Implications of LHC results for TeV-scale physics
CERN, 29/08/2011

CMS-ATLAS VV scattering: any hope soon or reappraisal?

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on behalf of ATLAS and CMS

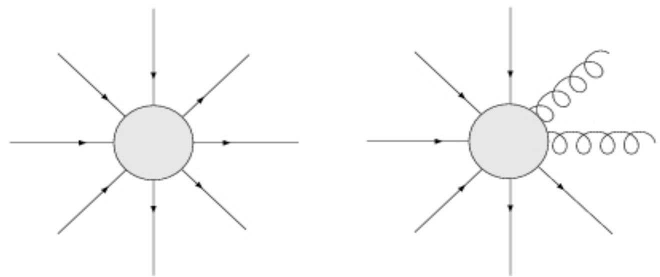
motivations

- VV scattering is the key process to probe EWSB
  - **If the SM Higgs is not excluded** a resonance will be observed in the M_{VV} spectrum in correspondence of M_H
    - search for ~1TeV resonances
    - study of the low mass Higgs couplings
  - **Without the Higgs**, the V_L's interact strongly at high energy and the V_LV_L cross-section violates the unitarity at M_{VV} ~ 1 TeV → deviation from SM prediction
    - investigation of the M_{VV} spectrum variations
- The large M_{VV} region gives indications on the M_H range
- Whether H exists or not, V_LV_L should be studied in detail to verify if weak or strong interactions occur

the VV scattering vertex

- the 2 → 6 gauge invariant vertex needs the exact calculation for the M_{VV} spectrum study
- PHANTOM [1] is a full **six fermions final state** generator
- **exact matrix elements**, no approximation
- generates **all EW processes** with six fermions in the final state at $\mathcal{O}(\alpha_{EW}^6) + \mathcal{O}(\alpha_{EW}^4 \times \alpha_{QCD}^2)$:
  - **VV-scattering + irreducible background** (top-top, single top, non resonant, three bosons from TGC & QGC …)

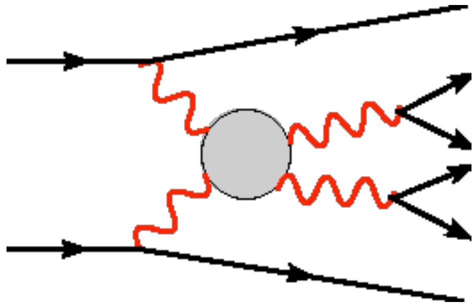
- *qq' → 6f*
- *qg → 1g5f*
- *gg→6f*
- *qq'→2g4f*

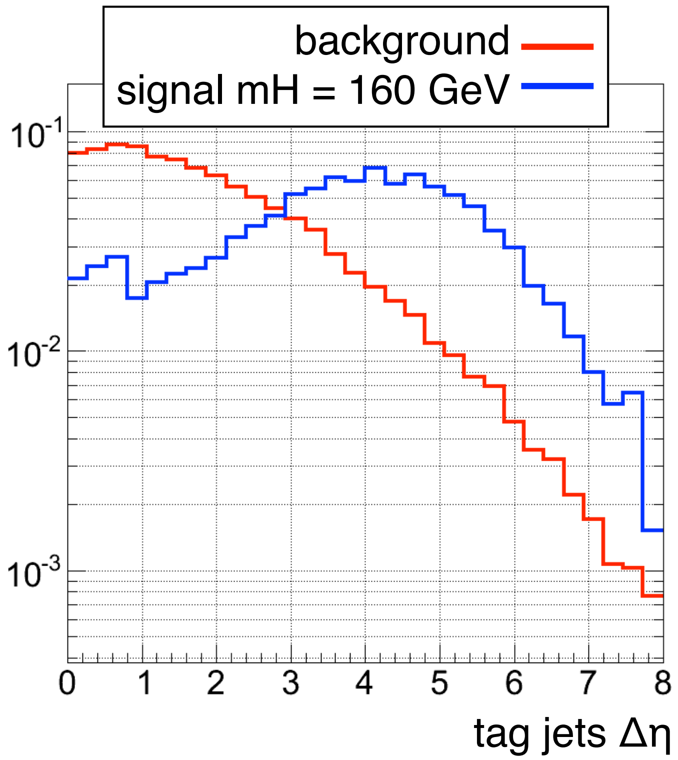


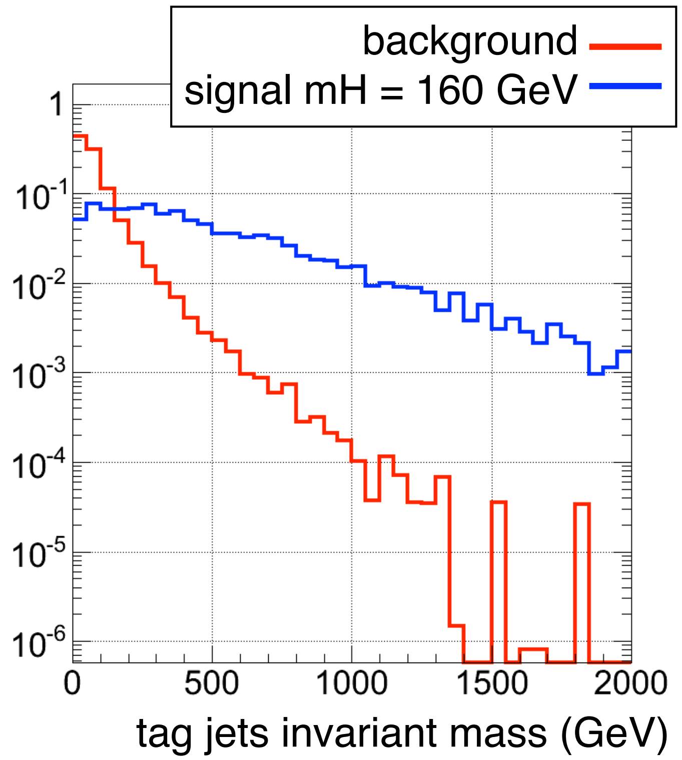
[1] A.Ballestrero, G.Bevilacqua, A.Belhouari, V. Kashkan, E.Maina, **PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders**, arXiv:0801.3359

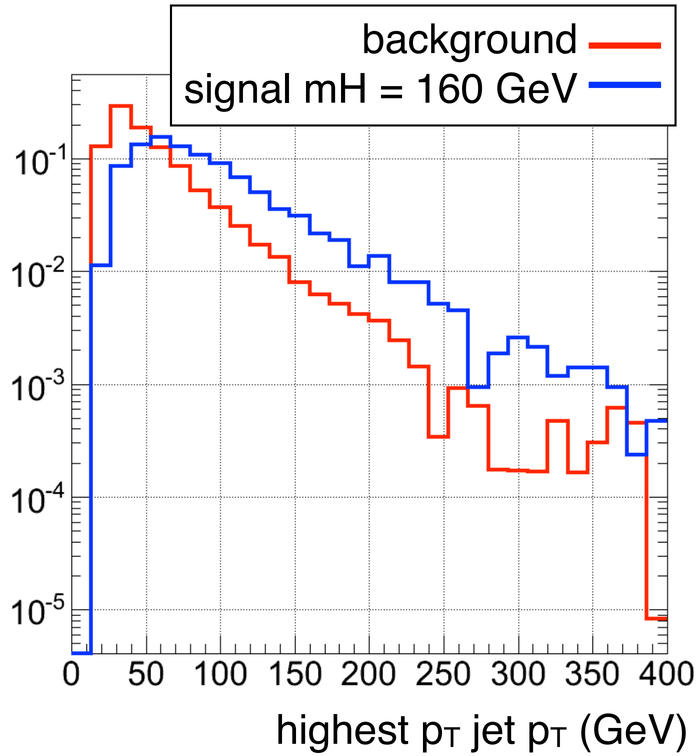
the VBF event topology

- **tag jets:** two jets coming from the protons: high pT, large Δη, large invariant mass
- tag jets need to be **identified** in each event



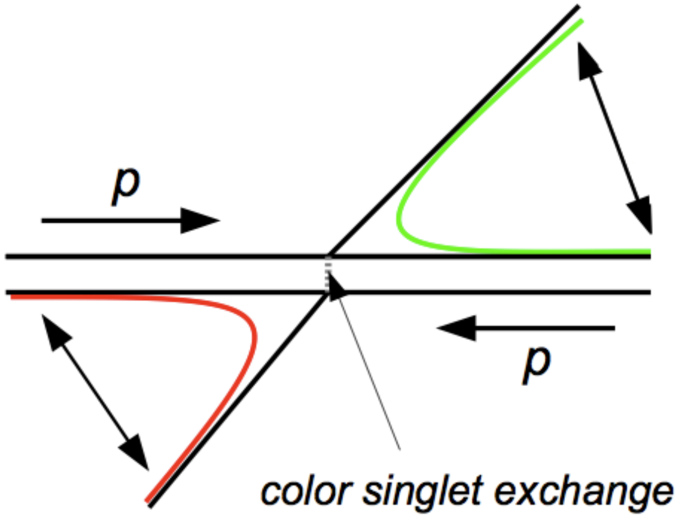


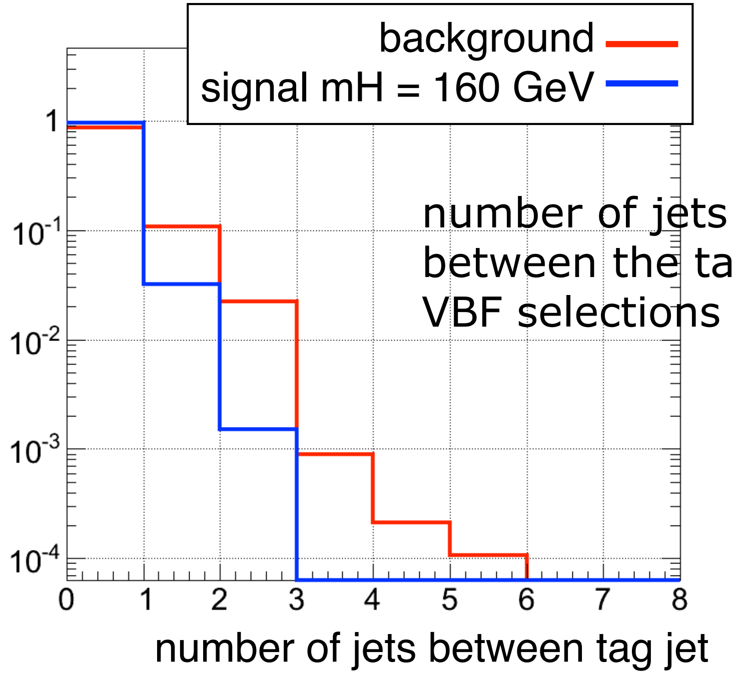




the central rapidity gap

- **central rapidity gap:** no hadronic activity between the two tag jets is expected, because of the EWK nature of the VBF





