Mass Reconstruction Techniques for Resonances in $W^\pm W^\pm$ Scattering

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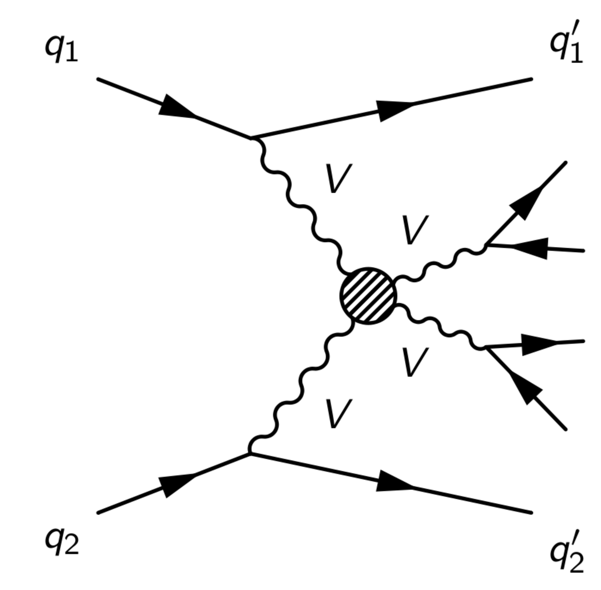
Motivation

Since the discovery of a SM like Higgs boson, the **scattering of two massive weak vector bosons (VBS)** has been the last piece in the Standard Model puzzle. Only recently a first evidence for processes involving a four-boson interaction vertex has been measured [1]. The study of VBS is inevitable for understanding the nature of **electroweak symmetry breaking (EWSB)**. With the existence of the Higgs boson unitarity is maintained for VBS amplitudes of longitudinally polarized vector bosons. Furthermore, new physics scenarios in this sector predict an enhancement in VBS represented by additional **heavy resonances**. Due to the best signal to background ratio, **same-sign $W^\pm W^\pm jj$** is the most favorable final state for a first glance at resonances in VBS at a hadron collider such as the LHC. Investigating observables for discovering and measuring the mass of such resonances is the main goal of this work where a special emphasis lies on **mass reconstruction** via the **technique of constrained minimization**.



Model-Independent Resonances in EW

- linearized chiral Lagrangian introduces new physics in the EW sector
  $\rightarrow$ SM evolves as a low-energy effect
- resonances as new degrees of freedom coupling to the EW SM gauge boson sector
- assumption: custodial symmetry of weak isospin valid also at high energies $\rightarrow$ only the following resonances of spin J and isospin I couple to a system of two vector bosons [3]:

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 ("Higgs")	$[\omega^0]$ (γ'/Z')	f^0 (KK graviton)
$I=1$	$[\pi^\pm,\pi^0]$ (2HDM)	$\rho^\pm,\rho^0$ (W'/Z')	$[a^\pm,a^0]$
$I=2$	$\phi^{\pm\pm},\phi^\pm,\phi^0$ (Higgs triplet)	—	$t^{\pm\pm},t^\pm,t^0$

- case: same charge-sign W boson scattering
  $\rightarrow$ only isotensor resonances ($I=2$, Φ and t) possible
- mass M and coupling g of resonances can be adjusted freely
- partial widths Γ for resonances decaying into longitudinally polarized vector bosons:

$$\Gamma = \Gamma_{res}\cdot\frac{g^2}{64\pi}\cdot\frac{M^3}{v^2} \quad \text{with} \quad \Gamma_\Phi = \frac{1}{5} \quad \text{and} \quad \Gamma_t = \frac{1}{30}$$

- effective theories can violate the unitarity of scattering amplitudes $a(s)$
  $\rightarrow$ explicit implementation of unitarity bounds required
- k-matrix unitarisation model: projection of the spin-isospin-eigenamplitudes onto the Argand circle ($|a(s)-i/2| = 1/2$).

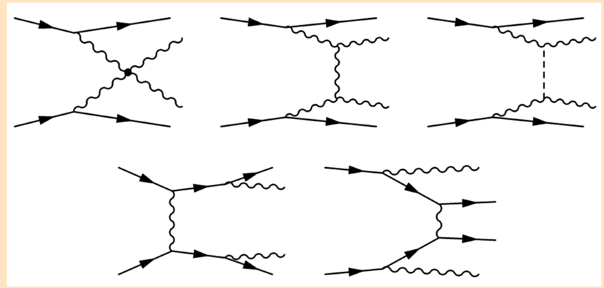
True invariant mass of the WW system for Φ (left) and t (right) resonances for varying mass parameters

