Study of Weak Boson Scattering with Pile-up with the ATLAS Detector at the LHC

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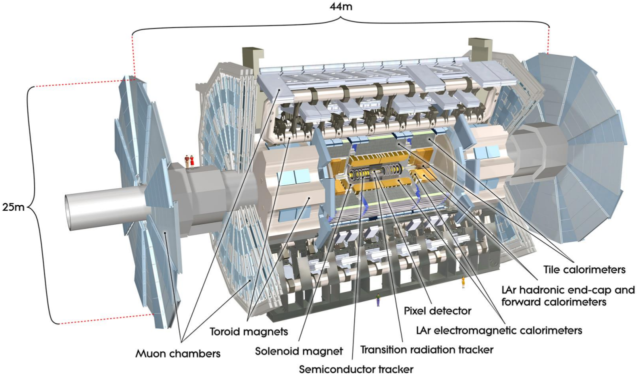
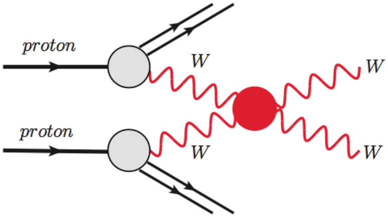
A Toroidal LHC ApparatuS (ATLAS)



- Excellent particle reconstruction and identification performance
- Precise calorimeters with large coverage (up to $|\eta| \approx 4.9$ for jets)
- Toroidal magnetic field for muon p_{T}

Vector Boson Scattering



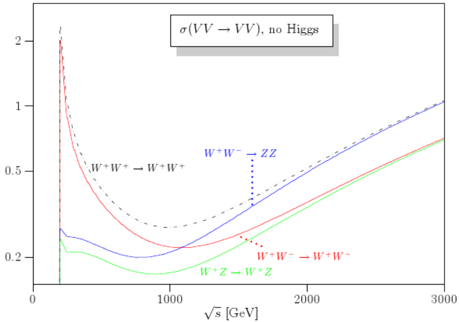
- Naive Standard Model without Higgs: Scattering of longitudinal W bosons rises infinitely:

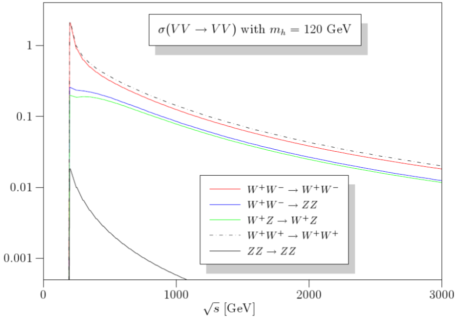
$$\sigma\left(W_{\mathrm{L}} W_{\mathrm{L}} \to W_{\mathrm{L}} W_{\mathrm{L}}\right) \xrightarrow{\sqrt{s_{\mathrm{WW}}}\to\infty} \infty$$

- 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

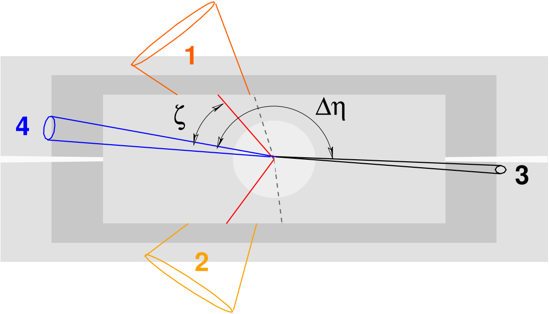
EWChL and Unitarization

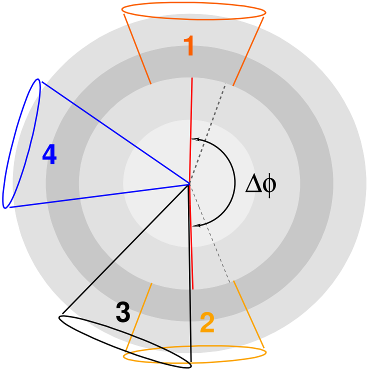
- Effective Electroweak Chiral Lagrangian (EWChL):
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{LO}} + \alpha_4(\text{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 + \alpha_5(\text{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2 + \dots$
  - Approximates the rising edge of a resonance beyond the accessible mass 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 masses M and couplings g to weak bosons

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

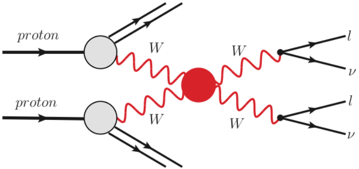
- K-matrix formalism guarantees unitarization