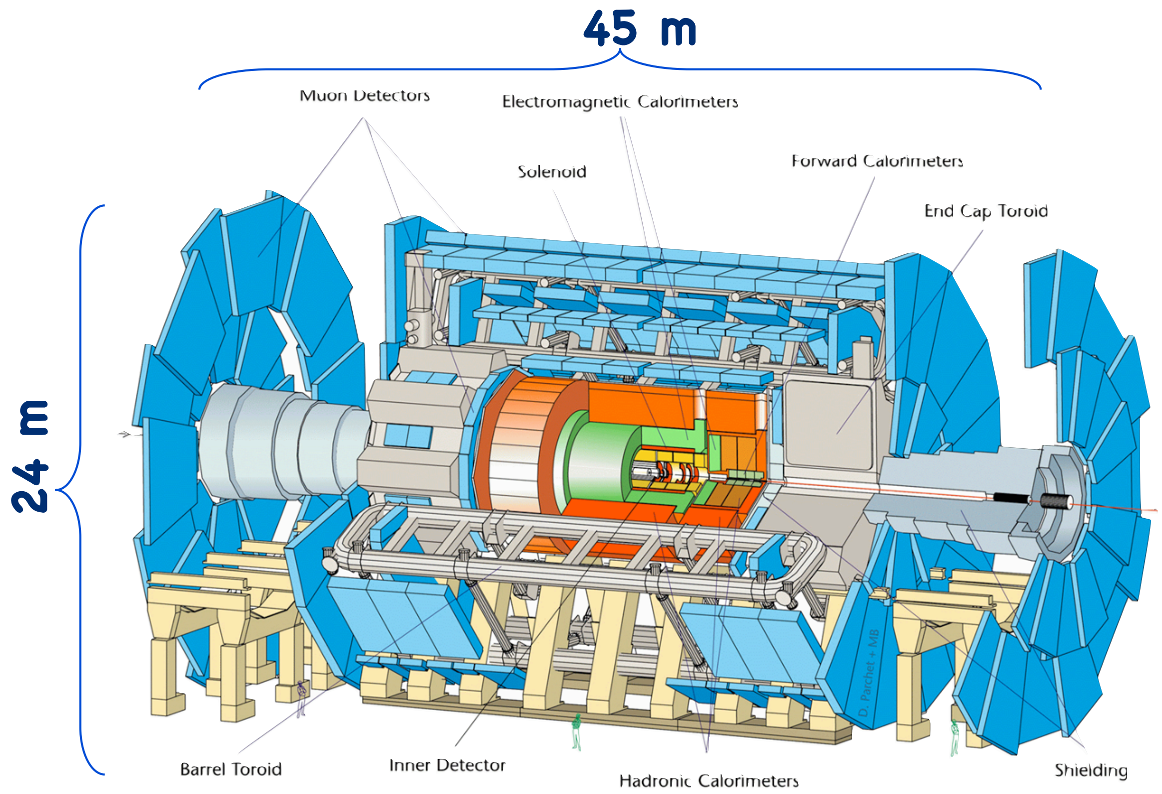
number of jets (pT > 30 GeV) between the tag jets, after VBF selections

the two tag jets naturally define the region where no activity is expected

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

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

the ATLAS Detector



7000 tones

- Tracking and muon coverage: $|\eta|<2.5$
- Calorimeters with presamplers: $|\eta|<1.8$
- Forward calorimeters : $3.2<|\eta|<5.9$

- e/γ energy resolution

  $\sigma/E \approx 10\text{-}15\%/\sqrt{E} \oplus \sim 1\%$
- Central jet energy resolution

  $\sigma/E \approx 60\%/\sqrt{E} \oplus 3\%$
- Missing $E_{x,y}$ resolution

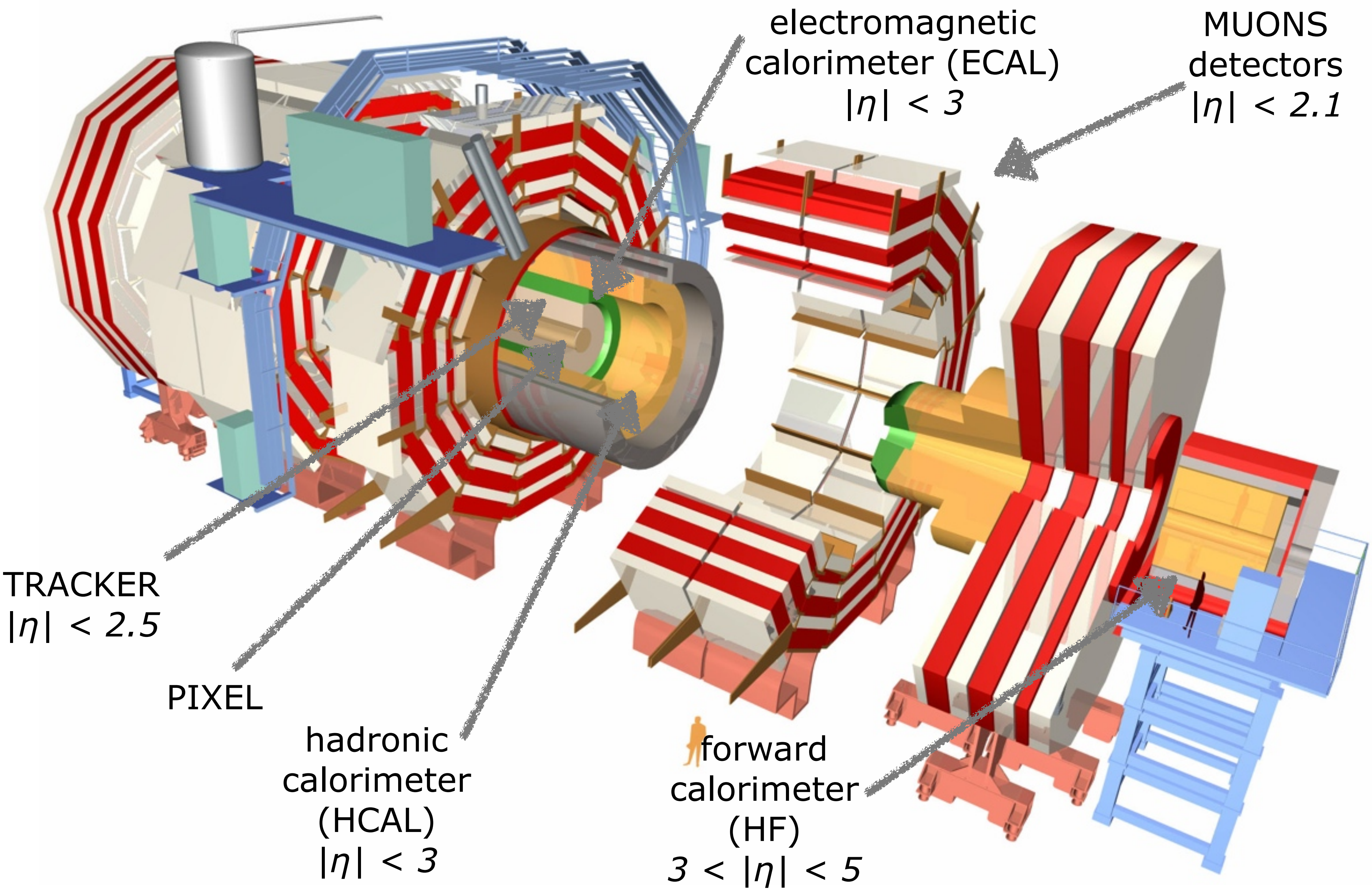
  $\sigma \approx 0.55\text{GeV} \times \sqrt{(\Sigma E_T)}$
- Track inverse-P_T resolution

  $\sigma_{\{1/PT\}} \approx 35\text{TeV}^{-1} \times (1 \oplus 50/P_T)$
- Muon system standalone momentum resolution

  $\sigma/P_T < 10\%$ up to 1 TeV

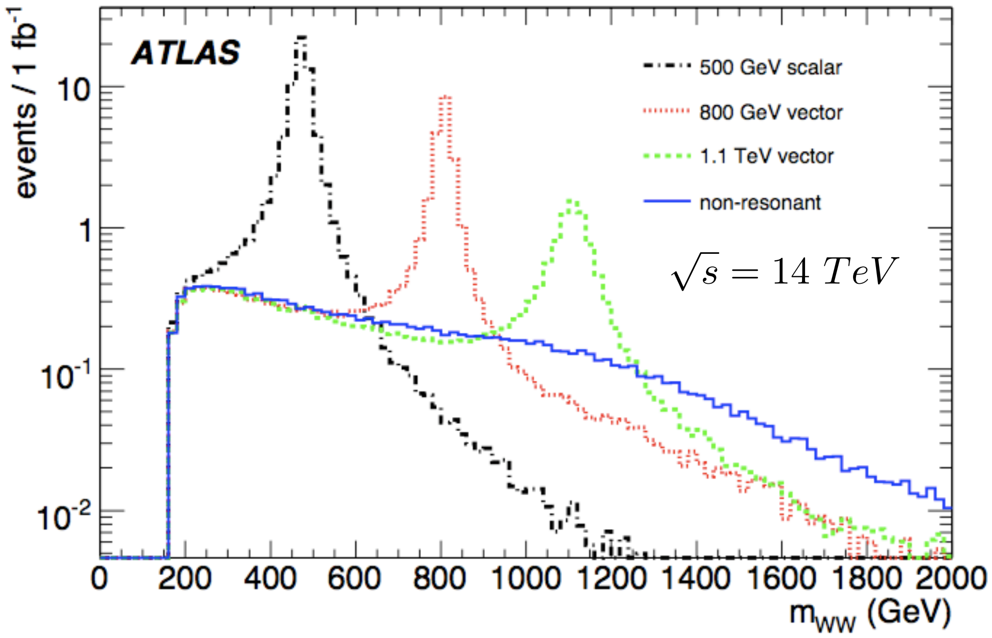
Backup slides: η dependence

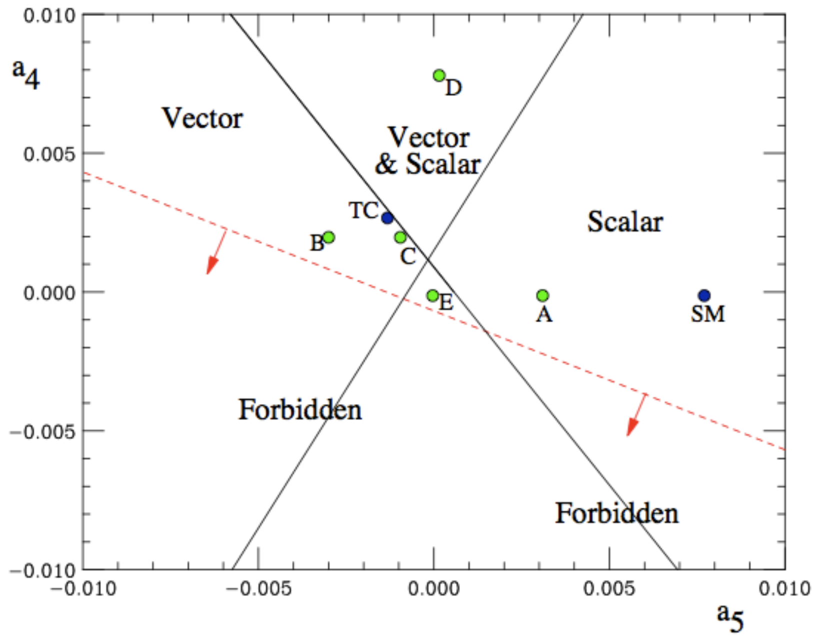
the CMS detector



search for ~1 TeV resonances

- **model-independent** treatment of physics below some scale Λ: electroweak chiral Lagrangian with Padé unitarization
- different possibilities tested
- particular attention to **semi-leptonic processes**: qqH > VV > jjX





