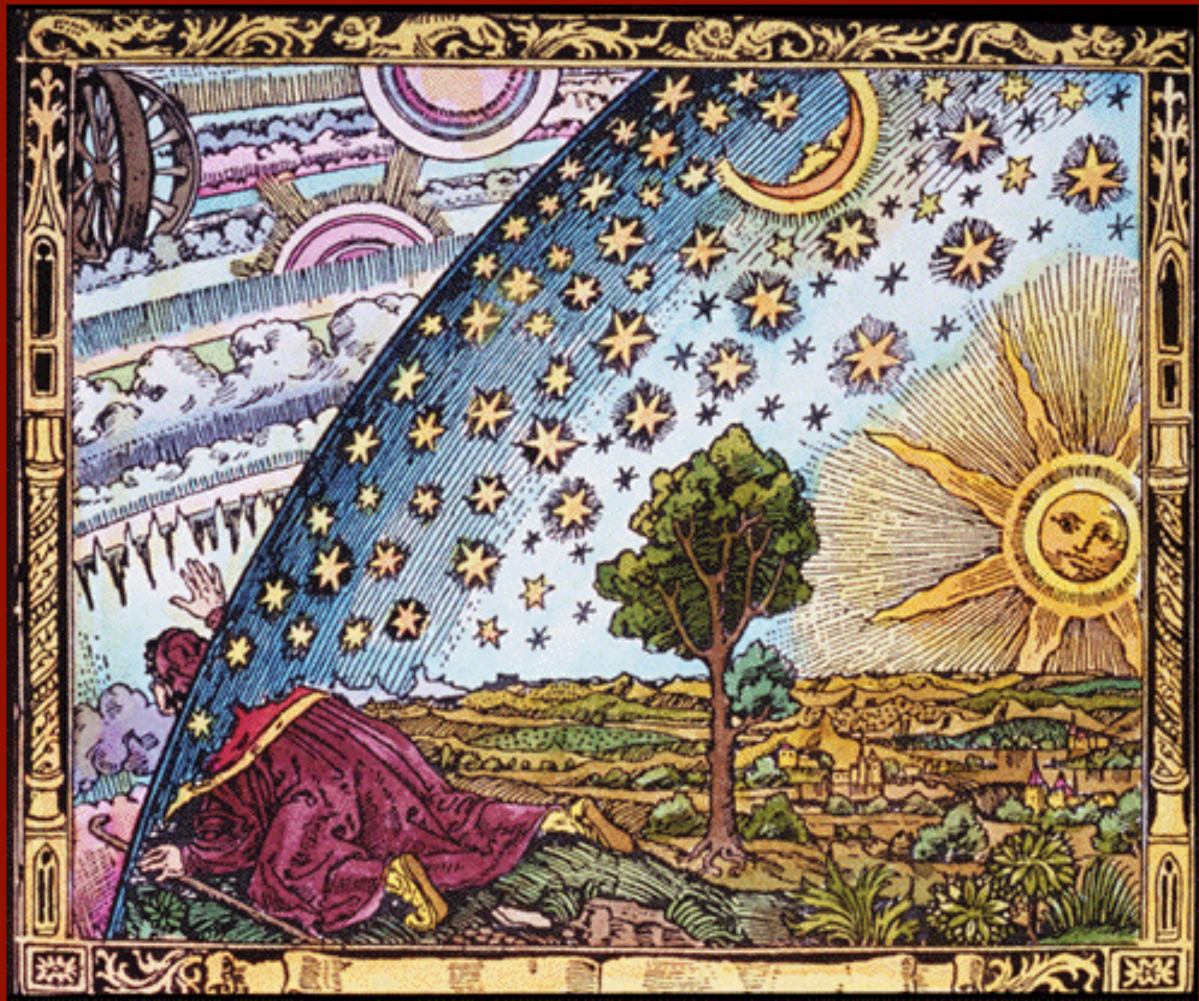
Vector Boson Scattering



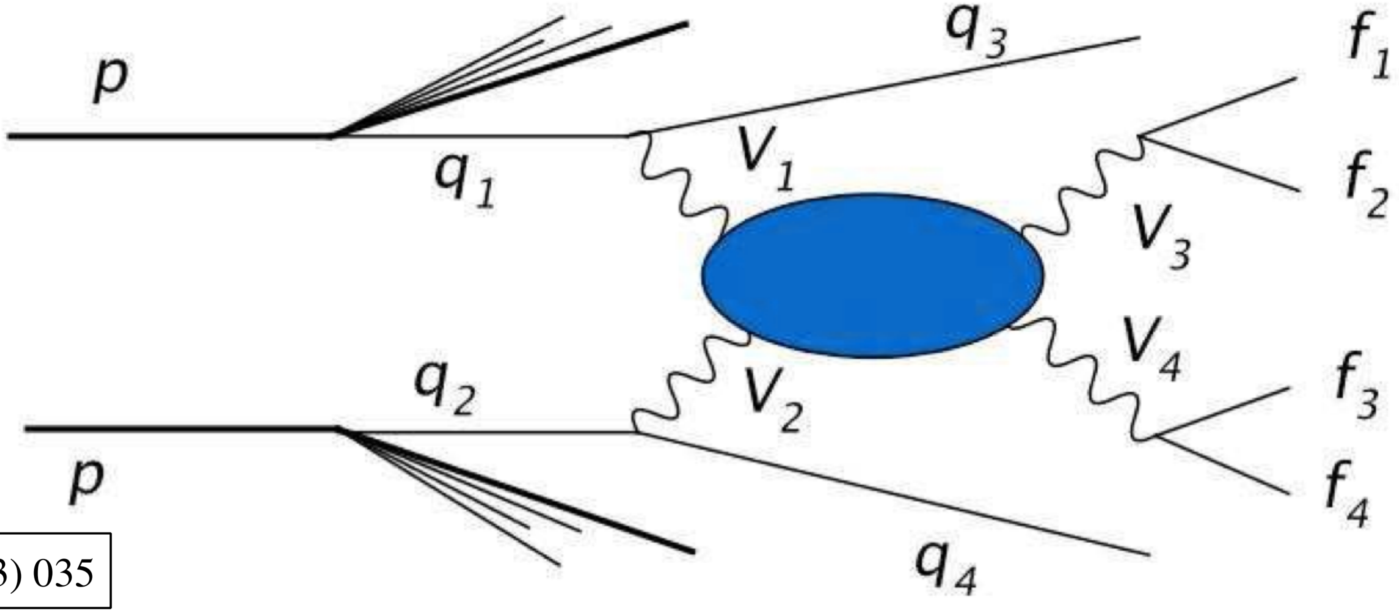
Pietro Govoni, Chiara Mariotti, Chiara Roda

La Biodola, 22 maggio 2014

ATLAS EXPERIMENT
http://atlas.ch

CMS
Compact Muon Solenoid

LHC: the large vector boson collider



JHEP 1307 (2013) 035

High energy vector boson scattering continues to play a central role,

- either as a **test of the Higgs boson nature**:
  If the discovered Higgs boson contributes fully to EWSB, conventional wisdom tells us that the scattering of longitudinal weak gauge bosons would not grow strong at high energies.

- or as one of the main experimental (and **model independent**) grounds to the understanding of **which alternative theory is at work**:
  if the 125.5 GeV Higgs boson is only partially responsible for EWSB, and the rest is very heavy, then the VV scattering could get strong for a range of energy

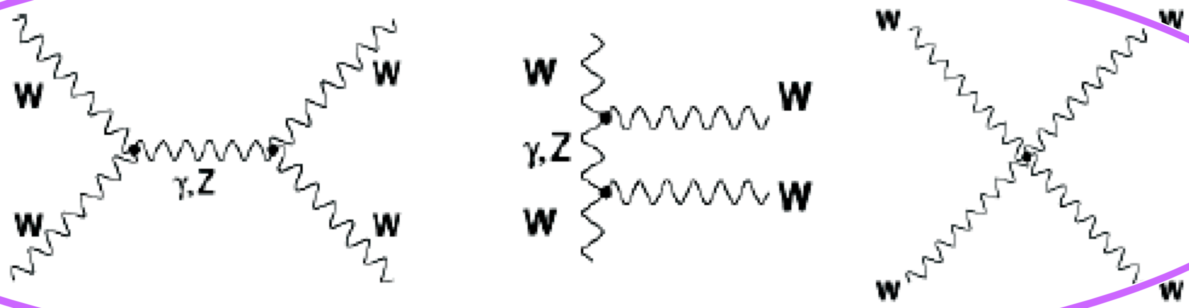
The SM Higgs

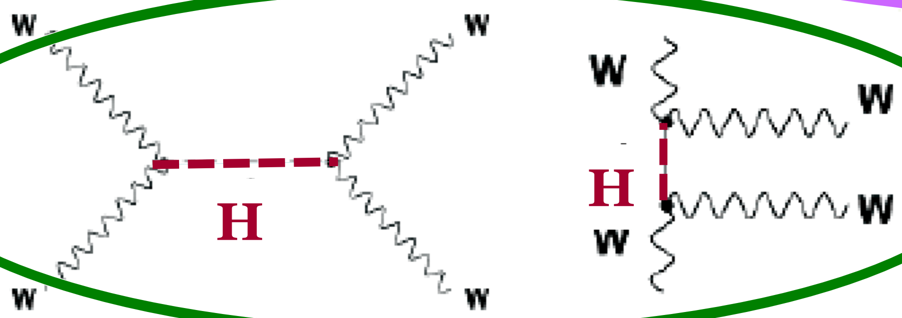
The Higgs mechanism explains how the elementary particles get mass.

The W and Z acquire the longitudinal degree of freedom (W_L, Z_L).

Without the Higgs, **$V_LV_L \rightarrow V_LV_L$ would break perturbative unitarity**

(for $\sqrt{s}$>~1.2 TeV).



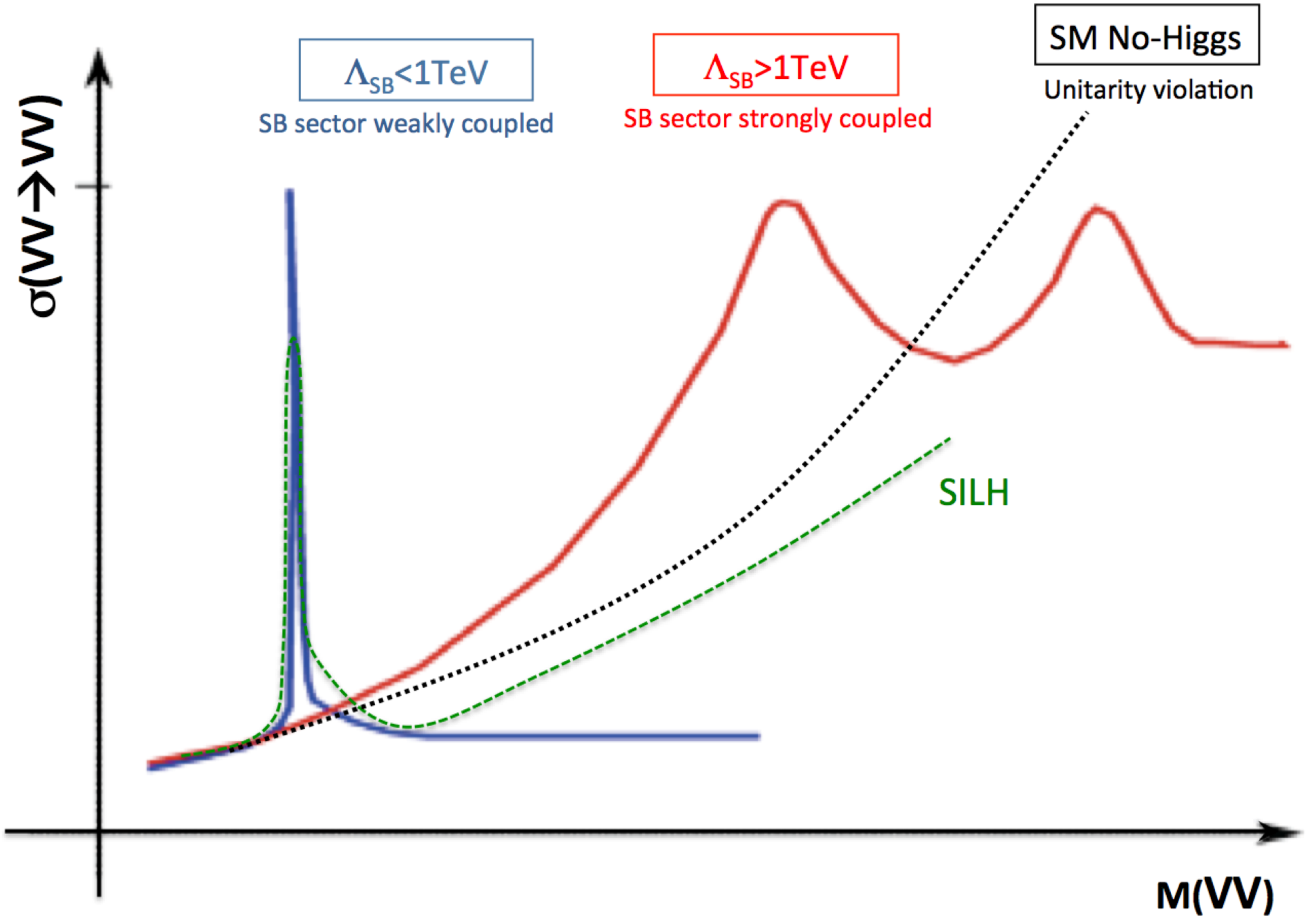


$$\sigma_{V_LV_L \rightarrow V_LV_L} \propto \left[-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right]$$

SM or new physics?