Experimental Signature



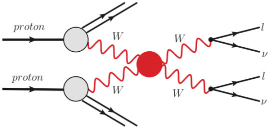


- Tagjets (large p_{T}, large distance in η)
- Few jets between tagjets
- Final state $l\nu l\nu$:
  - Missing E_{T}
  - Decay products between tagjets

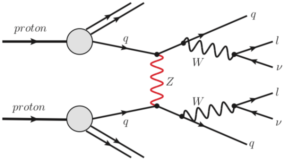


Signal and Background Processes

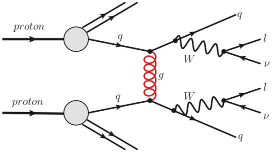
Details . . .



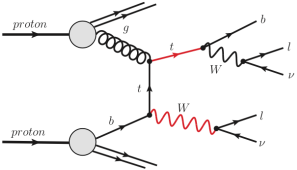
- Signal: Resonance



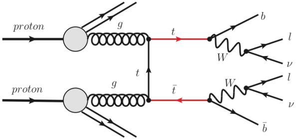
- Irreducible BG: EW
- Also all SM triple and quartic boson vertices (except Higgs) included



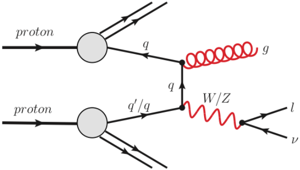
- Irreducible BG: QCD



- Single top (Wt)



- Top pairs $t\bar{t}$



- W/Z + jets

Event Generator WHIZARD

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

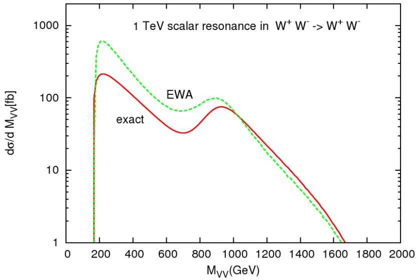
- Only generator that implements K-matrix unitarization with resonances
- `http://projects.hepforge.org/whizard/`

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: $100\,\mathrm{fb}^{-1}$ (not an early study)
- All samples with 14 TeV
- ATHENA release 14.2.25

Pile-up

- In-time pile-up: More than one proton-proton interaction per bunch crossing
- First studies with available samples to see 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

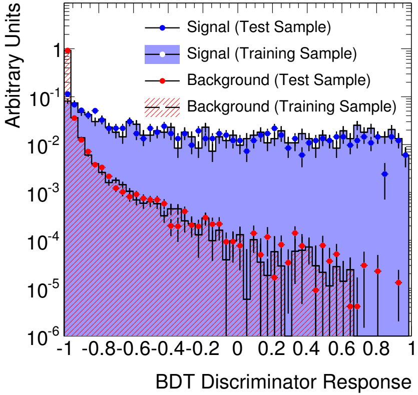
TMVA (Toolkit for Multivariate Analysis), Release 4.0.6
http://tmva.sourceforge.net

Input variables

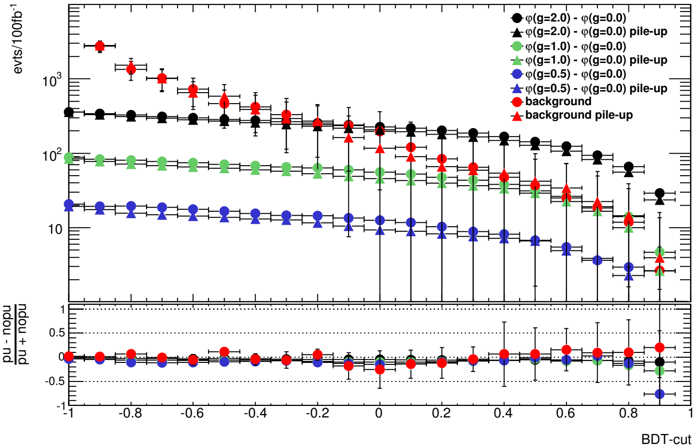
Distributions...

