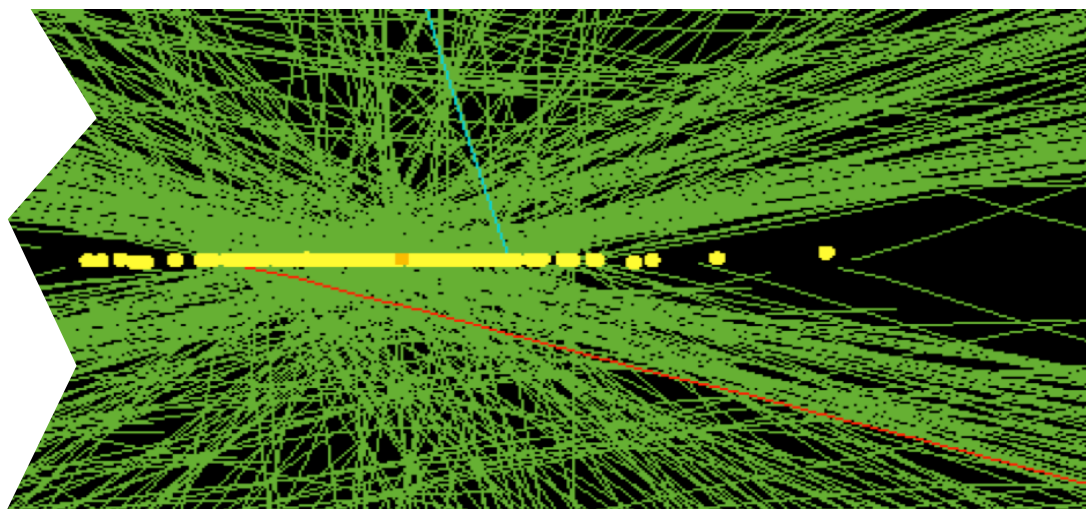# Experimental aspects of VBS studies
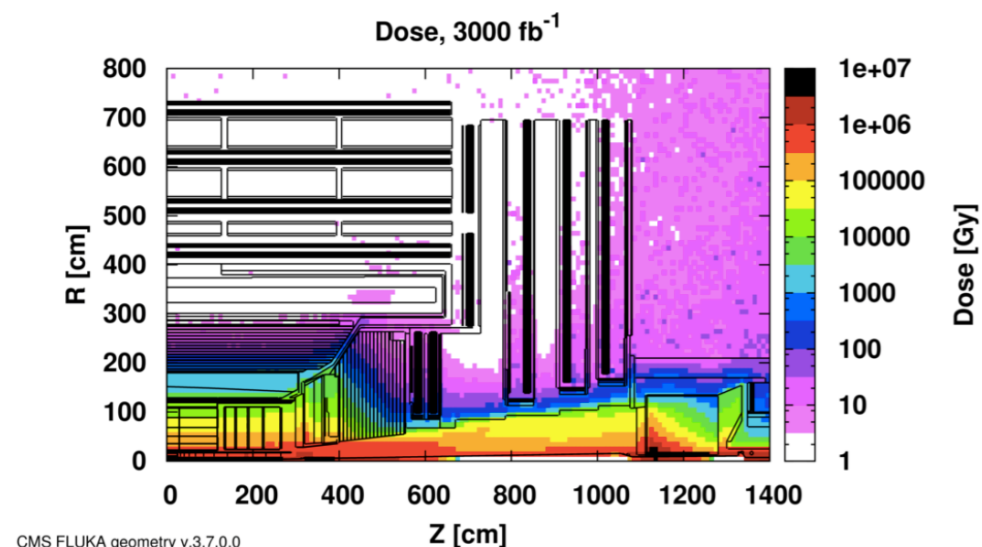
P. Govoni
University and INFN of Milano-Bicocca

11th May 2015, Physics at the High-Luminosity LHC

- account from **radiation damage**
- **huge pile-up**: 140 events on average
- maintain **event reconstruction** performances
- **trigger** in a high luminosity environment

ATLAS PHASE 2

- new pixel and strip tracker
- calorimeter
- trigger system

CMS PHASE 2

- new tracker
- extended muons coverage
- calorimetry electronics upgrade
- forward calorimeter upgrade

Vector Boson Scattering in ATLAS

- **new physics**
  - $SU(2)_L \times U(1)_Y$ gauge-invariant, CP-even operators with dimension larger than 4 in the SM Lagrangian
  - general EW Chiral Lagrangian anomalous terms (high mass resonances)
- **simplified detector performance**:
  - **single physics objects** response studied in detailed simulation with dedicated samples
  - parametrised efficiencies and resolutions used to **smear the analysis samples**
- several final states considered:

$WW \to \ell\nu\ell\nu$	a_4
$WW \to \ell\nu jj$	a_4, a_5
$ZZ \to 4\ell$	$c_\phi W$
$W^\pm W^\pm \to \ell^\pm\nu\ell^\pm\nu$	f_{S0}
$WZ \to \ell\nu\ell\ell$	f_{T1}

physics objects

- leptons: $p_T > 25$ GeV, $|\eta| < 2.5$
- jets: $p_T > 50$ GeV, $|\eta| < 4.9$
- tag jets: two largest p_T ones

ATLAS-PHYS-PUB-2012-005, ATLAS-PHYS-PUB-2013-006

backgrounds

- ttbar production
- di-boson production
- lepton fakes negligible
- DY absent in this case

selections

- one *e* and one μ with opposite charge
- MET > 50 GeV
- at least two jets
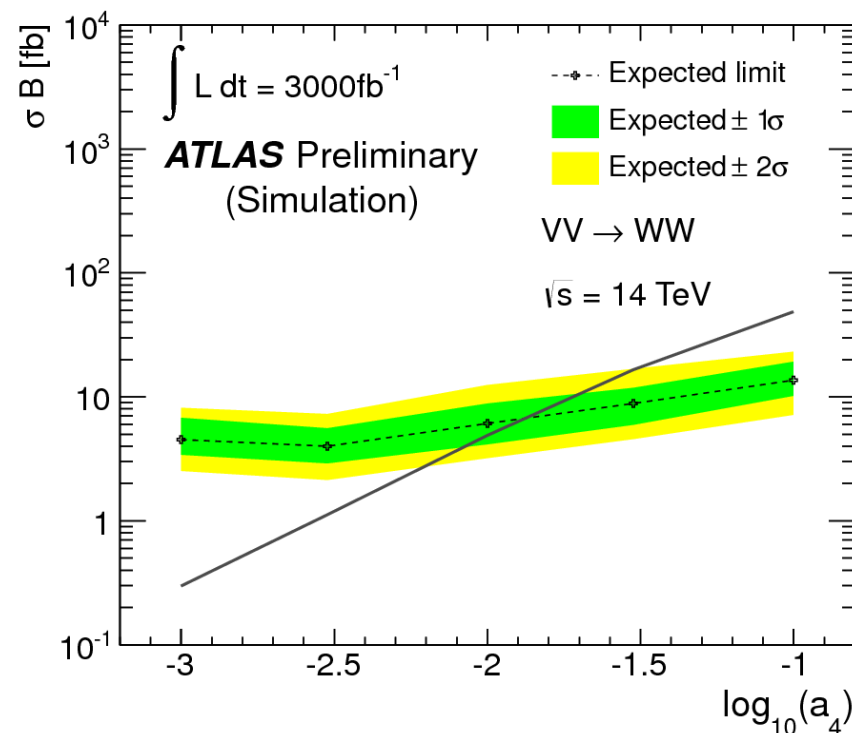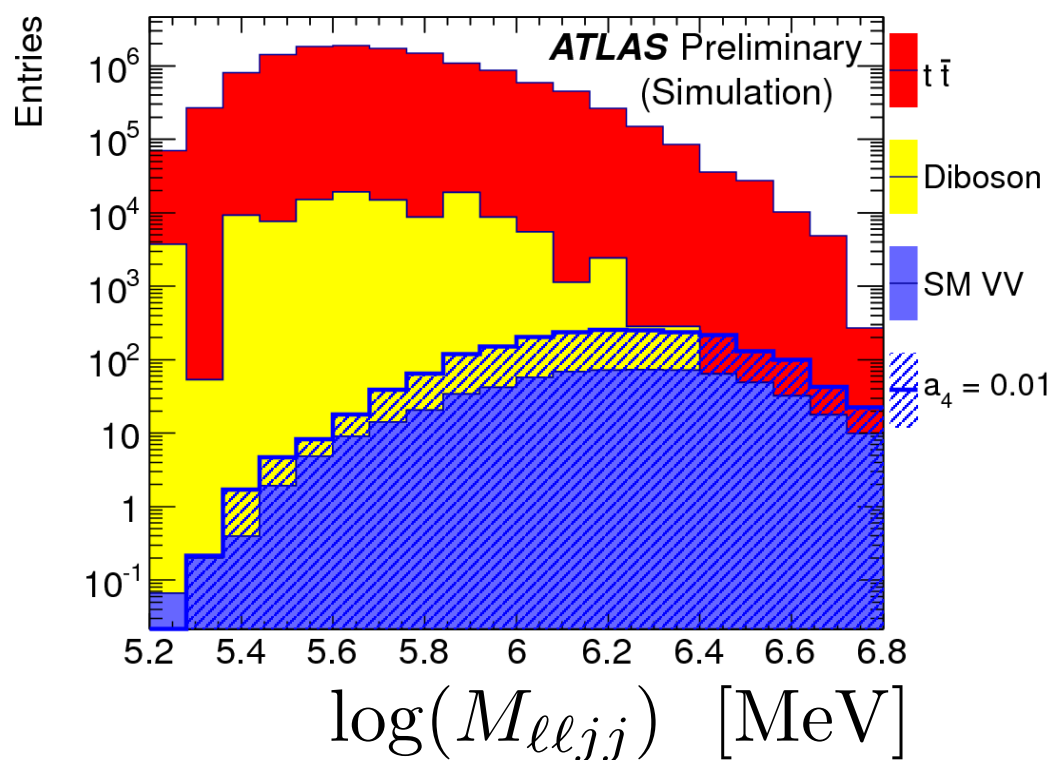
backgrounds

- ttbar production
- di-boson production
- W + jets not significant

selections

- one lepton p_T > 60 GeV
- MET > 25 GeV
- $W_{\ell\nu}$ p_T > 200 GeV
- 1 fat jet with pT > 300 GeV and $M_J \in$ (60, 100) GeV
- $M_{(tag\ jet)}$ > 250 GeV, $\Delta\eta_{(tag\ jet)}$ > 5
- top mass resonances vetoed

| model	SM	500 GeV scalar	800 GeV vector	1150 GeV vector
(a_4, a_5)	$(0, 0)$	$(0.01, 0.009)$	$(0.009, -0.007)$	$(0.004, -0.004)$
S/B	$(3.3 \pm 0.3)\%$	$(0.7 \pm 0.1)\%$	$(4.9 \pm 0.3)\%$	$(5.8 \pm 0.3)\%$
$S/\sqrt{B}$ ($L = 300\text{fb}^{-1}$)	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ ($L = 3000\,\text{fb}^{-1}$)	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

sensitivity to various resonance hypotheses
(mc stats uncertainty in parentheses)