WW Scattering to test the degree of EWSB of the Discovered Higgs

Qualitatively:



Ballestrero, Bolognesi, LHC2TSP

SILH :

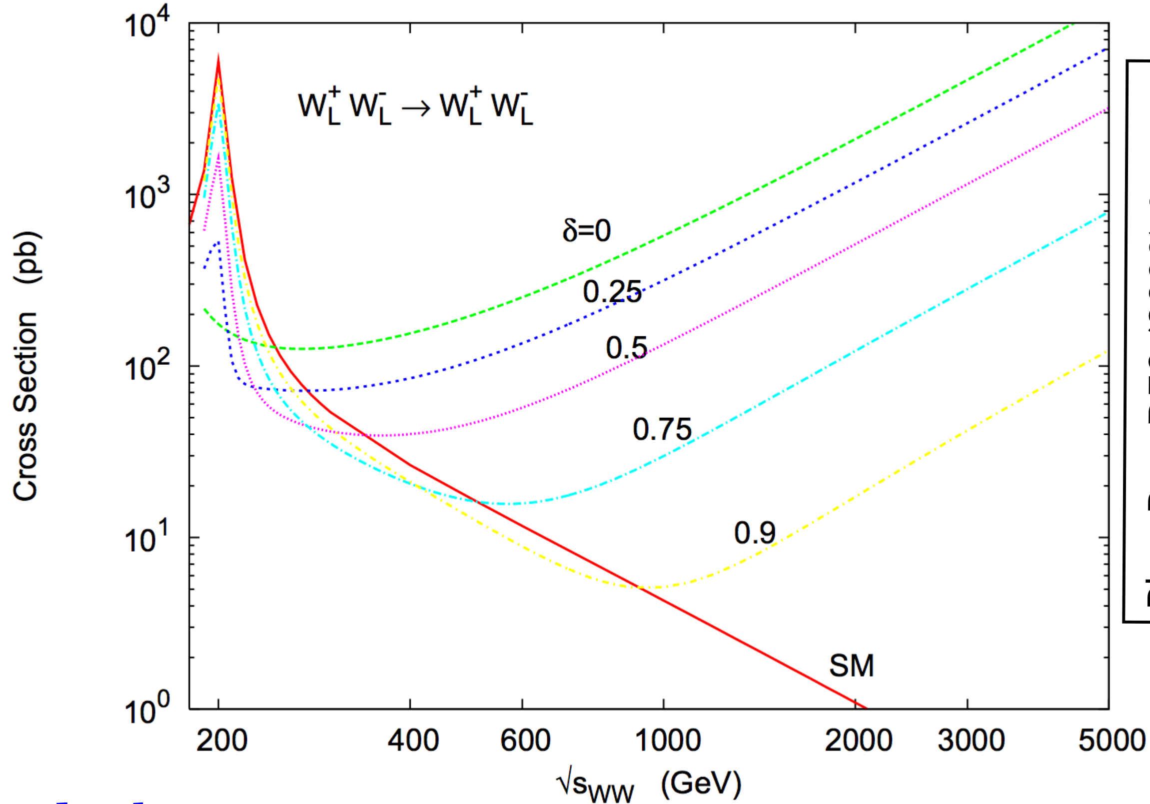
Higgs a pseudo Goldstone Boson of a new strong sector
Both a light Higgs and Bosons strongly coupled
Modified higgs coupling $g_h \rightarrow g_h / \sqrt{1+\xi c_H}, \xi = v^2 / f^2$

SILH Giudice et al arXiv:hep-ph/0703164v2

Partially Strong $W_L W_L$ Scattering

If the cancellation of the Higgs diagrams is not complete, then we expect a **g_{hWW} coupling smaller than the SM**.

The $W_L W_L$ will **keep growing** with √s, up to the the new resonance, or more generally to the new physics scale Λ.



Phys.Rev. D78 (2008) 051701

Suppose the Higgs-WW coupling is **√δ of the SM** value, then the amplitudes become

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4m_W^2}\,u + \mathcal{O}((E/m_W)^0)$$

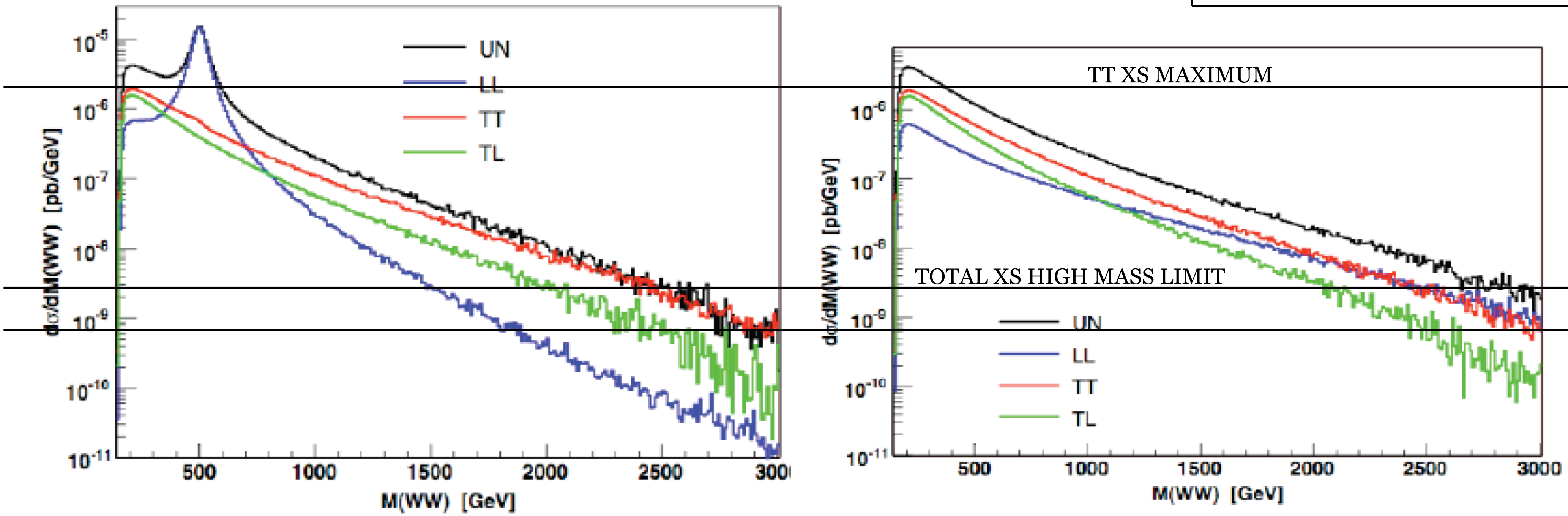
$$i\mathcal{M}^{\text{higgs}} = i\frac{g^2}{4m_W^2}\,u\,\delta + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{all}} = -i\frac{g^2}{4m_W^2}u(1-\delta) + \mathcal{O}((E/m_W)^0)$$

→ **Measure with high precision hVV coupling and $V_L V_L$ scattering**

V_L and V_T at hadron colliders

Accomando et al: hep-ph/0512219



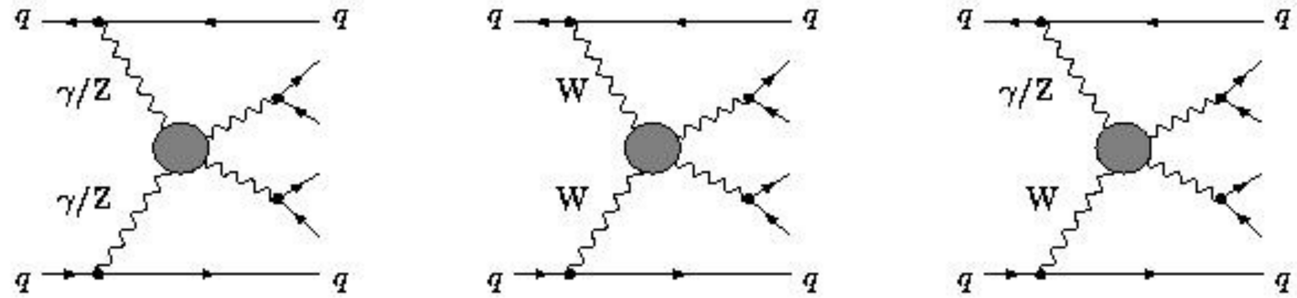
- At large M(VV) the LL XS is of the same order as the TT one (in the no-Higgs case)
- LL XS gives information on **the scale at which the symmetry breaks**.

If there is a new resonance at a scale Λ, the LL XS will not decrease until Λ.

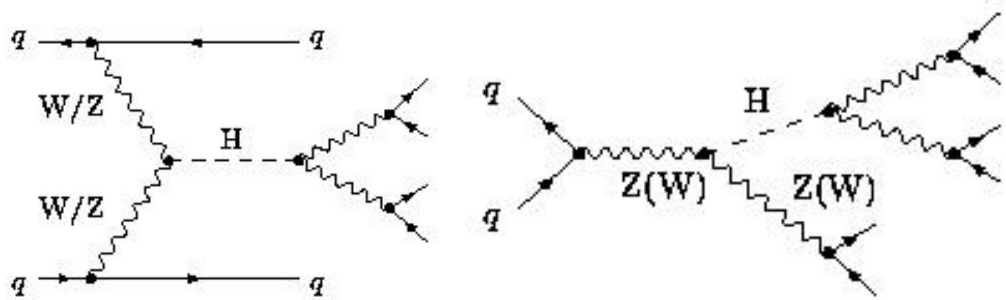
→ **enhance LL wrt TT and measure XS at the highest M(VV)**

- The cross section decreases rapidly due to **PDF** – Hard life for LHC @14 TeV !
- The invariant VV mass is the equivalent of the **CM energy** of the elastic VV scattering

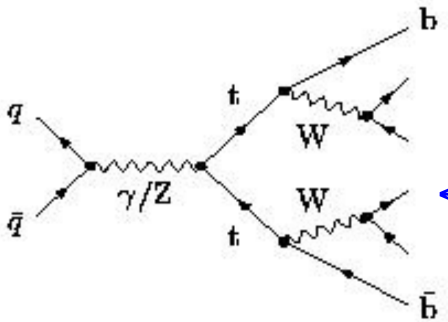
6 fermions final state at α^6_{EW} ... and more



← VV-fusion

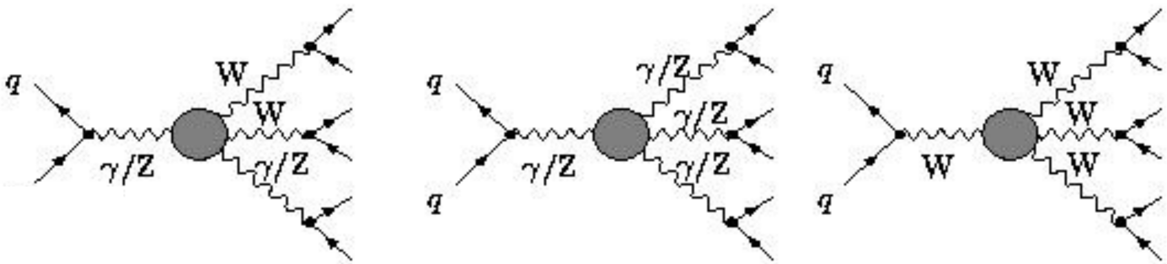


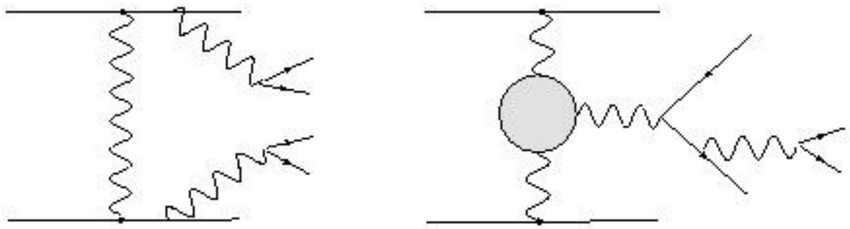
Higgs →



← top-top (EW)

