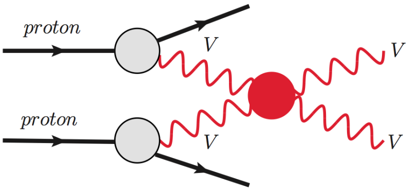
Study of Vector Boson Scattering including Pile-up with the ATLAS Detector

•Philipp Anger, Jan Schumacher, Michael Kobel, Anja Vest
philipp.anger@physik.tu-dresden.de

Institut für Kern- und Teilchenphysik der Technischen Universität Dresden

Terascale Workshop Dresden 02/12/2010

Vector Boson Scattering



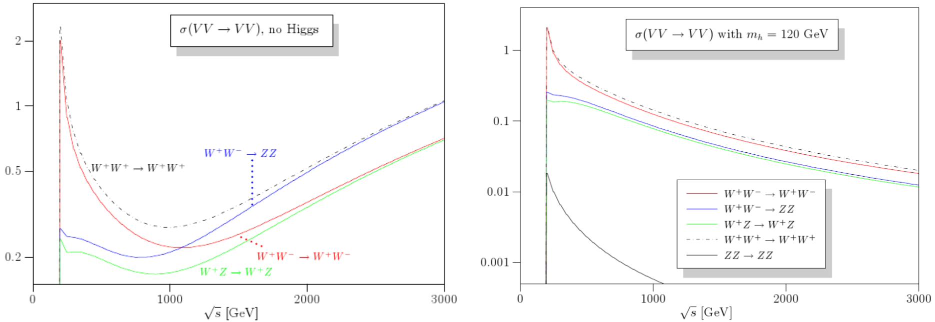
- Naive Standard Model without Higgs: Scattering of longitudinal W bosons rises infinitely:

$$\sigma \left(W_{\mathrm{L}} W_{\mathrm{L}} \rightarrow W_{\mathrm{L}} W_{\mathrm{L}} \right) \xrightarrow{\sqrt{s_{\mathrm{WW}}} \rightarrow \infty} \infty$$

- Intimately related to electro-weak symmetry breaking
- Perturbation theory violates unitarity above $\sqrt{s_{\mathrm{WW}}} \approx 1.2\ \mathrm{TeV}$
- Vector Boson Scattering at LHC reaches this limit in parts of the phase space

Flagship Solution: Higgs Mechanism

- Also solves problem of masses in the Standard Model
- Introduction of a new scalar particle: Higgs boson



But: Higgs boson not discovered in experiment up to now

No Higgs Observed

Unitarity conservation requires physics beyond the Standard Model

- Strong Electroweak Symmetry Breaking *(review e.g. hep-ph/0203079)*
- Technicolor *(S. Weinberg, Phys. Rev. D13 (1976) 974)*
- Neutrino condensation *(C. T. Hill, M. A. Luty and E. A. Paschos, Phys. Rev. D43 1991)*
- Top see-saw *(B. A. Dobrescu and C. T. Hill, Phys. Rev. Lett. 81 1998)*
- Advantage: Particular signals
- Disadvantage: A lot of them

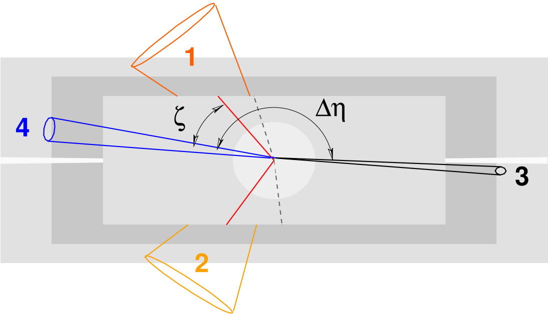
EWChL and Unitarization

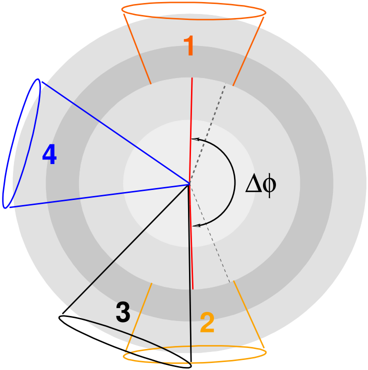
- Effective Electroweak Chiral Lagrangian (EWChL):
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{LO}} + \alpha_4(\text{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 + \alpha_5(\text{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2 + \dots$
  - Approximates the rising edge of a resonance beyond the accessible mass range (anomalous couplings)
- No longer valid at LHC energies
  - "*Resonances and Unitarity in Weak Boson Scattering*"
    A. Alboteanu, W. Kilian and J. Reuter (arXiv:0806.4145v1)
  - Need resonance(s) with mass(es) m and coupling(s) g to weak bosons