- 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 samples trained with pile-up samples and vice versa



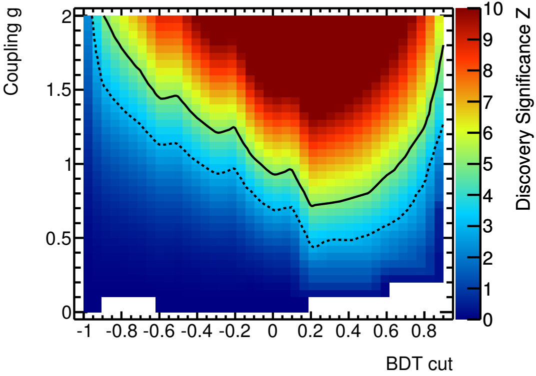
Cutflow of Boosted Decision Tree Output



- WHIZARD irreducible background most important background
- Reducible backgrounds disappear for BDT cuts > 0.3
- Separate backgrounds. . .

Discovery Significance

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

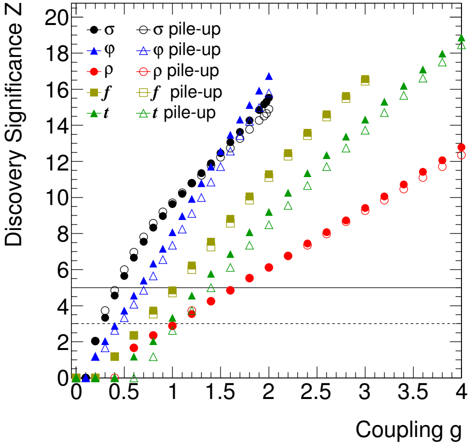


Discovery Significance Results for 850 GeV

Minimal couplings discoverable with 5σ and effect of pile-up:

	$g_{\min}$ no pile-up	pile-up	pile-up effect
σ	0.44	0.41	-6.3%
φ	0.65	0.71	10.1%
ρ	1.64	1.64	0%
f	1.02	1.04	2.3%
t	1.27	1.40	10.1%

- Pile-up trained with pile-up and no pile-up trained with no pile-up



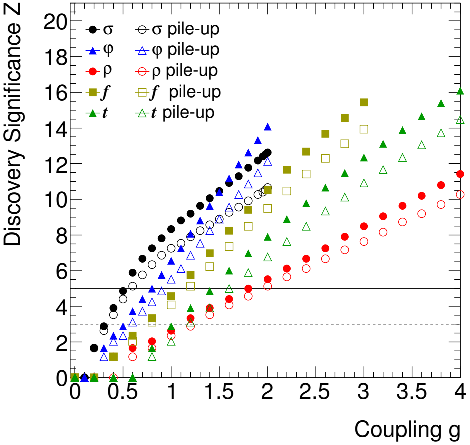
5σ discovery sensitivity for:

- All resonances with $g \lessapprox 2.5$
- SM Higgs (σ, $g = 1$)

Systematic Uncertainties (not all included yet Details...)

Minimal couplings discoverable with 5σ including systematic uncertainties and pile-up:

	$g_{\min}$	systematics effect	pile-up effect
σ	0.58	40.5%	13.7%
φ	0.92	28.1%	15.0%
ρ	1.95	18.6%	8.3%
f	1.17	12.0%	9.3%
t	1.60	14.2%	11.9%



5σ discovery sensitivity for:

- All resonances with $g \lesssim 2.5$
- SM Higgs (σ, $g = 1$)

Summary

This Analysis:

- ATLAS has discovery potential in the Vector Boson Scattering two lepton channel at $100\,\mathrm{fb}^{-1}$ at $850\ \mathrm{GeV}$ in relevant coupling range $g \lessapprox 2.5$
- Effect of systematic uncertainties: $\approx 20\%$ (will increase with all uncertainties included)
- Contribution of low luminosity pile-up: $\approx 15\%$

Analyis of Jan Schumacher:

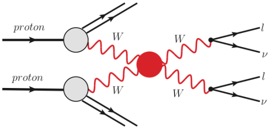
- Upper limit setting potential
- Discoverable minimal couplings for $m = 1150\ \mathrm{GeV}$ up to 100% worse compared to $m = 850\ \mathrm{GeV}$

Thank you!

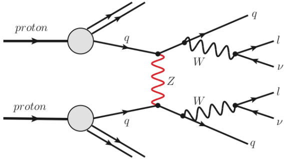
BACKUP

Signal and Irreducible Backgrounds

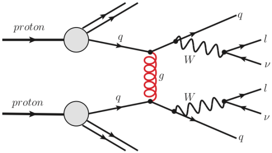
Back ...



