell^+\ell^-\ell^+\ell^-$ j j QCD = 2, QED = 6
  Cross-section: $1.008 \cdot 10^{-2} \pm 7.791 \cdot 10^{-5}$ pb
- Phantom:
  pp $\to e^+e\ \mu^+\mu$ j j QCD = 0, QED = 6
  Cross-section $= 4.273 \cdot 10^{-4} \pm 2.1778 \cdot 10^{-7}$ pb (with extra generator cuts)

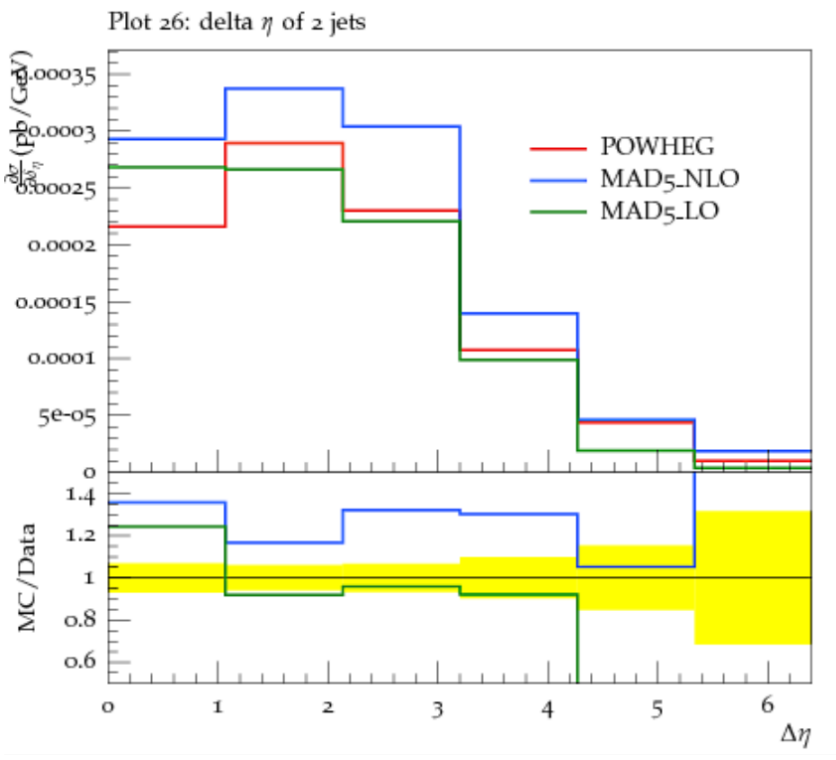
Invariant mass of the 4ℓ final state: $ZZ \rightarrow 4\ell + 2j$ Vs. VBS (ZZ)

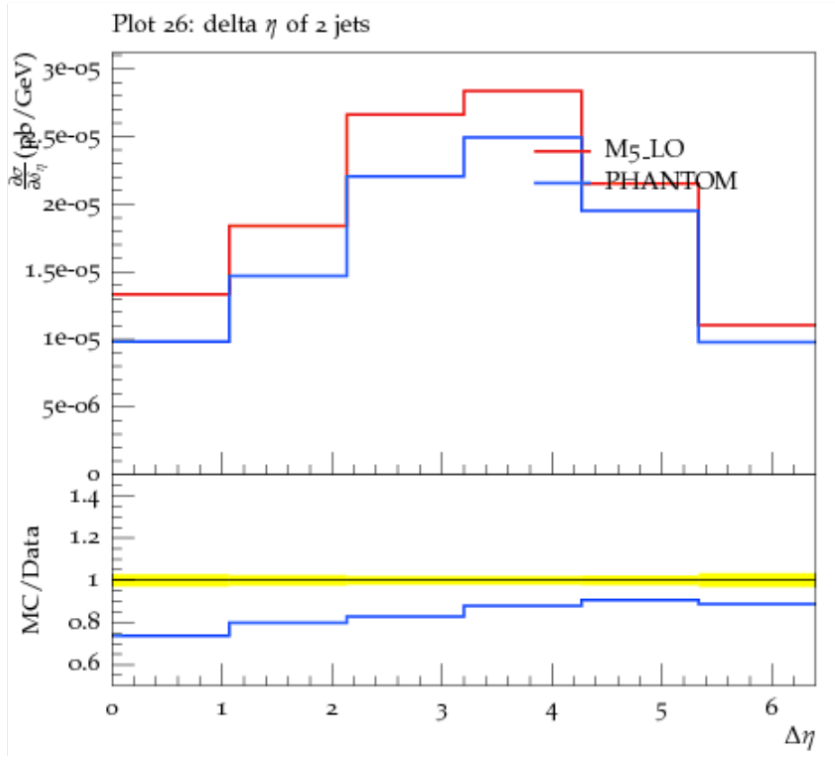




The number of events per bin is two orders of magnitude smaller in the VBS channel