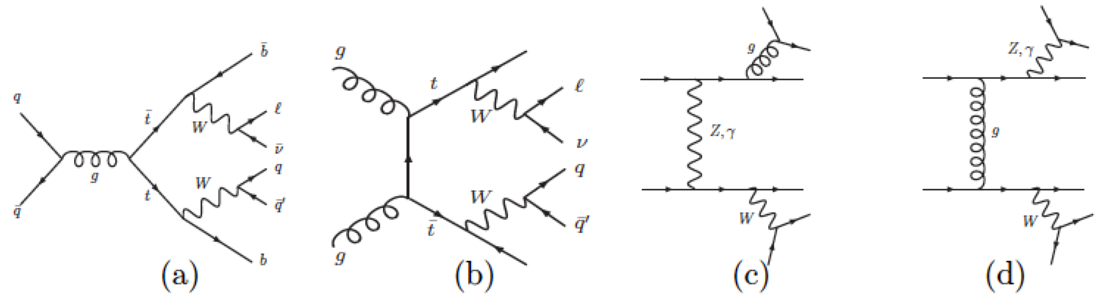
TGC & QGC →



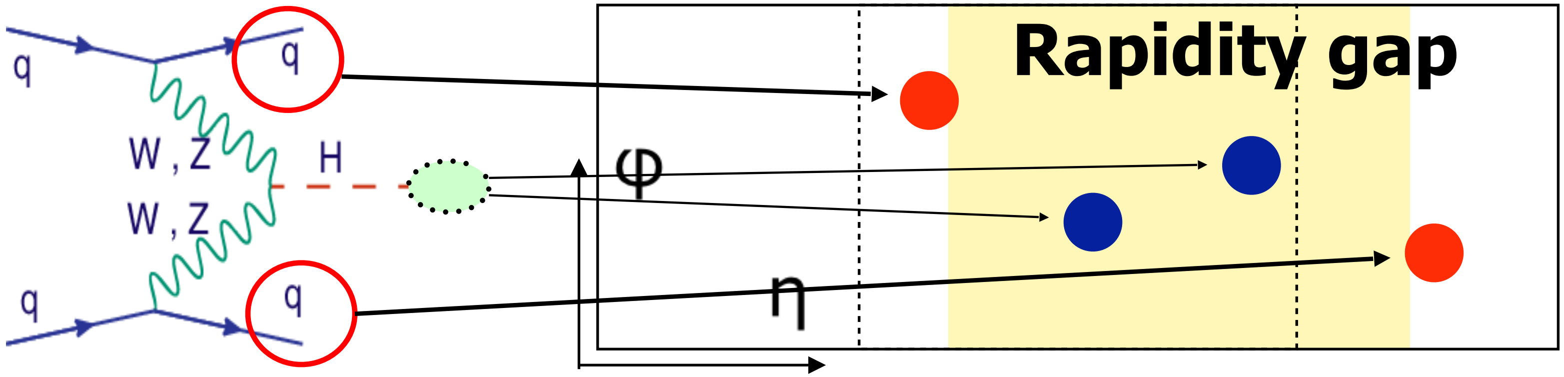


← VV and non resonant

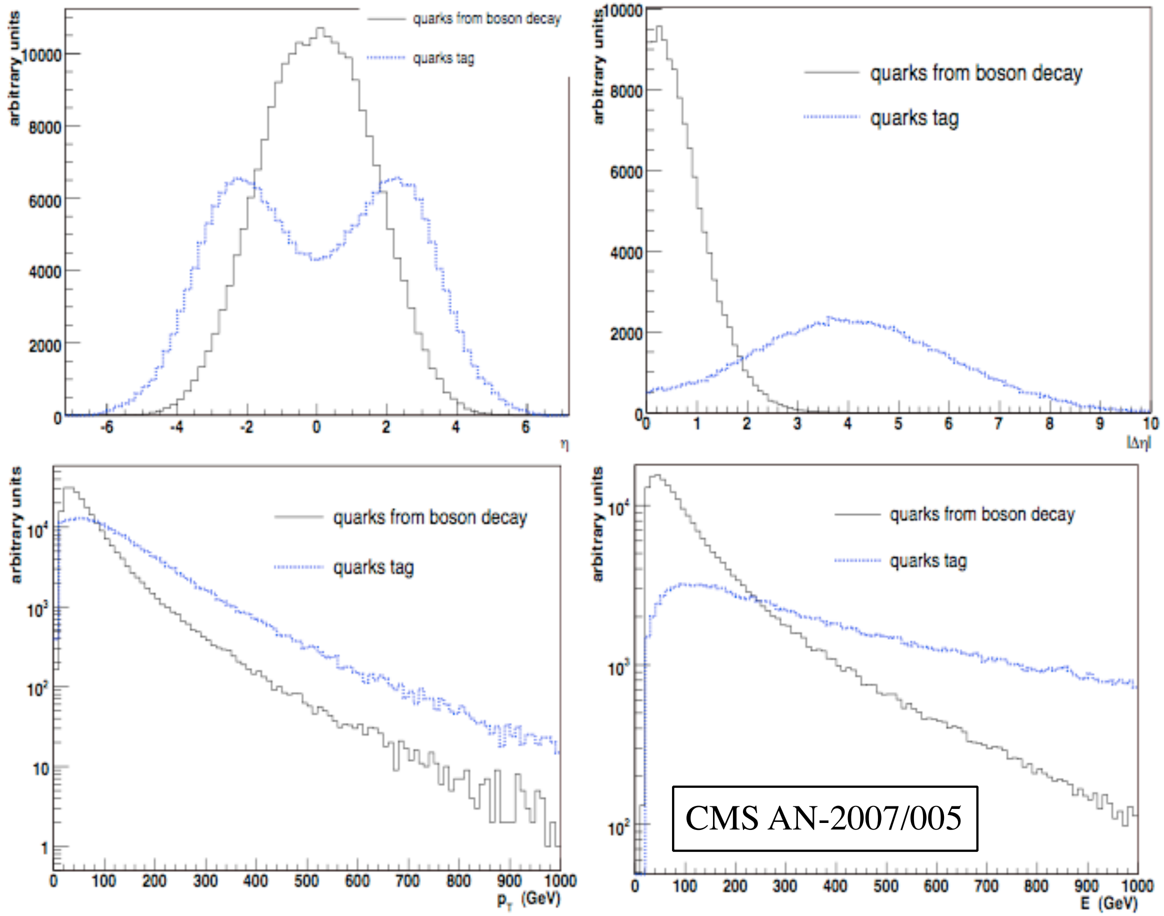
And $\alpha^2_s\alpha^4_{EW}$ →



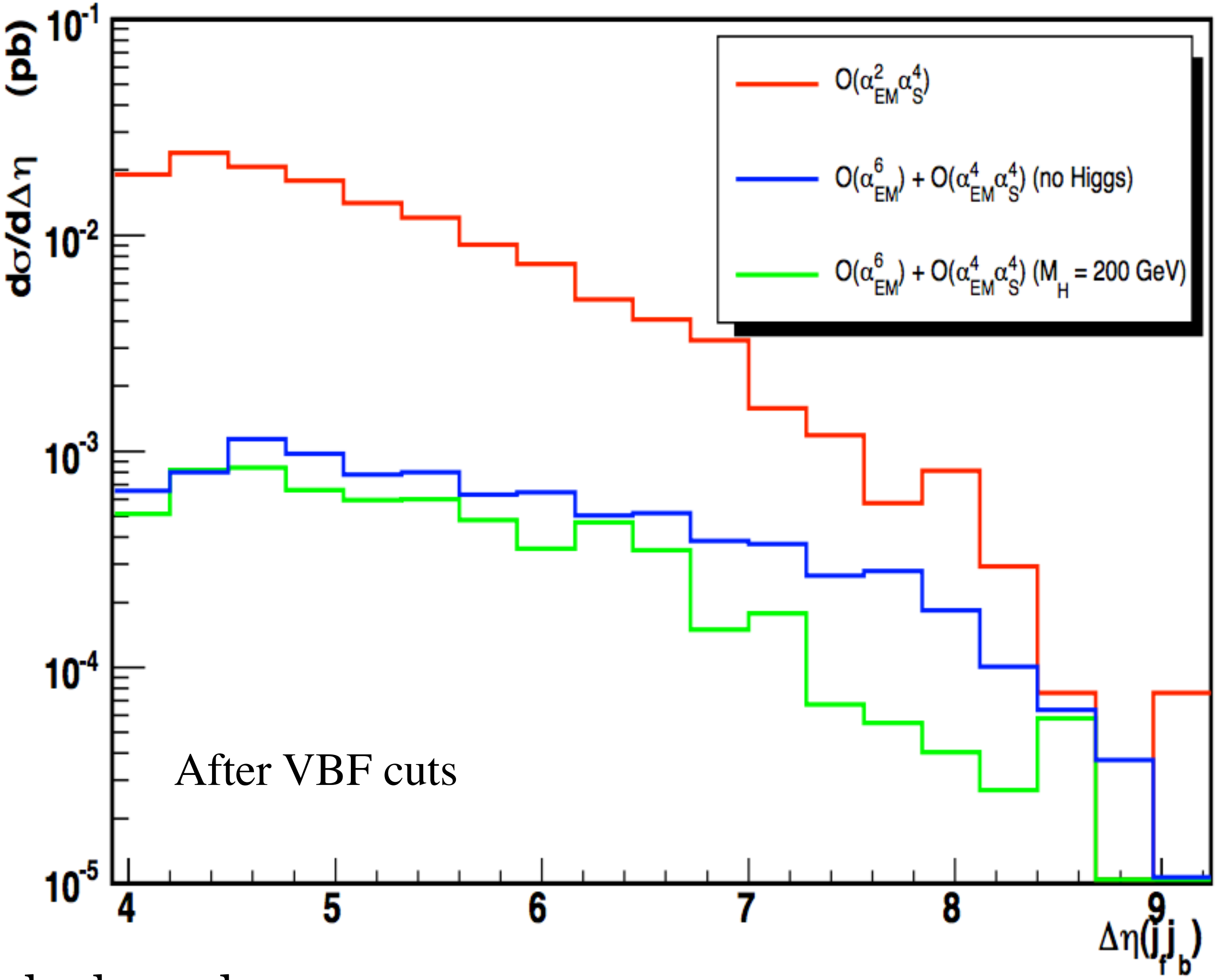
The signal VBF or VBS



- -Energetic jets in the forward and backward directions ($p_T > 50$ GeV)
- -Large rapidity separation
- -Large invariant mass of the two tagging jets
- -Higgs/VV decay products between tagging jets
- -Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange
  - →central jet veto: no extra jets between tagging jets



The EW contribution is very small



pp → jj lνlν channel
400 fb^{-1} to get 3 sigma for the EW signal.

Ballestrero et al arxiv:0812.5084

Some old studies

The QCD background is huge. Very good resolution on **M(jj)** is needed to discriminate VV from V+jets.

B-tagging needed to suppress top background.

Many channels available:

fully leptonic		*semi-leptonic*	
pp	***ZW***	pp→jjjjlν	***WW / WZ***
pp	***ZZ***	pp	***WZ / ZZ***
pp	***ZZ / WW***		
pp	***same sign WW***		

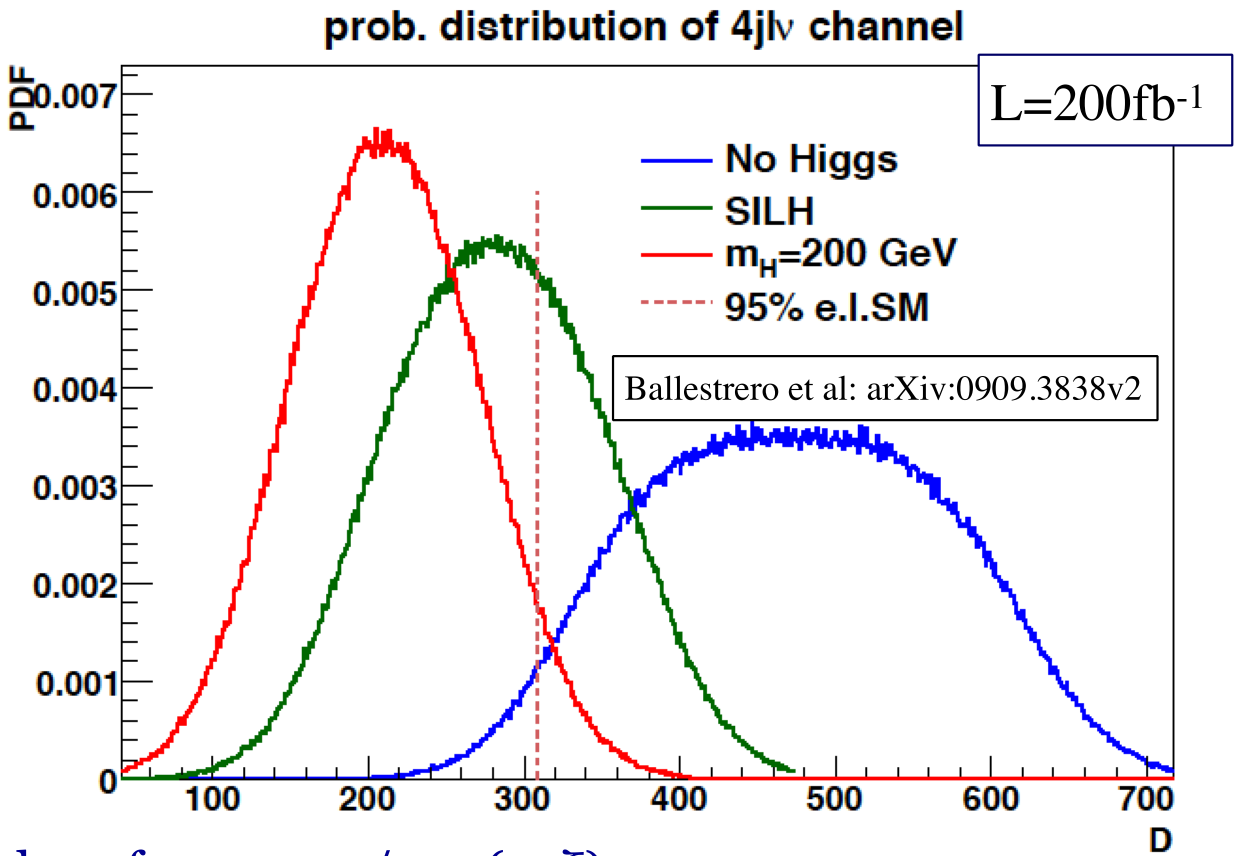
- CMS: 10%-30% efficiency — CMS AN-2007/005
- Same sign W, pp->jj$\mu^+\mu^+\nu\nu$ → 4σ H/noHiggs with 6 ab^{-1}

  (first measurement @ 8 TeV by ATLAS) — B.Zhu et al: arxiv:1010.5848

The nature of the Higgs – lνjjjj channel

Green: SILH with $\xi = 1$
$\xi = v/f$ = degree of compositeness

SILH Giudice et al arXiv:hep-ph/0703164v2



The HVV couplings are multiplied by a factor $c=1/\mathrm{sqrt}(1+\xi)$.
The SILH plot is done for $\xi=1$ ($c\sim0.71$)

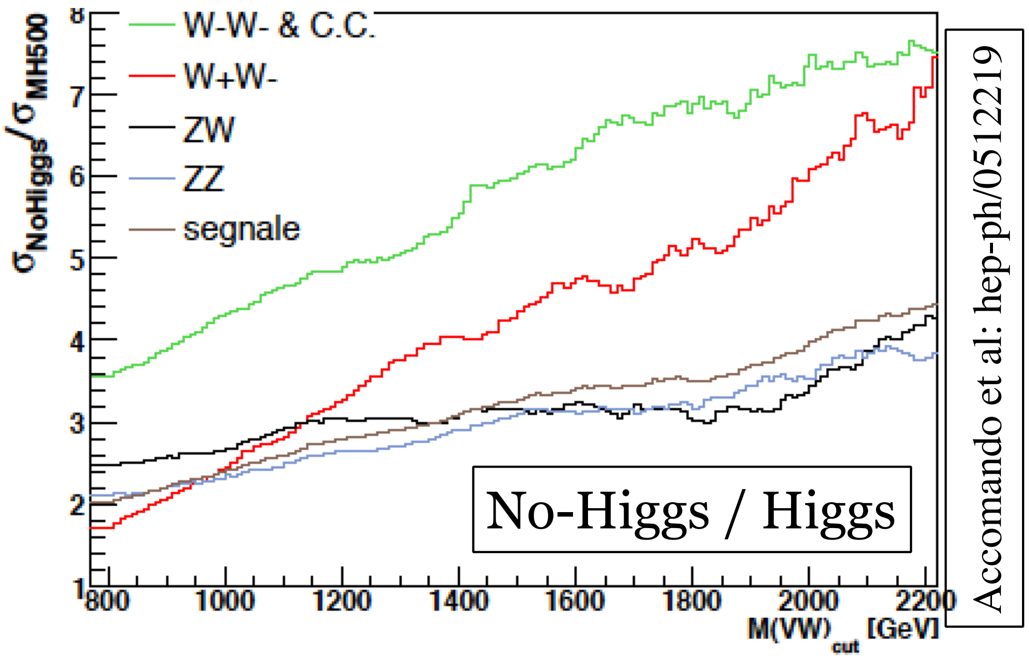
From the fit to LEP and LHC there is now a bound on $\xi < 0.2$ ($c\sim0.91$)
The red curve has c=1, the blue curve c=0, thus new bound pushes the green curve closer to the red, making it hard to distinguish.

