Search for Anomalous Electroweak production of WW/WZ/ZZ Boson Pairs in Association with two jets in p-p Collision at 13 TeV

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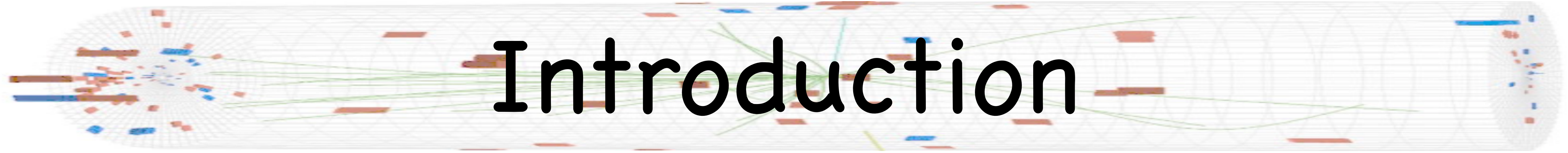
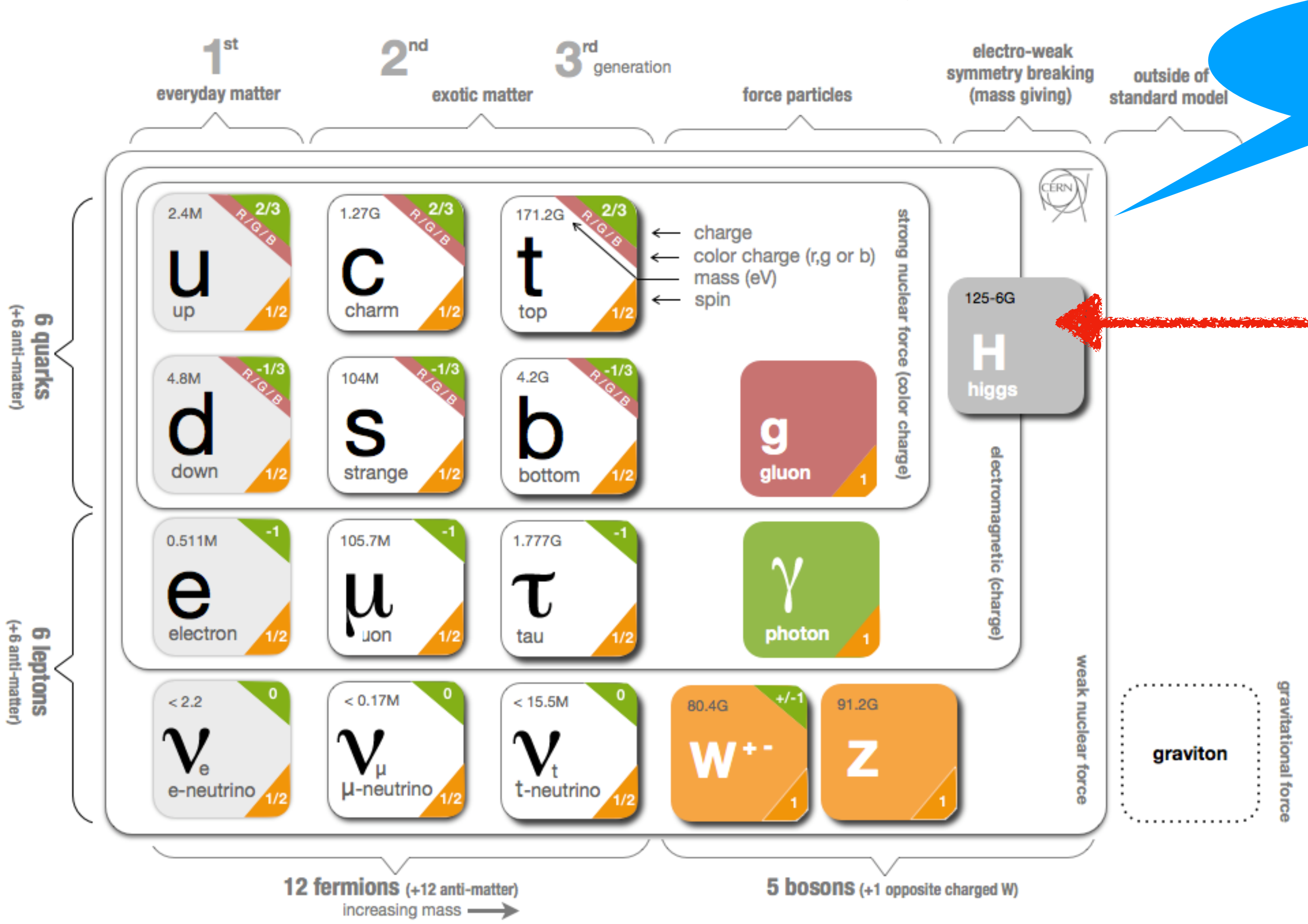
Ram Krishna Sharma, Dr. Md. Naimuddin
On Behalf of CMS Collaboration



Introduction

Particle physics is a modern name for the centuries old effort to understand the basic laws of physics.

- Edward Witten



Periodic Table of Standard Model

Last missing piece of SM

Finally observed at CMS & ALTAS detector at LHC, CERN.

After Higgs Discovery???

➡Important task is to understand the mechanism behind the Electroweak Symmetry Breaking!!!