backgrounds

- SM ZZ production only (EWK and QCD ZZ + 2jets)
- mis-ID bkgs are small

selections

- 4 leptons p_T > 25 GeV
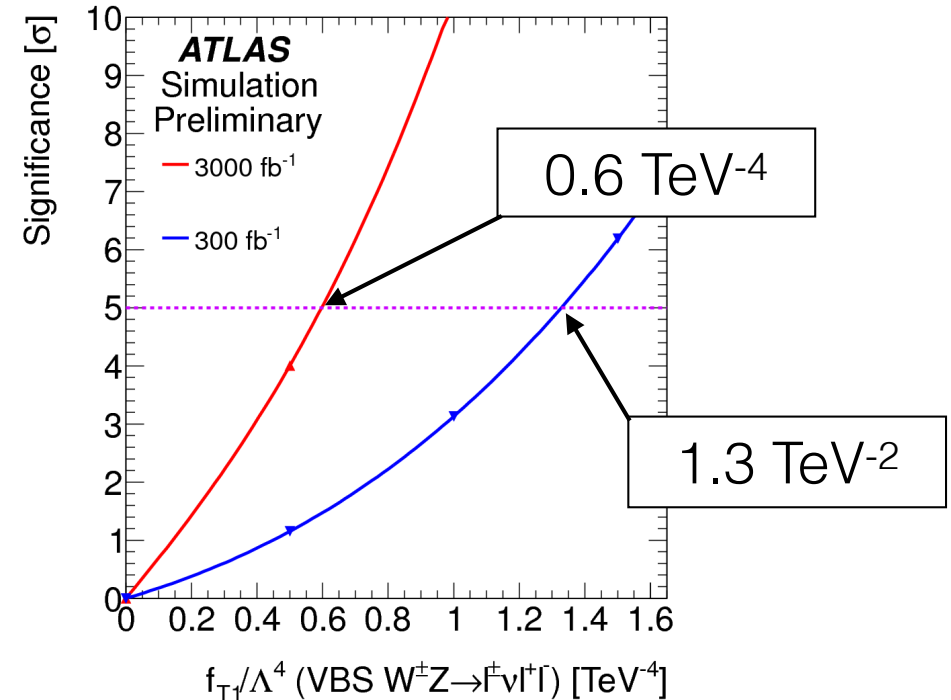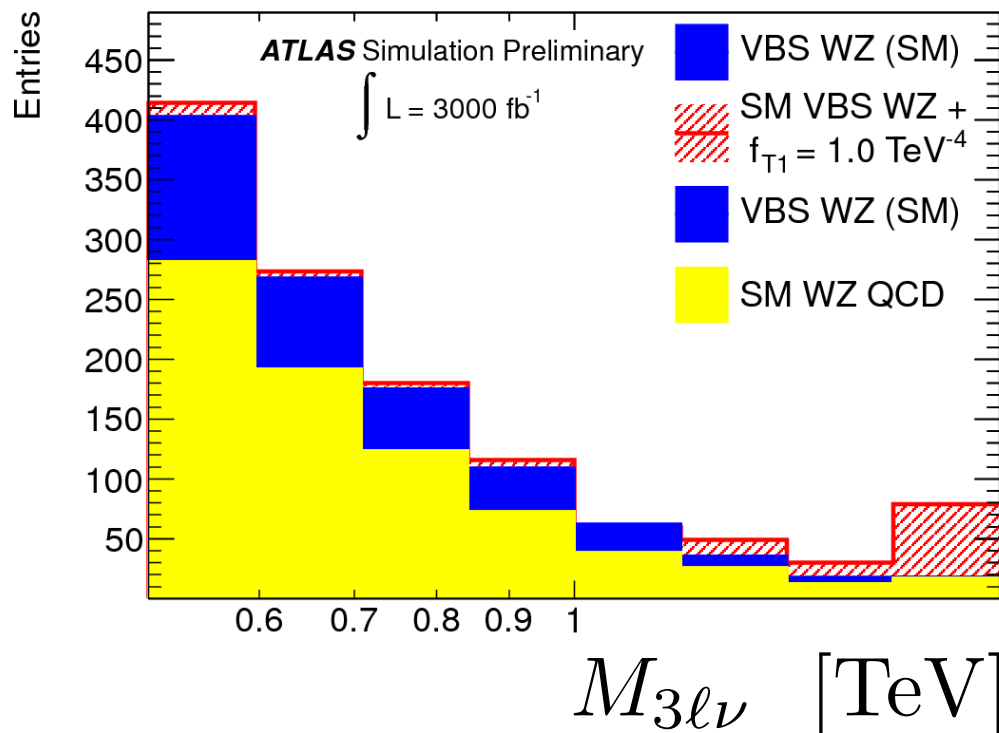 - 2 OS, same flavour pairs
- $M_{(tag\ jet)}$ > 1 TeV
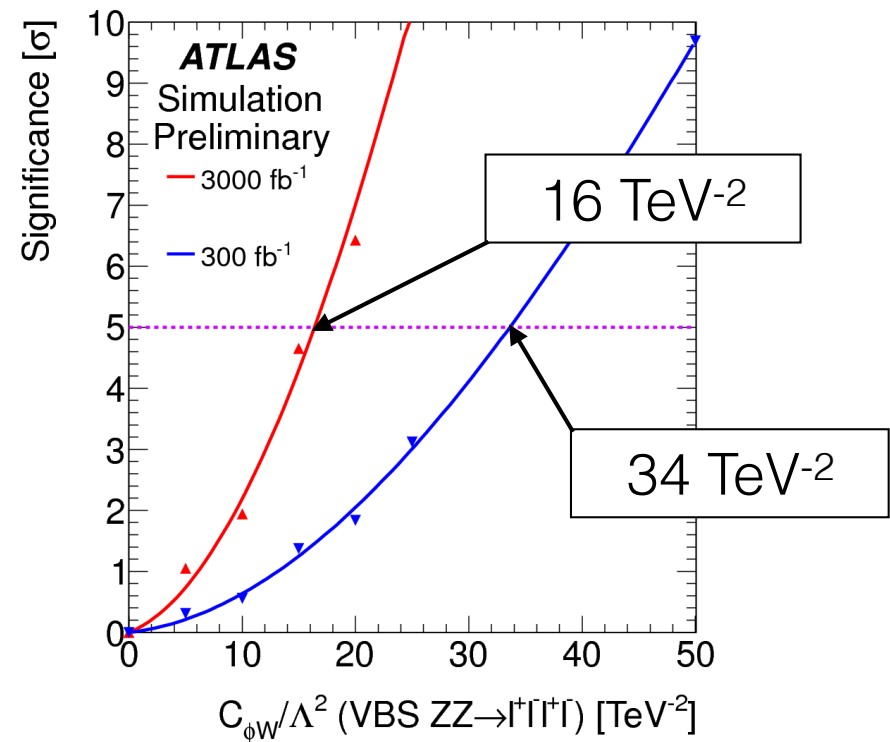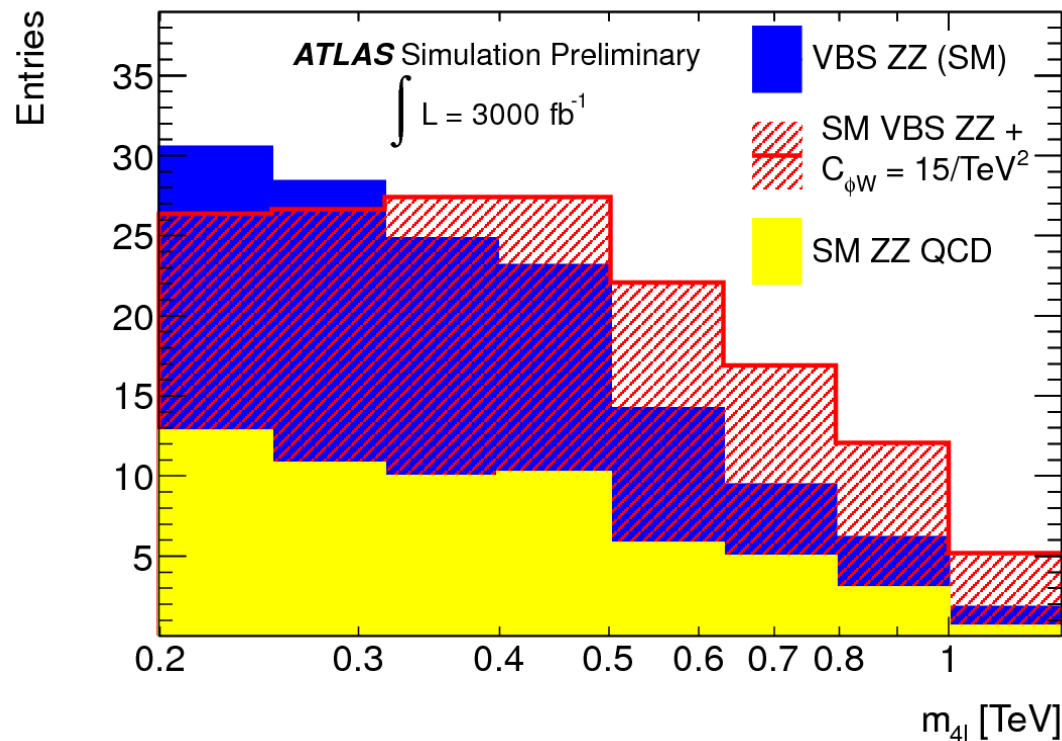
backgrounds

- SM WZ production only (EWK and QCD WZ + 2jets)
- mis-ID bkgs are small

selections

- 3 leptons p_T > 25 GeV
  - 1 OS, same flavour pair
  - third lepton ID based on m_Z constraints
- $M_{(tag\ jet)}$ > 1 TeV

Entries

ATLAS Simulation Preliminary

$\int L = 3000\ fb^{-1}$

VBS WZ (SM)

SM VBS WZ + f_{T1} = 1.0 TeV^{-4}

VBS WZ (SM)

SM WZ QCD

$M_{3\ell\nu}$ [TeV]

Significance [σ]

ATLAS
Simulation
Preliminary

— 3000 fb^{-1}

— 300 fb^{-1}

0.6 TeV^{-4}

1.3 TeV^{-2}

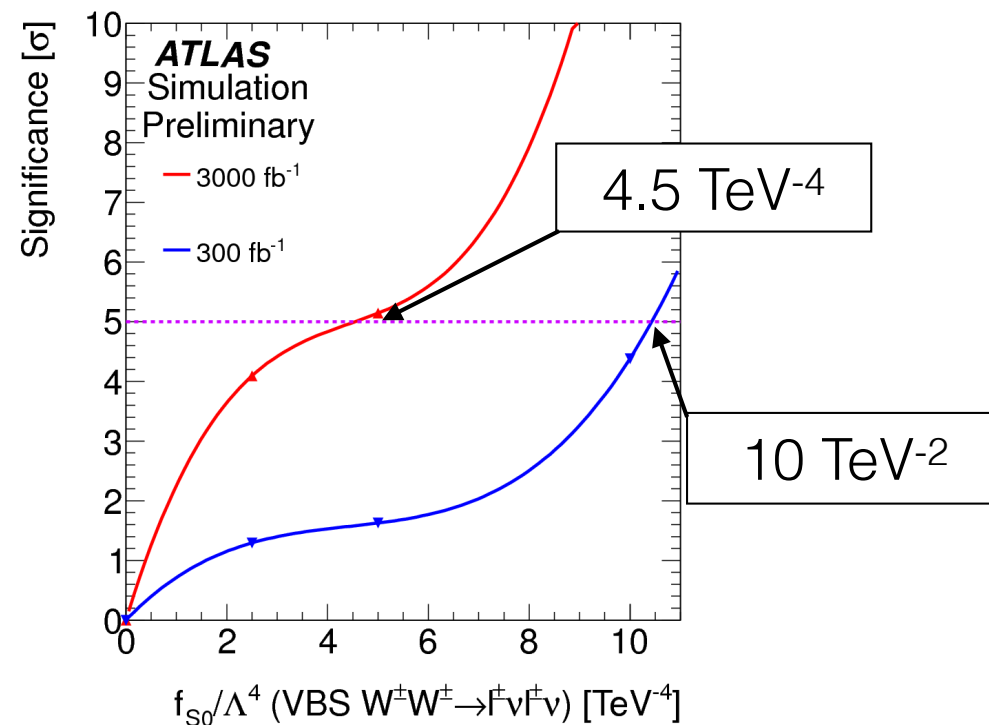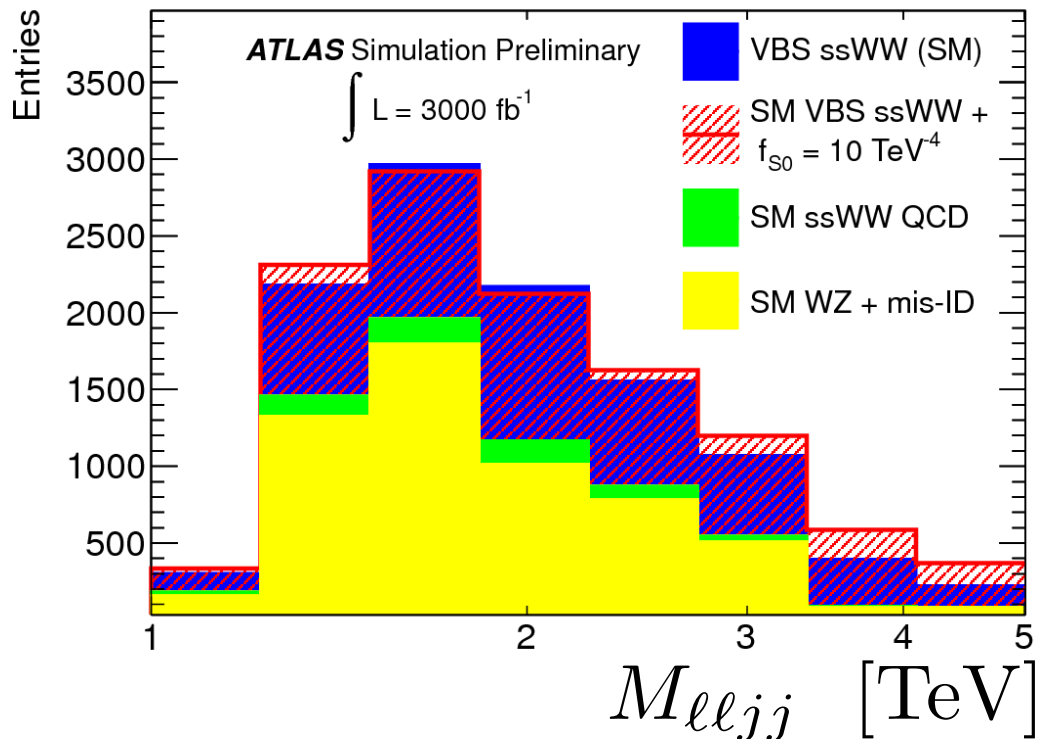f_{T1}/Λ^4 (VBS $W^{\pm}Z \to \ell^{\pm}\nu\ell^+\ell^-$) [TeV^{-4}]