→ More Lumi/ better discrimination is needed and more channels

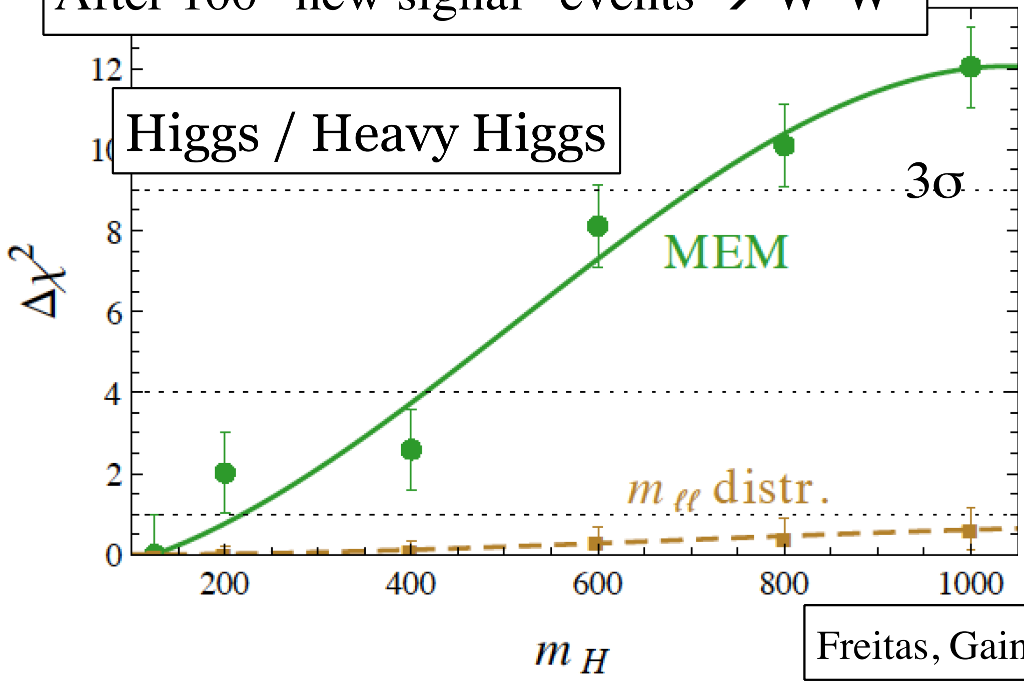
Using more variables

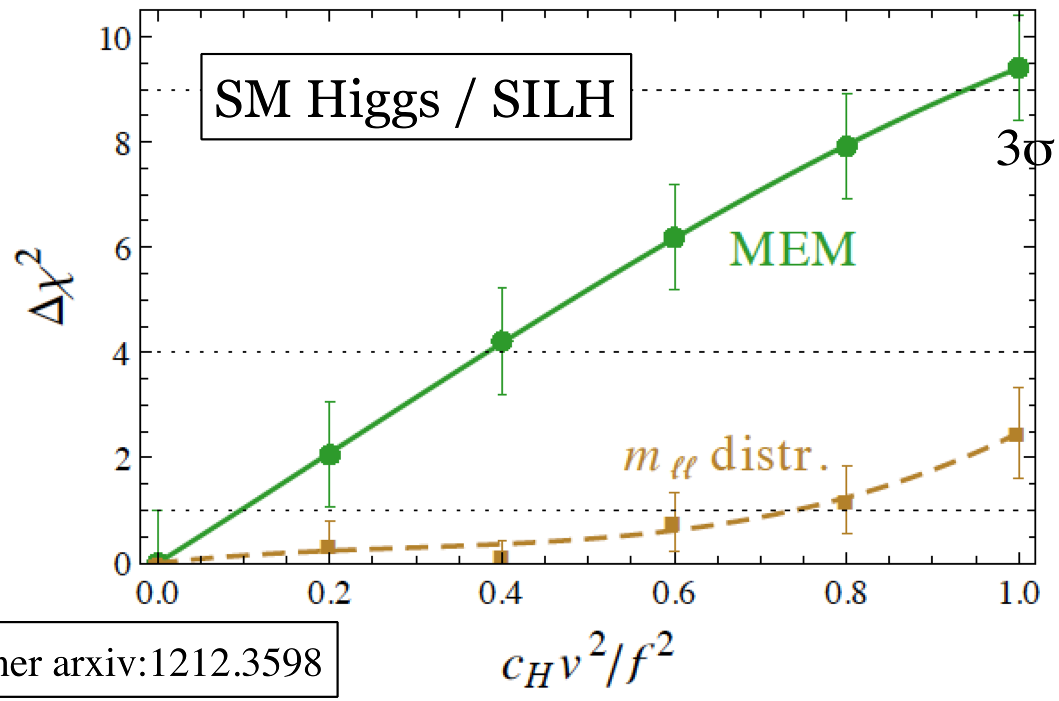
Using NN or Matrix Element Method to increase the $V_T V_T / V_L V_L$ difference.

The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background



After 100 "new signal" events → W+W+



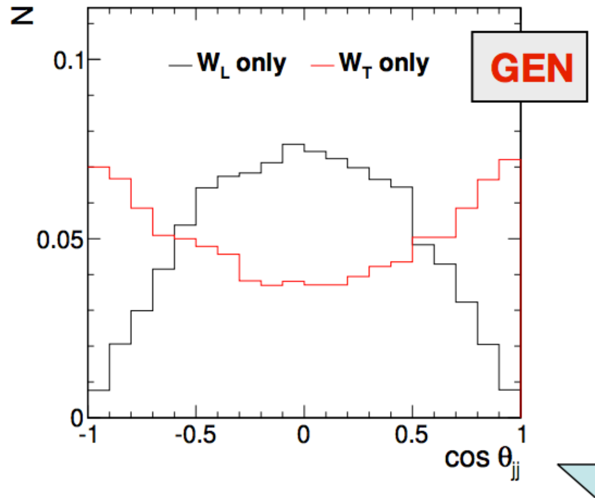


Freitas, Gainer arxiv:1212.3598

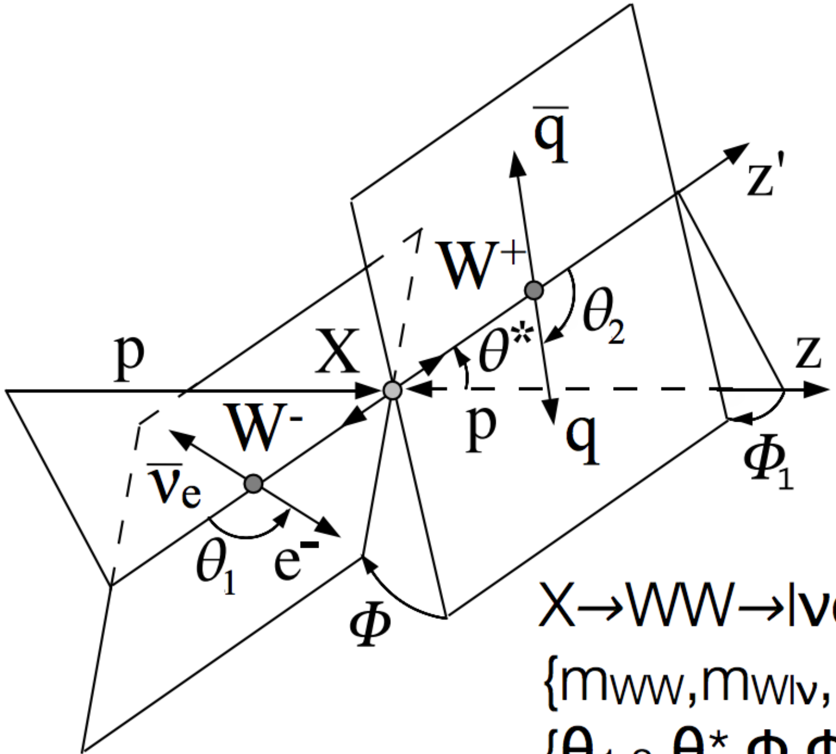
Using more variables

Ultimately we want use the full kinematics of the system in order to understand the **$W_L W_L$ component**

A full set of kinematic observables can be exploited even in a merged jet system



“MELA” analysis:

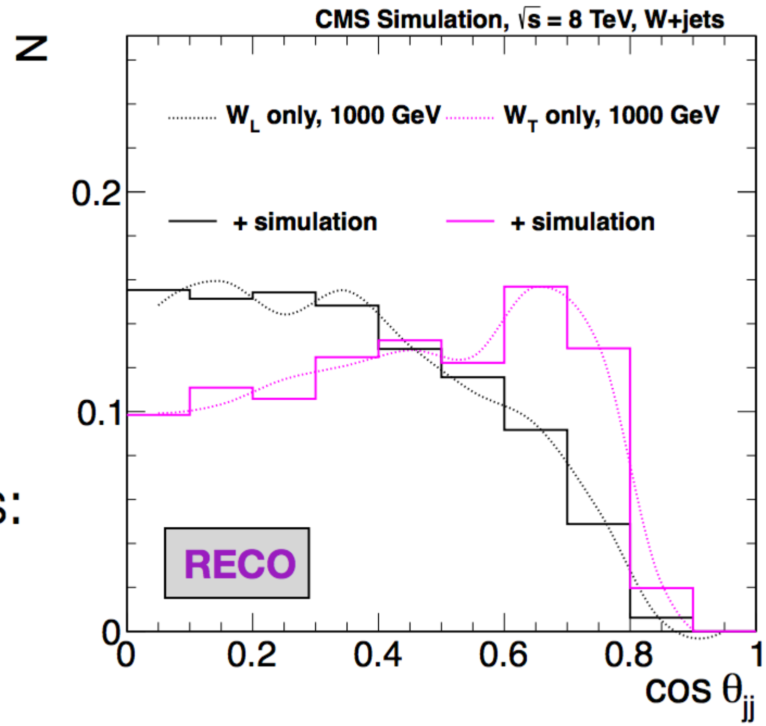


CMS preliminary studies

X→WW→lνqq observables:

$\{m_{WW}, m_{Wl\nu}, m_{Wjj}\}+$

$\{\theta_{1,2}, \theta^*, \Phi, \Phi_1\}$

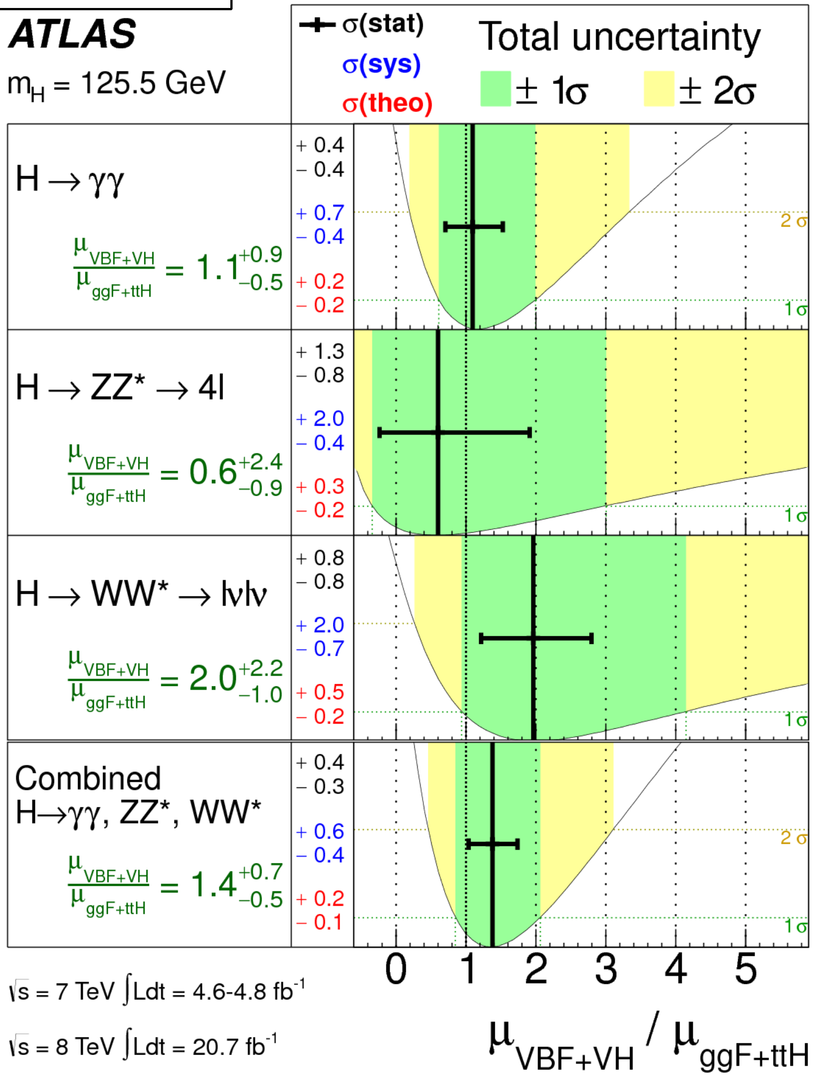


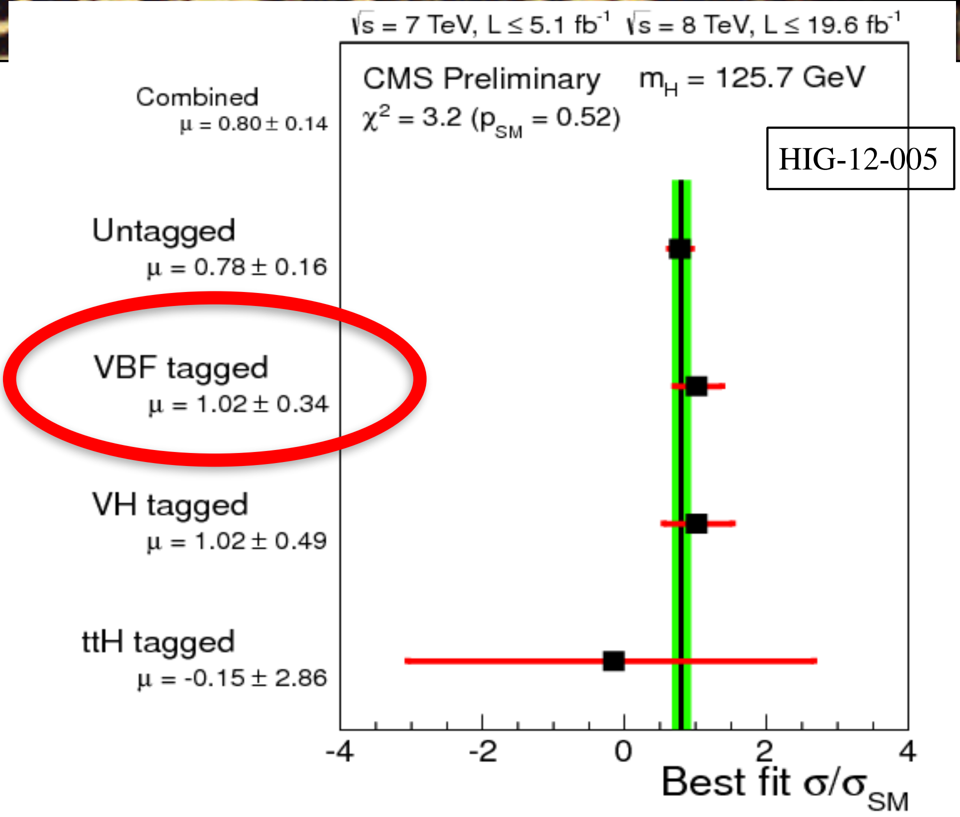
Some results with the 7+8 TeV data

VBF Higgs production

Evidence at ~3 sigma of the Higgs produced in VBF

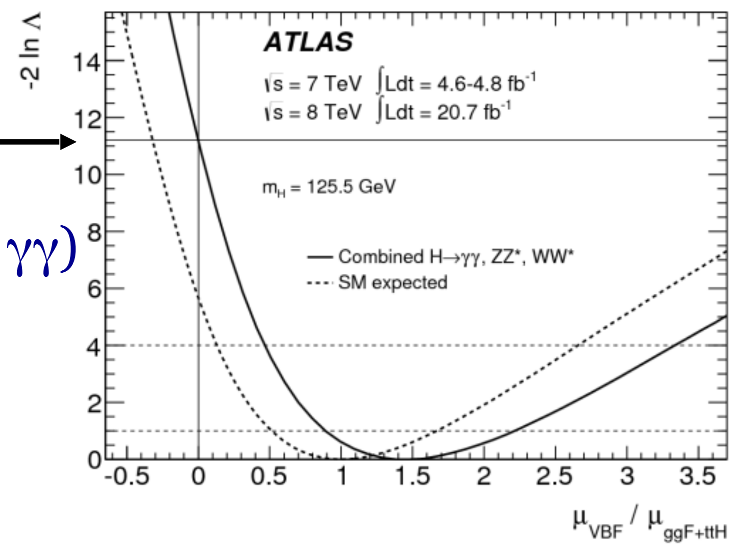
PLB 726, 88 (2013)