parameters plane of the theory

J.M. Butterworth *et al.* **WW scattering at LHC** arXiv:hep-ph/0201098v1

The ATLAS Collaboration *et al.* **Expected Performance of the ATLAS Experiment Detector, Trigger and Physics** CERN-OPEN-2008-02

channels considered

$$\sqrt{s} = 14\ TeV$$

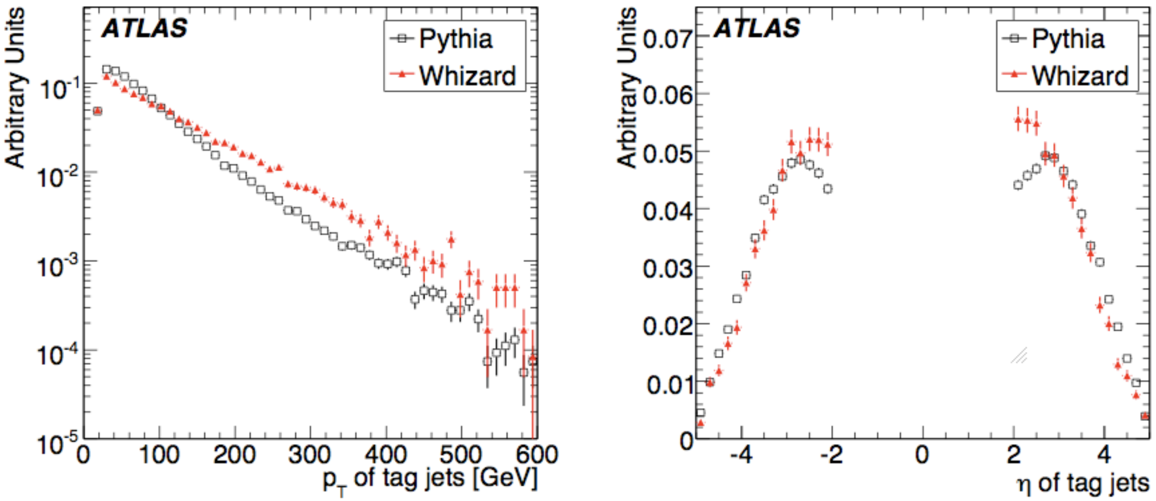
Sample name	Generator	$\sigma \times Br$, fb
$qqWZ \to qqjj\ell\ell$, $m = 500$ GeV	PYTHIA-73	25.2
$qqWZ \to qq\ell\nu jj$, $m = 500$ GeV	PYTHIA-73	83.9
$qqWZ \to qq\ell\nu\ell\ell$, $m = 500$ GeV	PYTHIA-73	8.0
$qqWZ \to qqjj\ell\ell$, $m = 800$ GeV	PYTHIA-ChL	10.5
$qqWZ \to qq\ell\nu jj$, $m = 800$ GeV	PYTHIA-ChL	35.2
$qqWZ \to qq\ell\nu\ell\ell$, $m = 800$ GeV	PYTHIA-ChL	3.4
$qqWZ \to qqjj\ell\ell$, $m = 1.1$ TeV	PYTHIA-ChL	3.7
$qqWZ \to qq\ell\nu jj$, $m = 1.1$ TeV	PYTHIA-ChL	12.3
$qqWZ \to qq\ell\nu\ell\ell$, $m = 1.1$ TeV	PYTHIA-ChL	1.18
$qqWW \to qq\ell\nu jj$, $m = 499$ GeV (s)	PYTHIA-ChL	66.5
$qqWW \to qq\ell\nu jj$, $m = 821$ GeV (s)	PYTHIA-ChL	27.5
$qqWW \to qq\ell\nu jj$, $m = 1134$ GeV (s)	PYTHIA-ChL	17.0
$qqWW \to qq\ell\nu jj$, $m = 808$ GeV (v)	PYTHIA-ChL	29.8
$qqWW \to qq\ell\nu jj$, $m = 1115$ GeV (v)	PYTHIA-ChL	17.9
$qqWW \to qq\ell\nu jj$, non-resonant	PYTHIA-ChL	10.0
$qqZZ \to qq\nu\nu\ell\ell$, $m = 500$ GeV	PYTHIA-ChL	4.0
$jjWZ \to jj\ell\nu\ell\ell$, background	MADGRAPH	96
$jjZZ \to jj\nu\nu\ell\ell$, background	MADGRAPH	45.5
		σ (no Br), pb
$W^+ + 4$ jets	MADGRAPH	165 ± 0.1
$Z + 4$ jets	MADGRAPH	87 ± 0.7
$W^+ + 3$ jets	MADGRAPH	6.2 ± 0.02
$Z + 3$ jets	MADGRAPH	3.8 ± 0.02
$t\bar{t}$	MC@NLO	833 ± 100

signals

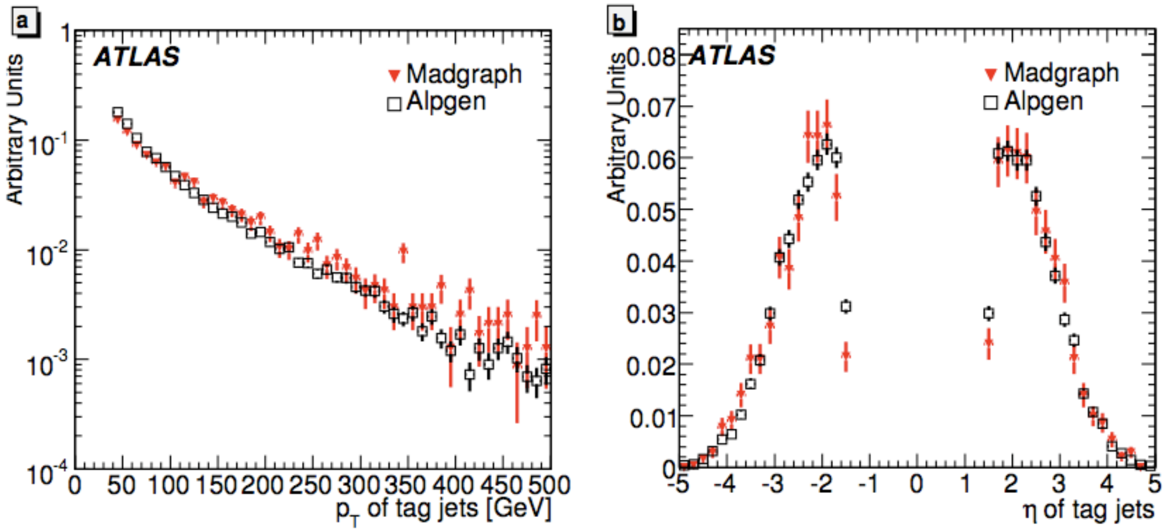
backgrounds

cross-check the simulation

- the chiral Lagrangian in PYTHIA, cross-checked with the full 2 → 6 matrix element from WHIZARD

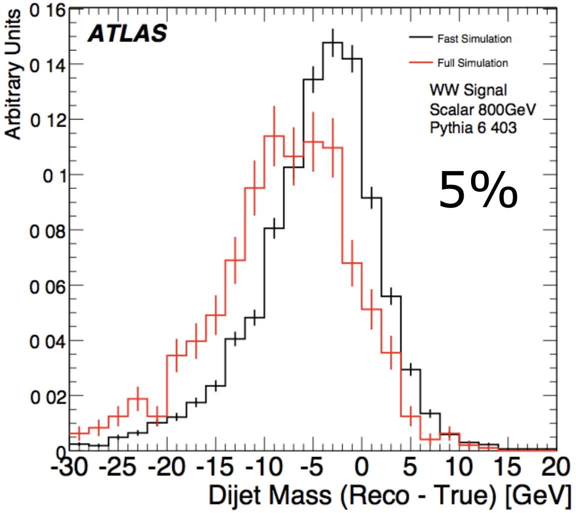


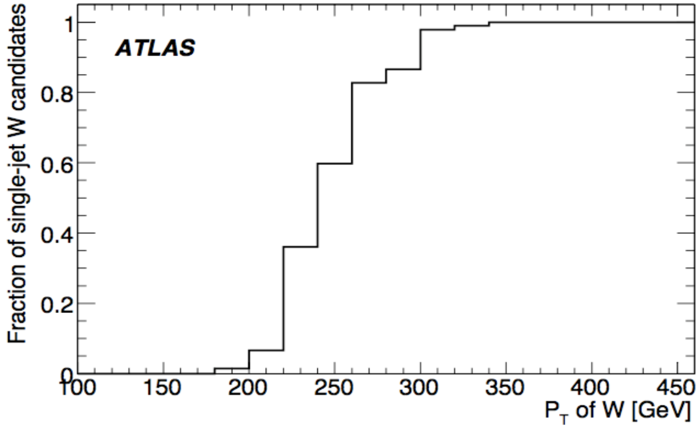
- V+jets generated with MADGRAPH, ttbar with MC@NLO and HERWIG/JIMMY