weak isospin I		$I=0$	$I=1$	$I=2$
spin J	$J=0$	σ^0		$\varphi^0,\ \varphi^\pm,\ \varphi^{\pm\pm}$
	$J=1$		$\rho^0,\ \rho^\pm$	
	$J=2$	f^0		$t^0,\ t^\pm,\ t^{\pm\pm}$

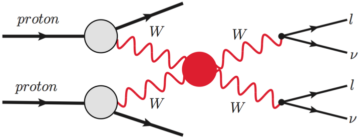
- K-matrix formalism guarantees unitarization

Experimental Signature



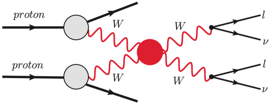


- Tagjets (3,4, large p_{T}, large distance in η)
- Few jets between tagjets
- Final state $\ell\nu\ell\nu$:
  - Missing E_{T}
  - Decay products (1,2) between tagjets

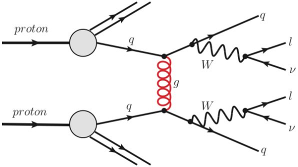


Signal and Background Processes

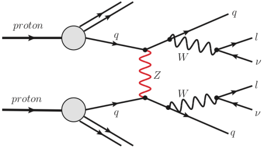
Details . . .



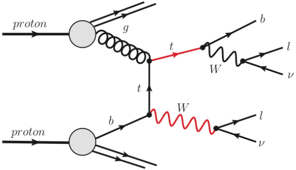
- Signal: Resonance



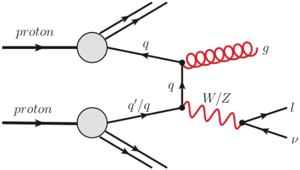
- Irreducible BG: QCD



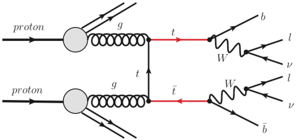
- Irreducible BG: EW
- Also all SM triple and quartic boson vertices (except Higgs) included



- Single top (Wt)



- W/Z + jets



- Top pairs $t\bar{t}$

Event Generator WHIZARD

WHIZARD: *W. Kilian, T. Ohl, J. Reuter. FR-THEP-07-01, SI-HEP-2007-07, Aug 2007.*

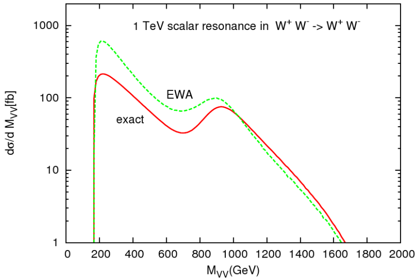
- Only generator that implements K-matrix unitarization with resonances
- `http://projects.hepforge.org/whizard/`

No Effective *W* Approximation

- Quark splitting "W/Z p.d.f."

Full matrix element for the six-fermion final state

- Angular correlations preserved
- Irreducible backgrounds included



Analysis

- Assumed integrated luminosity: $100\,\text{fb}^{-1}$ (not an early study)
- All samples for 14 TeV center-of-mass energy

Pile-up

- In-time pile-up: More than one proton-proton interaction per bunch crossing
- First studies with available samples to study general influence of pile-up
  - Poisson-distributed mean number of pile-up collisions: 6.9
  - Luminosity: $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (low luminosity pile-up)
- Goal: High luminosity pile-up

Boosted Decision Tree

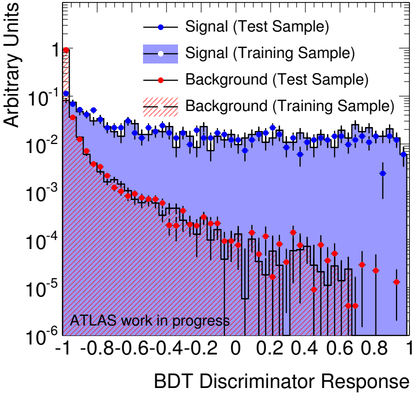
TMVA (Toolkit for Multivariate Analysis), Release 4.0.6
http://tmva.sourceforge.net