➡Two possible ways:

1. Precision measurement of the Higgs and the vector boson properties.
2. Study of the vector boson scattering.

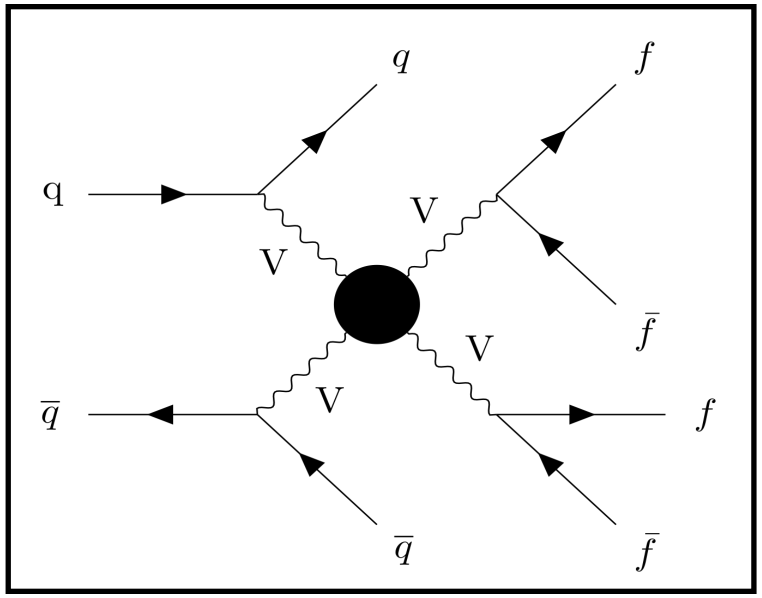
Vector Boson Scattering

- Without Higgs, VBS cross section would violate unitarity at the TeV scale.

- Vector boson scattering at the LHC probes triple and quartic gauge couplings

- Anomalous triple and quartic gauge couplings (aTGC, aQGC) would indicate the presence of new physics
    - Increases the cross-section at large di-boson mass and transverse momentum.
    - sensitive to new physics contributions in the kinematic tail.

- Anomalous couplings can be introduced as a model independent way using Effective Field Theory (EFT).



aQGC in the EFT Framework

- BSM search using model independent way:
  - Modify triple and quartic gauge couplings by redefining SM Lagrangian.

$$L_{SM} \longrightarrow L_{eff} = L_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_I^{(n+4)}$$

  - $\Lambda >> m$ & $L_{eff} \rightarrow L_{sm}$ as $\Lambda \rightarrow \infty$
  - An effective field theory is the low energy approximation to the new physics, where "low" means < Λ
- Sample was generated using MadGraph5 at leading-order (LO)
  - Used reweighting feature to save information about different parameter points for each operator.

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

aQGC parameters to probe

- **Dimension 8 operators:** Lowest dimension operators that modify the quartic boson interactions.

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

The operators in the red box are the one which we considered in our analysis.

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

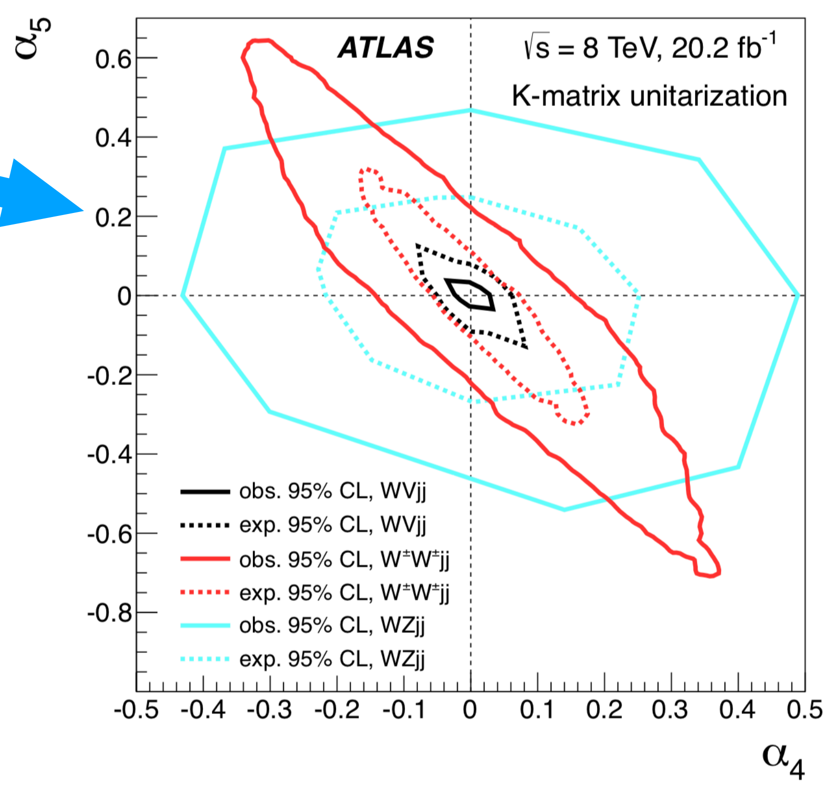
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Ref: Phys.Rev. D74 (2006) 073005