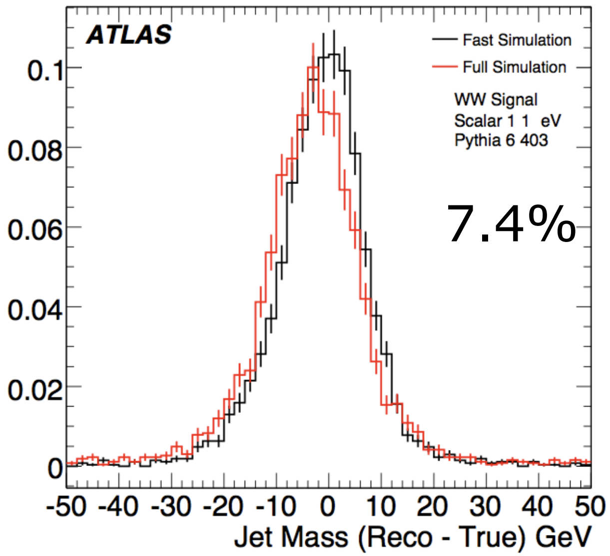
hadronic W reconstruction

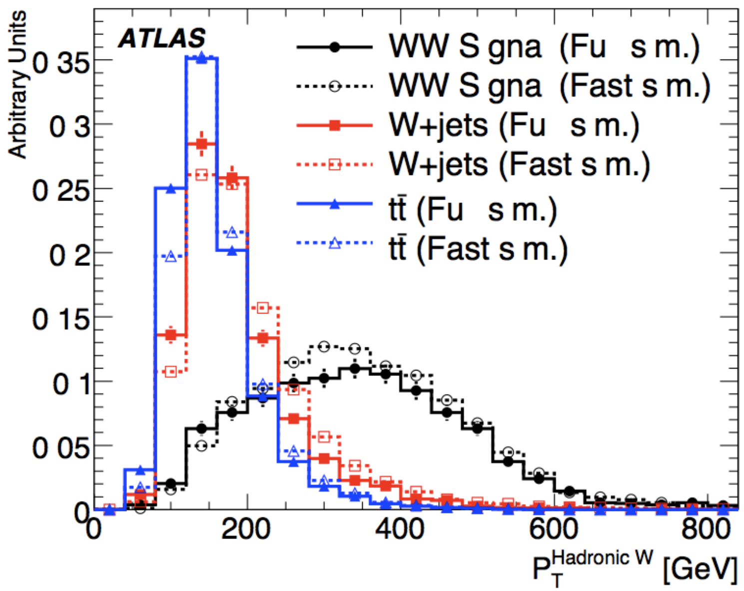
- high pT Ws reconstructed as **single jets in the detector**

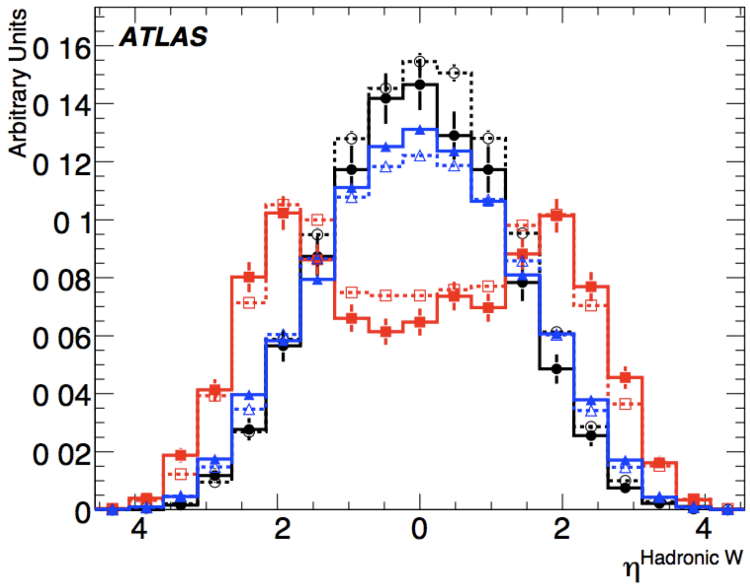




←double single→

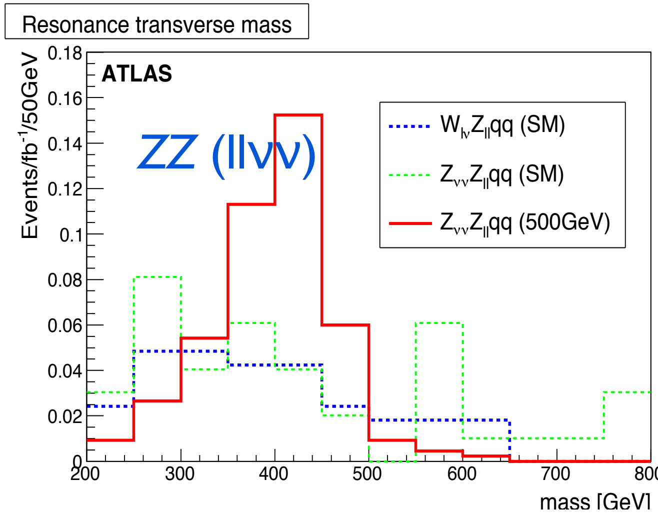


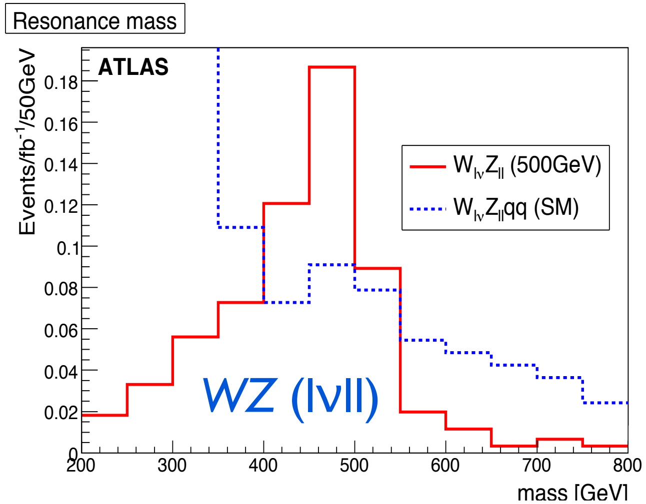


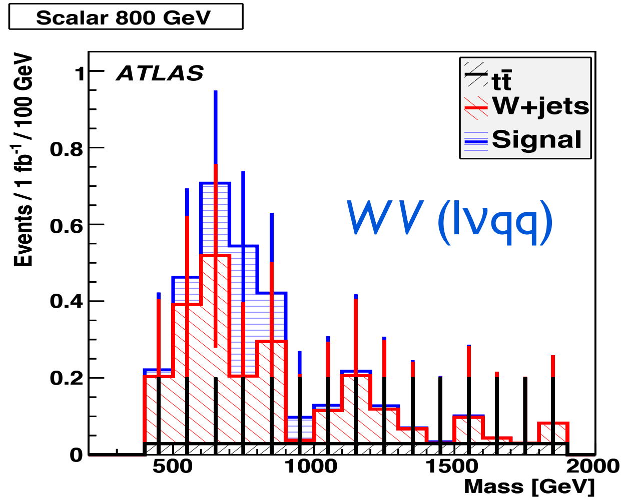


results

- evaluate signal and background in the resonance mass window







$$\text{significance} = \sqrt{2((S+B)\ln(1+S/B)-S)}$$

Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\ jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_jZ_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_jZ_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

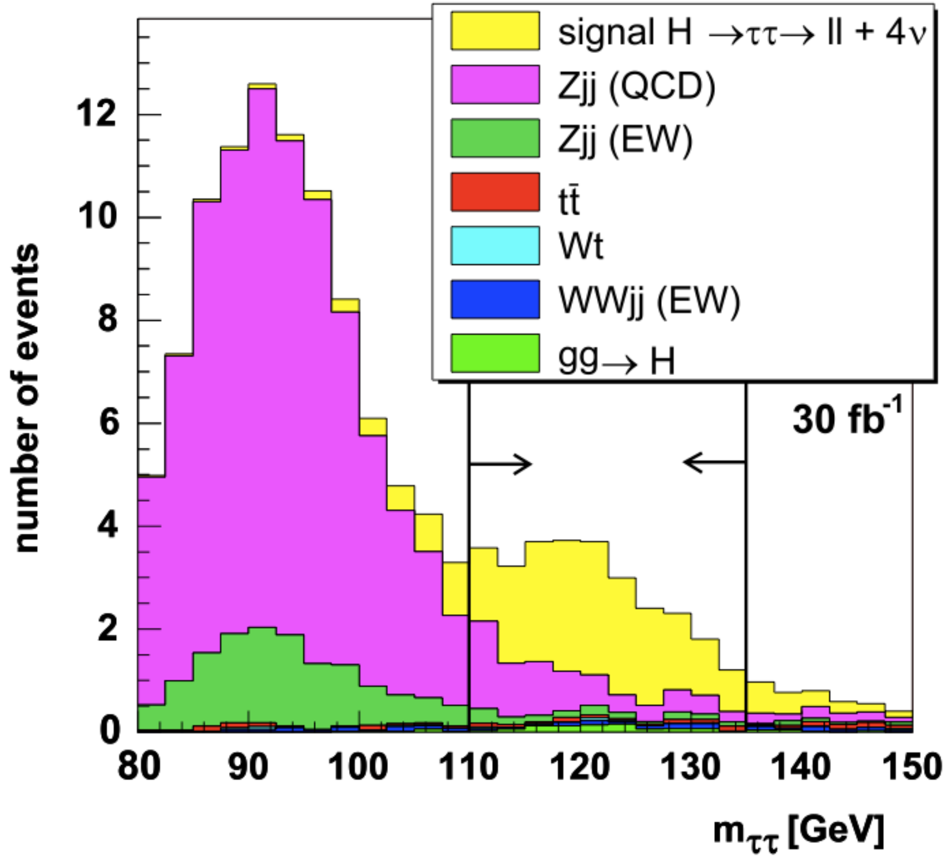
← 800 GeV

← 500 GeV

← 1.1 TeV

Higgs couplings

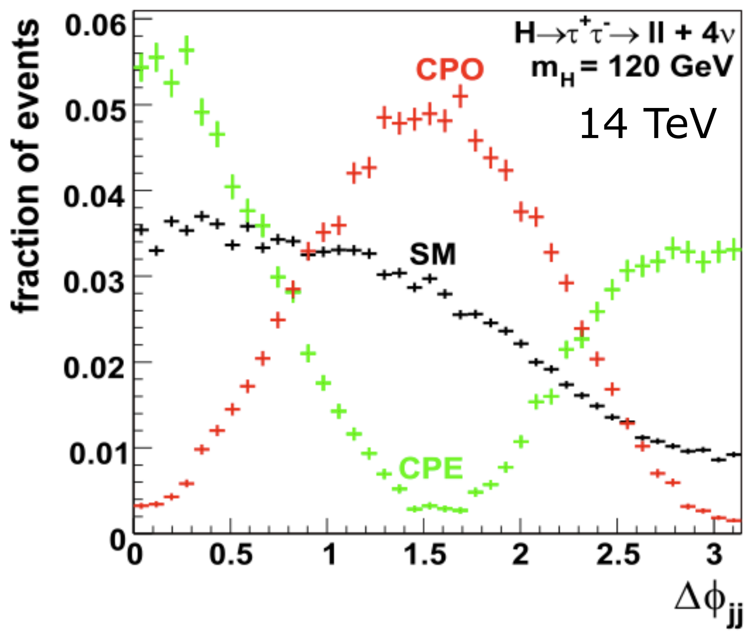
- if the Higgs is found, one wants to **know its properties**
- study its **coupling to vector bosons** though the VBF topology
- LO generation of signal and backgrounds
- ATLAS fast simulation, **14 TeV**
- Higgs mass @ **120 GeV**