Input variables

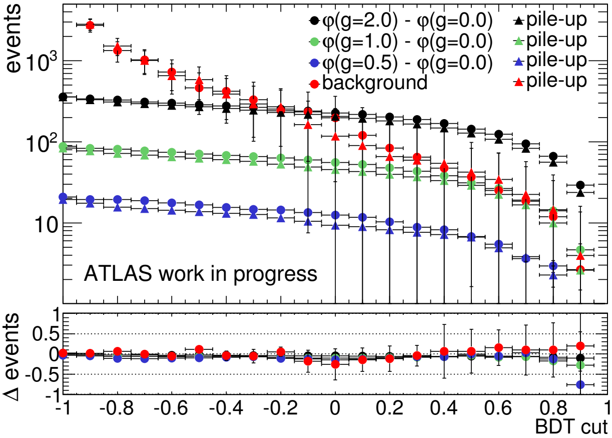
Distributions...

- *b*-tag
- p_{T} of leptons
- invariant tagjet mass
- $\Delta\eta$ between tagjets
- transverse mass
- p_{T} of tagjets
- missing E_{T}
- lepton centrality ζ
- p_{T} balance
- minijet veto

- Training: Pile-up events trained with pile-up events and vice versa



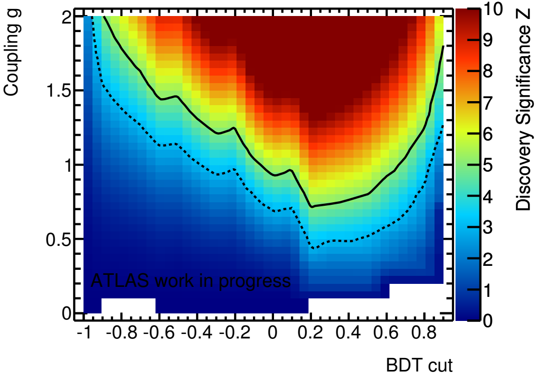
Cutflow of Boosted Decision Tree Output



- Δevents $\equiv$ (pile-up $-$ no pile-up)/(pile-up $+$ no pile-up)
- Reducible backgrounds disappear for BDT cuts $r_{\text{cut}} > 0.3$
- EW irreducible background most important background
- Separate backgrounds...

Discovery Significance

- Example: Discovery significance for φ resonance with $m = 850\ \mathrm{GeV}$ and pile-up
- Profile likelihood method
- Optimal cut on BDT output: $r \geq 0.2$ (best 5-sigma discovery significance)
- Assumed experimental luminosity: $100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14\ \mathrm{TeV}$
- Amount of Monte Carlo scaled to $100\,\mathrm{fb}^{-1}$

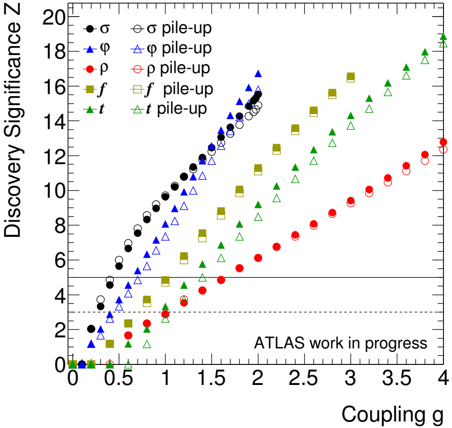


Discovery Significance

Couplings discoverable (5σ) including pile-up and systematic uncertainties:

	g	Pile-up	Systematics
σ:	> 0.70	12.7%	69.9%
φ:	> 1.05	7.2%	46.5%
ρ:	> 2.34	9.4%	42.2%
f:	> 1.43	14.1%	37.1%
t:	> 2.15	26.3%	53.7%

- Mass of resonances: 850 GeV
- Pile-up trained with pile-up and no pile-up trained without pile-up
- Reasonable couplings: $g \lessapprox 2.5$
- Higgs (σ, $g = 1$) discoverable
- Systematic uncertainties ...