backgrounds

- SM WW production only (EWK and QCD WW + 2jets)
- WZ with one lost lepton
- Wγ$^{(*)}$ with γ conversions
- jets faking leptons

selections

- 2 leptons p_T > 25 GeV
  - have the same charge
- $M_{(tag\ jet)}$ > 1 TeV

Vector Boson Scattering in CMS

- **physics cases**
  - EWK scattering **cross-section**
  - **non-unitarized scenarios** simulated as the absence of Higgs
  - **anomalous couplings** in the EFT approach
- **simplified detector performance**:
  - **Delphes** description of the CMS detector (current, current aged, upgraded)
  - **pile-up configurations** according to the scenarios (50 or 140 on average)
  - **reducible backgrounds** considered as well
- two final states considered:

| |
|---|
| $W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu$ |
| $WZ \rightarrow \ell\nu\ell\ell$ |

- leptons: $p_T > 25$ GeV, $|\eta| < 2.5$
- jets: $p_T > 30$ GeV, $|\eta| < 4.7$
- tag jets: two largest p_T ones

additional selections

- MET > 30-40 GeV
- $m_{jj} > 600$-800 GeV, $\Delta\eta_{jj} > 2$-4
- jets: $p_T > 50$ GeV, $|\eta| < 4.9$
- H_T (track jets) < 125-150 GeV
- Z selections vetoes when needed
- b-veto in the WW case

- results obtained with **2D template fits** on sensitive variables for all the cases
- **uncertainties** affect normalisation and shapes of the samples
- **pseudo-data** fitted to obtain the expected results
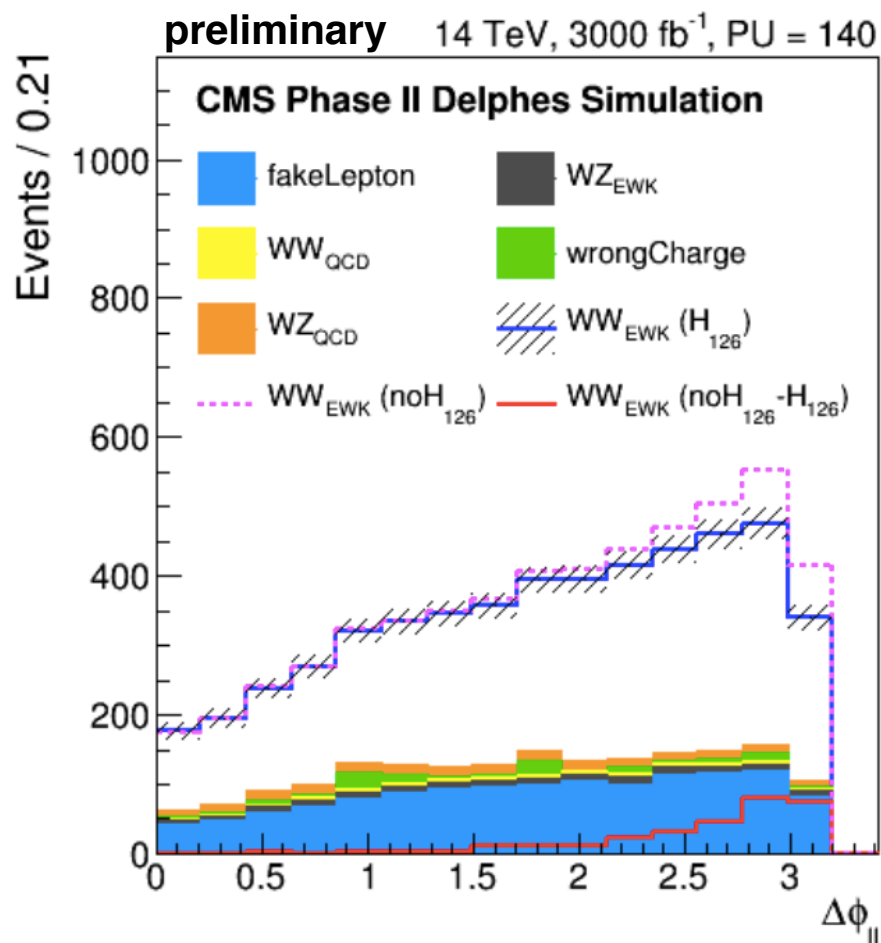
source	PI-NA	PI-A	PII-TK-UP
jet energy scale	1–3%	1.5–4%	1–3%
jet energy resol.	5%	6.5%	5%
muon energy scale	1%	2%	1%
muon energy resol.	1%	2%	1%
electron energy scale	2%	4%	2%
electron energy resol.	2%	4%	2%
lepton efficiency	2%	2%	2%
lepton fake rate	30%	30%	30%
lepton wrong charge	30%	30%	30%
b-tag efficiency	4%	5.5%	4%
signal acceptance	2%	2%	2%
QCD scale choice	3%	3%	3%
parton densities	7%	7%	7%
LHC luminiosity	2.6%	2.6%	2.6%

- for the **same-sign WW**, the uncertainty on the EWK component of the total cross-section is at the order of 5% and **systematically limited**