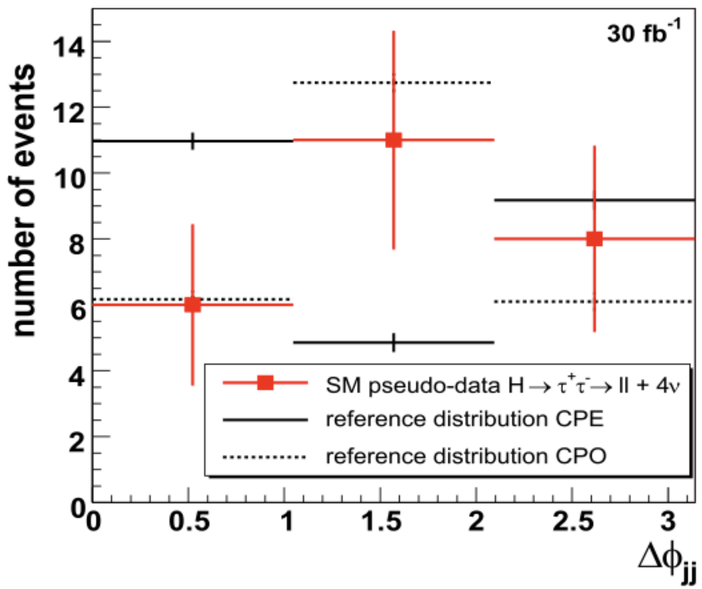


C. Ruwiedel, M. Schumacher, N. Wermes **Prospects for the measurement of the structure of the coupling of a Higgs boson to weak gauge bosons in weak boson fusion with the ATLAS detector** Eur. Phys. J. C 51, 385–414 (2007)

the main coupling

- determine the Higgs coupling to the vector bosons **from the azimuthal angle between the tagging jets**
- **anomalous couplings** parametrized with an effective Lagrangian
- test the possibility of **distinguishing SM** from anomalous couplings





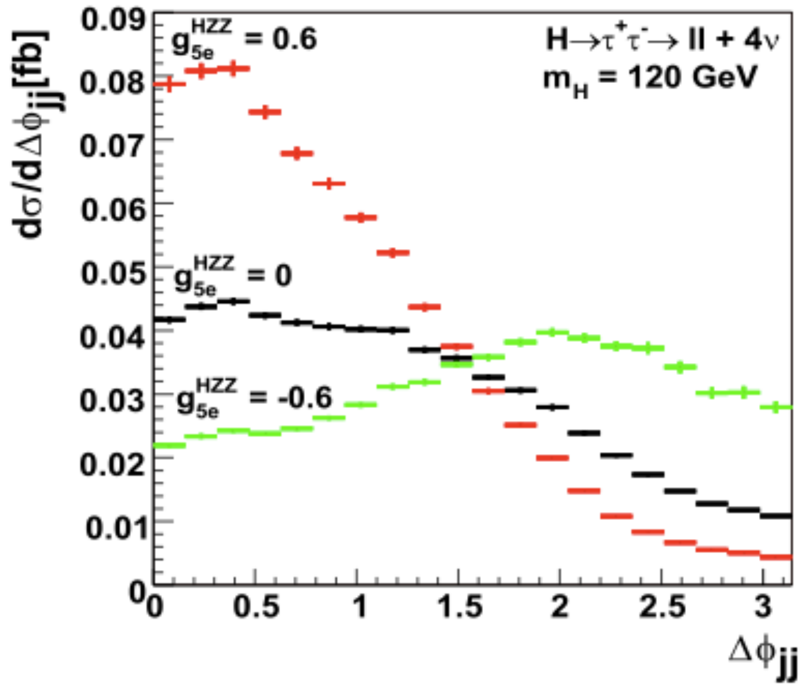
integrated luminosity, hypothesis tested		probability for $> 5\sigma$	probability for $< 5\%$	median χ^2-prob.	median dev. in σ
$H \to W^+W^- \to ll\nu\nu$					
10 fb^{-1}	CPE	59%	100%	1.3×10^{-7}	5.3σ
	CPO	35%	98%	6.0×10^{-6}	4.5σ
30 fb^{-1}	CPE	100%	100%	–	–
	CPO	100%	100%	–	–
$H \to \tau^+\tau^-$ combined					
30 fb^{-1}	CPE	2%	68%	1.2×10^{-2}	2.5σ
	CPO	0%	52%	4.3×10^{-2}	2.0σ

an additional coupling

- search for **additional anomalous CP-even couplings**, besides the dominant one, from the azimuthal angle between tagging jets

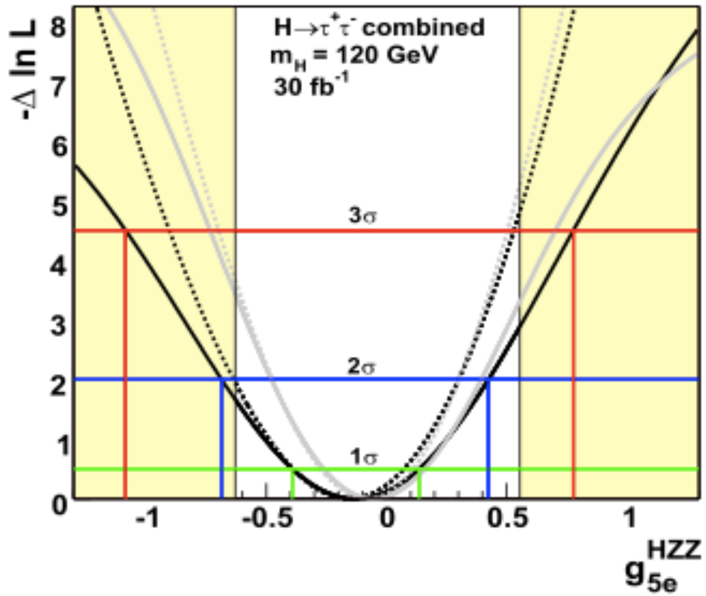
- test anomalous couplings not excluded by experimental limits

- fit a likelihood to determine the coupling **on top of the SM behaviour**



background included:

		minimum $-\Delta \ln L$	1σ interval	2σ interval	3σ interval	σ estimate
$H\rightarrow W^+W^-\rightarrow ll\nu\nu$						
$10\ fb^{-1}$	non-extended	-0.09	$[-0.30, 0.11]$	$[-0.50, 0.31]$	$[-0.73, 0.54]$	0.20
	extended	-0.07	$[-0.26, 0.12]$	$[-0.44, 0.31]$	$[-0.64, 0.51]$	0.19
$30\ fb^{-1}$	non-extended	-0.11	$[-0.22, 0.00]$	$[-0.34, 0.12]$	$[-0.45, 0.23]$	0.11
	extended	-0.10	$[-0.21, 0.01]$	$[-0.31, 0.12]$	$[-0.42, 0.23]$	0.11
$H\rightarrow\tau^+\tau^-\rightarrow ll+4\nu$						
$30\ fb^{-1}$	non-extended	-0.25	$[-0.64, 0.12]$	$[-1.23, 0.53]$	–	0.38
	extended	-0.25	$[-0.59, 0.07]$	$[-0.97, 0.40]$	$[-1.38, 0.74]$	0.33
$H\rightarrow\tau^+\tau^-$ combined						
$30\ fb^{-1}$	non-extended	-0.13	$[-0.40, 0.13]$	$[-0.69, 0.42]$	$[-1.08, 0.78]$	0.27
	extended	-0.16	$[-0.40, 0.06]$	$[-0.64, 0.40]$	$[-0.90, 0, 53]$	0.23



M_{VV} spectrum measurement

- qq → qqVV has been analyzed with different final states:

qqVW	qq qq μν (eν)
qqVZ	qq qq μμ (ee)
qqZZ	qq μμ μμ
qqZW	qq μμ μν
qqW±W±	qq μ±ν μ±ν

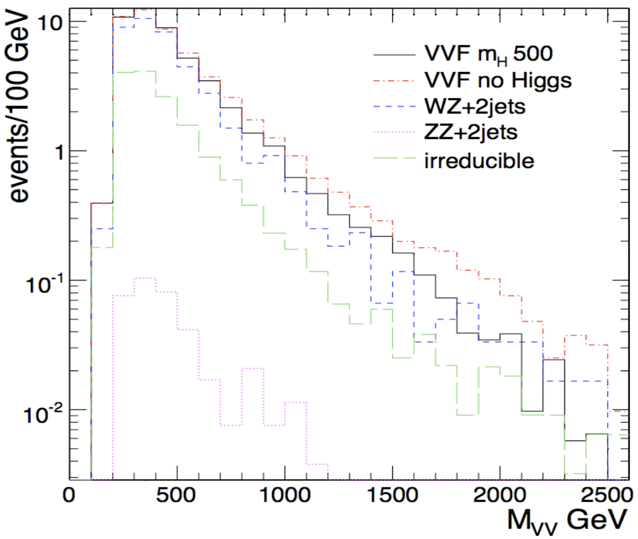
- All processes have:
  - **High pT lepton(s)** → Trigger
  - **2 "tag" jets** in the fwd/bwd region to identify a 6-fermion process
  - E_{CM} = 14 TeV, low luminosity PU
- Two different scenarios: Higgs (M_H=500 GeV) and no-Higgs (M_H=∞)