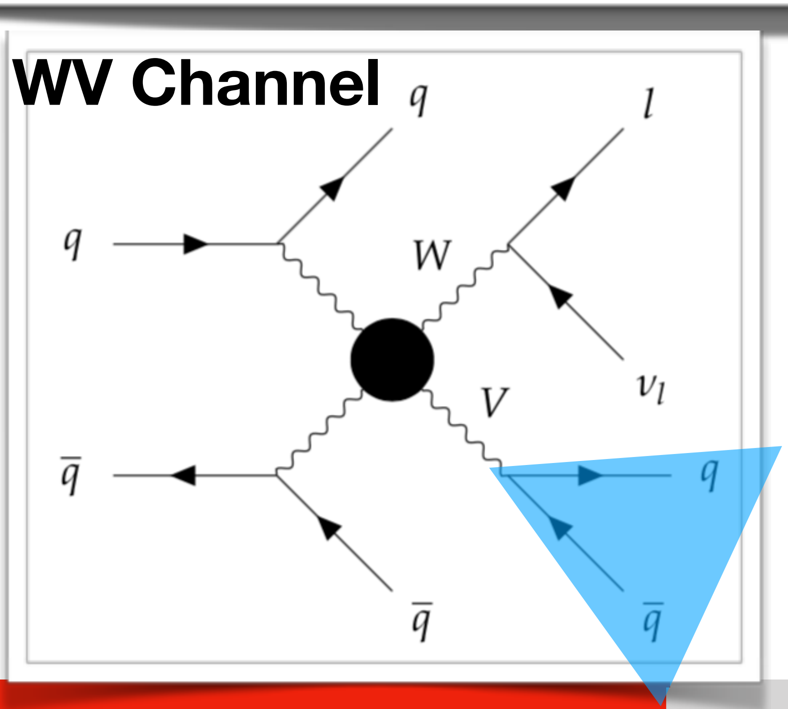
Anomalous Quartic Gauge Coupling

- WV/ZV production in association with two jets
    - Semi-leptonic final state with a boosted hadronic W/Z
- Stringent aQGC bounds for WV channel was set by ATLAS using 8 TeV data sample
- **Benefits for WVjj Channel (includes contribution from $W^\pm W^\pm jj$, $W^\pm W^\mp jj$, $W^\mp Zjj$, ZZjj)**:
    - larger branching ratio than same sign WWjj analysis.
    - Full WW invariant mass reconstruction (neutrino p_z calculation by constraining W-boson mass).
    - Low background in kinematical tails using boosted jets topology.
    - aQGC contribution from all possible vertex:
        - WWWW, ZZWW, γγWW, γZWW, ZZZZ, Zγγγ, ZZγγ, ZZZγ
    - **It should significantly improve the current sensitivity.**

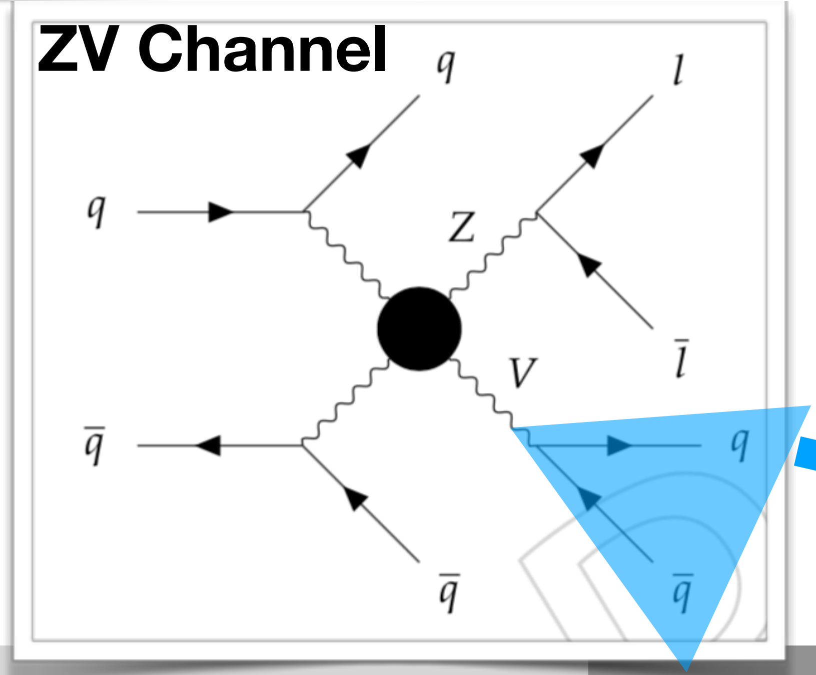
Phys. Rev. D 95 (2017) 032001



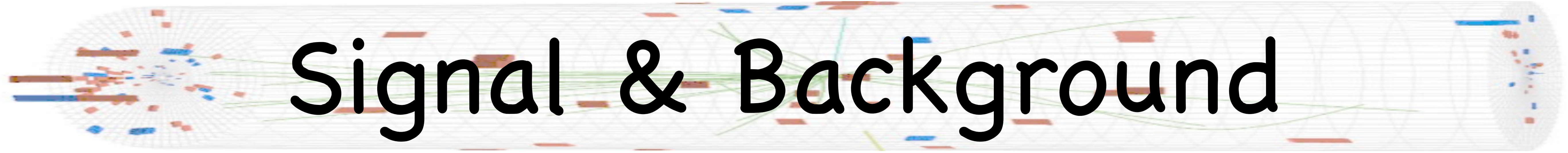
WV Channel



ZV Channel



Reconstructed as a merged jet



Signal & Background

- **VVJJ (EWK) :** Electroweak production of WWJJ.

- **VVJJ (aQGC EWK):** Electroweak production of VVJJ with contributions from aQGC.

- **W+Jets:** Most dominating background.

- **VVJJ (QCD initiated)**: Irreducible background for analysis.

- tt **Jets**: Top quark always decays to one b-quark and one W boson. So, $t\bar{t} \rightarrow bWbW \rightarrow bl\nu l\nu$, if we mis-measure one lepton and one b quark form jets.

- **Drell-Yan:** Z/Gamma decays to l^+l^- and we mis-measure one l because of acceptance or inefficiency effects, gives missing energy.

- **Single top production**: Here $t \rightarrow bW \rightarrow bl\nu$, and 3 jets is reconstructed.

Centrality and Zeppenfeld Definition

Boson Centrality (Phys. Rev. D 95, 032001)

$$\xi_V = min\{\Delta\eta_-, \Delta\eta_+\}$$

where,

$$\Delta\eta_- = min\{\eta(V_{had}), \eta(V_{lep})\} - min\{\eta_{j1}, \eta_{j2}\},$$
$$\Delta\eta_+ = max\{\eta_{j1}, \eta_{j2}\} - max\{\eta(V_{had}), \eta(V_{lep})\}$$

- **ξ > 0 : Both W's should be within VBF jets**
- **ξ < 0 : One or both lepton are at larger |η| than the VBF jets**

Zeppenfeld w.r.t. Leptonic W (Phys. Rev. D 54, 6680)

$$Z_{Whad} = \frac{\eta_{Whad} - \frac{\eta_{j1} + \eta_{j2}}{2}}{|\eta_{j1} - \eta_{j2}|}$$

Zeppenfeld w.r.t. Leptonic W (Phys. Rev. D 54, 6680)

$$Z_{Wlep} = \frac{\eta_{Wlep} - \frac{\eta_{j1} + \eta_{j2}}{2}}{|\eta_{j1} - \eta_{j2}|}$$

Event Selection

WV Channel

- Final Selection Electrons (Muons)
  - Exactly 1 lepton
  - For electrons exclude region $1.4442 < \eta < 1.566$
  - MET > 80 GeV (50 GeV)
  - Fat Jet (having radius parameter 0.8):
    - $65 < m_W < 105$, **Tau2/Tau1** < 0.55
  - VBF jets (having radius parameter 0.4):
    - $m_{jj} > 800$ GeV, dEta > 4.0
  - Boson-Centrality > 1.0
  - Leptonic zeppenfeld < 0.3
  - Hadronic zeppenfeld < 0.3
  - $m_{WV} > 600$

ZV Channel

- Final Selection
  - Exactly 2 leptons
  - $76 < m_{LL} < 107$
  - Large radius parameter jet:
    - $65 < m_Z < 105$, **Tau2/Tau1** < 0.55
  - VBF jets:
    - $m_{jj} > 800$ GeV, dEta > 4.0
  - $m_{ZV} > 600$
- Fit m_{VV} distribution to get limits

Small value represents higher probability for a jet to be composed of two sub-jets.