- **interference** tested to be small and neglected for this study
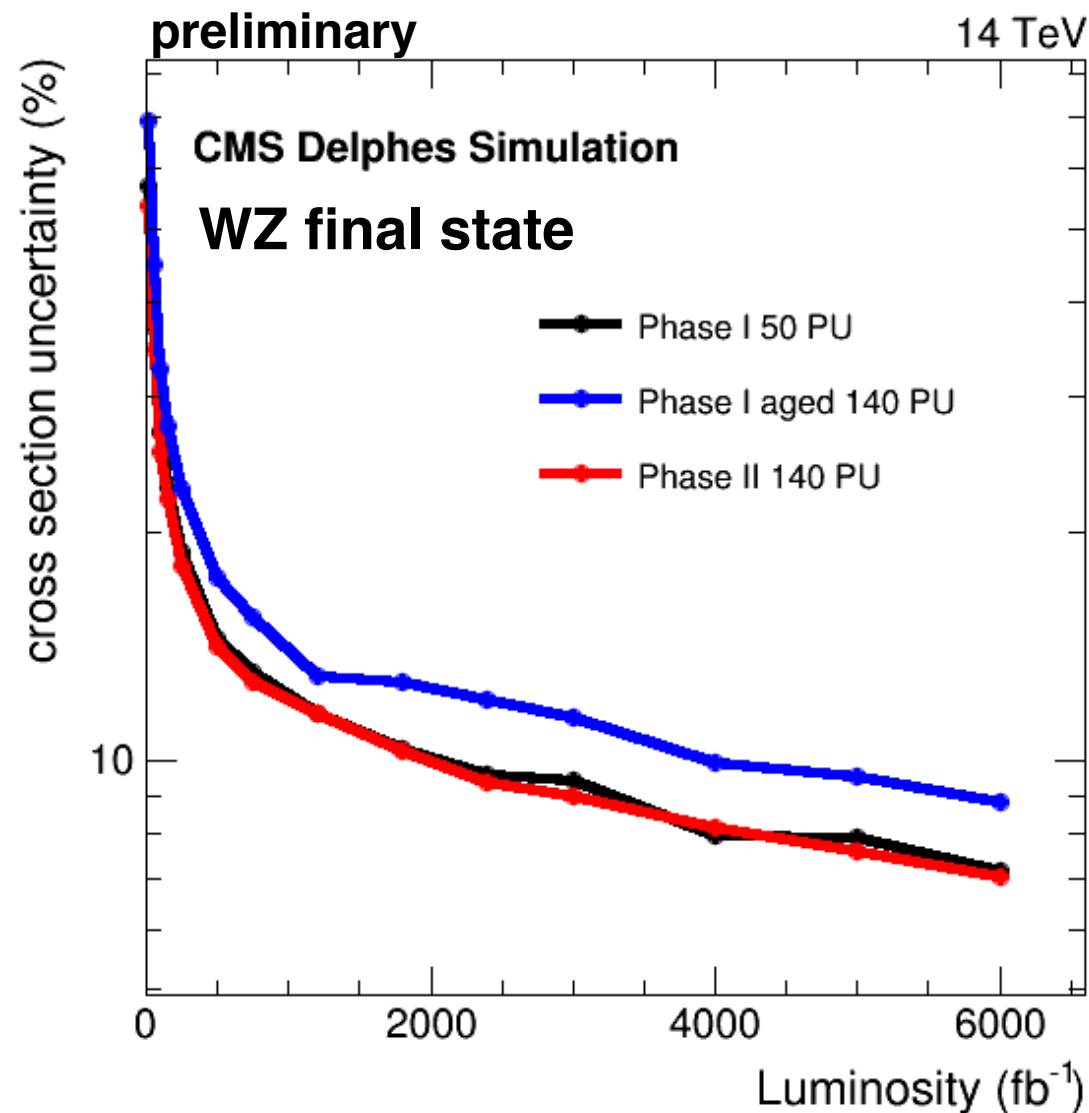
- **same-sign WW** gives the best performances
- treat the **difference between a no-Higgs scenario and SM** as signal
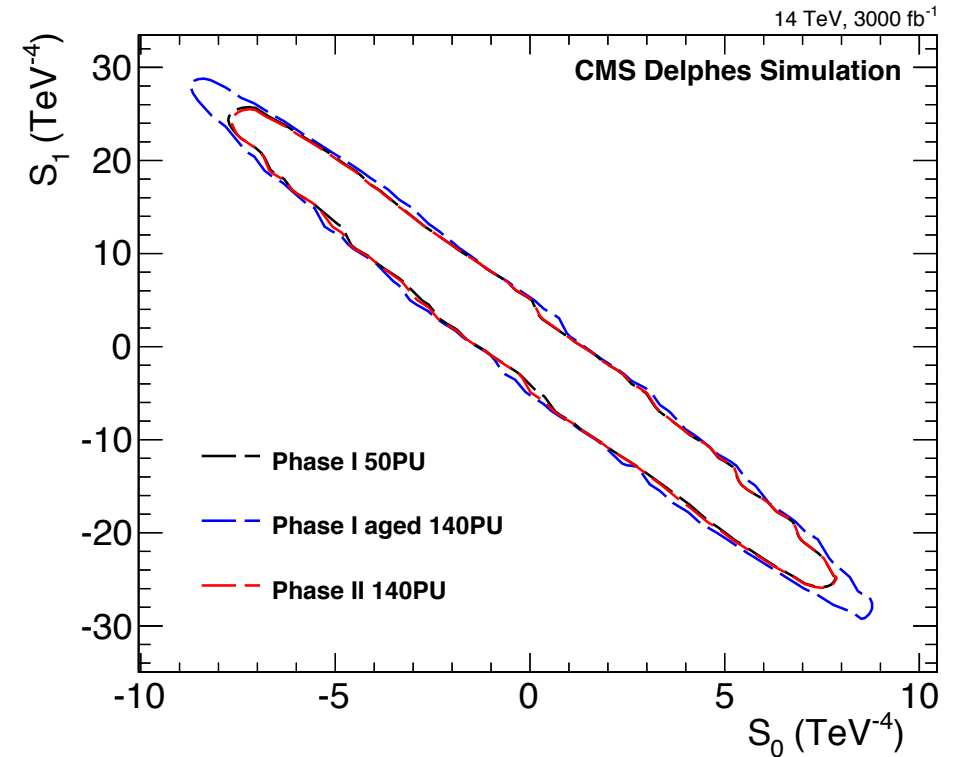- the **excluded signal strength** is an indication of the analysis sensitivity
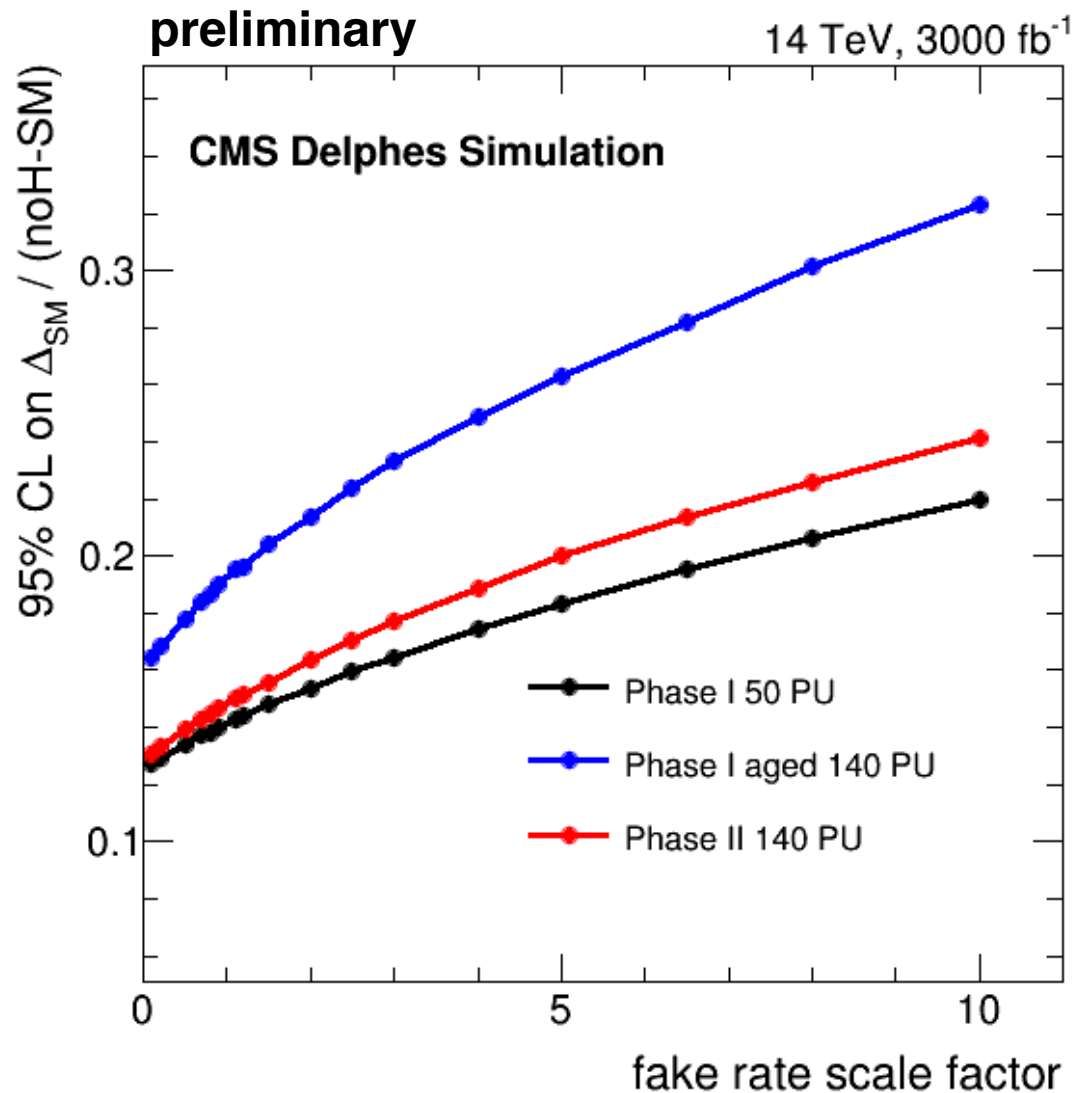
samples generated with
the Phantom code

0801.3359

result as a function of
jets-faking-leptons rate
scale factor

- study performed in the **same-sign WW** case only
- additional **dimension-eight** terms only
- **95% CL limit** on the coupling coefficients

	phase I	phase II	phase I aged
S_0	1.06	1.07	1.17
S_1	3.51	3.55	3.87
M_0	0.78	0.75	0.82
M_1	1.10	1.06	1.14
M_6	1.56	1.49	1.63
M_7	1.37	1.32	1.45
T_0	0.067	0.077	0.083
T_1	0.036	0.033	0.036
T_2	0.119	0.111	0.119

14 TeV, 3000 fb^{-1}

CMS Delphes Simulation

- - - Phase I 50PU
- - - Phase I aged 140PU
- - - Phase II 140PU

S_1 (TeV^{-4}) vs S_0 (TeV^{-4})

Limits in the 8 TeV analysis are 30 - 60
times higher than these ones

Phys.Rev.Lett. 114 (2015)

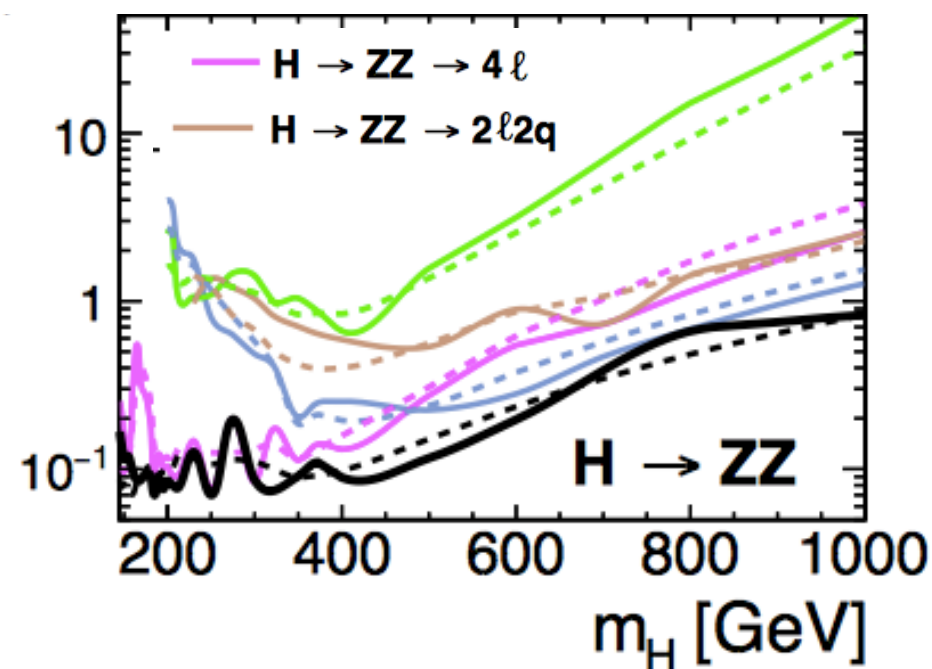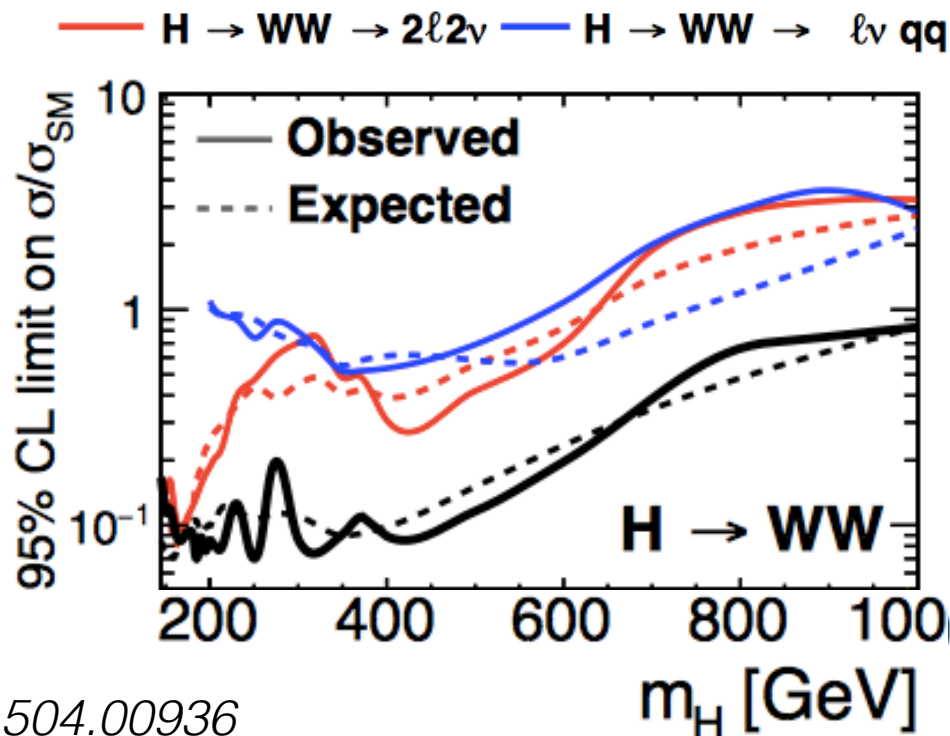# semi-leptonic final states

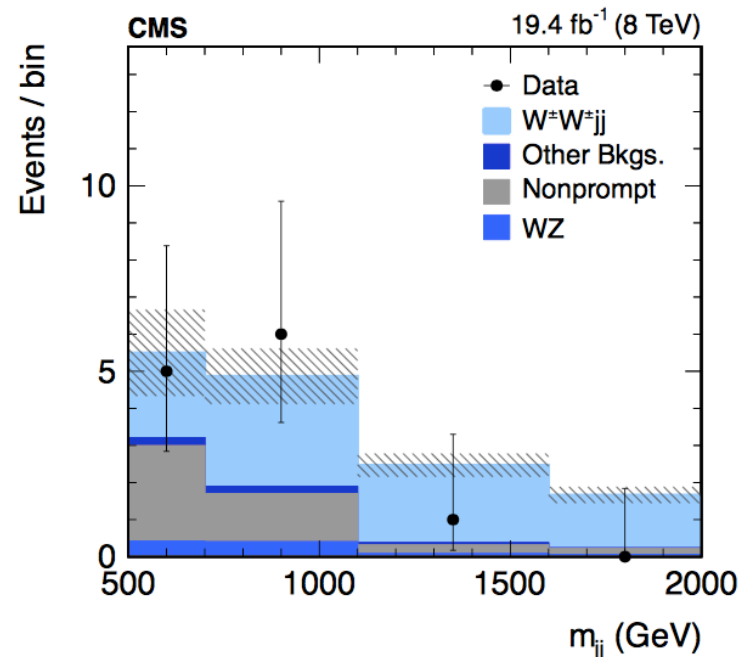| CONS	PROS
• hard charge determination • jet ID ambiguities • larger backgrounds from V+jets • harder reconstruction and PU subtraction	• additional channels • larger statistics wrt fully leptonic • full reconstruction of the final state in case of WW