N. Amapane *et al.* **Study of VV-scattering processes as a probe of electroweak symmetry breaking**, CMS AN-2007/005

signal and backgrounds

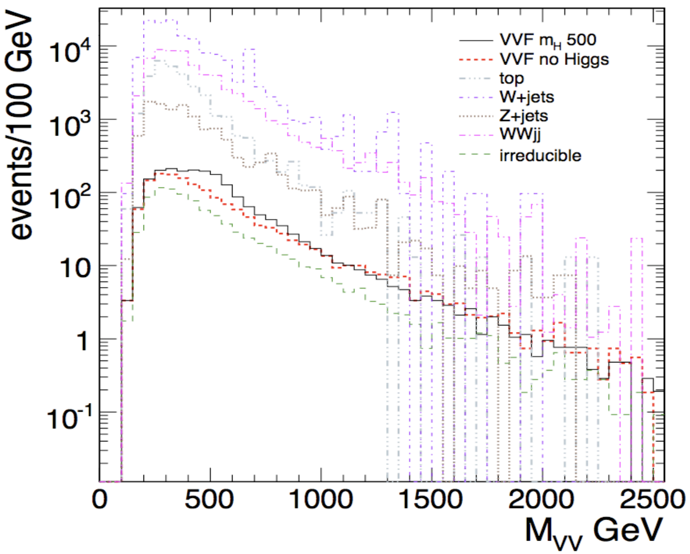
- signal and background **selected events**
- **500 GeV Higgs** and **no Higgs cases** (significance with 60 fb^{-1})

qqμμμν final state



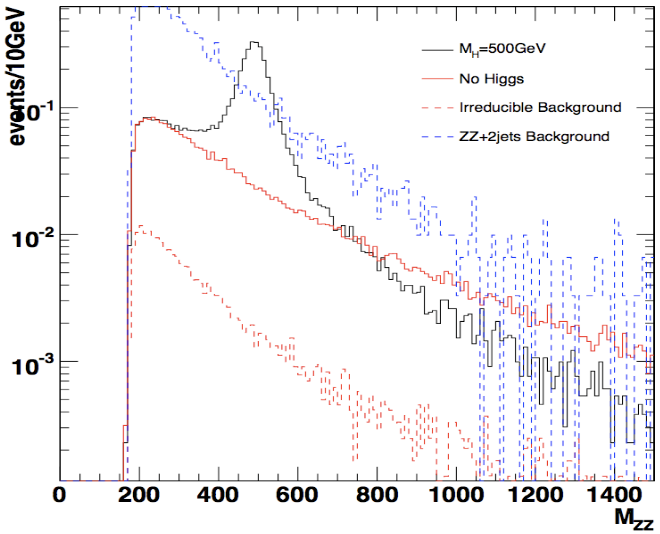
-
1.51
significance

qqqqμν final state



2.86
1.13
significance

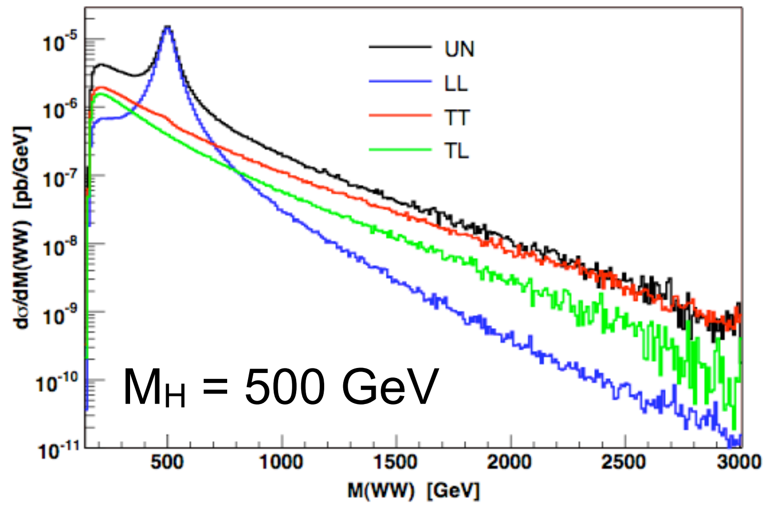
qqμμμμ final state

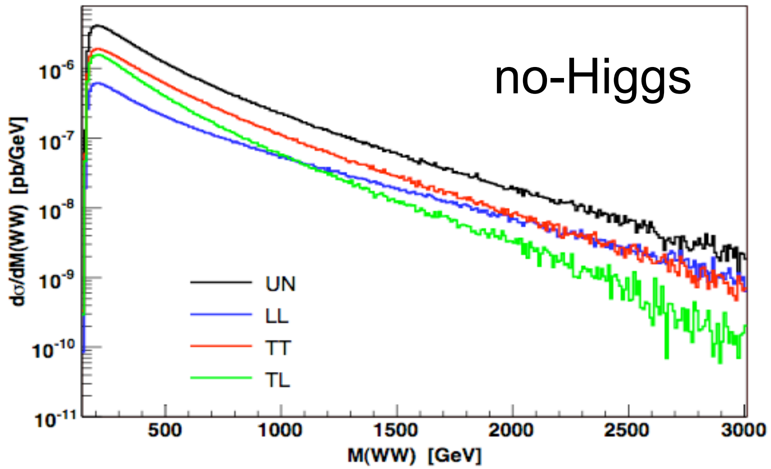


1.66
0.27
significance

the high mass region

- The cross section σ(qq→qqVV) and the V polarization **depend on the presence of the Higgs**:
  - **V_T is independent** of the Higgs presence (~NO coupling)
  - **V_L couples to Higgs** ⇒ diverges* at high masses if the Higgs does not exist





E. Accomando *et al.*
arXiv:hep-ph/0512219v2

- If the Higgs exists, **V_LV_L dominates under the peak**, while at high masses (M_{VV} > 1TeV) V_TV_T dominates
- If the Higgs does not exist **V_L and V_T are of the same order** at M_{VV} > 1TeV

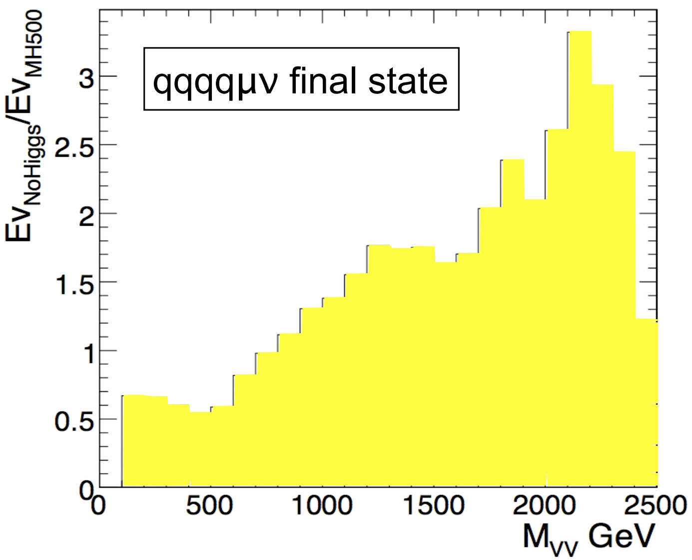
✳ *suppressed by the pdfs decrease*

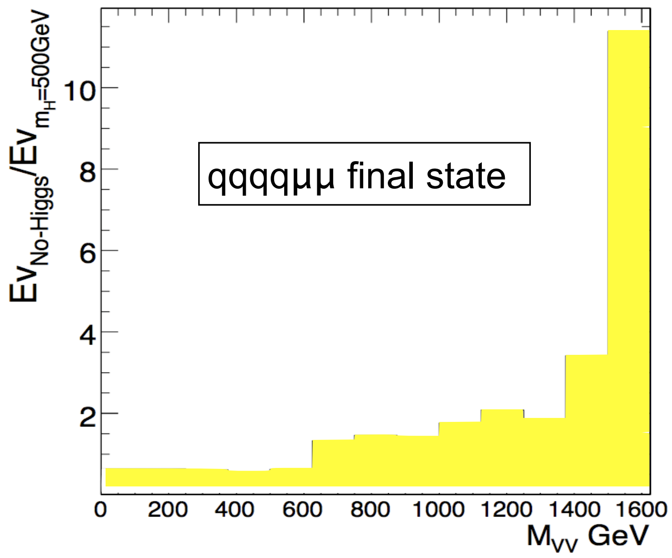
Higgs/no-Higgs ratio

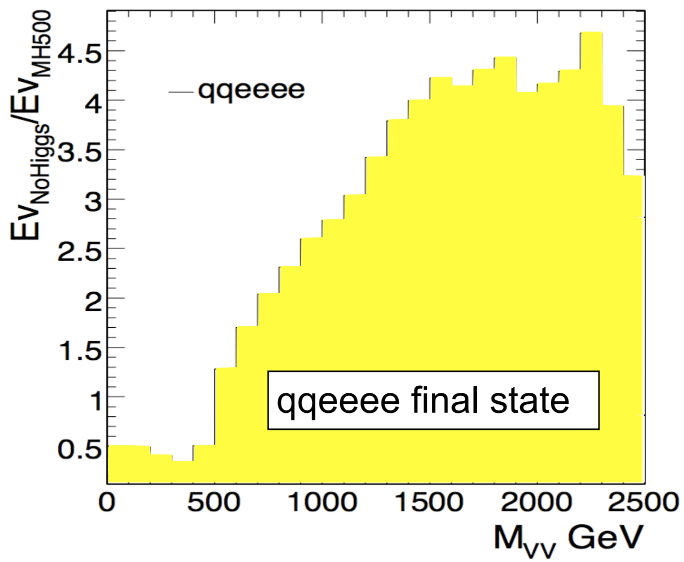
- differences are expected to appear **in the high M_{VV} region**
- the ratio is calculated in this region, **as a function of the M_{VV} minimum cut**

$$\frac{\int_{M_{cut}}^{\infty} dM_{VV} \frac{d\sigma_{noHiggs}}{dM_{VV}}}{\int_{M_{cut}}^{\infty} dM_{VV} \frac{d\sigma_{m_H=500\ GeV}}{dM_{VV}}}$$

- at reconstructed level, additional selections have been added to enhance the difference between Higgs and no Higgs: $|\eta_V| < 2$ & $|\eta_j - \eta_V| > 0.7$







resolution on invariant masses

- Important to:
  - discriminate signal from background (**M_V**)
  - define the energy scale at which symmetry breaks (**M_{VV}**)

	$qqqq\mu\nu$	$qqqqe\nu$	$qqqq\mu\mu$	$qqqqee$	$qq\mu\mu\mu\mu$	$qqeeee$	$qq\mu\mu\mu\nu$
$Z \to ll$	—	—	1.5%	1.5%	1.5%	2.0%	2.1%
$W/Z \to jj$	27%	20.5%	20%	25%	—	—	—
$VV \to 4f$	22%	19.0%	9.5%	9.5%	1.1%	1.5%	9.4%