Summary

This Analysis:

- ATLAS has discovery potential in the di-leptonic Vector Boson Scattering channel for resonances with a mass of 850 GeV in the relevant coupling range of $g \lessapprox 2.5$ for $100\,\mathrm{fb}^{-1}$ of data at 14 TeV center-of-mass energy
- Effect of systematic uncertainties: $\approx 50\%$
- Contribution of low luminosity pile-up: $\approx 15\%$

Similar analyis of Jan Schumacher without pile-up:

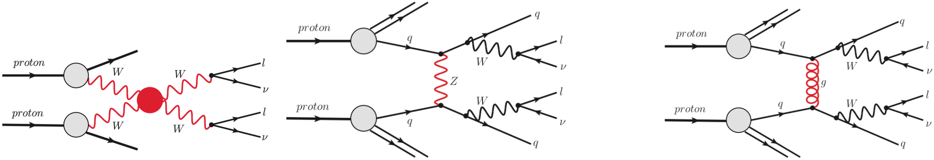
- Upper limit setting potential
- Discoverable minimal couplings for $m = 1150$ GeV up to 100% worse compared to $m = 850$ GeV

Thank you!

BACKUP

Signal and Irreducible Backgrounds

▸ Back . . .

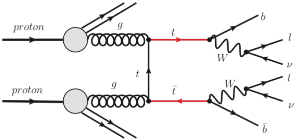


- Signal: Resonance
- Background: EW
- Background: QCD

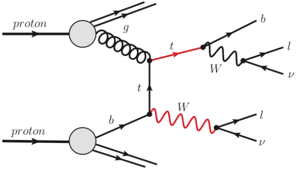
- All generated with WHIZARD for 14 TeV
- Signal entangled with irreducible background
- WHIZARD $qql\nu l\nu$ samples available:
  - EW . . . Resonances and QCD switched off
  - Signal + EW . . . QCD switched off
  - QCD + EW . . . Resonances switched off
- Realistic detector simulation using GEANT
- Assumed Monte Carlo Luminosites: $100\,\text{fb}^{-1}$
- Pile-up and no pile-up samples available
- Five resonance types at 850 GeV and 1150 GeV each

Reducible Backgrounds

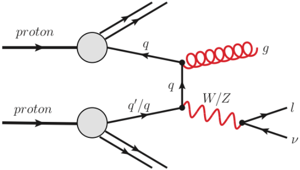
Back . . .



- Top pairs $t\bar{t}$
- MC@NLO
- Two-lepton filter
- ATLFAST-II



- Single top (Wt)
- ACERMC
- Two-lepton filter
- ATLFAST-II
- no pile-up available



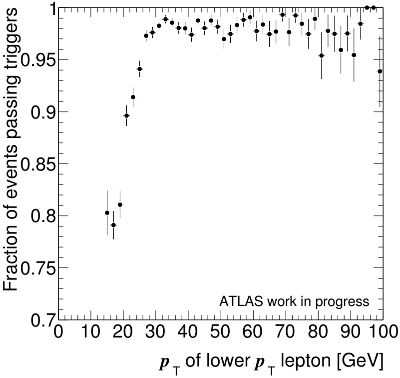
- W/Z + jets
- ALPGEN

Training options

- Number of trees: 1 000
- Boosting type: Gradient
- Shrinkage: 0.3
- Separation type: Gini index
- Pruning method: Cost Complexity
- Pruning strength: 50
- Maximum number of nodes: 5