Data driven background estimation (Alpha-Ratio Method)

- **To get V+jet contribution from data in signal region:**

$$N_{signal}^{Data,W+Jets}(M_{WW}) = \alpha(M_{WW}) \times N_{sideband}^{Data}(M_{WW})$$

- **Alpha (taken from MC) is defined as:**

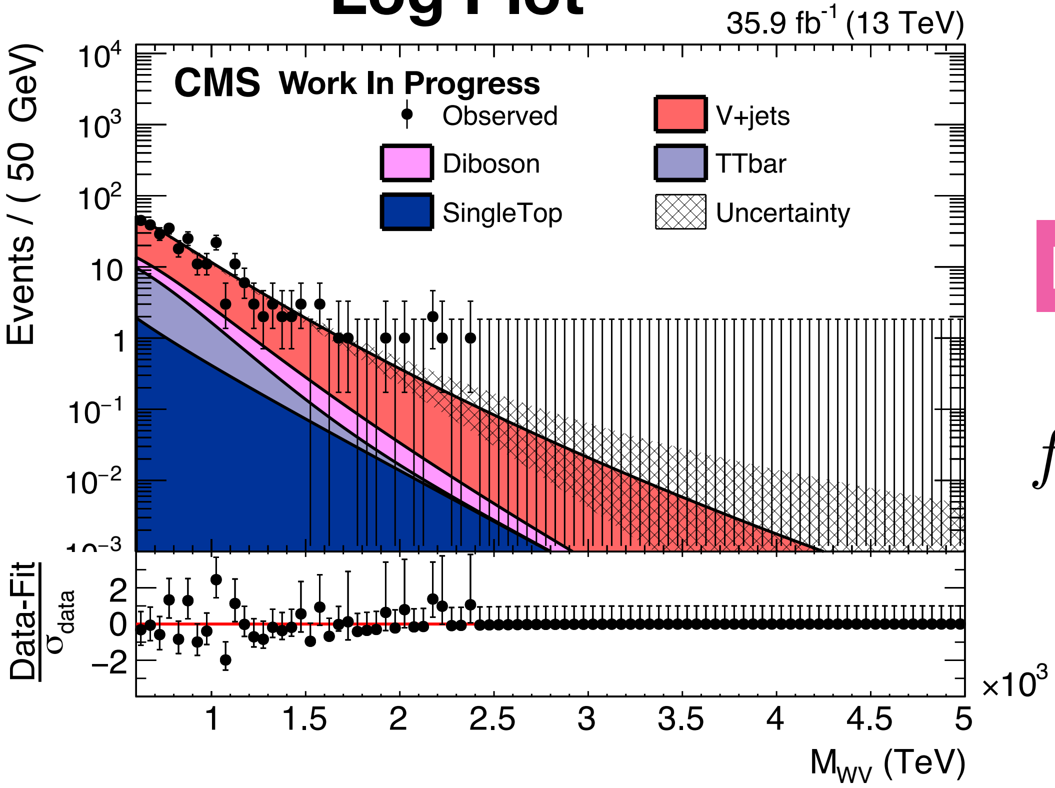
$$\alpha(M_{WW}) = \frac{N_{signal}^{MC,W+Jets}(M_{WW})}{N_{sideband}^{MC,W+Jets}(M_{WW})} = \frac{N_{signal}^{Data}(M_{WW})}{N_{sideband}^{Data}(M_{WW})}$$

- In this formula there are three sources of uncertainty.
    - Uncertainty in alpha (dominated by MC statistics)
    - Uncertainty coming from W+jet shape
    - Statistical uncertainty coming from data