• in high mass H searches show **similar performances** to fully lept. analog

1504.00936

- **same expected sensitivity** (2.8 and 3.1 σ respectively)
- quite **similar selections on physics objects** and of VBF cuts
- **very different background** composition
- specific **detector features** could make the difference between the two experiments
- **detailed simulations** are necessary to consolidate the parametric studies
- **judgement calls** remain necessary until data arrive
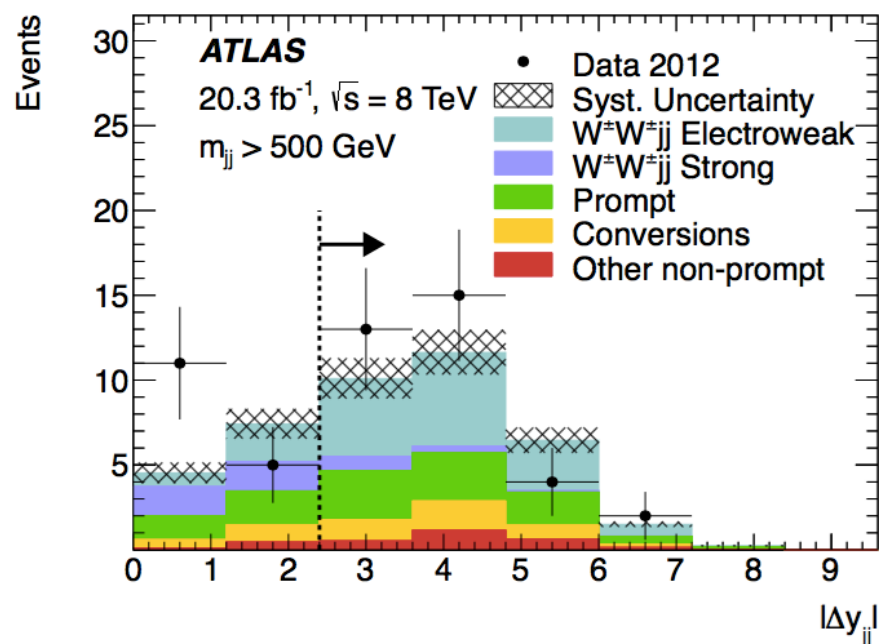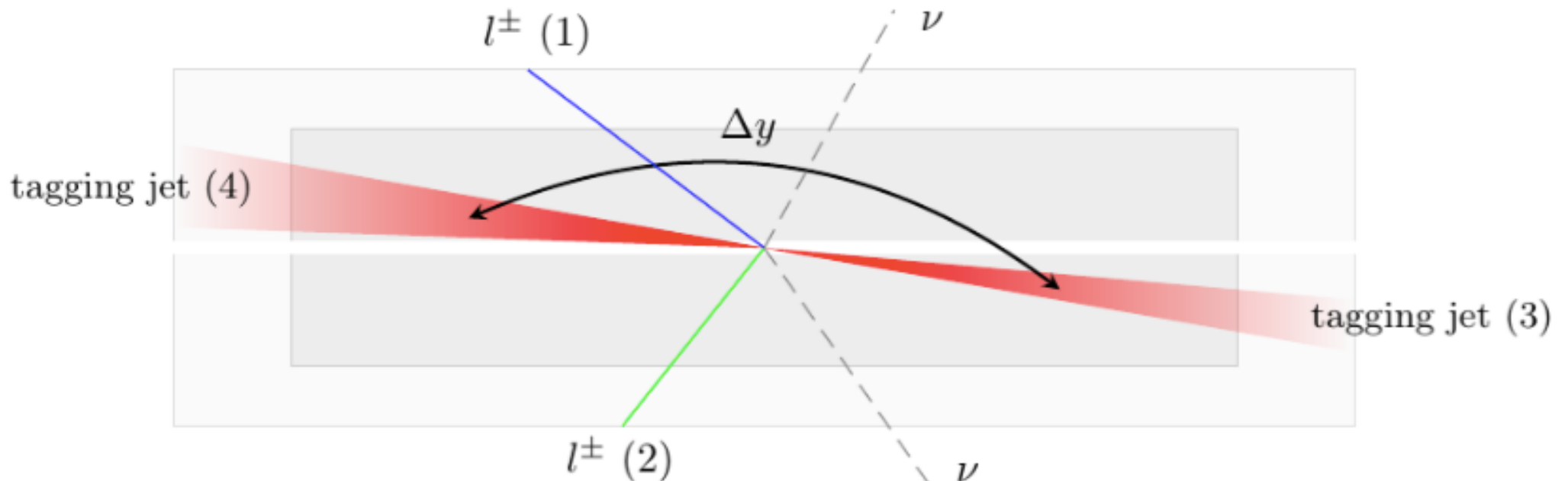

Phys. Rev. Lett. 113, 141803 (2014)   *Phys. Rev. Lett. 114, 051801 (2015)*

- **140 events** per bunch crossing on average used as benchmark for the HL expectations
- **add 70 GeV energy** in 0.4 jet cones (and in lepton isolation cones)
- generate **fake jets**
- worsen the **MET** resolution
- impact on the **central rapidity veto**
- affect **lepton isolation**

- the PU reduction comes at the price of **hard jets identification efficiency**
- **the number of jets gets flat** after the PU subtraction
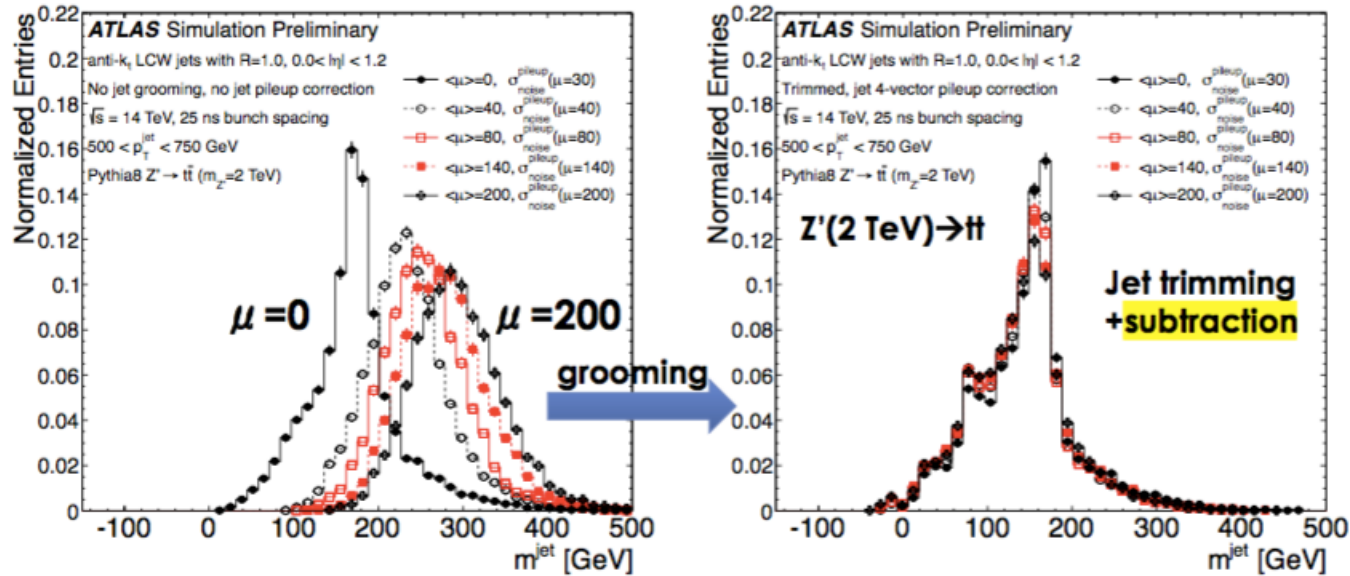- the situation for **VBS jets** is less simple, since they are in the forward region

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PileupSuppressionECFA2014
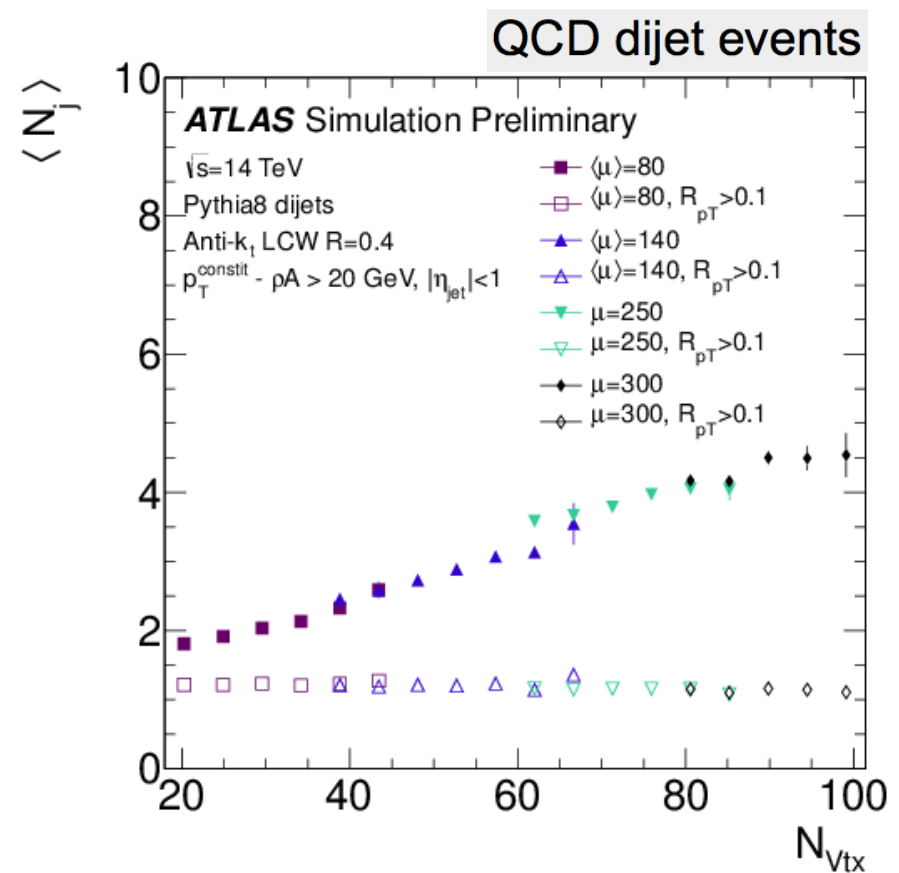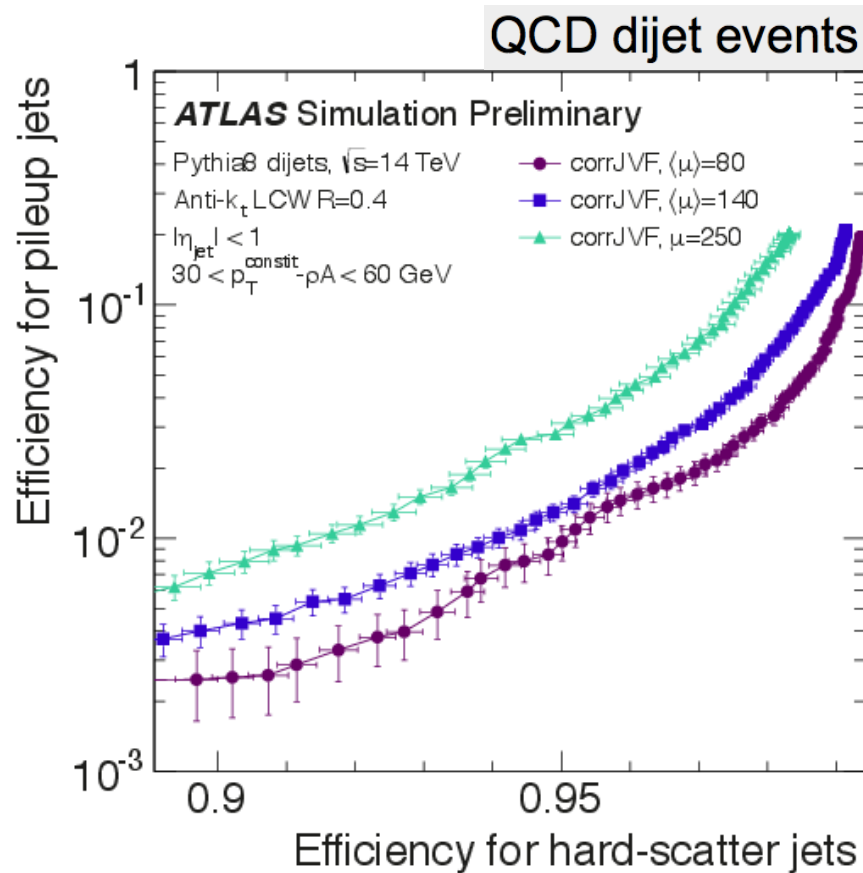
- at large p_T, hadronic decay products (e.g. W → qq) are **collimated in to a single jet**
- **rule of thumb:** the opening angle has $1/p_T$ dependence
- in the high m_{VV} region of interest for VBS, vector bosons originate **single fat jets** in the detector