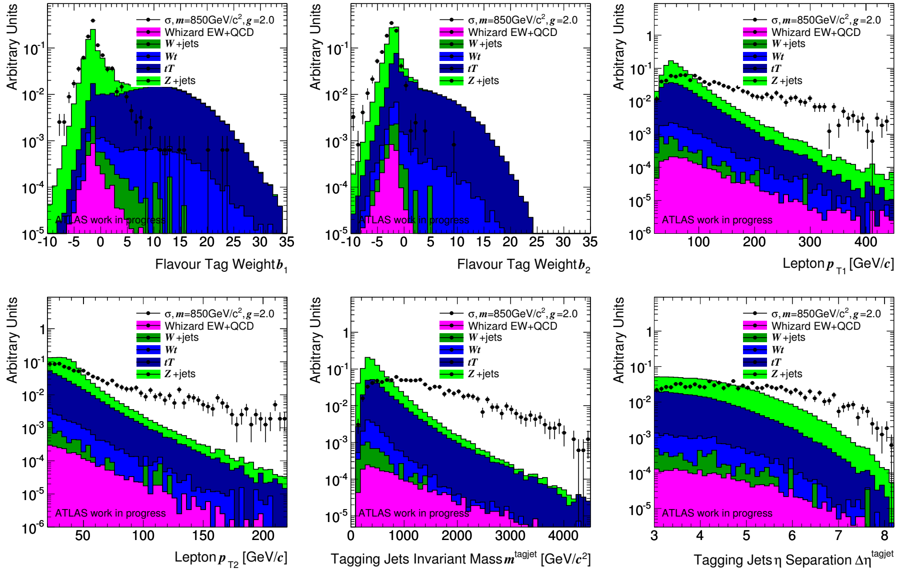
Event Selection - Fiducial Precuts

- $\Delta\eta$ between tagjets > 3.0
- p_{T} of tagjets > 20 GeV
  - Generator level
- p_{T} of 1st and 2nd lepton > 30 GeV
  - Generator level
  - Trigger plateau
- $m_{\mathrm{leplep}} > 150$ GeV
  - Removing Z+jets background
  - Caveat: Sample has a cut $m_{\mathrm{leplep}} < 200$ GeV
- Triggers:
  - Electron trigger: 25 GeV
  - Muon trigger: 20 GeV



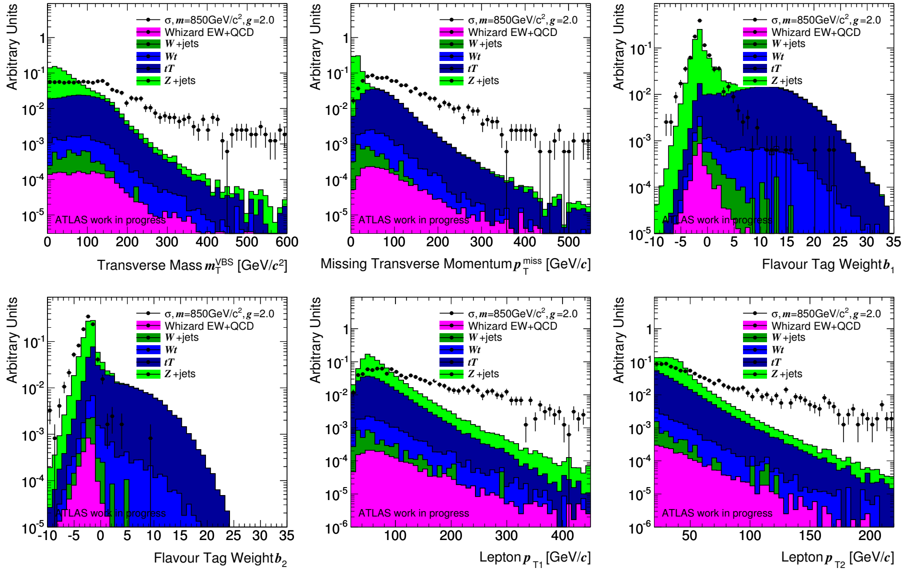
Input Variables Distributions

Back to *Boosted Decision Tree* . . .



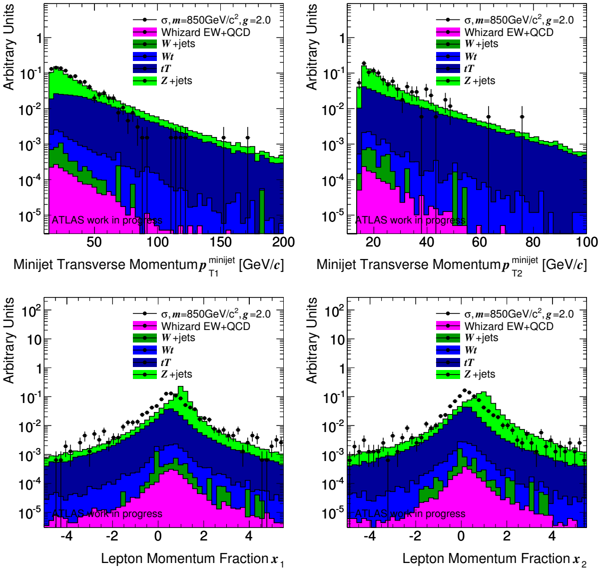
Input Variables Distributions

Back to *Boosted Decision Tree* . . .