M_{WW} Fits

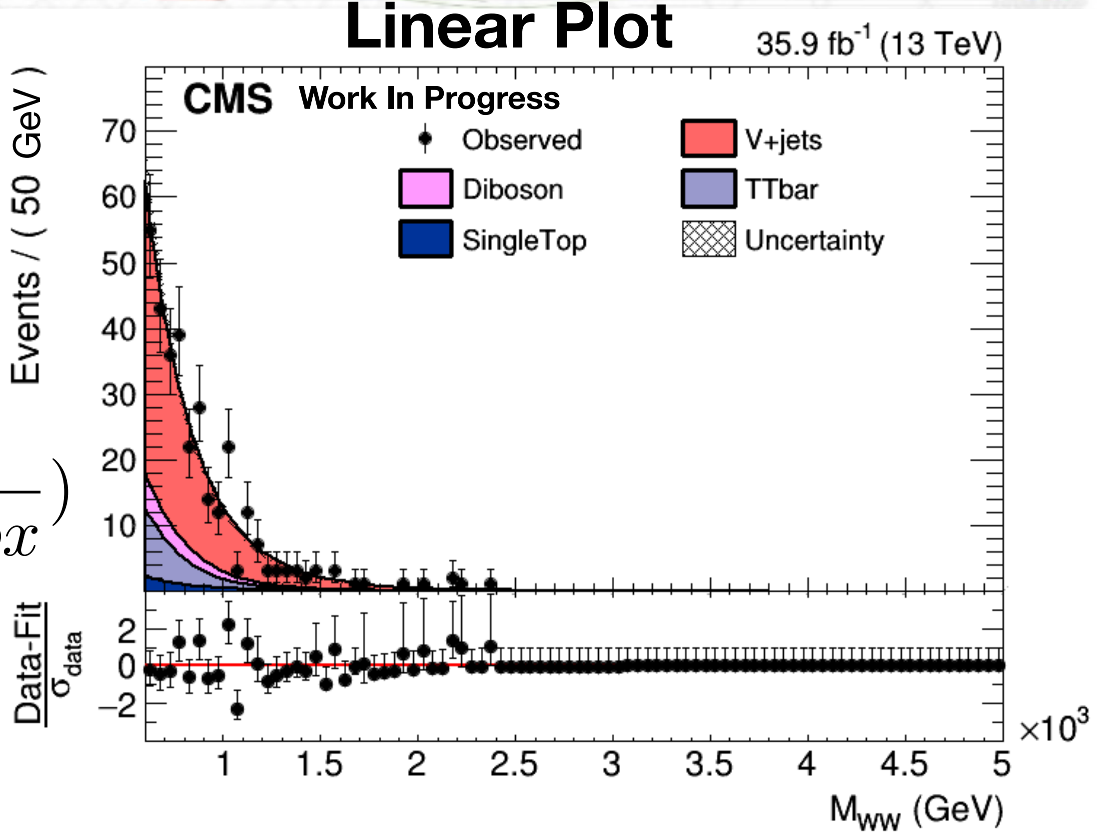
Log Plot

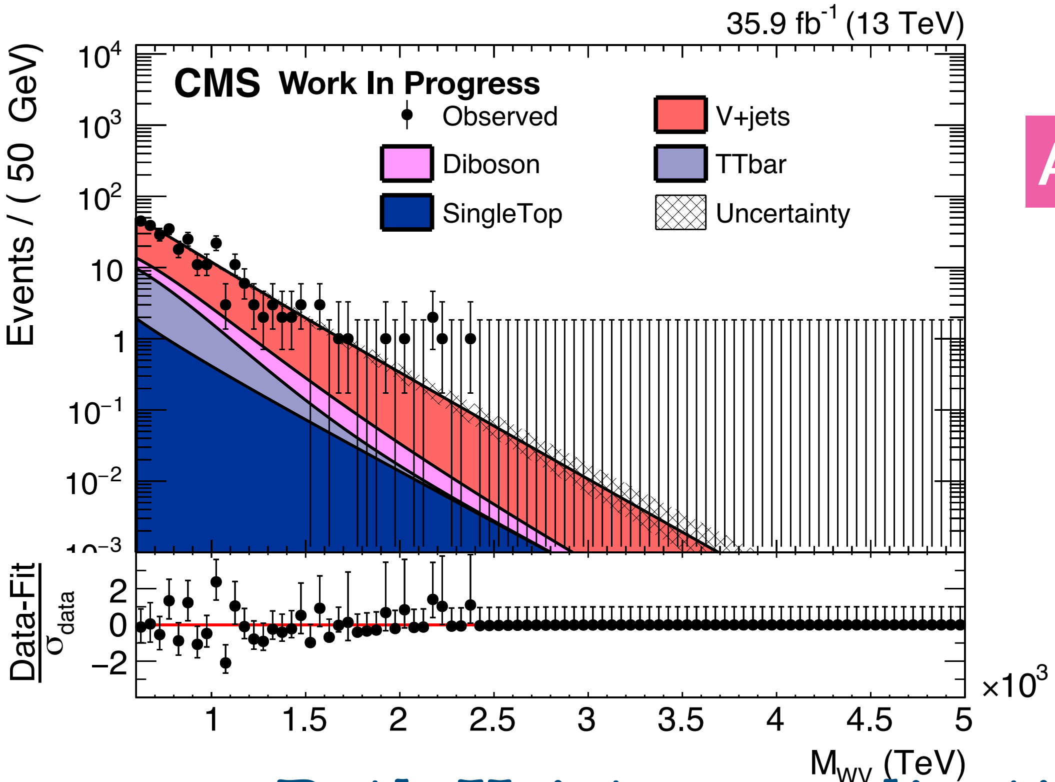
Linear Plot



Nominal Function

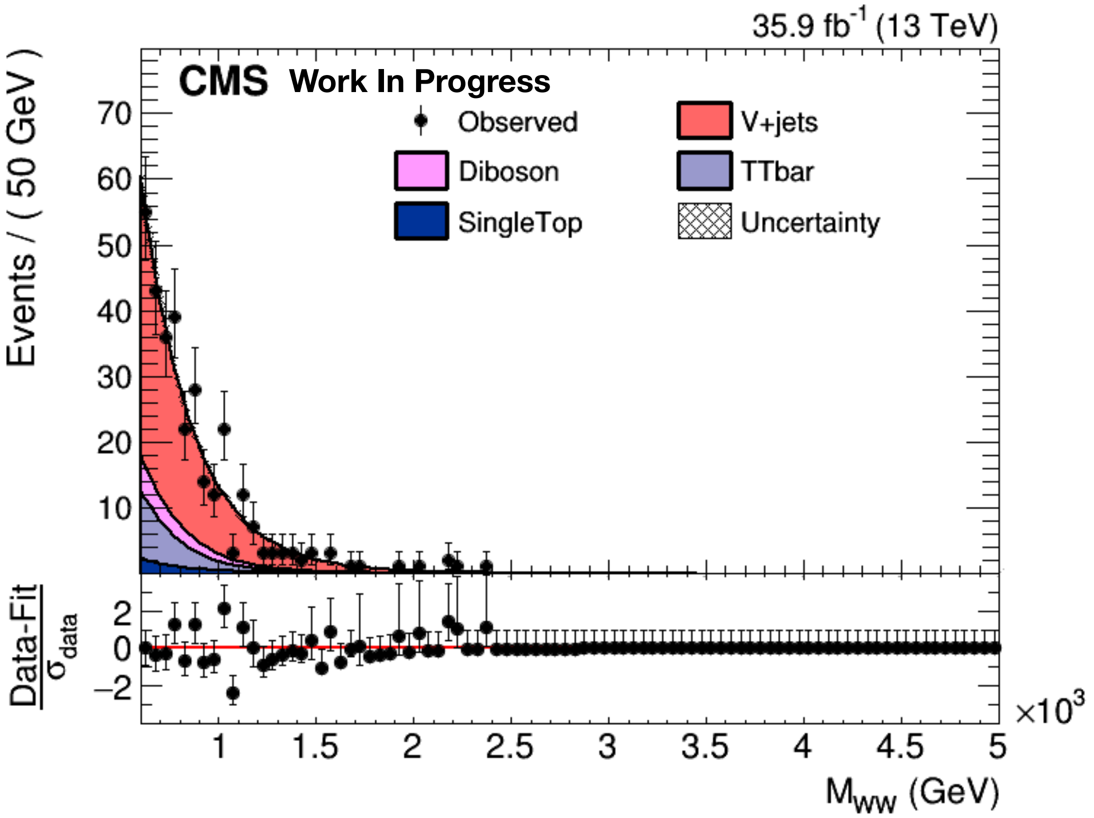