$\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}(stat)^{+0.6}_{-0.4}(sys)$

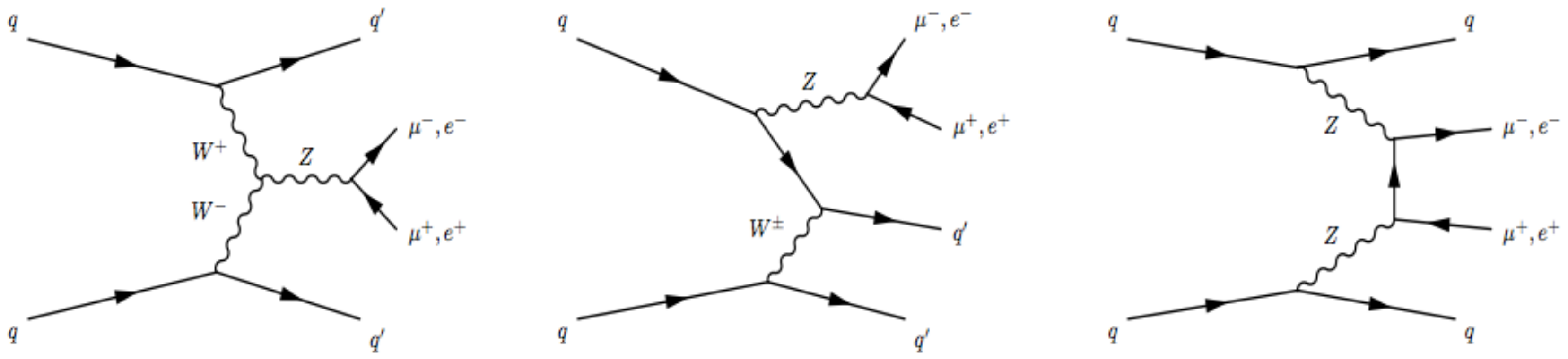
3.3σ evidence for VBF production (driven by H → γγ)



Vector Boson Scattering Z - production

Important benchmark

- Comparable σ and topology to SM H
- Use it to refine forward jet selection, central jet veto, test NLO calculations



(a) vector boson fusion (b) Z-boson bremsstrahlung (c) non-resonant $\ell^+\ell^- jj$

Signal extraction

- large rapidity gap between tag jets, MVA used to extract signal

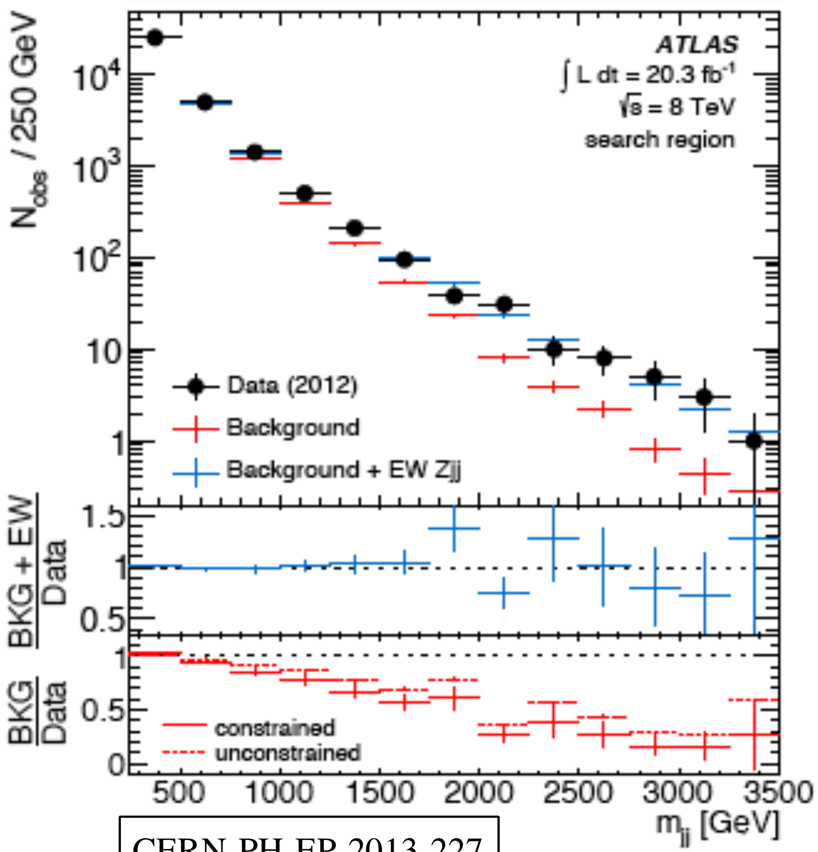
$p_T(j1)>65$, $p_T(j2)>40$, $|\eta^j|<3.6$

$|y^*|=|y_Z-0.5(y_{j1}+y_{j2})|<1.2$

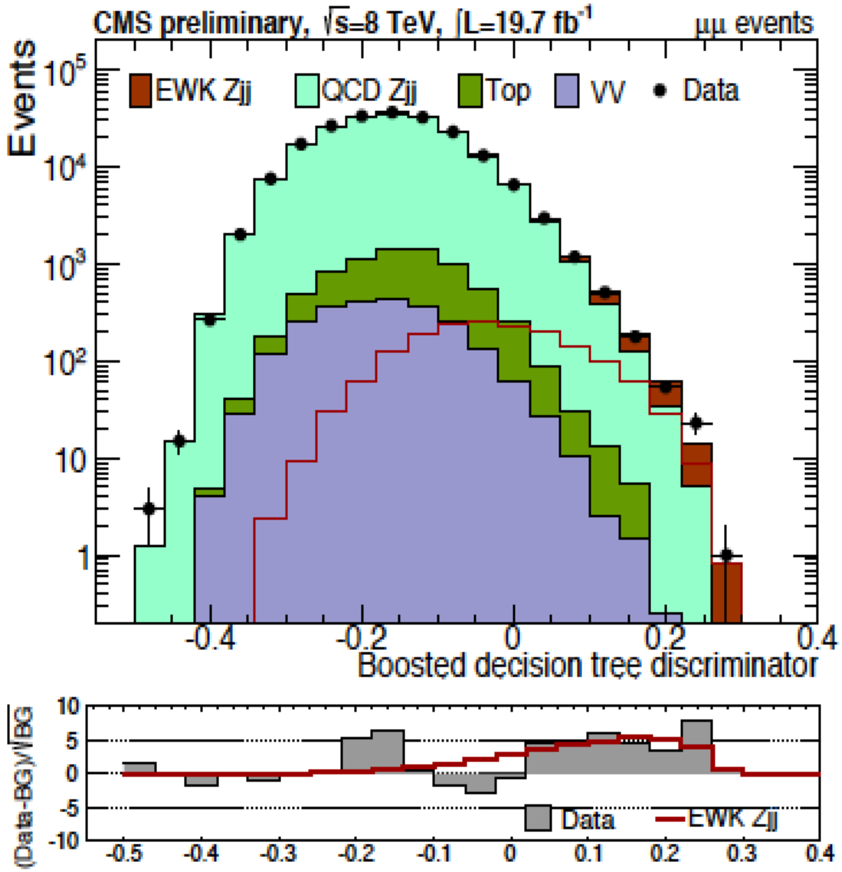
$M_{jj} > 600$

results

Signal regions at M_{jj}>250 GeV



CERN-PH-EP-2013-227

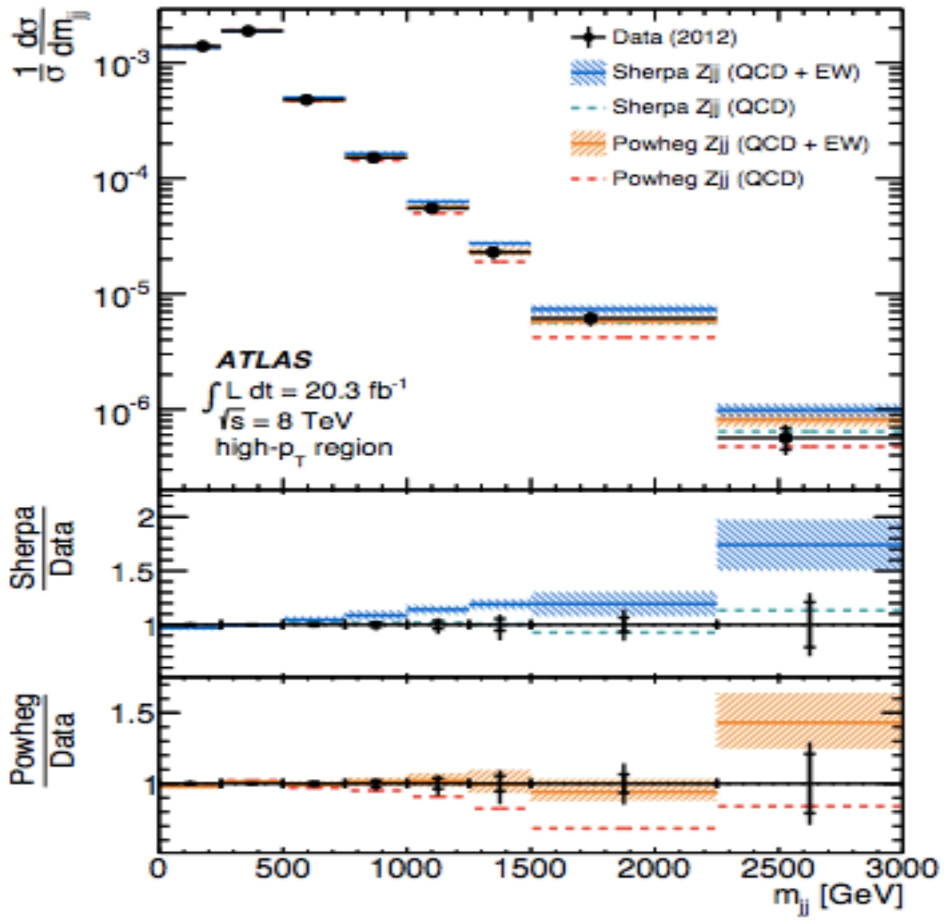


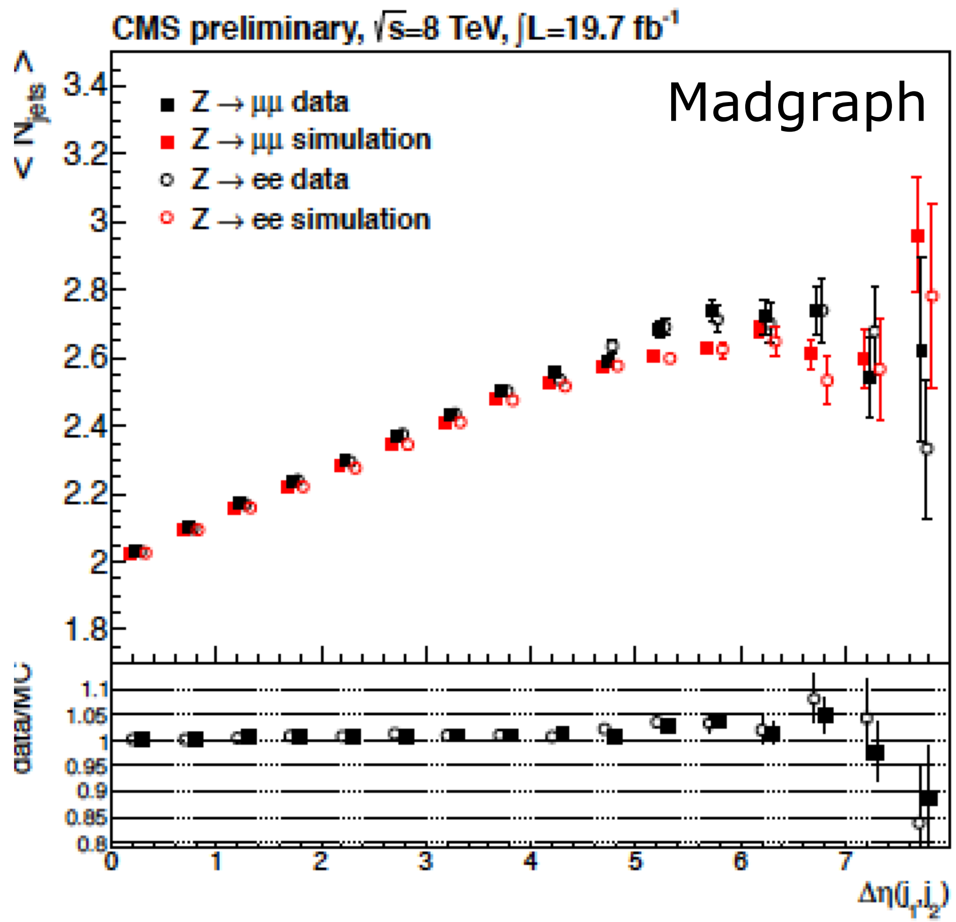
CMS-PAS-FSQ-12-035

Measured σ with mjj > 1 TeV:
σ_{EW} = 10.7 ± 2.1 fb,
Theo (NLO): 9.38 ± 0.320 fb

Measured σ using μμ+ee:
σ_{EW} = 226 ± 26 ± 35 (sys) fb
Theo (NLO): 239 fb

differential distributions





Efficiency of the central jet veto for various $|\Delta\eta_{jj}|$ cut

data, simulation	$\|\Delta\eta_{j1j2}\| > 2.5$	$\|\Delta\eta_{j1j2}\| > 3.5$	$\|\Delta\eta_{j1j2}\| > 4.5$
data	0.56±0.03	0.58±0.03	0.62±0.04
simulation	0.56	0.57	0.58

EFT to look for new physics

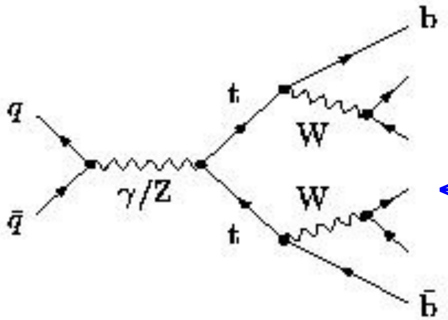
Extension of the SM Lagrangian by introducing additional dimension-6 (or 8) operators.