- Signal: Resonance



- Background: EW

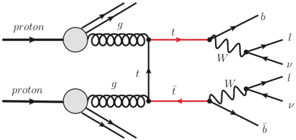


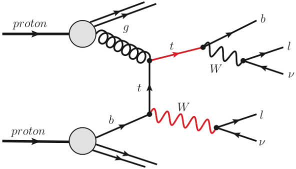
- Background: QCD

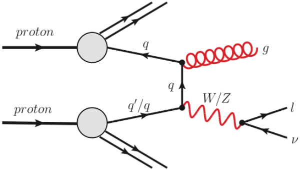
- All generated with WHIZARD for 14 TeV
- Signal entangled with irreducible background
- WHIZARD $qql\nu l\nu$ samples available:
  - EW ... Resonances and QCD switched off
  - Signal + EW ... QCD switched off
  - QCD + EW ... Resonances switched off
- Realistic detector simulation using GEANT
- Assumed Monte Carlo Luminosites: $100\,\mathrm{fb}^{-1}$
- 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

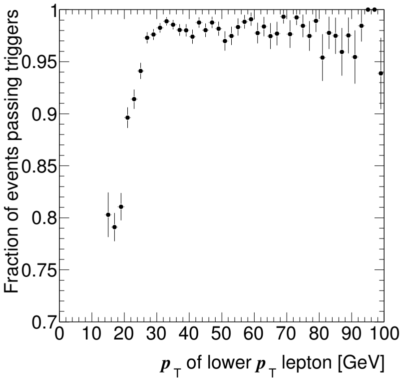
- W/Z + jets
- ALPGEN

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

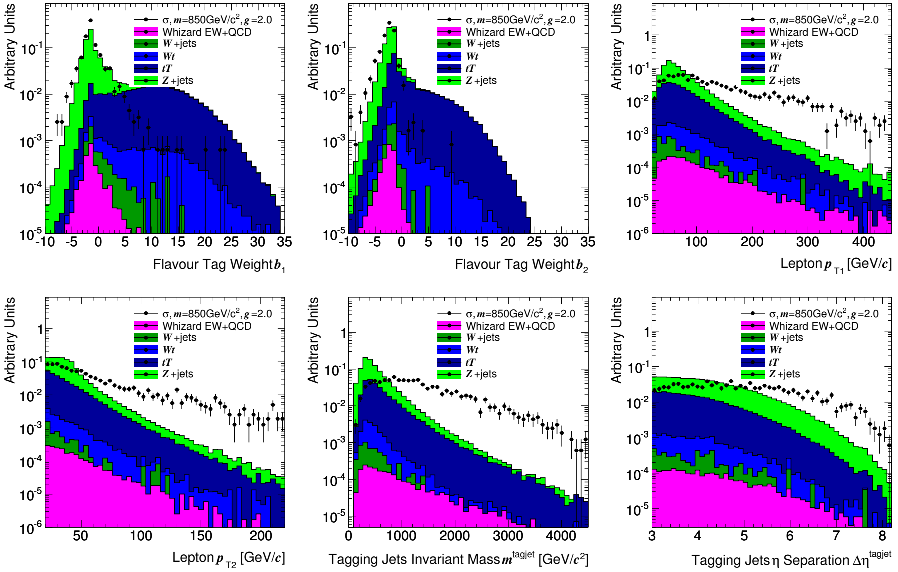
Event Selection - Fiducial Precuts

- $\Delta\eta$ 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