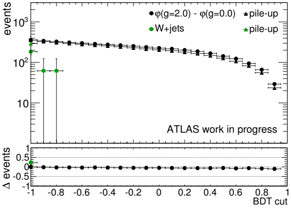
Input Variables Distributions

Back to *Boosted Decision Tree* ...

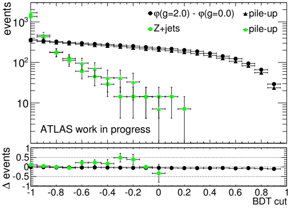


Boosted Decision Tree Results

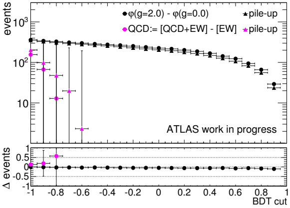
Back to BDT Cutflow...



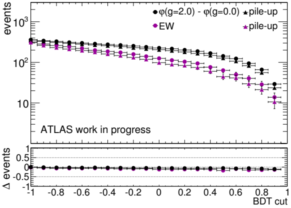
W+jets background



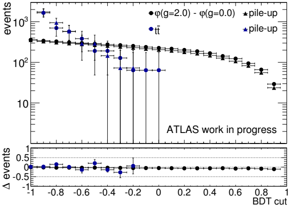
Z+jets background



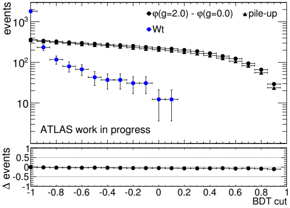
QCD background



EW background



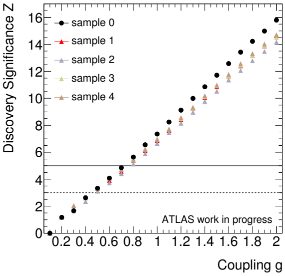
$t\bar{t}$ background



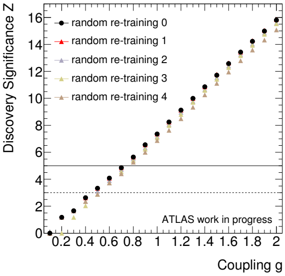
Wt background

TMVA Training Crosschecks

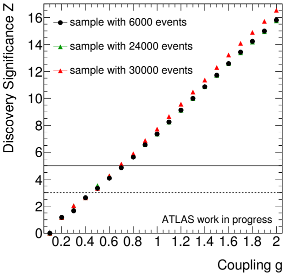
Trust a multivariate method? Statistical uncertainty of training?



Retraining with equivalent subsamples of the same size



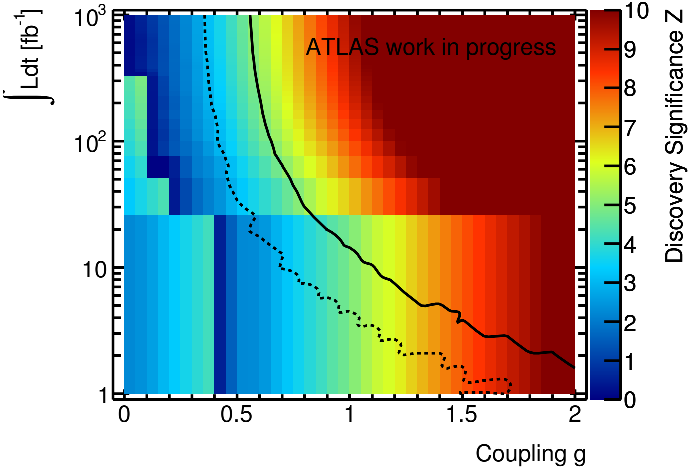
Retraining with random picking of training events inside TMVA



Retraining with samples with different number of events

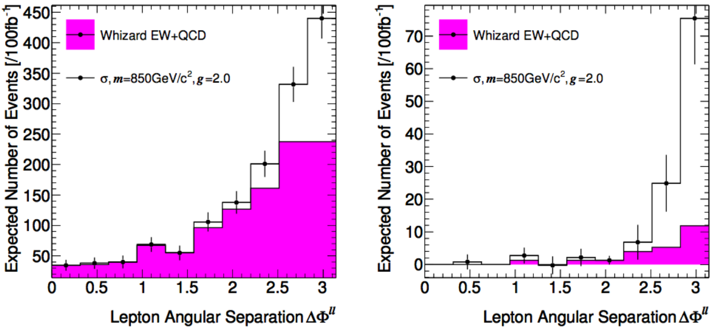
- φ resonance with $m = 850$ GeV and pile-up
- Training uncertainty: 2.8%