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

- suppressed if Λ is large compared with the experimentally-accessible energies.
- an effective field theory is the low-energy approximation to the new physics, where "low" means <Λ.

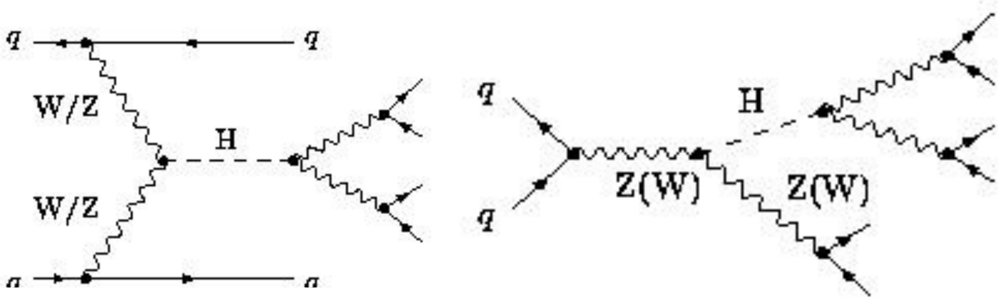
- operators (non homogenous naming) :
  - coefficients in **dimention-6 (i.e. c_i/Λ^2):**
    $C_{\varphi W}/\Lambda^2$ (VBFNLO), $a^W{}_0/\Lambda^2$, $a^W{}_C/\Lambda^2$ (CALCHEP)… hep-ph/9908254
  - coefficients in **dimension-8 (i.e. c_i/Λ^4)**:
    $f_{S,0}/\Lambda^4$, $f_{T,1}/\Lambda^4$… hep-ph/0606118
  - Λ is the **scale of new physics**, e.g. 1-2 TeV

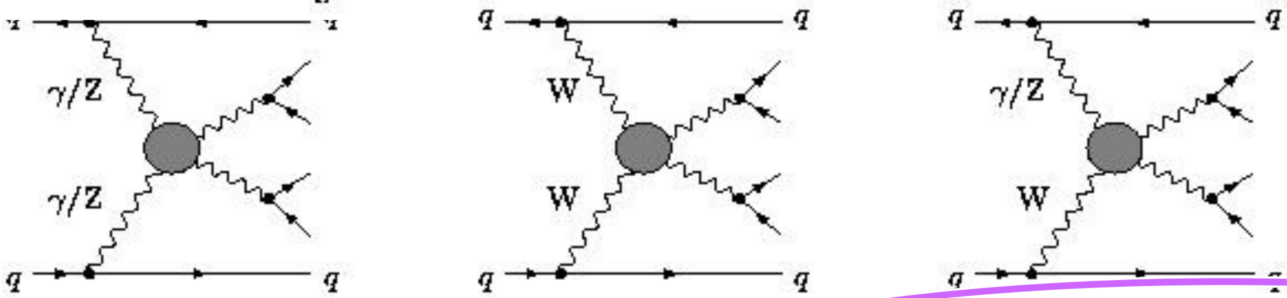
6 fermions final state at α^6_{EW} and more →QGC



← top-top (EW)

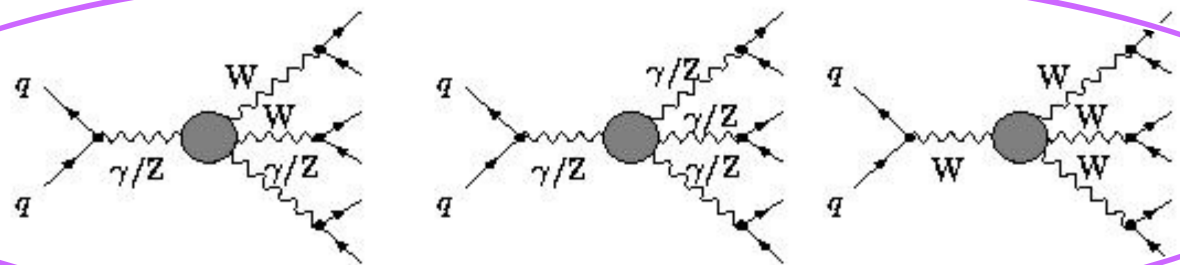
Higgs →

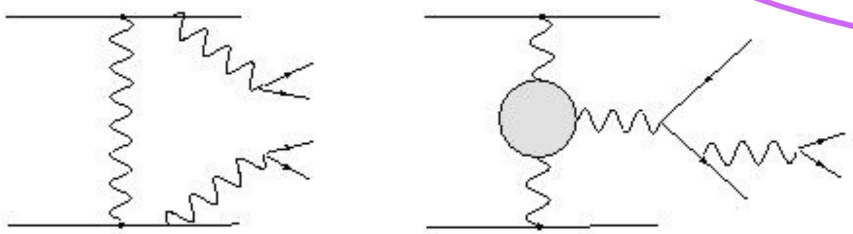




← VV-fusion

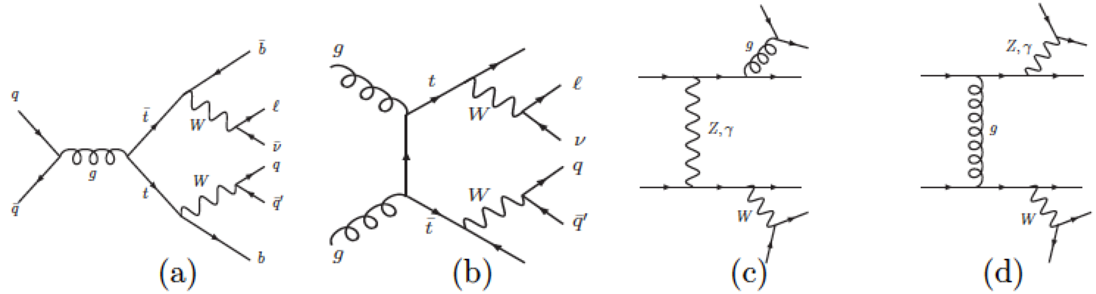
TGC & QGC →





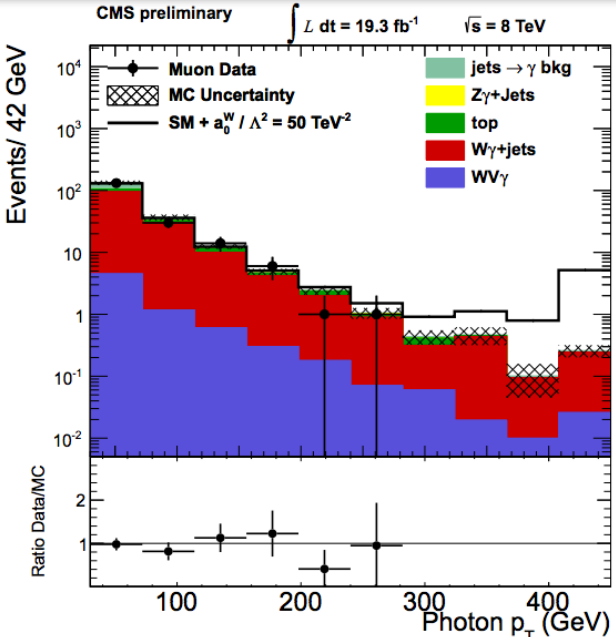
← VV and non resonant

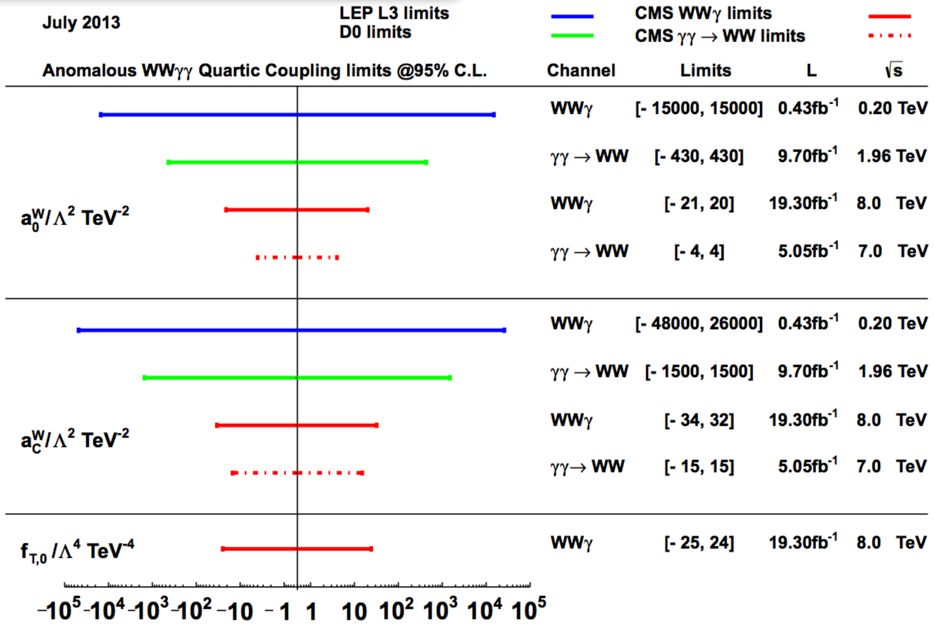
And $\alpha^2_s\alpha^4_{EW}$ →



QGC – limits on the anomalous couplings

CMS: WVγ → lv+jj+γ $p_T j$, $p_T \gamma$ >30GeV



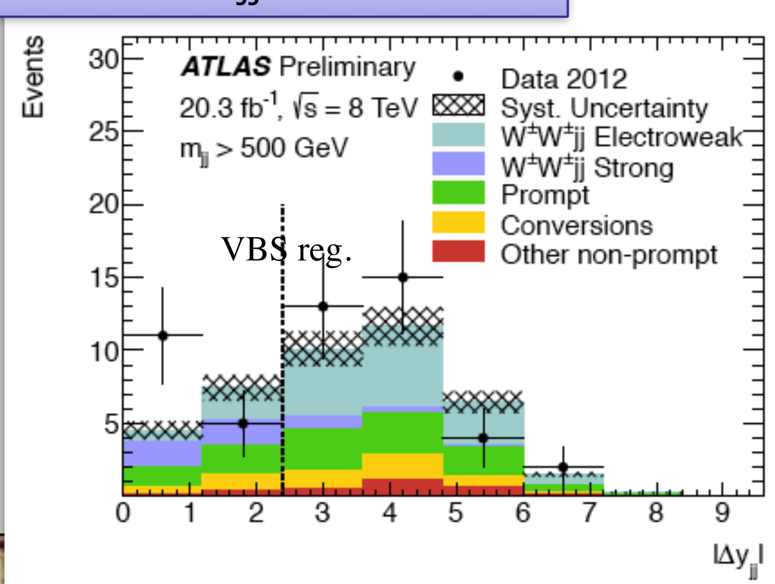


CMS SMP-13-009

ATLAS: $W^\pm W^\pm jj$ → lv+l'v+jj $p_T j$>30GeV M_{jj}>500 GeV

- In same sign WW production the strong production does not dominate over EWK production
- **First evidence of $W^\pm W^\pm jj$** @ 4.5σ (EWK+Strong) and of EWK $W^\pm W^\pm jj$ @ 3.6σ at 95%CL
  σ = 1.3 ± 0.4 ± 0.2 fb (VBS region)
- **First limits on** α_4 α_5 QGC parameters:

$$-0.14 < \alpha_4 < 0.16$$
$$-0.23 < \alpha_5 < 0.24$$

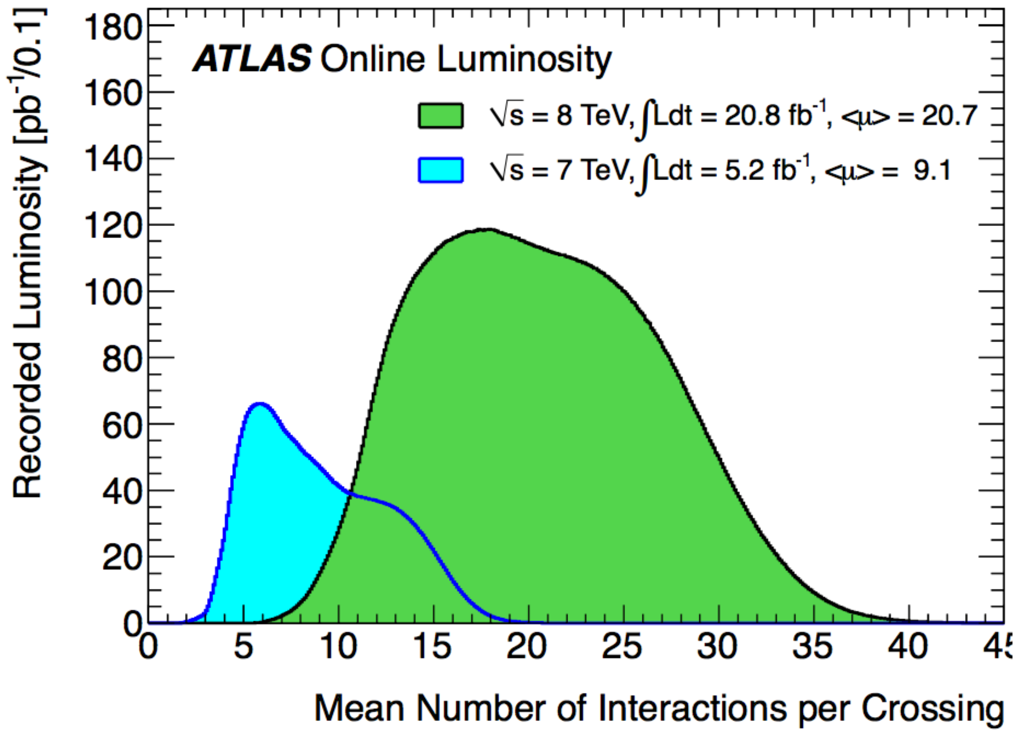


ATLAS-CONF-2014-013

The near and far future

The experimental challenge: pile-up

Pile-up will rise to **50** next year and then to **140** at the High Lumi phase:

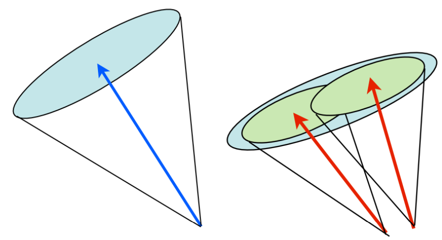


Many methods have been developed:

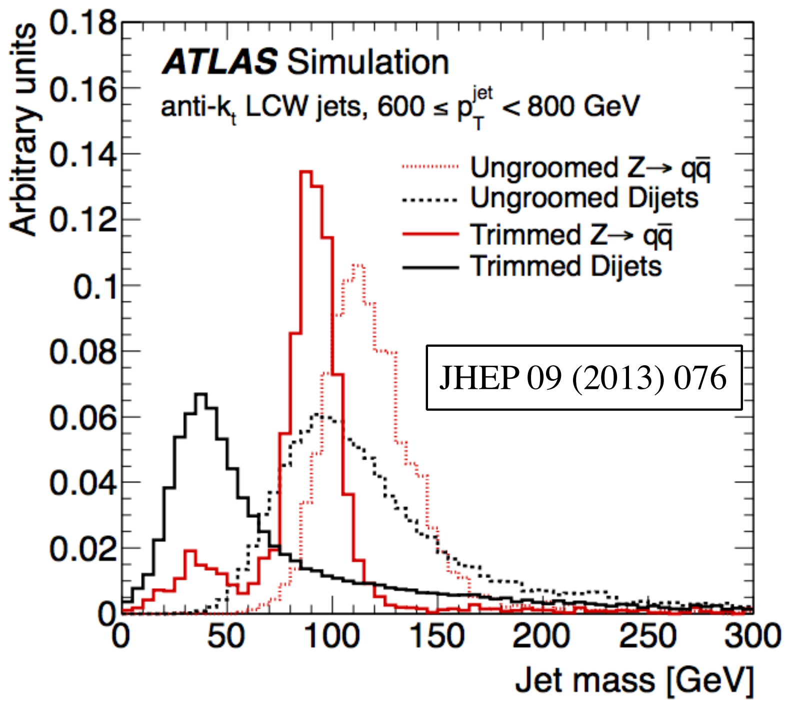
- to subtract it:
  - by only considering the charged tracks that came from the PV.
  - Jet energy corrections
  - By calculating a median- energy/track deposit in a given area
- to identify it:
  - MVA to distinguish jets from PU

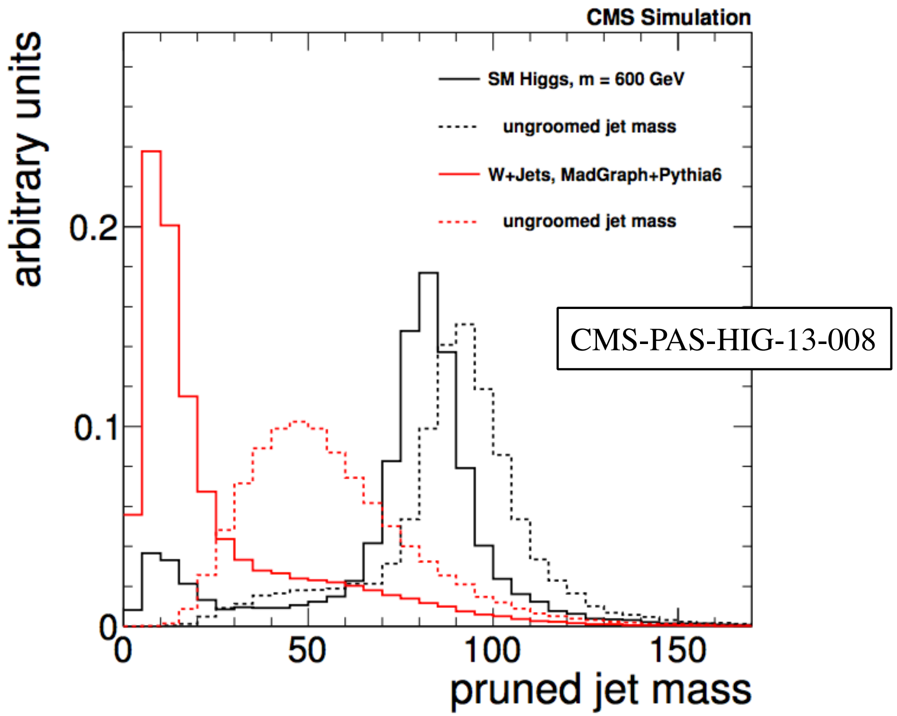
The experimental challenge: boosted object

- Z and W in VBS events can be very highly boosted
  (the boosted regime: $\Delta R \sim 2m/p_T$)
  → Z, W → 1 fat jet



- Necessary "grooming" techniques to subtract QCD and pile-up before computing properties



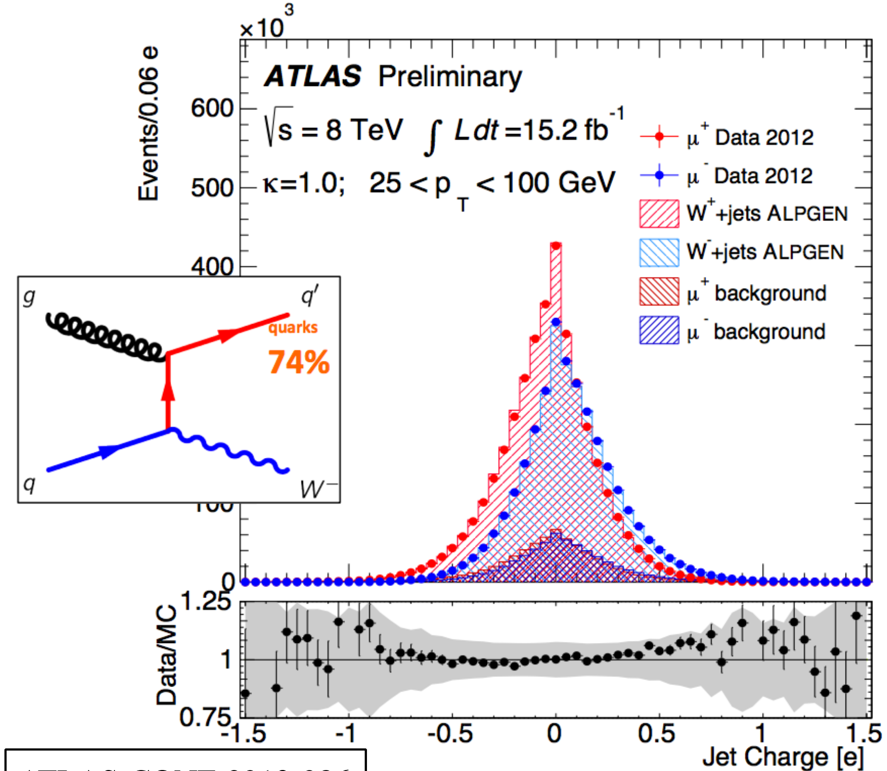


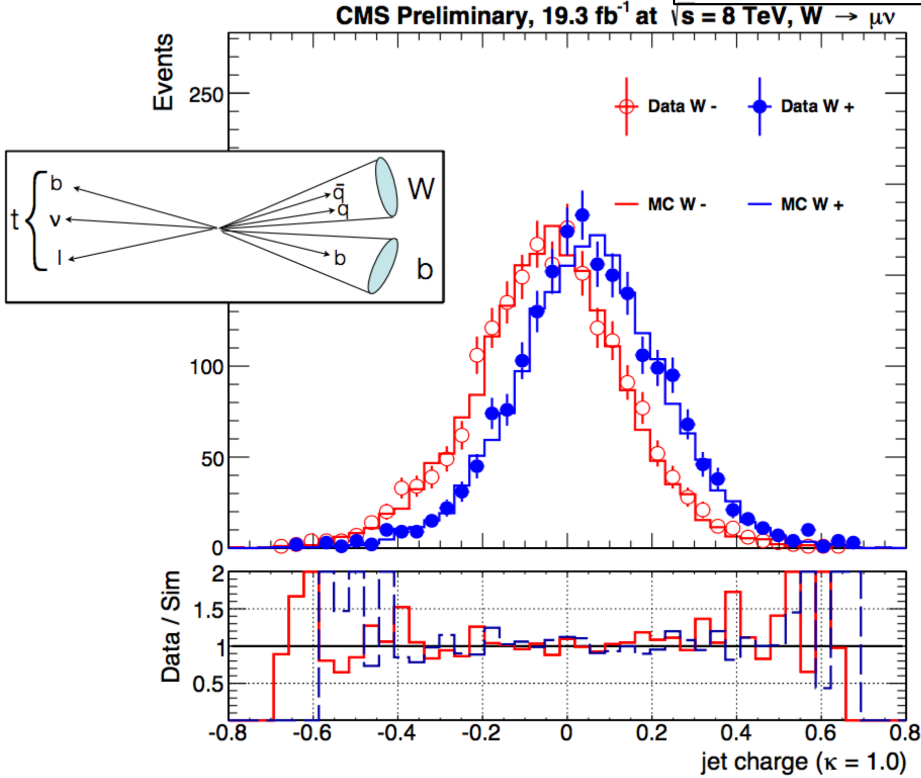
- vector bosons become a basic physics object at LHC

The experimental challenge: boosted object

- **mass** (4-vec sum of jet constituents)
- **substructure**: to split the fat jets into the components
  (2 sub-jets if from W, Z,   3 sub-jets if from top)
- **re-clustering**
- **shapes** to ID the parton (q/g)
- jet **charge** to distinguish W^+ from W^- →(“same sign” W signal)

CMS-PAS-JME-13-006

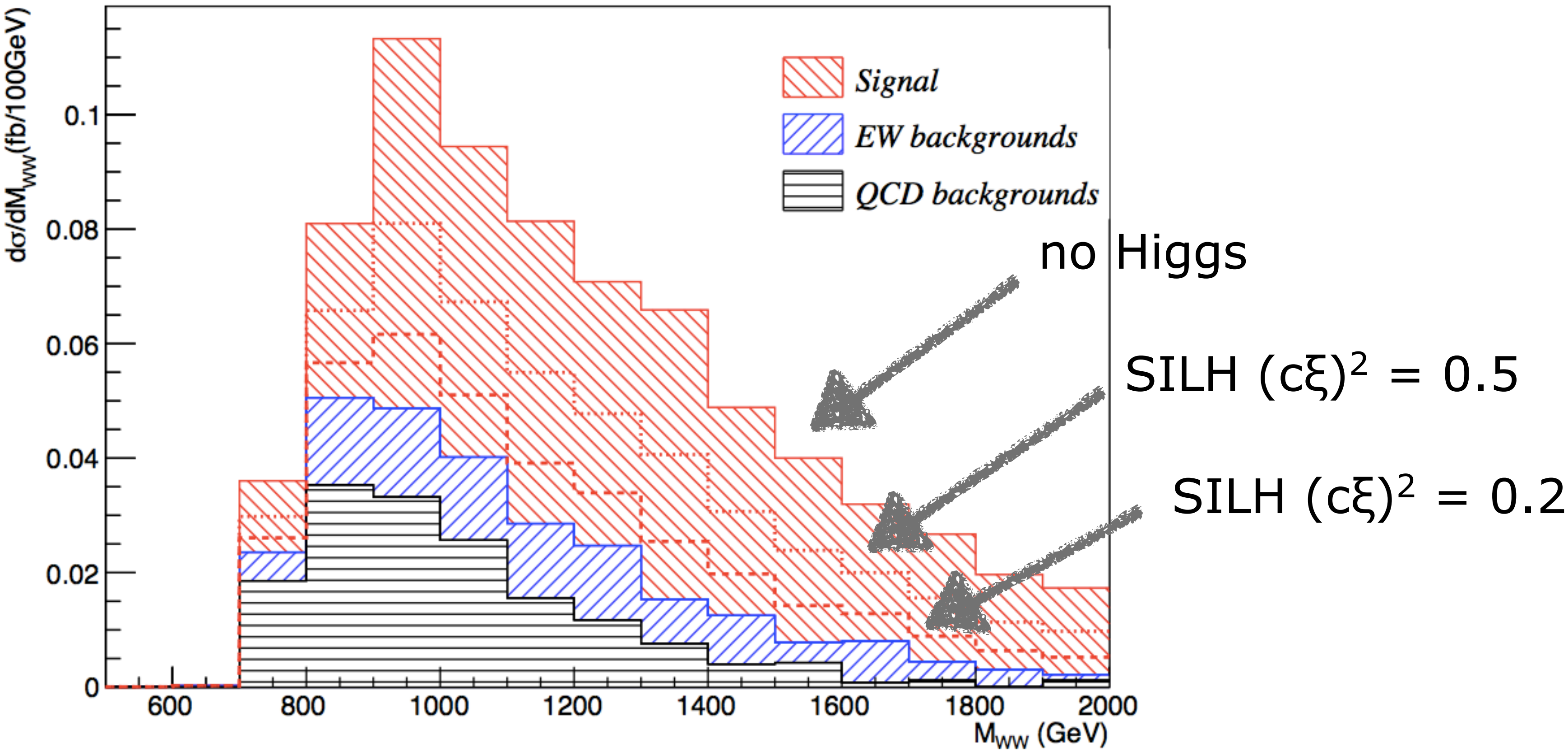




ATLAS-CONF-2013-086

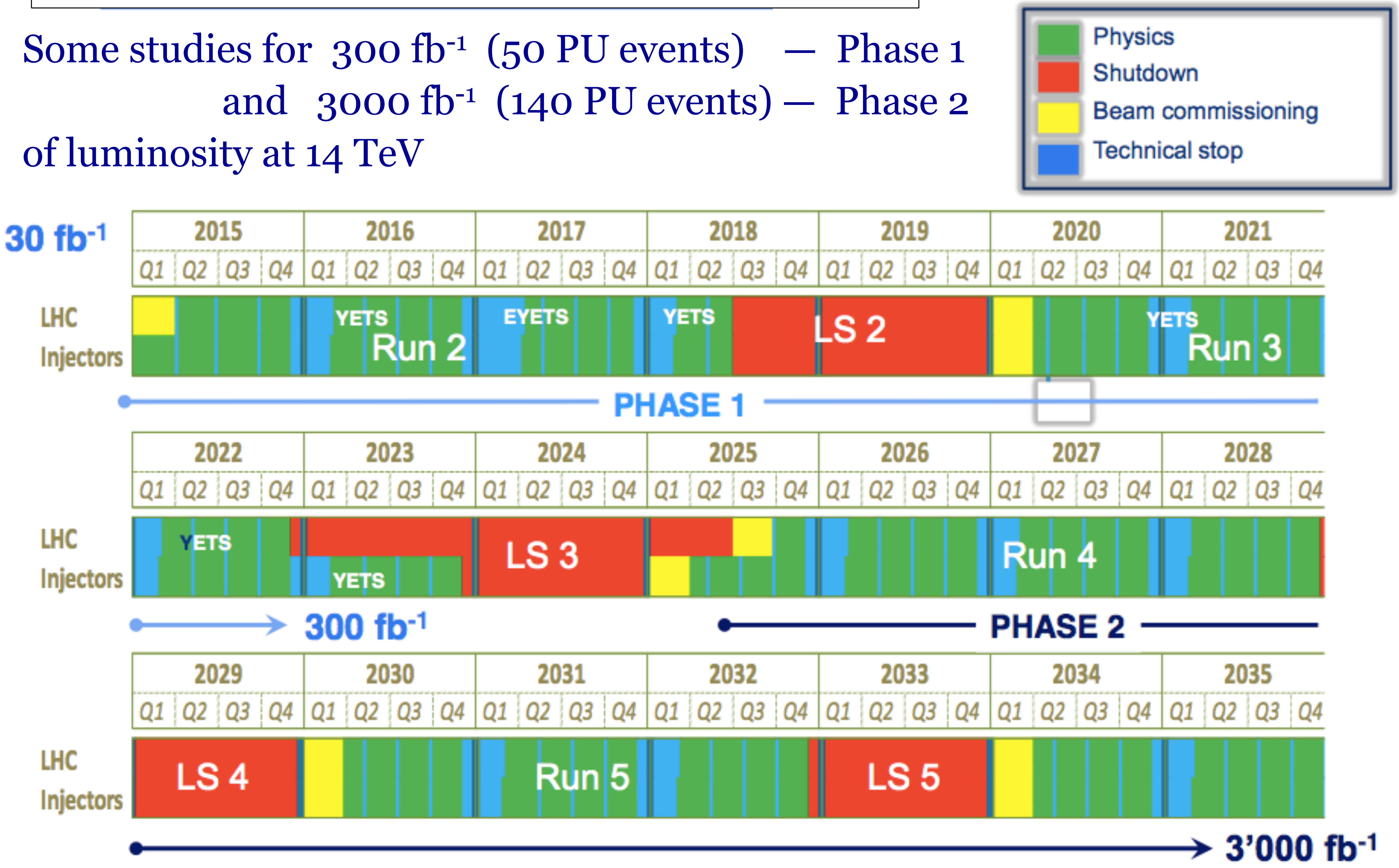
boosted objects at work

- use the **semi-leptonic WW final state** to gain statistics, reject the background with grooming techniques
- W_{had} originates a single merged jet
- no MVA discriminators applied yet