$$dr \sim \frac{2m}{p_T}$$

- study the **internal structure of these jets** to identify the boosted object
  - **find the decay products** of the vector boson
  - **eliminate PU and UE**
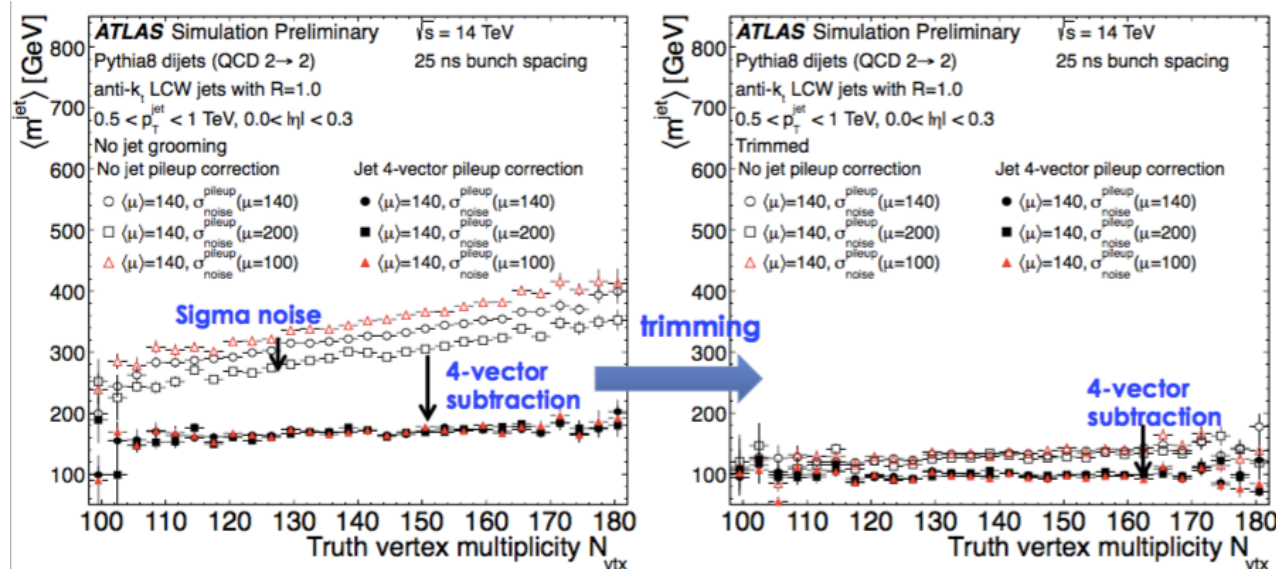 - control **soft radiation**

CMS PAS HIG-13-008
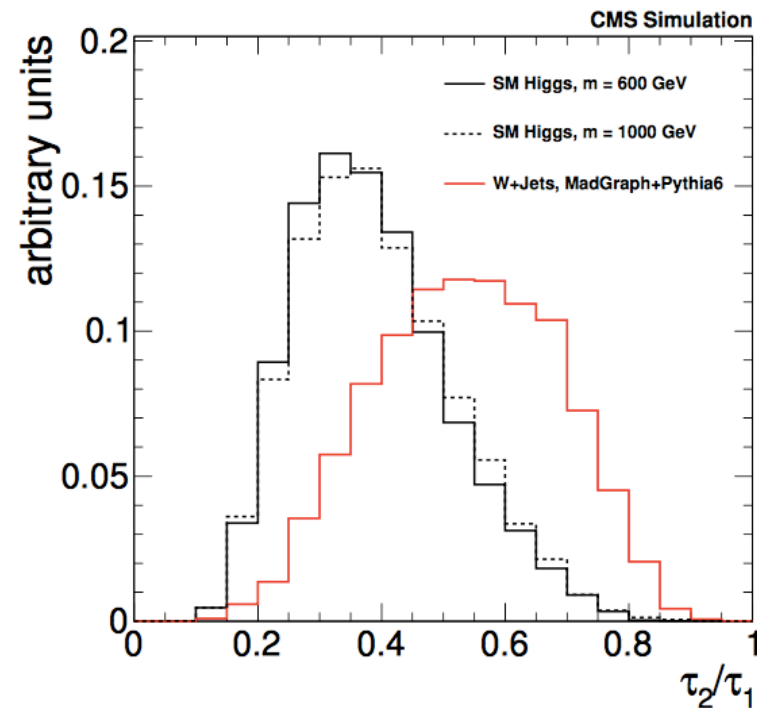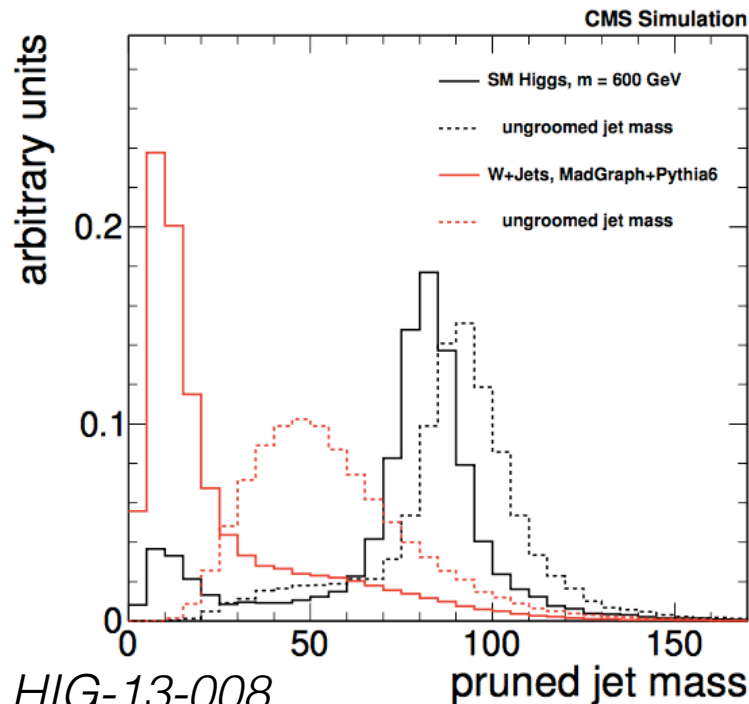
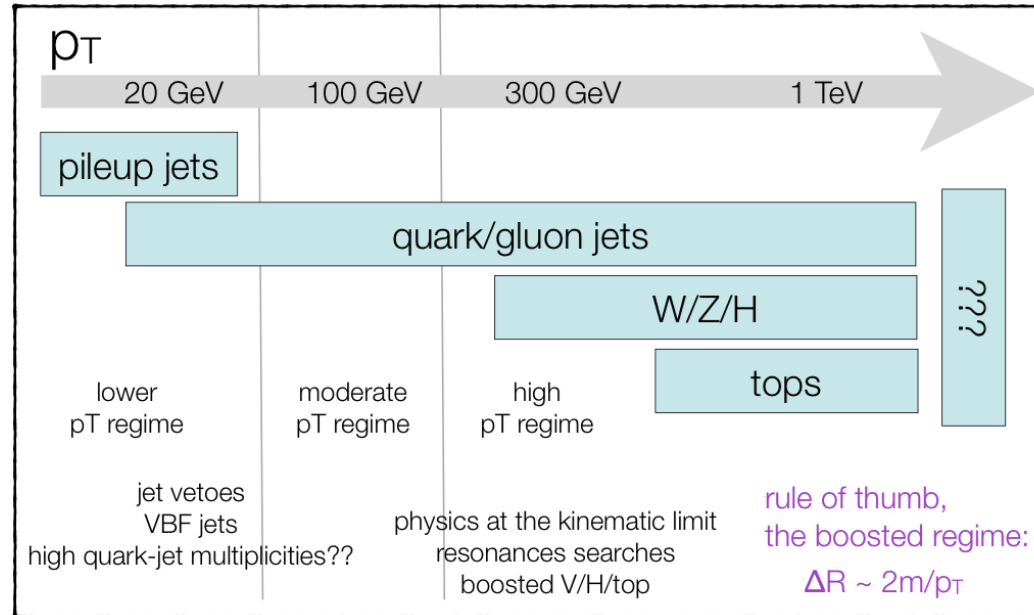- performances of grooming techniques seem promising in the first studies

Z' → ttbar

di-jet

A. Schwartzmann, BOOST13

e.g.
- PU reduction
- q/g separation
- color flow

p_T

| 20 GeV | 100 GeV | 300 GeV | 1 TeV |

pileup jets

quark/gluon jets

W/Z/H

tops

¿¿¿

lower pT regime

moderate pT regime

high pT regime

jet vetoes
VBF jets
high quark-jet multiplicities??

physics at the kinematic limit
resonances searches
boosted V/H/top

rule of thumb,
the boosted regime:
$\Delta R \sim 2m/p_T$

e.g.
- cleaning jets from PU and non-perturbative effects
- particle ID in boosted jets

- jet substructure gives also access to:
- **jet charge**
- **quark-gluon** discrimination
- **color flow** description inside jets
- …

- **need of theoretical understanding** of the details of the hadronisation and shower processes

ATLAS
anti-k_t R=0.4, $|\eta| < 0.8$
60 GeV < p_T < 80 GeV
$\int L\,dt = 4.7\ fb^{-1}$, $\sqrt{s} = 7$ TeV
MC11 Simulation

Data + Stat.
Pythia
Herwig++
Syst.