Signal Event Generation & Topology

- Whizard event generator with SM_km model
- $pp \rightarrow l^\pm \nu l^\pm \nu$ jj at $\sqrt{s} = 8$ TeV
- purely EW: $\mathcal{O}(\alpha^6_{EW})$
- resonances with parameters mass, width and coupling
- k-matrix unitarisation

Background
SM EW $\mathcal{O}(\alpha^6_{EW})$
$qq \rightarrow l^\pm\nu l^\pm\nu\, qq$

Signal
EW resonant scattering with
$W^\pm W^\pm \rightarrow X^{\pm\pm} \rightarrow W^\pm W^\pm$



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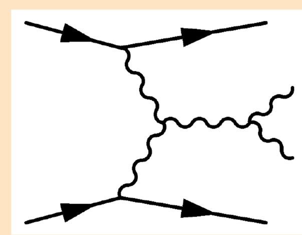
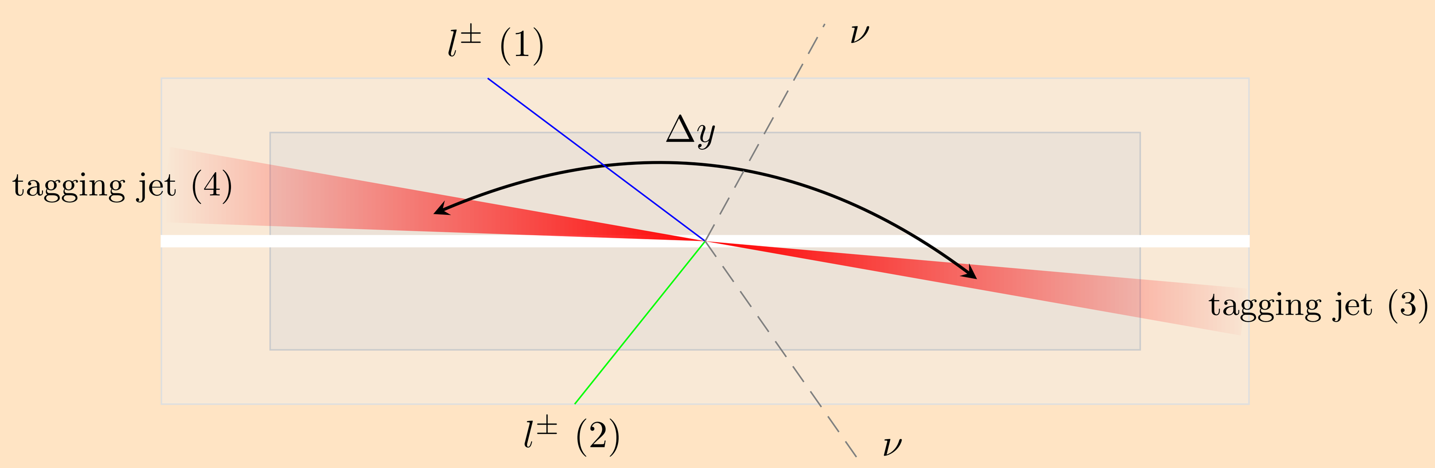


Signal event topology with both W bosons decaying leptonically, $W \rightarrow l\nu$:

- two energetic forward jets (initial quarks radiating off Ws) (3,4)
- two central leptons (e or μ, same electric charge) (1,2)
- missing pT from neutrinos



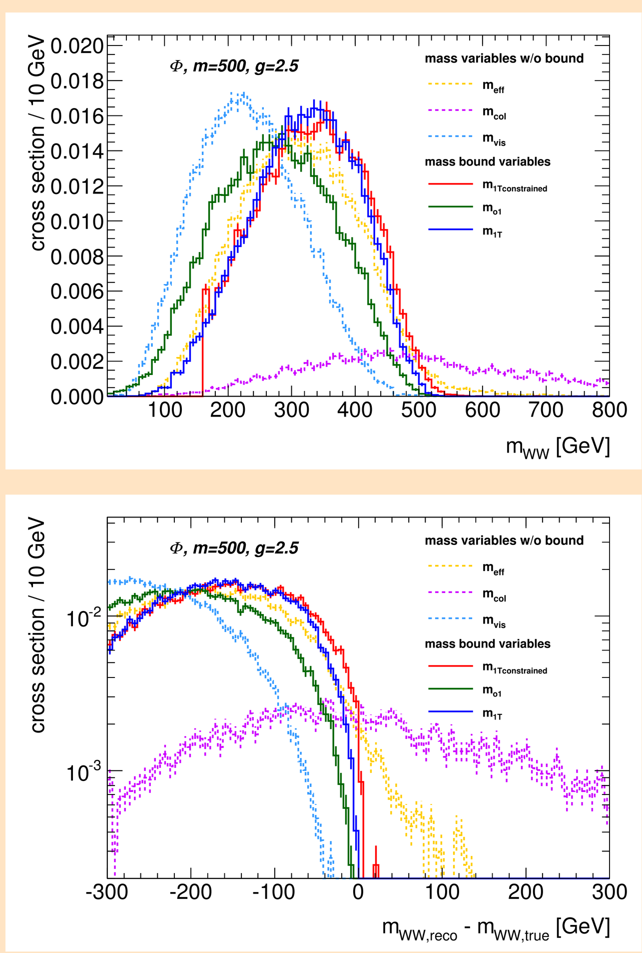
Mass Reconstruction [4]