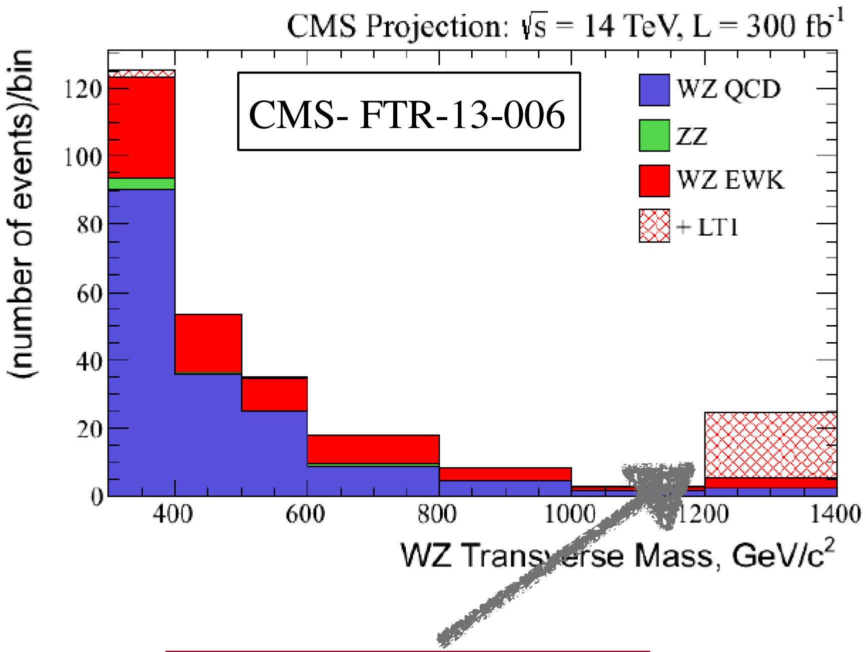
LHC roadmap

Some studies for 300 fb^{-1} (50 PU events) — Phase 1
and 3000 fb^{-1} (140 PU events) — Phase 2
of luminosity at 14 TeV



LHC projections

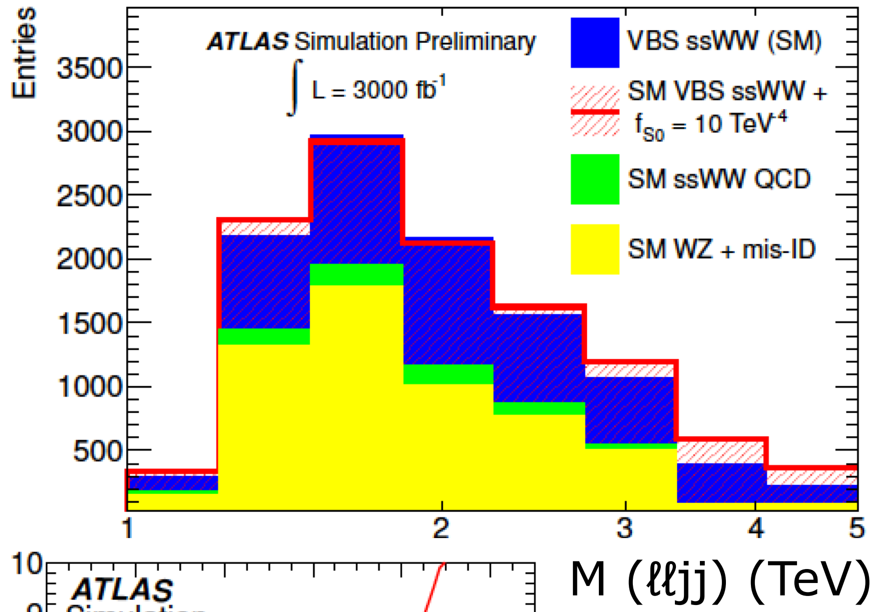
ZW > ll lv jj in CMS

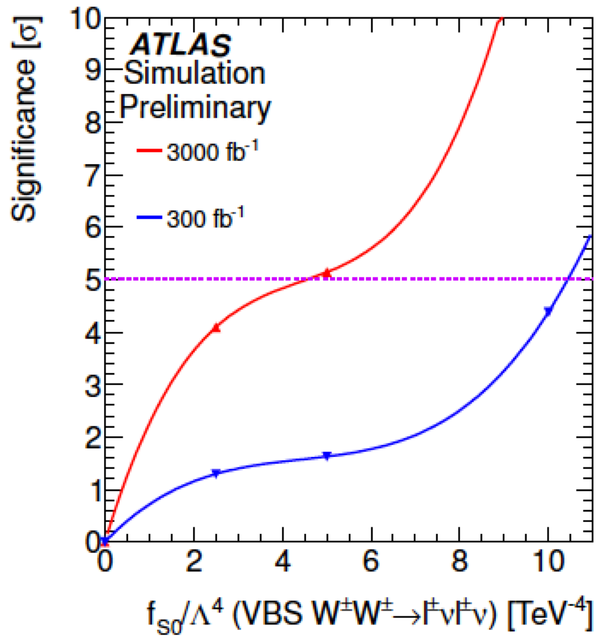


Additional contribution from aQGC with $f_{T1}/\Lambda 4 = 1$ TeV^{-4}.

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

same sign W±W± > lv lv jj in ATLAS



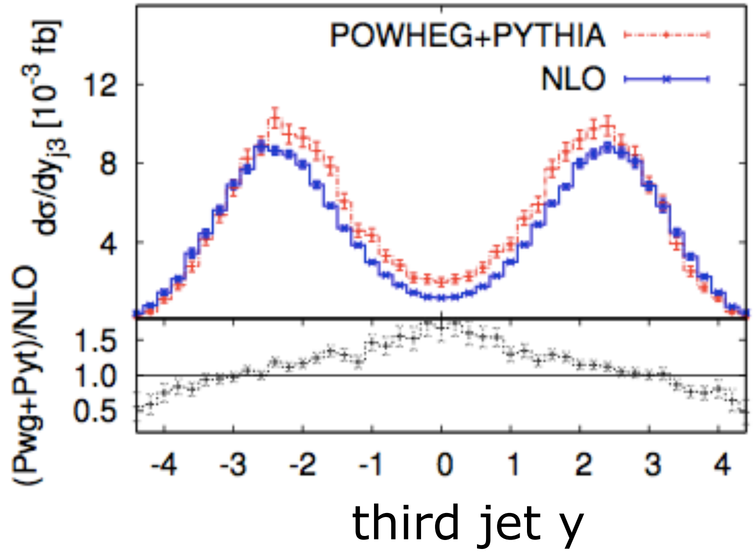


the simulation precision

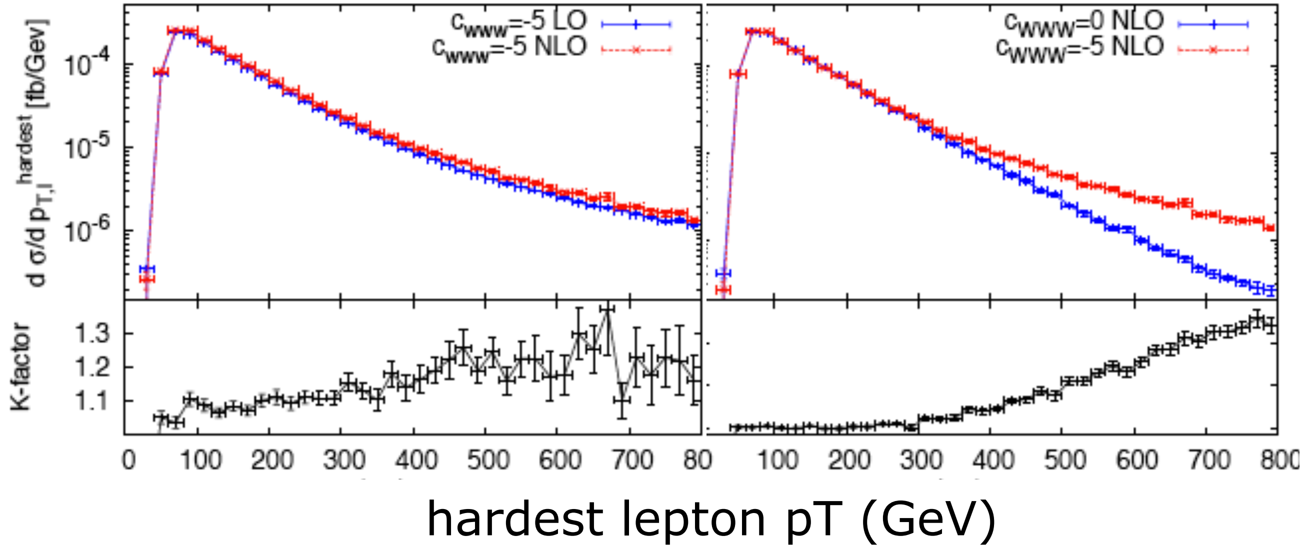
arXiv:1312.3252v1

- additional jets veto distinguishes purely EWK signal from QCD backgrounds, therefore it is a powerful tool and needs support of NLO QCD precision
- QCD NLO corrections can be comparable to sought deviations

W^+W^+jj



VBS ZZ > 4 leptons



- complicated in the semi-leptonic final states by one-loop virtual corrections with more than six internal legs → approximations
- need a proper matching to shower

VBS at a linear collider

hep-ph/0604048

- sensitive to aTGC and aQGC in the longitudinal EW bosons couplings, through total and differential XS in the EW boson production and decay angles
- c.o.m. energy of 1 TeV, total lumi of 1000 fb^{-1}. Beam polarisation of 80% for electrons and 40% for positrons

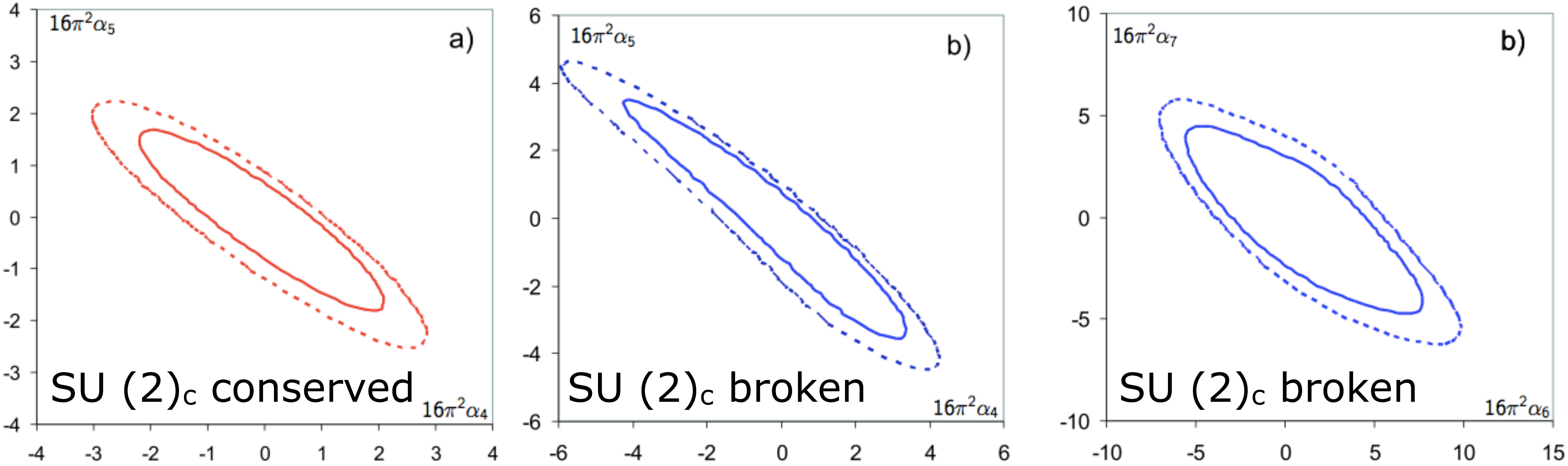


Table 4.6
Sensitivity to quartic anomalous couplings in the various quasi-elastic weak-boson scattering processes accessible at the ILC.

$e^+e^- \to$	α_4	α_5	α_6	α_7	α_{10}
$W^+W^- \to W^+W^-$	+	+	-	-	-
$W^+W^- \to ZZ$	+	+	+	+	-
$W^\pm Z \to W^\pm Z$	+	+	+	+	-
$ZZ \to ZZ$	+	+	+	+	+

And much more

More channels to study (many studies with W^+W^+, to be redone with the full detector simulation, + WW→ lv4j etc…)

From the experience we have reached so far, even if it will be very challenging and it will take few years:

SI PUO' FARE!

Interesting also to add more final states:

p.e.: Double Higgs Production → can be easier to be seen than VBS in case of composite Higgs (see for example Contino et al: arxiv:1309.7038)