Gluon Efficiency

Quark Efficiency
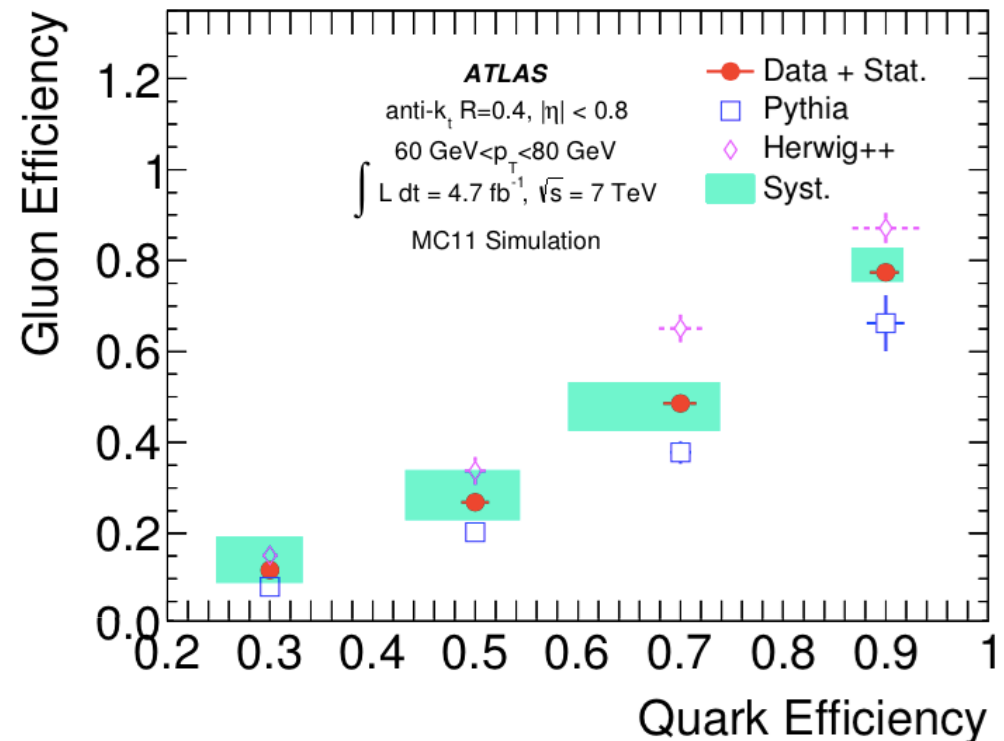
- **pile-up suppression relies on pointing information** of tracks to the primary vertex to ignore its charged component (e.g. CHS in CMS, JVF in ATLAS)
- we want an algorithm with **large efficiency** for the PV identification
- **the smallest overlap** possible between vertices
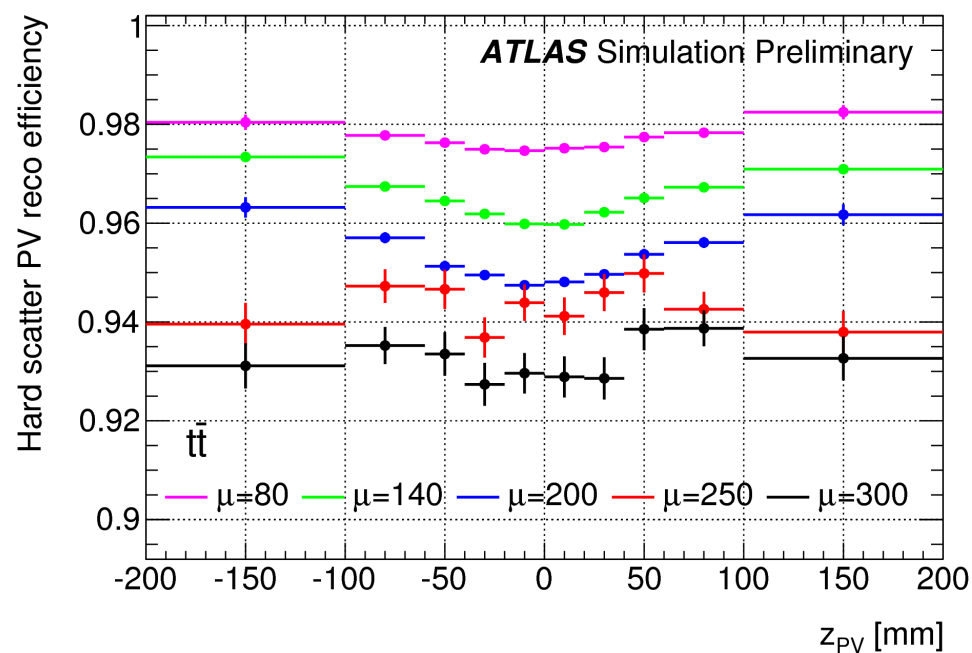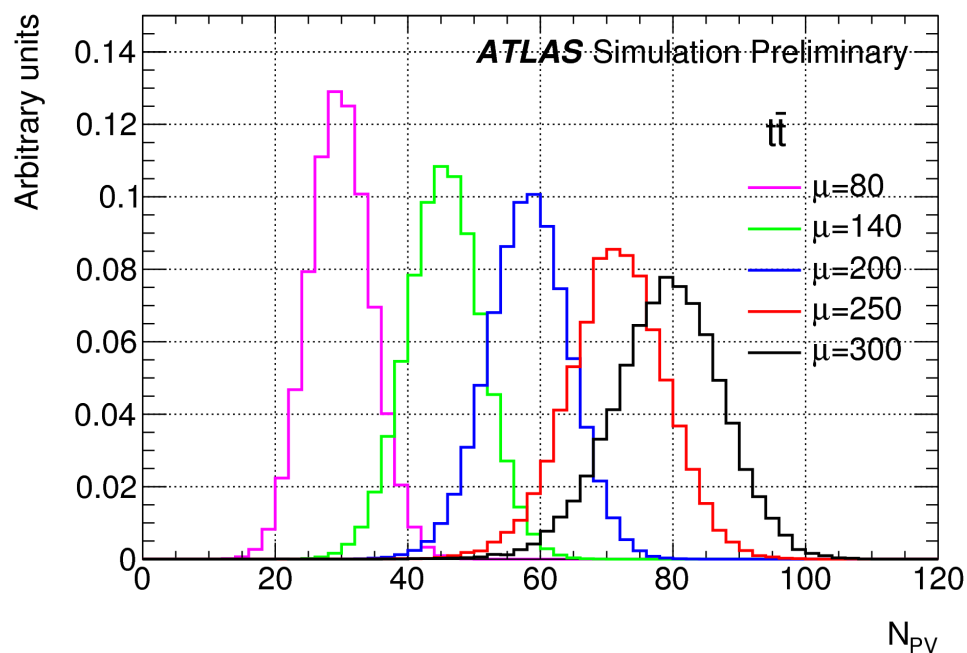
- ttbar sample close to VBS topology
- Run1 algorithms in use
- **large vertexing efficiency** even in high PU conditions

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/PLOT-UPGRADE-2014-003/

- **reducing the ttbar** background in the WW final states
- typical ID efficiencies used during Run1 are around 50% per b-jet
- **vertices will be much more more and closer** to each other, the tagging will be more difficult
- in VBS an **extension of the b-tagging capability to large eta** values would kill the residual background after VBS selections on jets
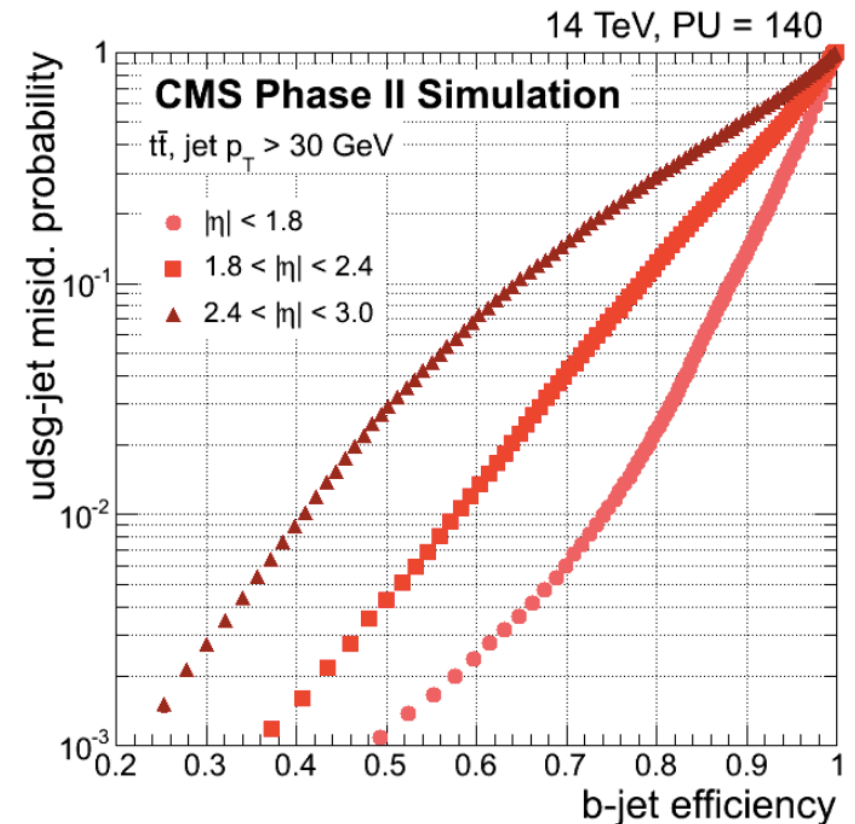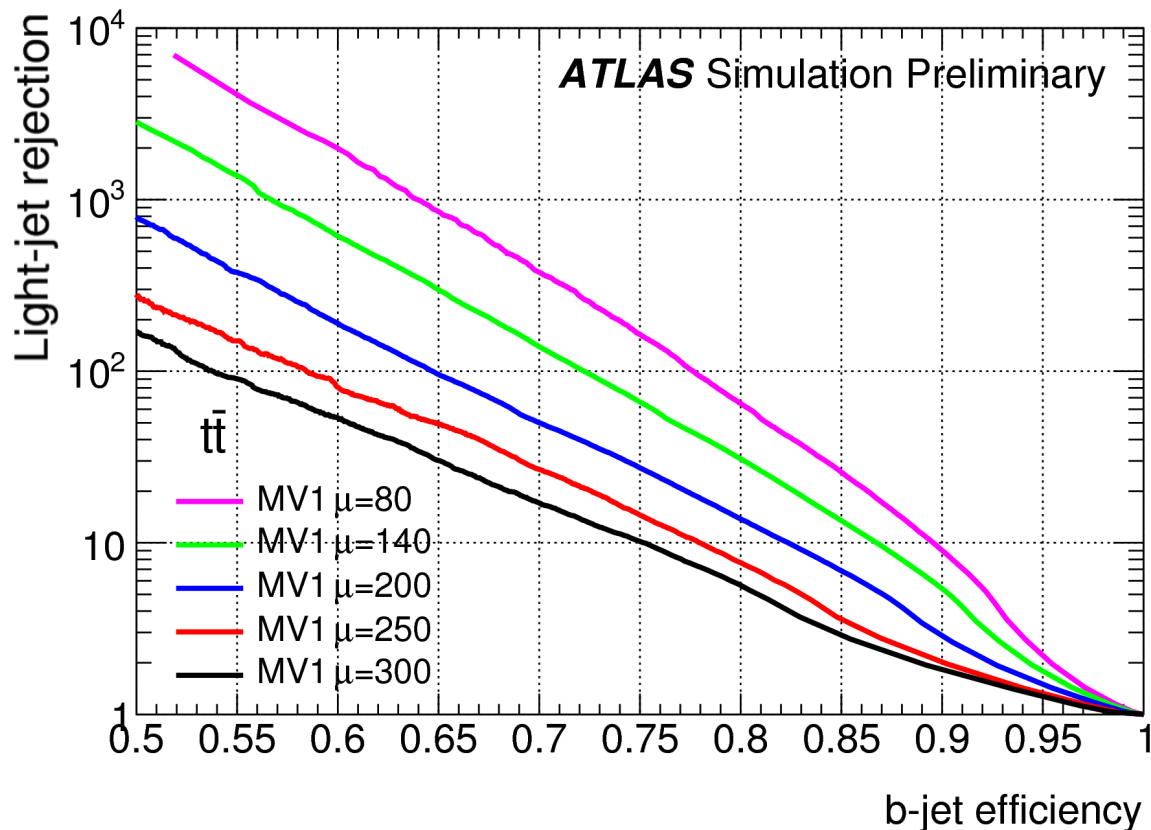
- **small hadronic activity between the tag jets** is expected for the signal (EWK process), on the contrary of the backgrounds
- the **large PU** reduces this effect → use variables robust against it (e.g. jets of tracks pointing to the primary vertex of the event)
- properly determine the **theoretical uncertainty** associated to the selection efficiency for signal and bkg