- full leptonic final state $\rightarrow$ **two neutrinos** $\rightarrow$ kinematics of resonance decay cannot be fully reconstructed
- measuring the missing transverse momentum fixes only two of the 6 invisible momentum components
- **technique of constrained minimization** eliminates the additional degrees of freedom
  $\rightarrow$ **saturated maximal lower mass bound**
- different mass bound variables considered depending on the implementation of the transverse projection:

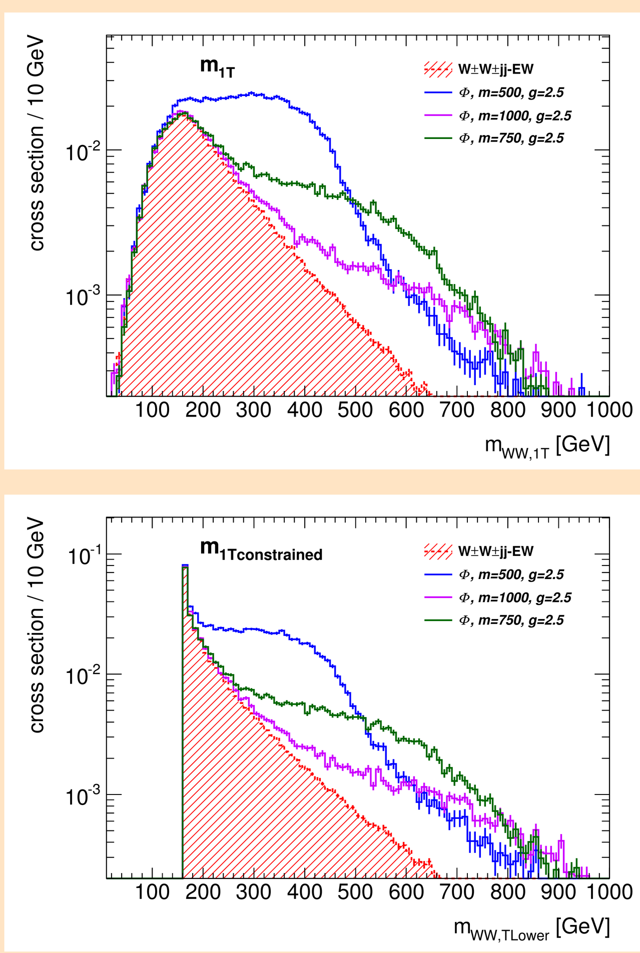
mass-preserving projection "$\top$":
$$m^2_{1\top} = \left(\sqrt{m^2_{ll} + \vec{p}^{\,2}_{1T}} + |\vec{p}_{Tmiss}|\right)^2 - (\vec{p}_{1T} + \vec{p}_{Tmiss})^2$$

massless projection "o":
$$m^2_{o1} = m^2_{eff} - (\vec{p}_{1T} + \vec{p}_{Tmiss})^2$$