Luminosity Studies



φ resonance with $m = 850$ GeV and pile-up

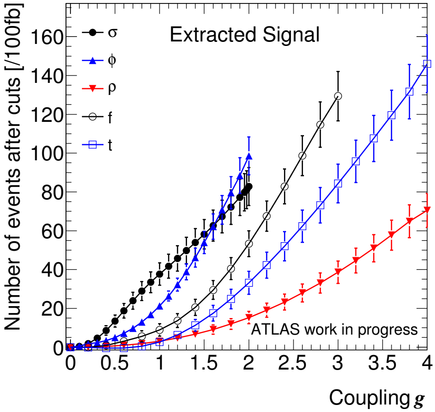
Angular Separation of Leptons



(a) Before BDT Cut **(b)** After BDT Cut $r \geq 0.7$

- Signal shows clear lepton angular separation
  - Preserved by WHIZARD
  - Motivation for $l\nu l\nu$ final state
- Lepton angular separation $\Delta\varphi^{\ell\ell}$ no input variable of BDT
- No cut on BDT output $\rightarrow$ Possible control region at low $\Delta\varphi^{\ell\ell}$
- After cut on BDT output $\rightarrow$ Separation power of $\Delta\varphi^{\ell\ell}$ lost

Disentangling Signal and Irreducible Backgrounds



- Samples reweighted from high to low coupling values
- $S(g) = n_{\text{Signal+EW}}(g) - n_{\text{Signal+EW}}(g = 0)$
- Reasonable couplings for strong EWSB: $g \lessapprox \sqrt{2\pi} \approx 2.5$

Systematic Uncertainties

Back to Results...

The following systematic uncertainties are considered:

- *Jet-energy scale*: $E'_{\text{jet}} = (1 + e_1)E_{\text{jet}}$ with $\sigma_1 = 3.5\%$ ($|\eta| \leq 3.5$) or $\sigma_1 = 7.5\%$ ($|\eta| > 3.5$)
- *Jet-energy resolution*: $E' = E + \Delta E$ with $\sigma_2 = 1$ and ΔE randomly drawn from a Gaussian with $\sigma(E) = \kappa\, e_2 \sqrt{E \times 1\ \mathrm{GeV}}$ and $\kappa = 0.45$ ($|\eta| \leq 3.5$) or $\kappa = 0.63$ ($|\eta| > 3.5$)
- *Electron-energy scale*: $E'_{\text{e}} = (1 + e_3)E_{\text{e}}$ with $\sigma_3 = 0.5\%$
- *Electron-energy resolution*: $E'_{\text{e}} = \left(1 + \frac{\Delta E_{\mathrm{T}}}{E_{\mathrm{T}}}\right) E_{\text{e}}$ with $\sigma_4 = 1$ and ΔE_{T} randomly drawn from a Gaussian with $\sigma(E_{\mathrm{T}}) = 0.0073\, e_4\, E_{\mathrm{T}}$
- *Muon-energy scale*: $E'_{\mu} = (1 + e_5)E_{\mu}$ with $\sigma_5 = 1\%$
- *Muon-reconstruction resolution*: $E'_{\mu} = \left(1 + p_{\mathrm{T}}\, \Delta\left(\frac{1}{p_{\mathrm{T}}}\right)\right)^{-1} E_{\mu}$ with $\sigma_6 = 1\%$ and $\Delta\left(\frac{1}{p_{\mathrm{T}}}\right)$ randomly drawn from a Gaussian with $\sigma(\frac{1}{p_{\mathrm{T}}}) = e_6 \sqrt{\left(\frac{0.011}{p_{\mathrm{T}}}\right)^2 + \left(\frac{0.00017}{\mathrm{GeV}}\right)^2}$
- *b-tag efficiency*: $b'_i = (1 + e_7)b_i$ with $\sigma_7 = 10\%$
- *Luminosity*: $\sigma_8 = 3\%$