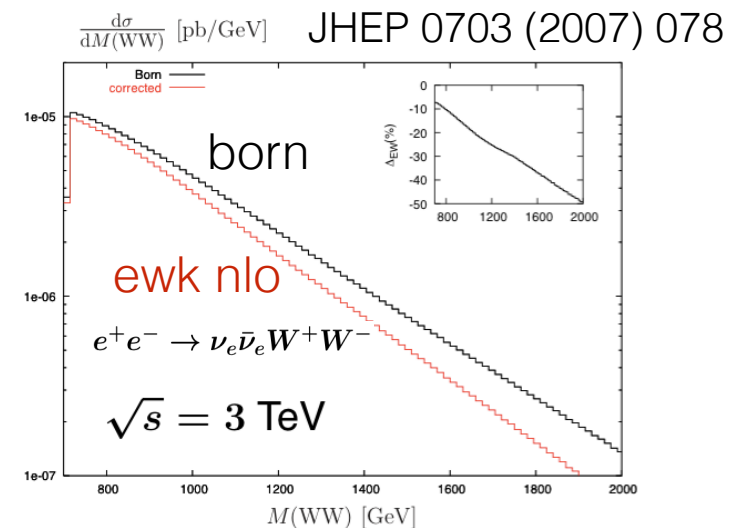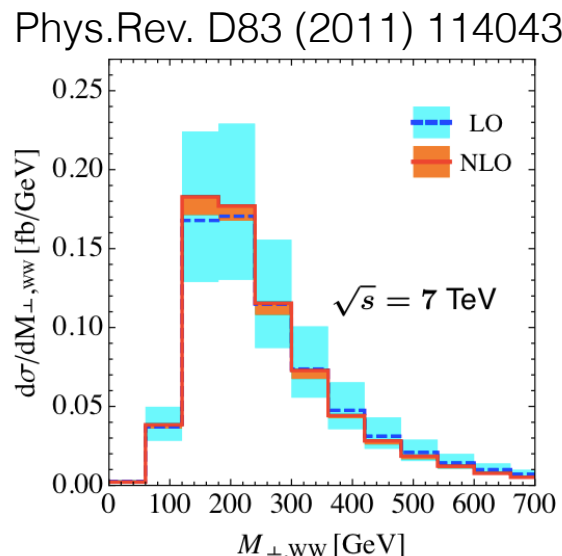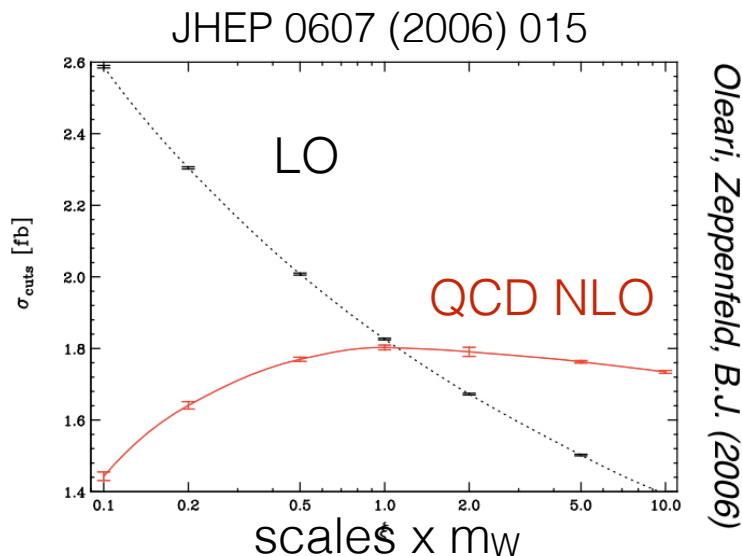- **new jet-veto variables** dependent on y that can be resummed at the same level of p_{Tj}

$$\mathcal{T}_{fj} = p_{Tj}\, f(y_j)$$
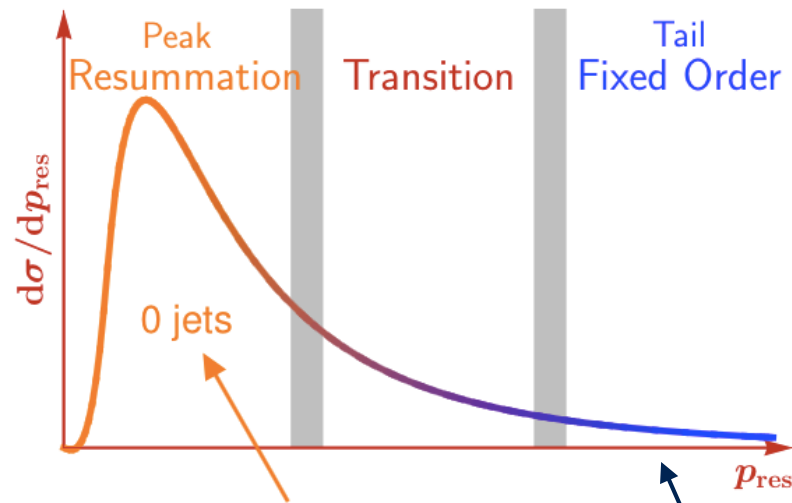
Stewart-Tackmann, JVE, yield and migration uncertainties.

higher order calculations

1308.4634, 1206.4998

arXiv:1412.4792
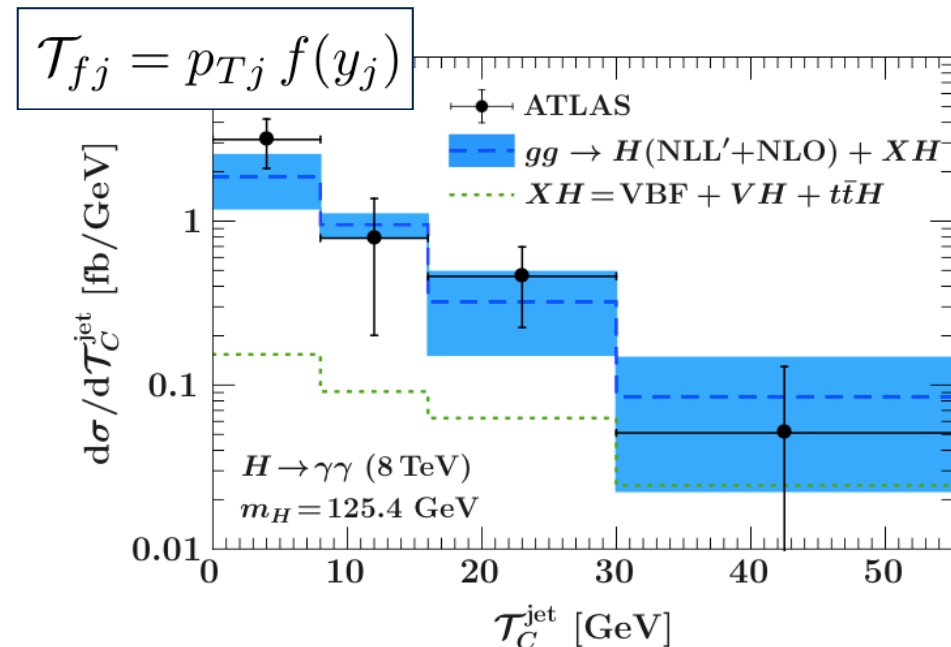
- after the Higgs boson discovery, the **BSM effects expected to be small**
- **exact LO** calculation and events well generation known (0801.3359)
- **NLO** calculations: available for most of the signals, for some of the bkg only
- **EWK** corrections: unknown, expected to be large
- **tri-boson production** might be important as well resonant and non-resonant contributions included
- calculations with **additional jets**, merged to 0 jets, do not exist: relevant for CJV
- BSM parameterisations available

JHEP 0607 (2006) 015

LO

QCD NLO

σ_{cuts} [fb]

scales x m_W

Oleari, Zeppenfeld, B.J. (2006)

Phys.Rev. D83 (2011) 114043

LO

NLO

$\sqrt{s} = 7$ TeV

dσ/d$M_{\perp,WW}$ [fb/GeV]

$M_{\perp,WW}$ [GeV]

$\frac{d\sigma}{dM(WW)}$ [pb/GeV]   JHEP 0703 (2007) 078

Born
corrected

born

ewk nlo

$e^+e^- \to \nu_e \bar{\nu}_e W^+ W^-$

$\sqrt{s} = 3$ TeV
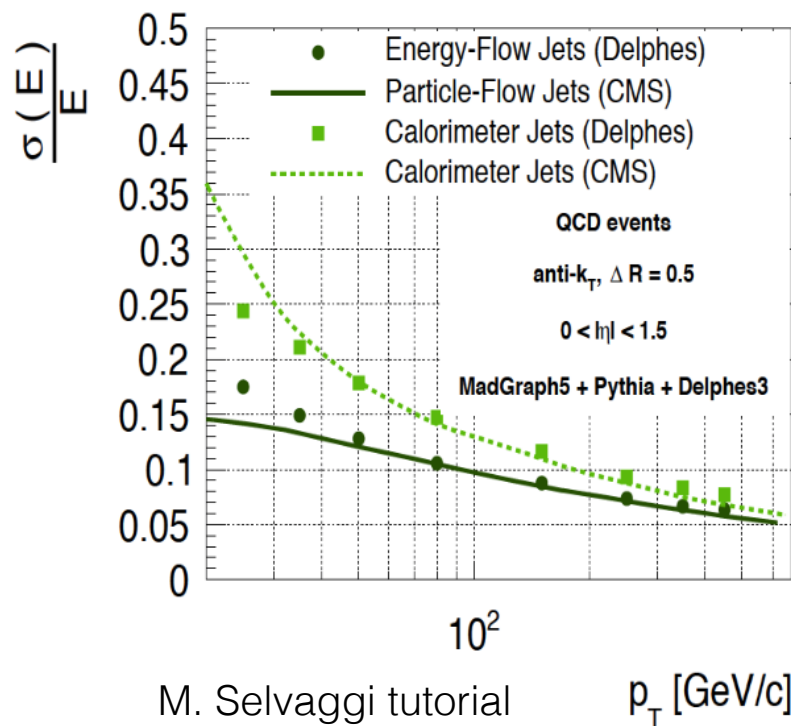
$\Delta_{EW}(\%)$

$M(WW)$ [GeV]

conclusions

- ATLAS and CMS performed **feasibility studies** for some final states already
- projections calculated so far with **parametric simulations**

- the final results depend upon **several ingredients** at very different levels
  - N(N?)LO **simulation** of the processes
  - low p_T objects and cross-**triggers**
  - detailed control of **detector effects** and reducible backgrounds
  - **physics objects reconstruction** dedicated to boosted objects and jets at large η
  - all in a **very high pile-up** environment

- the determination of **detector effects** is subject to a lot of unknowns
- while the potential of the **HL-LHC as vector bosons collider** looks very promising and its investigation is now just starting

thanks to Markus Schumacher, Anja Vest, Nhan V. Tran for useful discussions

backup slides

- **parametric simulation** particle-matter interaction
  - a lot of (reasonable) approximations
- realistic **models of detectors**
  - need a very close **interaction with the experiments**
  - easy to understand and modify C++ code
  - **detailed can be added or removed** depending on the analysis needs
- **preliminary physics studies** can be performed in short time (e.g SnowMass)
- can be used in parallel with full detector simulation

jet structure, multiplicities ...

Energy-Flow Jets (Delphes)
Particle-Flow Jets (CMS)
Calorimeter Jets (Delphes)
Calorimeter Jets (CMS)

QCD events

anti-k_T, $\Delta R = 0.5$

$0 < |\eta| < 1.5$

MadGraph5 + Pythia + Delphes3

$\frac{\sigma(E)}{E}$

p_T [GeV/c]

M. Selvaggi tutorial