$$f(x) = Exp(\frac{-x}{a+bx})$$





Alternate Function

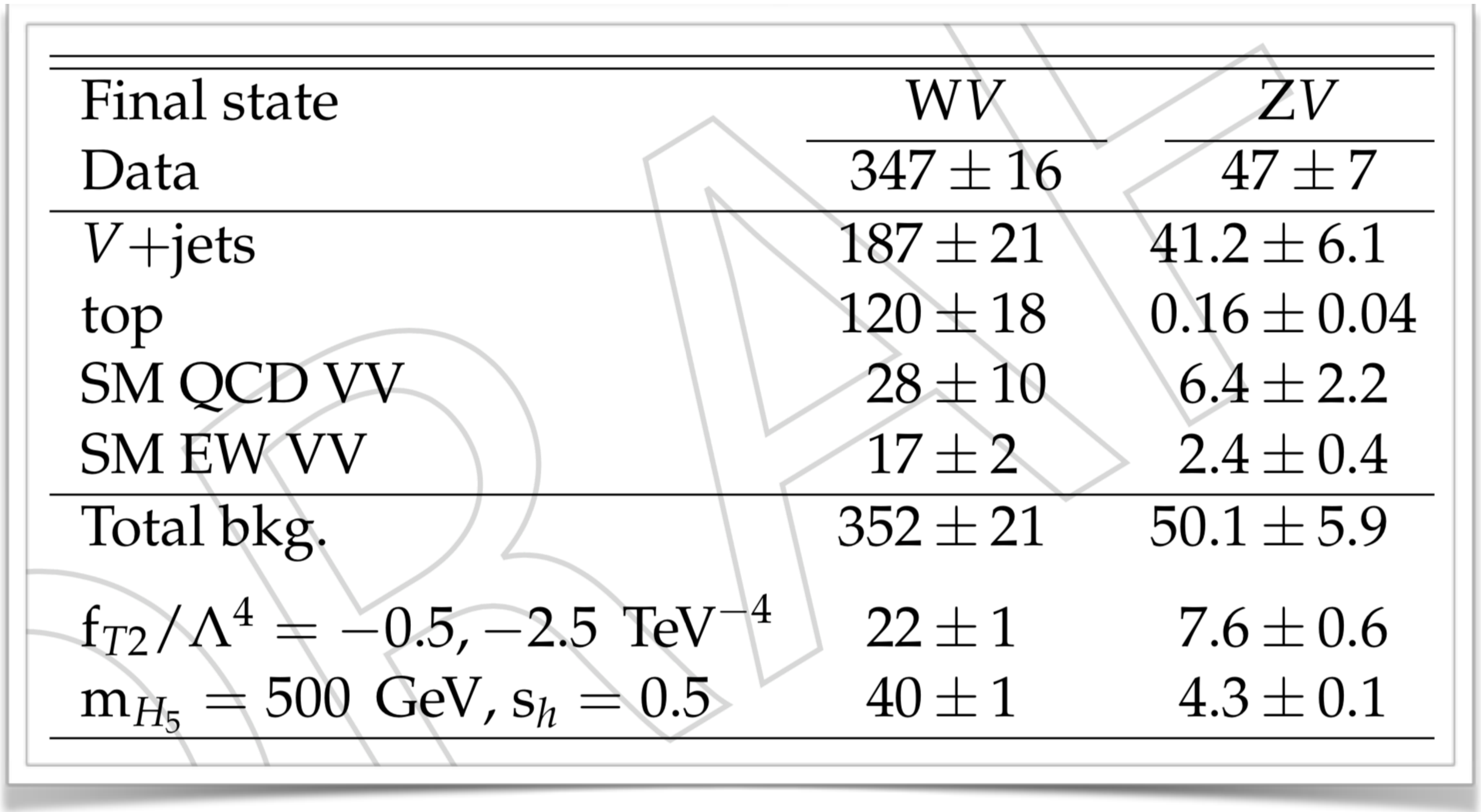
$$f_{Exp} = e^{nx}$$



- Both V+jet normalisation as well as shape is floating in this fit.