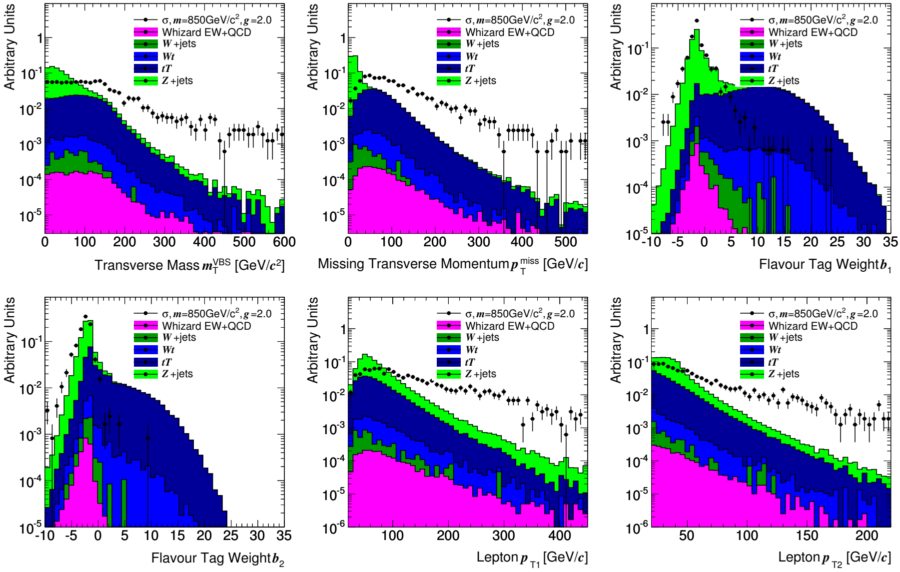
Input Variables Distributions

▸ Back to *Boosted Decision Tree . . .*



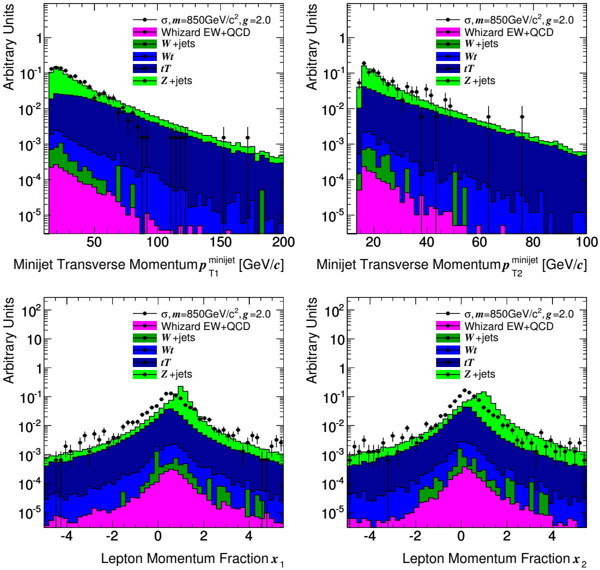
Input Variables Distributions

Back to *Boosted Decision Tree* . . .



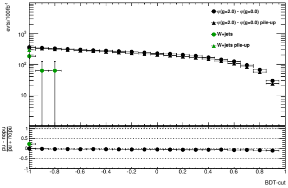
Input Variables Distributions

Back to *Boosted Decision Tree* ...

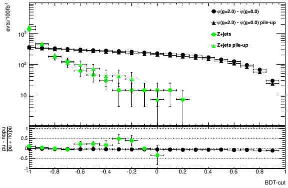


Boosted Decision Tree Results

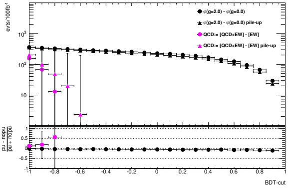
Back to BDT Cutflow...



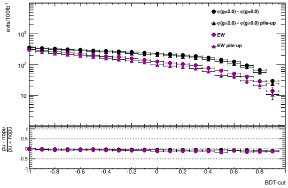
W+jets background



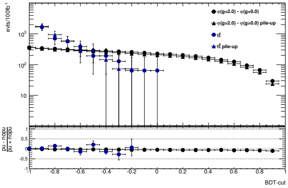
Z+jets background



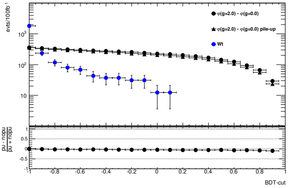
WHIZARD QCD



WHIZARD EW



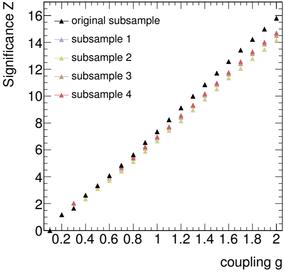
$t\bar{t}$ background



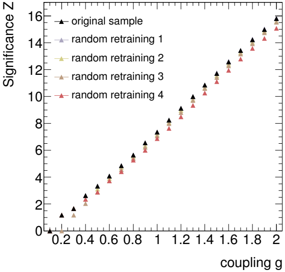
Wt background

TMVA Training Tests

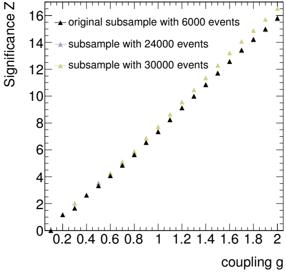
Trust a multivariate method?