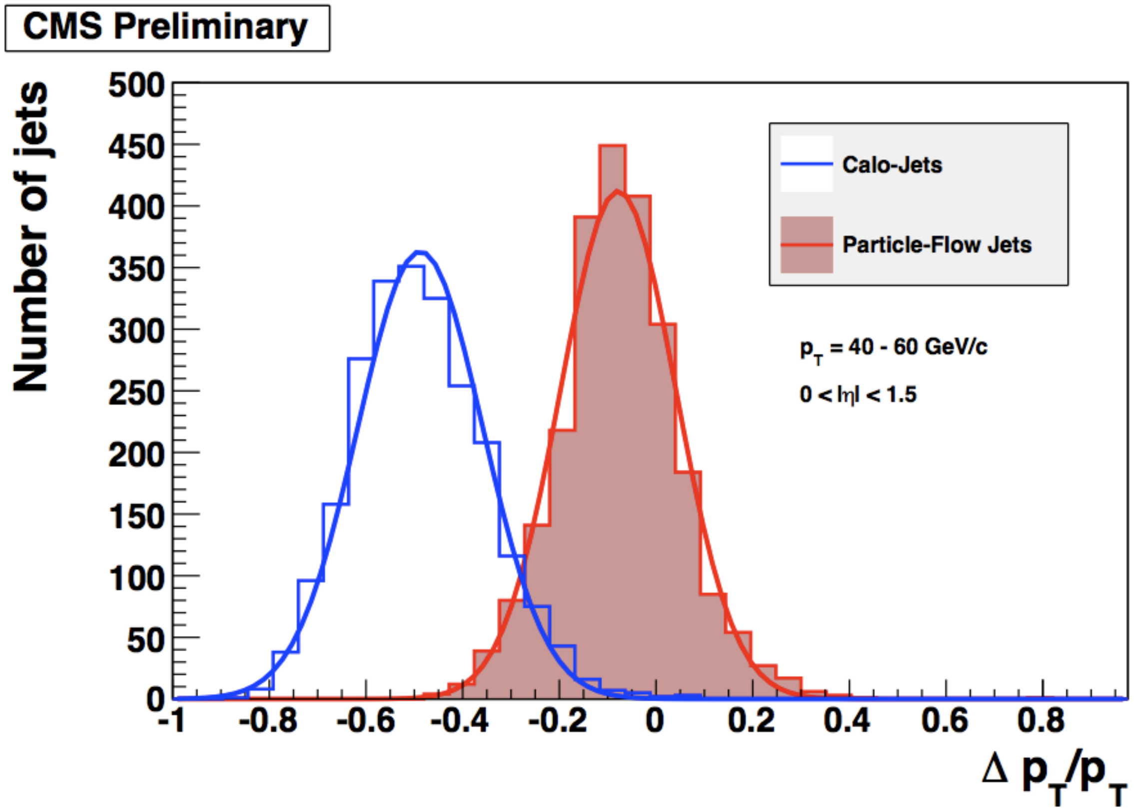
M_V and M_{VV} resolution for the various final states

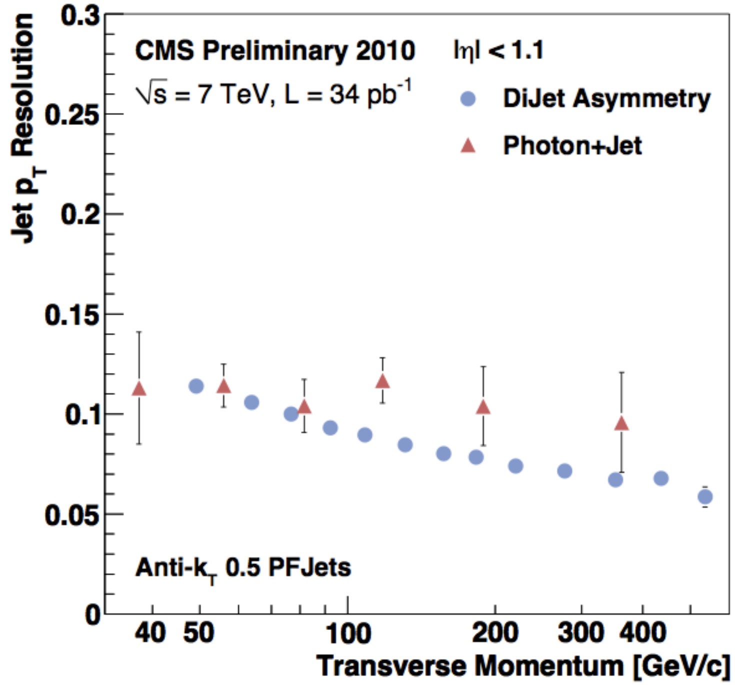
resolutions are dominated by the jet reconstruction, which at the time was featuring calorimetric jets only

qqqqμν and qqqqeν differ because different optimization procedures have been adopted

jet reconstruction

- the CMS study was carried out with calorimetric jets, limiting the V_{had} mass resolution
- the new reconstruction algorithm of CMS, **particle flow, has far better performances**

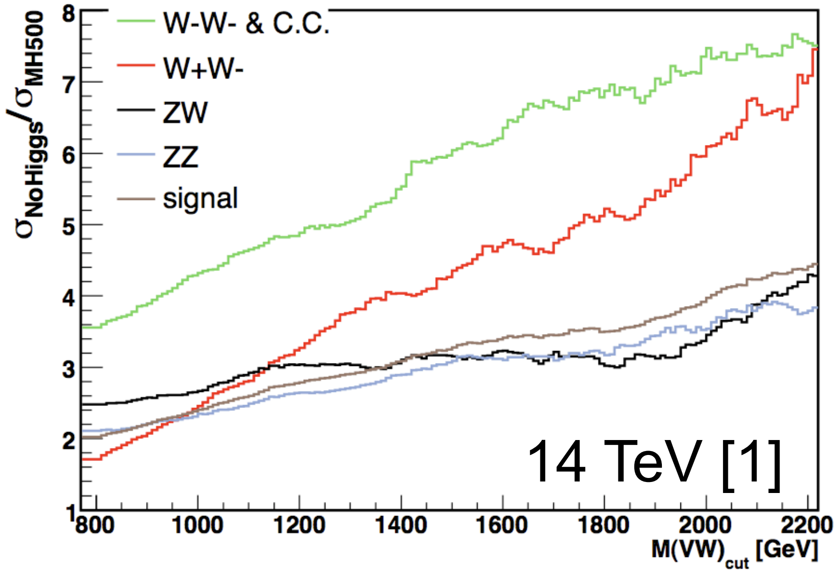


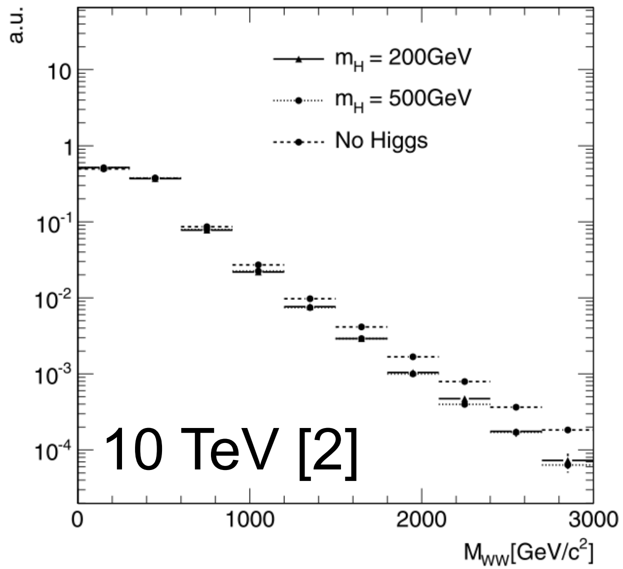


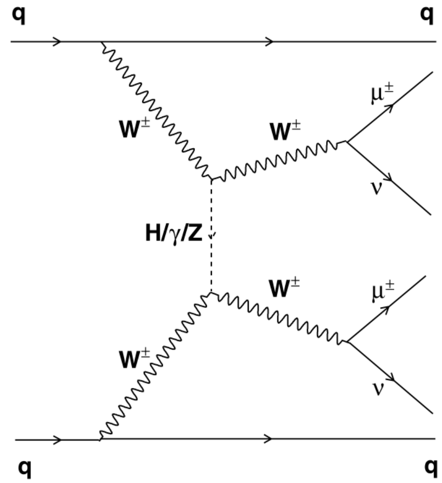
CMS Collaboration **Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss}**
CMS PFT/09/001

same sign Ws scattering

- the **same sign W±W± scattering** is sensitive to different scenarios







separation power between the two hypotheses (analysis optimization)

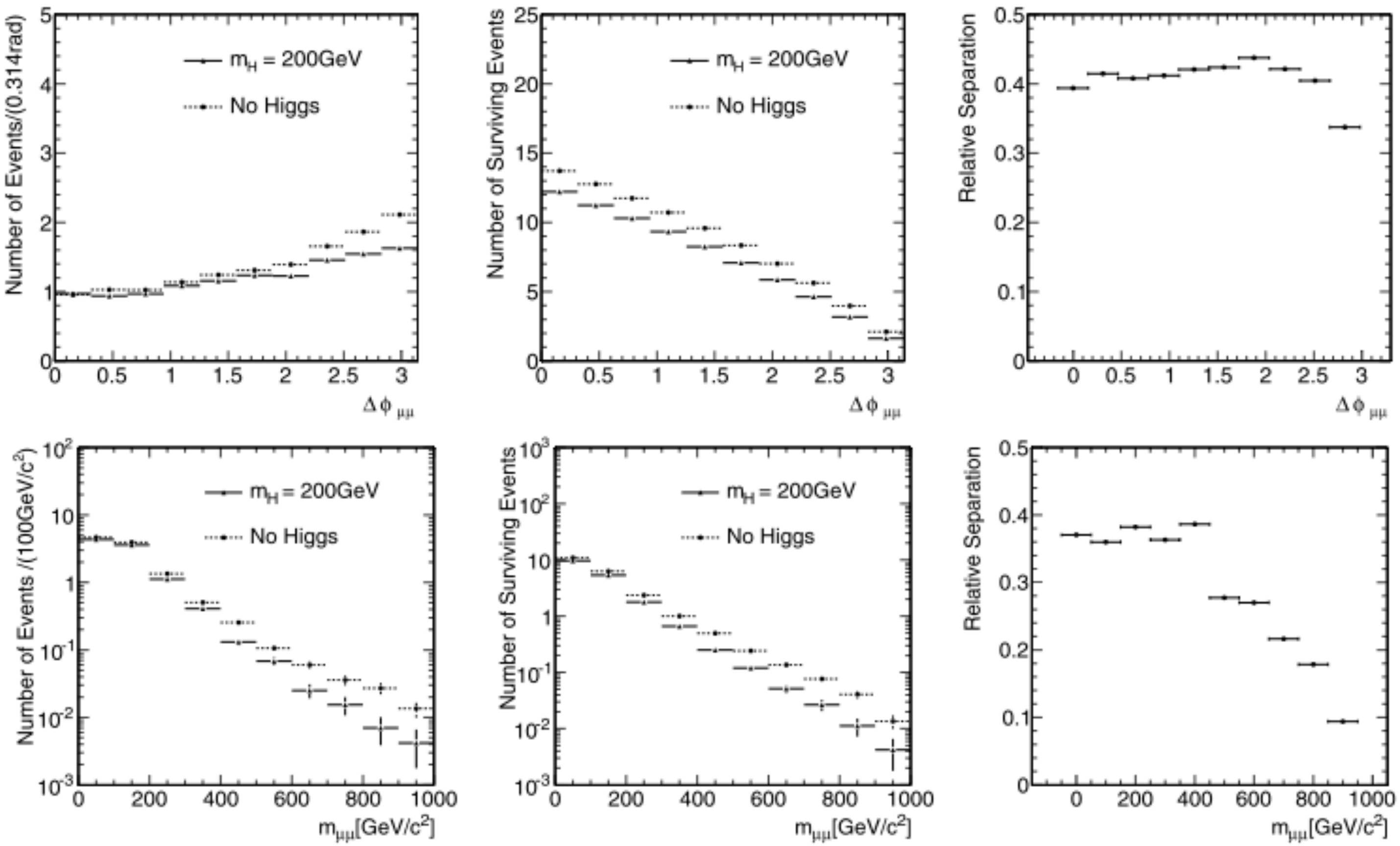
$$\alpha = \frac{N_{\mathrm{NoH}} - N_{m_{\mathrm{H}}(200)}}{\sqrt{N_{m_{\mathrm{H}}(200)} + N_{\mathrm{Bkg}}}}$$