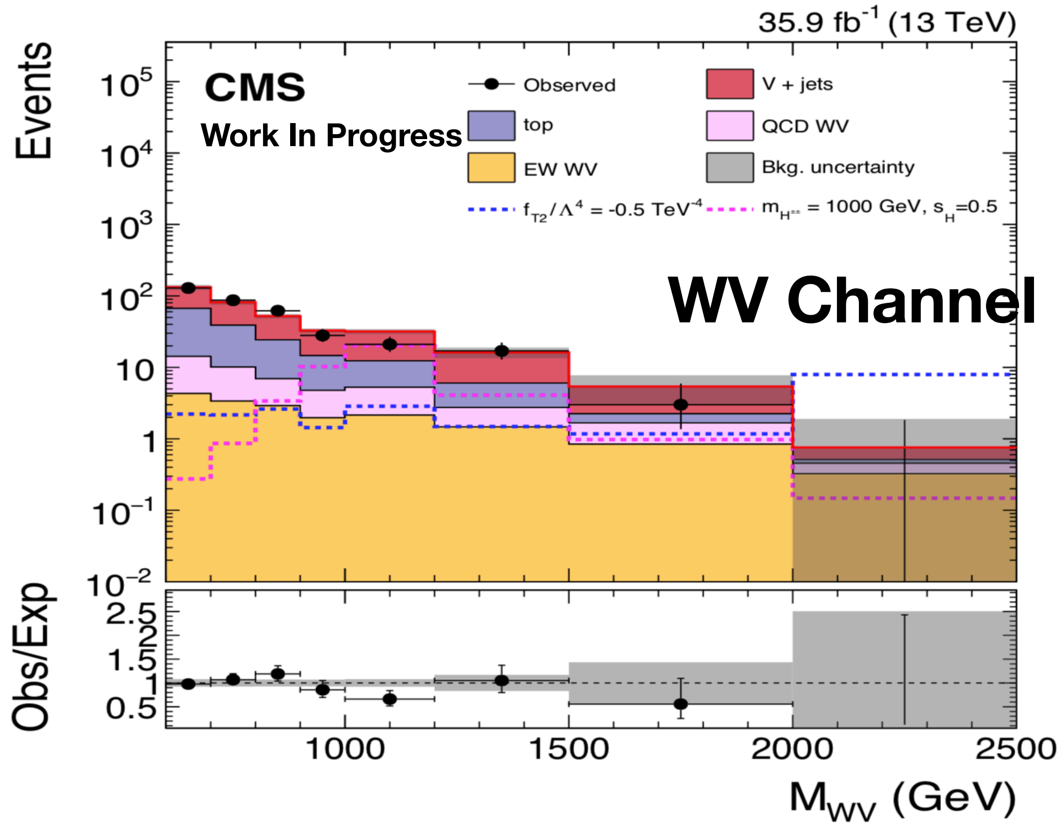
WV/ZV Signal Extraction

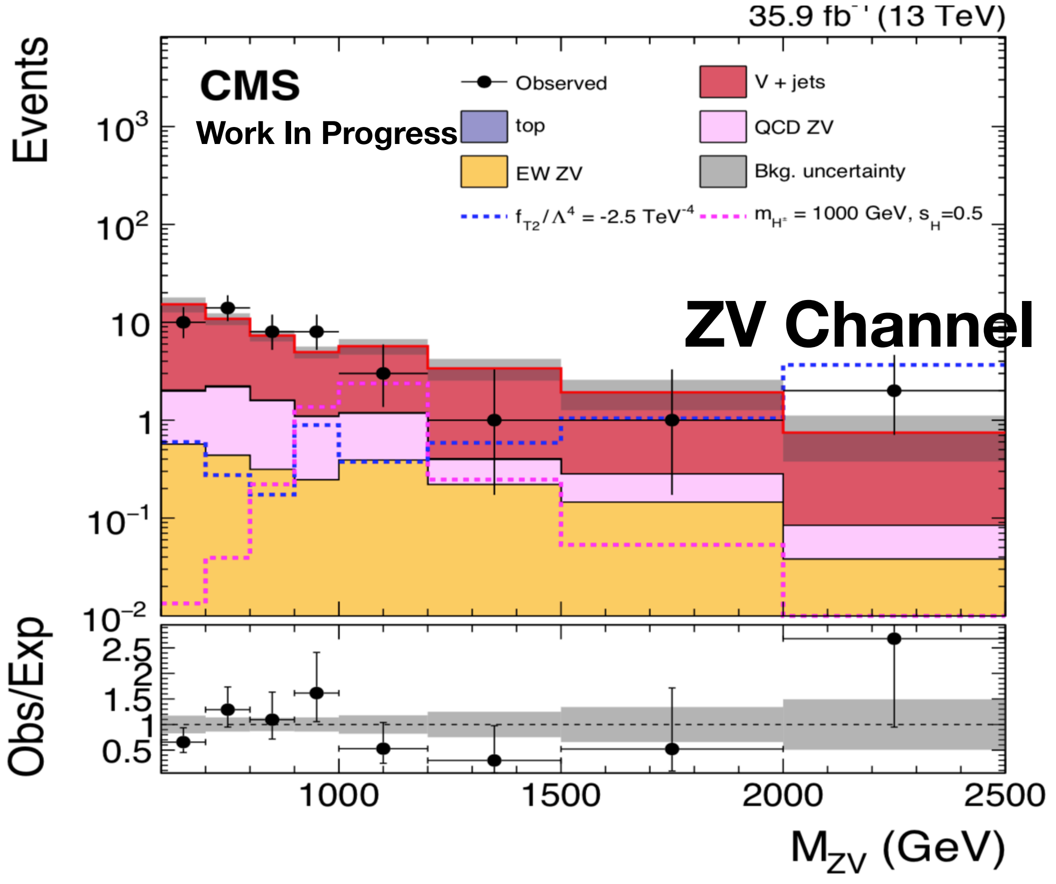
- We used M_{VV} distribution to get the limits for both WV and ZV channel.
    - SM EWK production is treated as background.



Final state	WV	ZV
Data	347 ± 16	47 ± 7
V+jets	187 ± 21	41.2 ± 6.1
top	120 ± 18	0.16 ± 0.04
SM QCD VV	28 ± 10	6.4 ± 2.2
SM EW VV	17 ± 2	2.4 ± 0.4
Total bkg.	352 ± 21	50.1 ± 5.9
$f_{T2}/\Lambda^4 = -0.5, -2.5\ \mathrm{TeV}^{-4}$	22 ± 1	7.6 ± 0.6
$m_{H_5} = 500\ \mathrm{GeV}, s_h = 0.5$	40 ± 1	4.3 ± 0.1