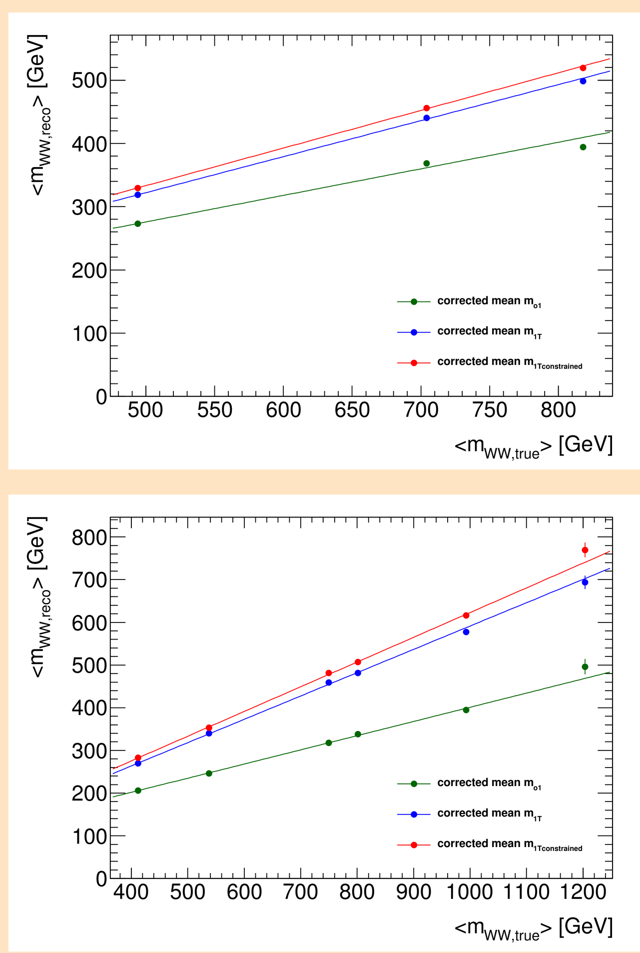
- additional constraints for on-shell W boson production $\rightarrow m_{1\top constrained}$
- mass bound variables are compared to traditional mass reconstruction variables: effective mass m_{eff}, collinear mass m_{col} and the mass of the di-lepton system m_{vis}



Comparison of different mass reconstruction variables (top)
Difference of reconstructed to true invariant WW mass (bottom)

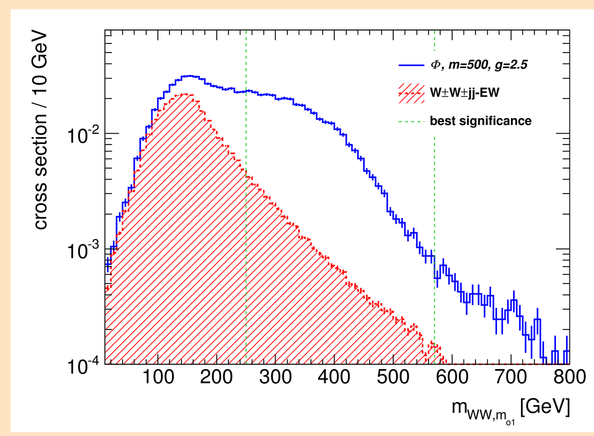


Comparison between unconstrained and both W on-shell constrained $m_{1\top}$ for signal and SM background (shaded)

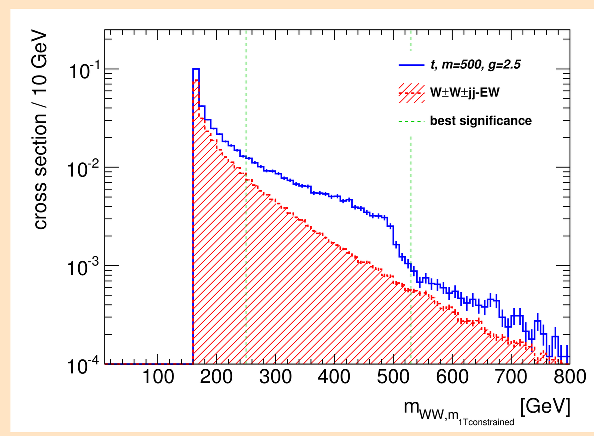


Calibration:
Mean of distribution of mass bound variable vs. true m_{WW}

Mass Variable with Best Detection Power $\frac{S}{\sqrt{B}}$



Best detection power for all Φ resonances: m_{o1}, due to best background rejection



Best detection power for all t resonances: $m_{1\top constrained}$, as it uses the most kinematic information

Conclusion

- Whizard can be used to model resonances in VBS
- Mass bound variables outperform the traditional variables in detection power
- Mass bound variables can be calibrated linearly
- Difference in $m_{1\top}$ and $m_{1\top constrained}$ clearly visible but no significant difference in detection power
- Best detection power: m_{o1} for Φ and $m_{1\top constrained}$ for t

References

[1] ATLAS collaboration. *Evidence for Electroweak Production of W±W±jj in pp Collisions at $\sqrt{s}=8$ TeV with the ATLAS Detector. 2014*

[2] J.Reuter, A. Alboteanu, W. Kilian. *Resonances and Unitarity in Weak Boson Scattering at the LHC.* JHEP, 0811:020, 2008

[3] J.Reuter, W. Kilian, M. Sekulla. *Simplified Models for New Physics in Vector Boson Scattering - Input for Snowmass 2013.*

[4] A.J. Barr et al. *A storm in a "T" cup: the connoisseur's guide to transverse projections and mass-constraining variables.* 2011. arXiv:1105.2977v2