[1] E. Accomando *et al.* **Boson-boson scattering and Higgs production at the LHC from a six fermion point of view: four jets + lν processes at $O(\alpha^6_{em})$** arXiv:hep-ph/0512219v2

[2] B. Zhu *et al.* **Same Sign WW Scattering Process as a Probe of Higgs Boson in pp Collision at s = 10 TeV** arXiv:1010.5848v3

test the separation power

- the **invariant mass of the two muons and the azimuthal angle between them** studied as main selections discriminators



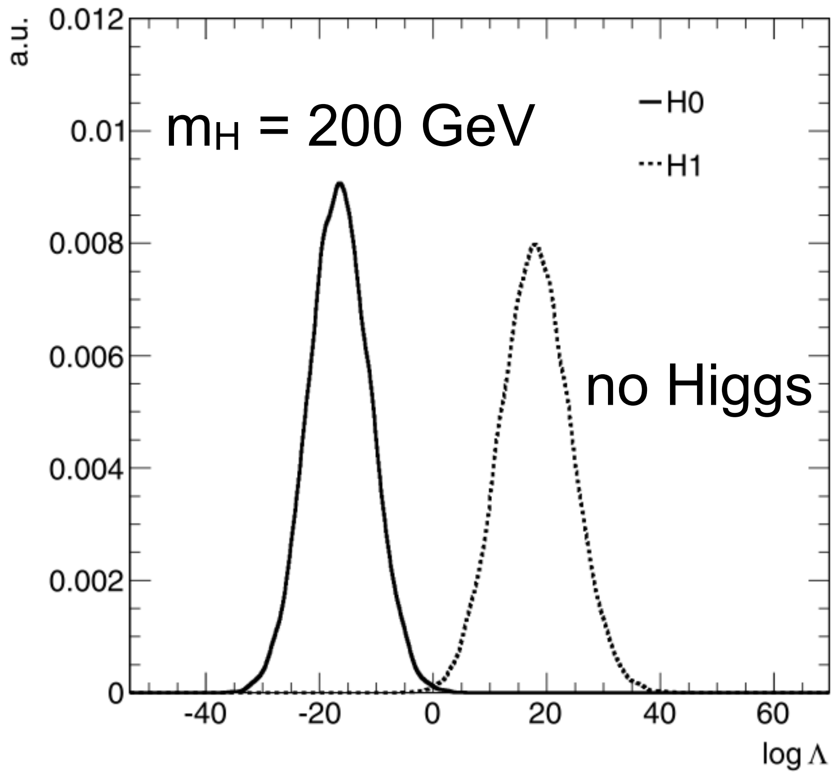
$$\sqrt{s} = 10\ TeV$$

$$\int \mathcal{L} = 60\ fb^{-1}$$

Discriminator	NoH	$m_{\mathrm{H}}(200)$	NoH/$m_{\mathrm{H}}(200)$	Background	Relative separation	$S_{(m_{\mathrm{H}}(200))}$	S_{NoH}
$m_{\mu\mu}$	2.4±0.1	1.8±0.1	1.3±0.1	1.0±0.8	0.35	1.5	1.9
$\Delta\phi_{\mu\mu}$	6.5±0.1	5.4±0.1	1.2±0.1	3.5±2.9	0.36	2.4	2.8

check the separation

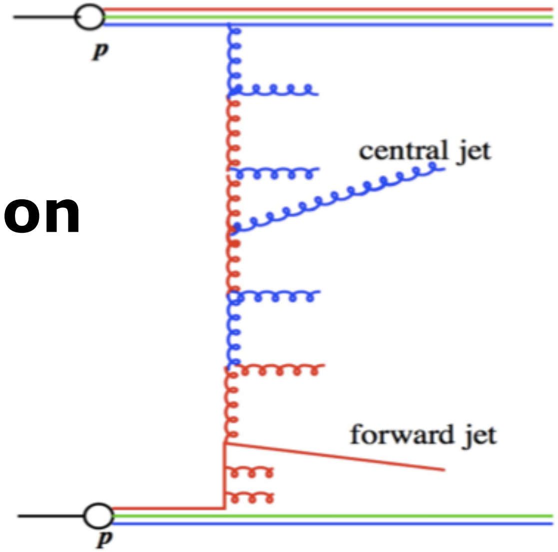
- at the end of the analysis selections, the actual discrimination power is tested with a **likelihood ratio** test
- With the total statistics expected from the ATLAS and CMS experiments at 14 TeV, the separation power between Higgs boson and no-Higgs boson scenarios will be **at the level of 4σ**.



$$\delta = \frac{|\max(LLR)_{H0} - \max(LLR)_{H1}|}{\sigma_{H0} \oplus \sigma_{H1}}$$

central + forward jets

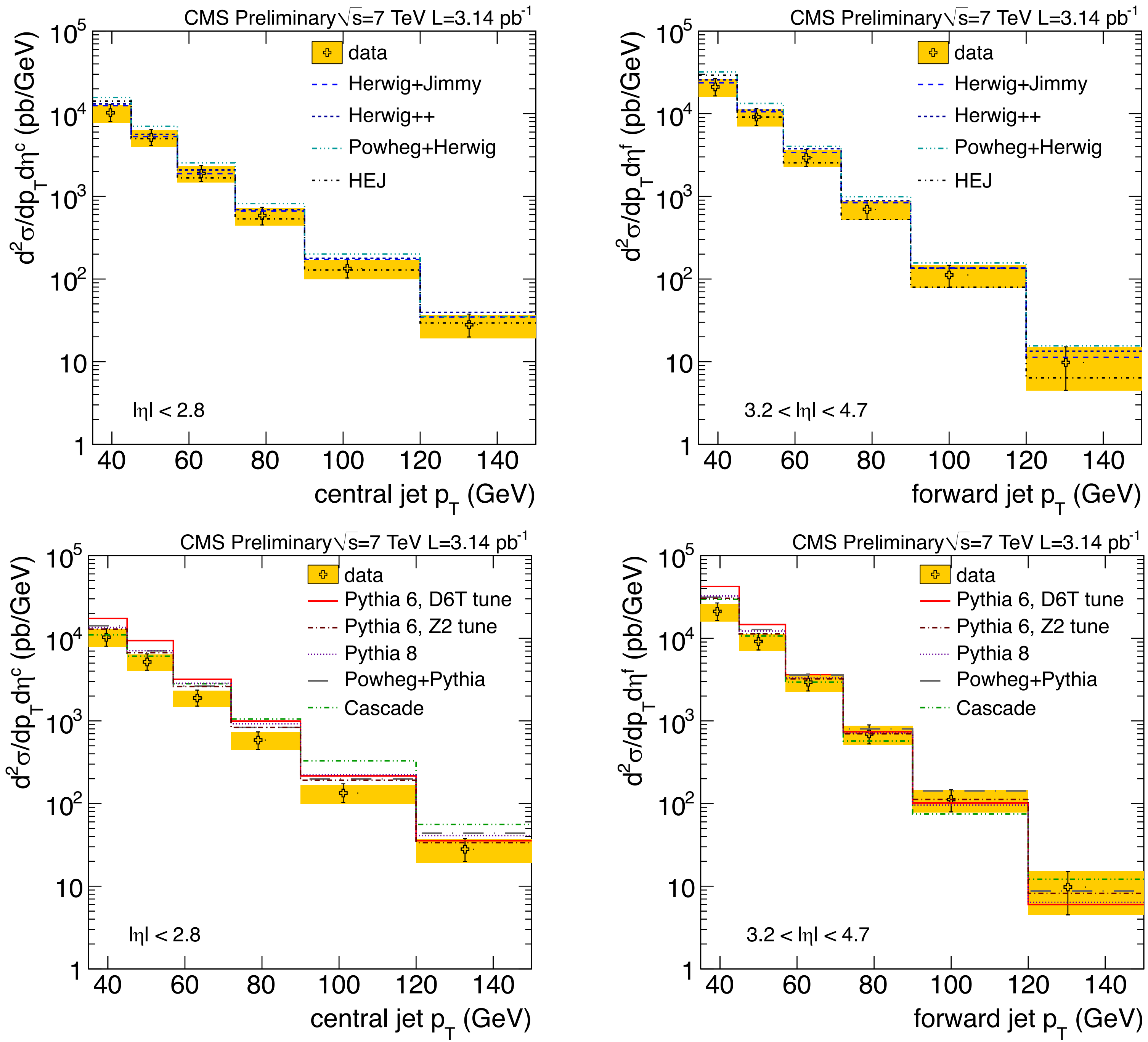
- investigate **VBF-like topologies** in the dijet production
- associated **central and forward jet production**
- $E_T > 35$ GeV, $|\eta| < 2.8$ or $3.2 < |\eta| < 4.7$
- compare the measured cross-sections to theoretical predictions



$$\frac{d^4\sigma}{dp_T^c\, dp_T^f\, d\eta^c\, d\eta^f}$$

$$\begin{cases} \dfrac{d^2\sigma}{dp_T^f d\eta^f} = \dfrac{1}{\Delta\eta^f} \cdot \left.\dfrac{d^4\sigma}{dp_T^c\, dp_T^f\, d\eta^c\, d\eta^f}\right|_{p_T^c > 35\mathrm{GeV}\, \wedge\, |\eta^c| < 2.8} \\ \\ \dfrac{d^2\sigma}{dp_T^c d\eta^c} = \dfrac{1}{\Delta\eta^c} \cdot \left.\dfrac{d^4\sigma}{dp_T^c\, dp_T^f\, d\eta^c\, d\eta^f}\right|_{p_T^f > 35\mathrm{GeV}\, \wedge\, 3.2 < |\eta^f| < 4.7} \end{cases}$$

the cross-sections



conclusions

- the **VV scattering** is one of the key processes to investigate EWSB in a model-independent way
- both ATLAS and CMS performed **feasibility studies** to exploit the VBF signature and isolate the VV scattering
- all the studies are **quite old**, in the meanwhile:
  - **the event reconstruction** in the detectors is improved (particle flow in CMS)
  - **new analyses** have been suggested (e.g. the talk by A. Ballestrero this Friday, arXiv:0909.3838, arXiv:0812.5084, CERN-PH-TH/2010-020, arXiv:hep-ph/0609075v2)
  - better understanding of the events with the **current LHC configuration** has been achieved: **PU, UE, MPI to be correctly considered, as their impact can be huge**
- **need to re-visit the studies** with the current LHC configuration, current detector knowledge and data

thanks to Chiara Mariotti and Markus Schumacher for fruitful discussions