Retraining with equivalent subsamples of the same size



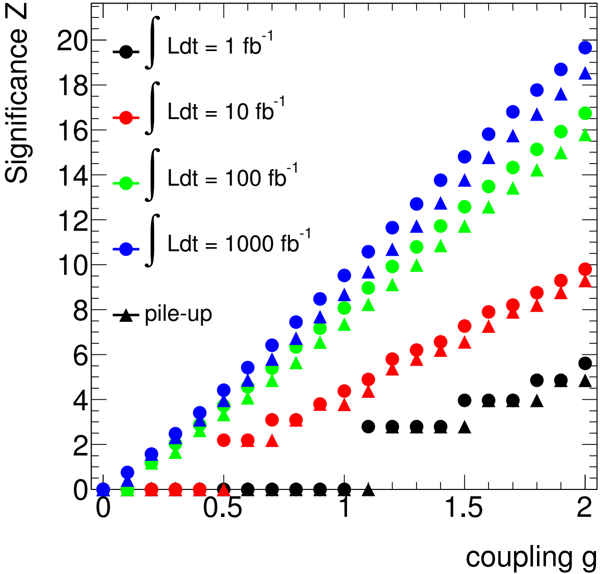
Retraining with random picking of training events inside TMVA



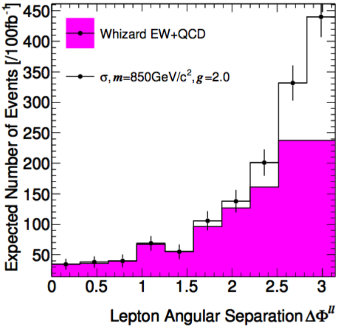
Retraining with samples with different number of events

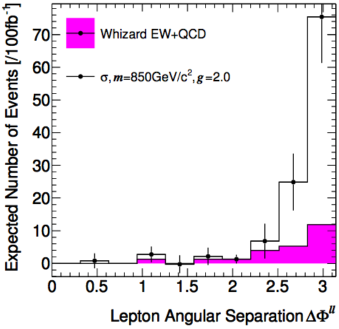
φ resonance with $m = 850\ \mathrm{GeV}$ and pile-up

Luminosity studies



Angular Separation of Leptons

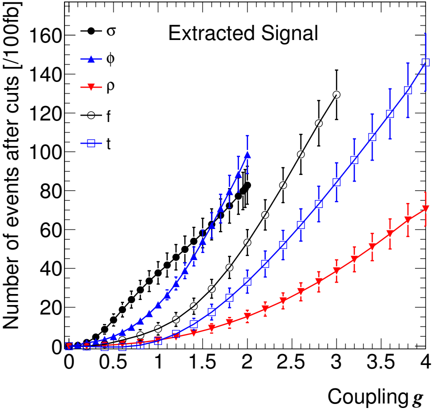




(a) Before BDT Cut **(b)** After BDT Cut $r \geq 0.7$

- Signal shows clear lepton angular separation
  - Preserved by WHIZARD
  - Motivation for $l\nu l\nu$ final state
- Lepton angular separation $\Delta\varphi^{\text{leplep}}$ no input variable of BDT
- No cut on BDT output $\rightarrow$ Possible control region at low $\Delta\varphi^{\text{leplep}}$
- After cut on BDT output $\rightarrow$ Separation power of $\Delta\varphi^{\text{leplep}}$ 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: $g \lesssim \sqrt{2\pi} \approx 2.5$

Systematic Uncertainties

Back to *Systematics...*

- Jet-energy resolution: $E' = E + e_2 \Delta E$ with
  - ΔE randomly drawn from a Gaussian with:
    - $\sigma(E) = 0.45\sqrt{E \times 1\ \mathrm{GeV}}$ for $|\eta| \leq 3.5$
    - $\sigma(E) = 0.63\sqrt{E \times 1\ \mathrm{GeV}}$ for $|\eta| > 3.5$
- Electron-energy scale: $E'_e = (1 + e_3)E_e$ with $e_3 = 0.5\%$
- Electron-energy resolution: $E'_e = \frac{E_\mathrm{T} + e_4 \Delta E_\mathrm{T}}{E_\mathrm{T}} E_e$ with
  - ΔE_T randomly drawn from a Gaussian with:
    - $\sigma(E_\mathrm{T}) = 0.0073 E_\mathrm{T}$
- Muon-energy scale: $E'_\mu = (1 + e_5)E_\mu$ with $e_5 = 1\%$