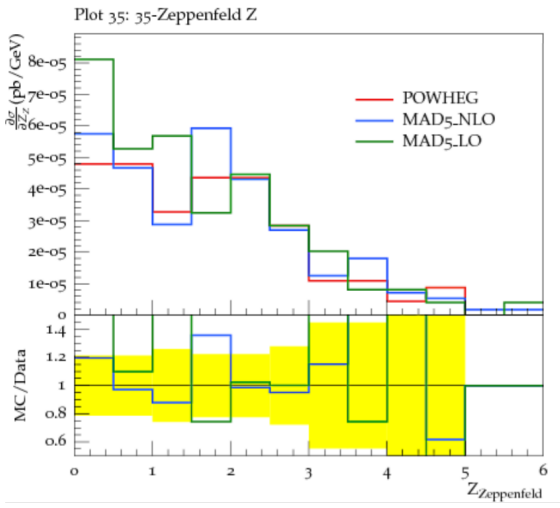
Delta η of the tagged jets: $ZZ \to 4\ell + 2j$ Vs. VBS (ZZ)

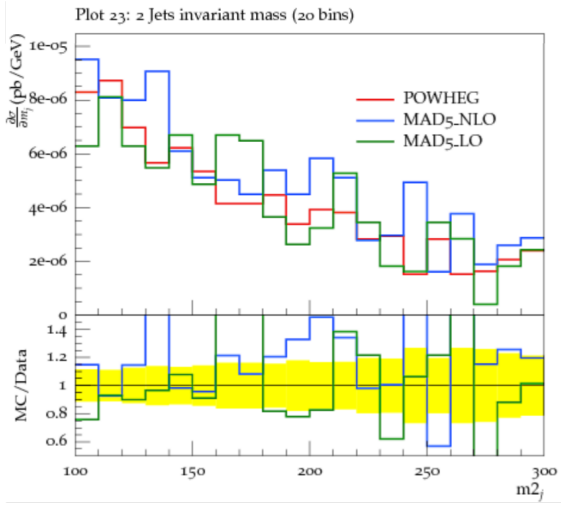


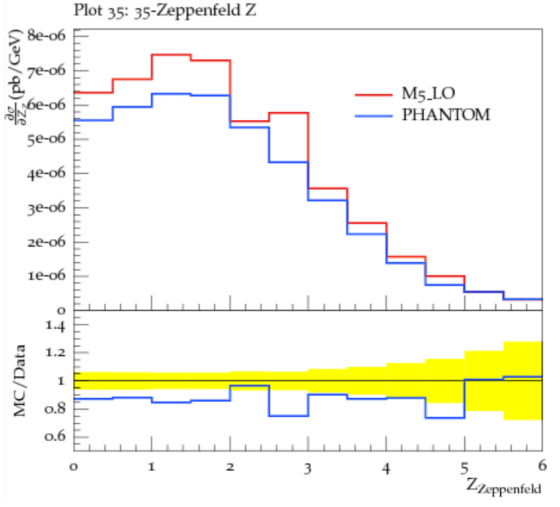


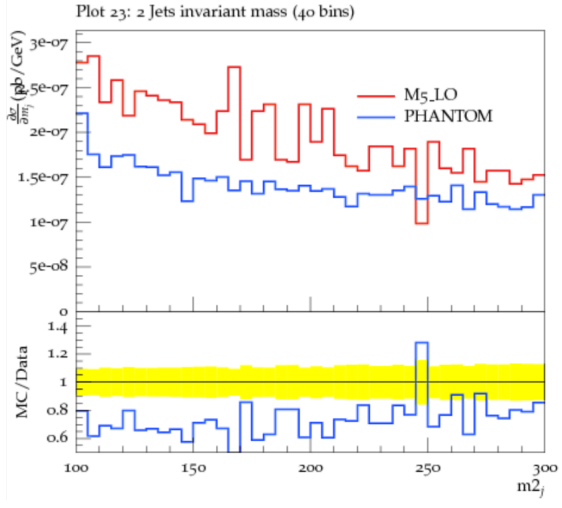
The shapes for VBS and ZZ$\to 4\ell$ are very easy to distinguish

Other interesting variables: Zeppenfeld z and Jets invariant mass









Next steps: the VBS analysis

- We are currently studying the MELA (Matrix Element Likelihood Analysis) technique. As an alternative to a conventional analysis.
- This method was already used in the Higgs discovery, and it is known to be a good signal/background discriminator.

Thank you