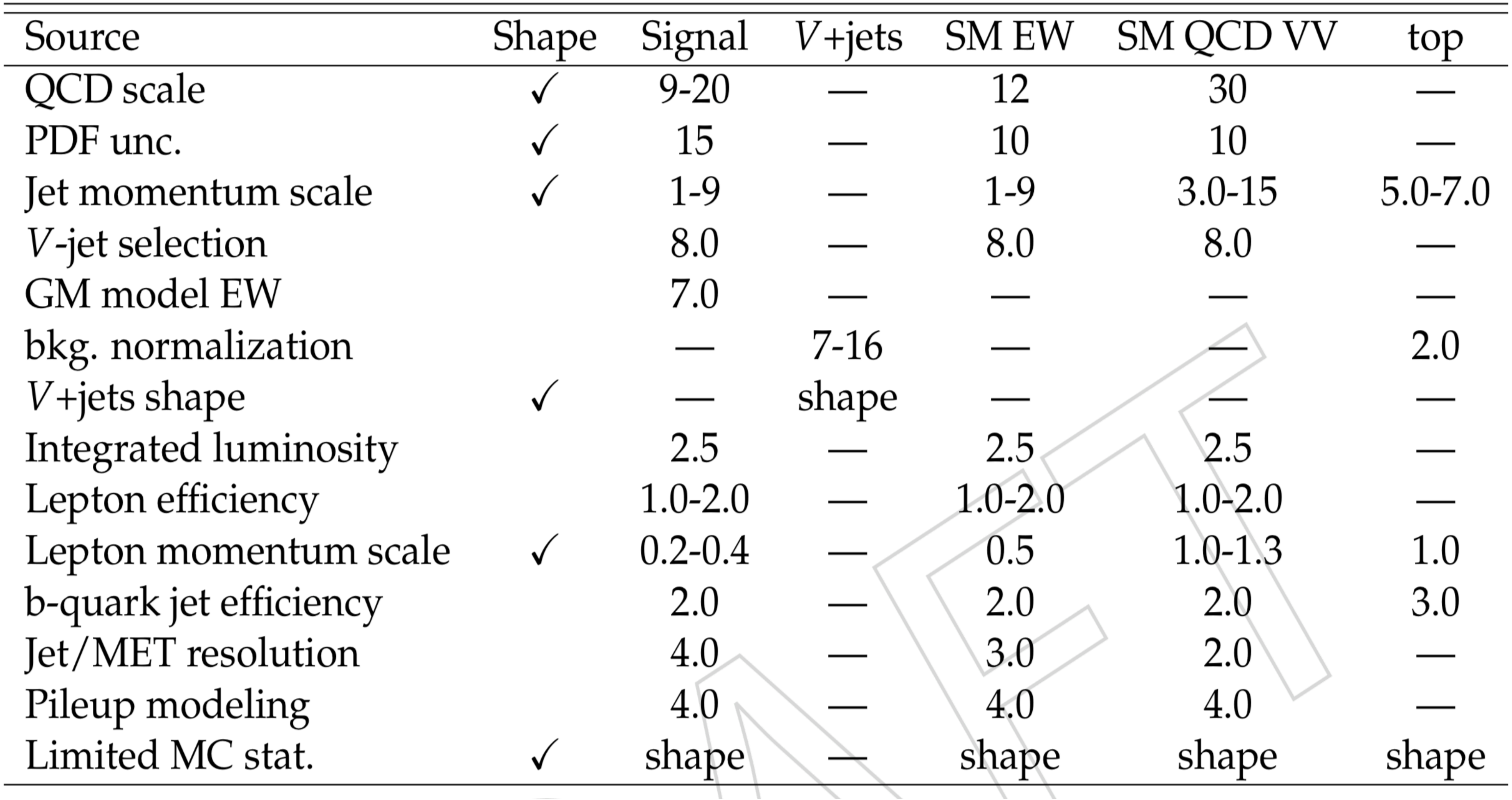
- Before doing this we estimated W+jets (for WV channel) and Z+jets (for ZV channel) in data driven way.





Systematic Uncertainty

- Major systematics are considered as shape based.
- Also, limited MC statistics uncertainty are considered bin-wise.



Source	Shape	Signal	V+jets	SM EW	SM QCD VV	top
QCD scale	✓	9-20	—	12	30	—
PDF unc.	✓	15	—	10	10	—
Jet momentum scale	✓	1-9	—	1-9	3.0-15	5.0-7.0
V-jet selection		8.0	—	8.0	8.0	—
GM model EW		7.0	—	—	—	—
bkg. normalization		—	7-16	—	—	2.0
V+jets shape	✓	—	shape	—	—	—
Integrated luminosity		2.5	—	2.5	2.5	—
Lepton efficiency		1.0-2.0	—	1.0-2.0	1.0-2.0	—
Lepton momentum scale	✓	0.2-0.4	—	0.5	1.0-1.3	1.0
b-quark jet efficiency		2.0	—	2.0	2.0	3.0
Jet/MET resolution		4.0	—	3.0	2.0	—
Pileup modeling		4.0	—	4.0	4.0	—
Limited MC stat.	✓	shape	—	shape	shape	shape

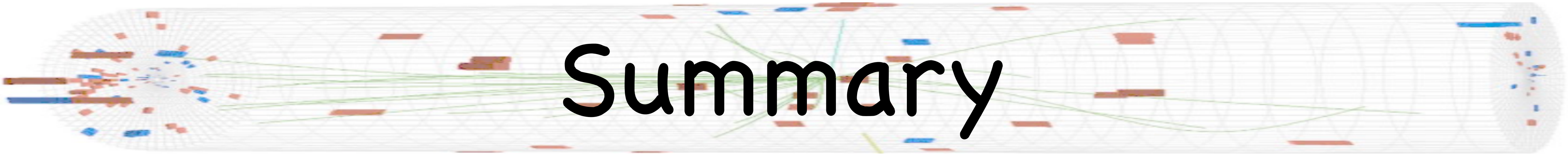
Results - Anomalous Coupling Limits

aQGC Parameters Previous published limits		Our Limits		
		WV Channel	ZV Channel	Combined Limit
FS0	[-7.7,7.7]			
FS1	[-22,22]			
FT0	[-0.46,0.44]			
FT1	[-0.28,0.31]			
FT2	[-0.89,1.0]			
FM0	[-4.2,4.2]			
FM1	[-8.7,9.1]			
FM6	[-12,12]			
FM7	[-13,13]			

Under Collaboration Review For Publication

Reference:

1. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results



Summary

- Analysed both WV and ZV channel for aQGC.

- Signal sample was generated using MadGraph at LO.

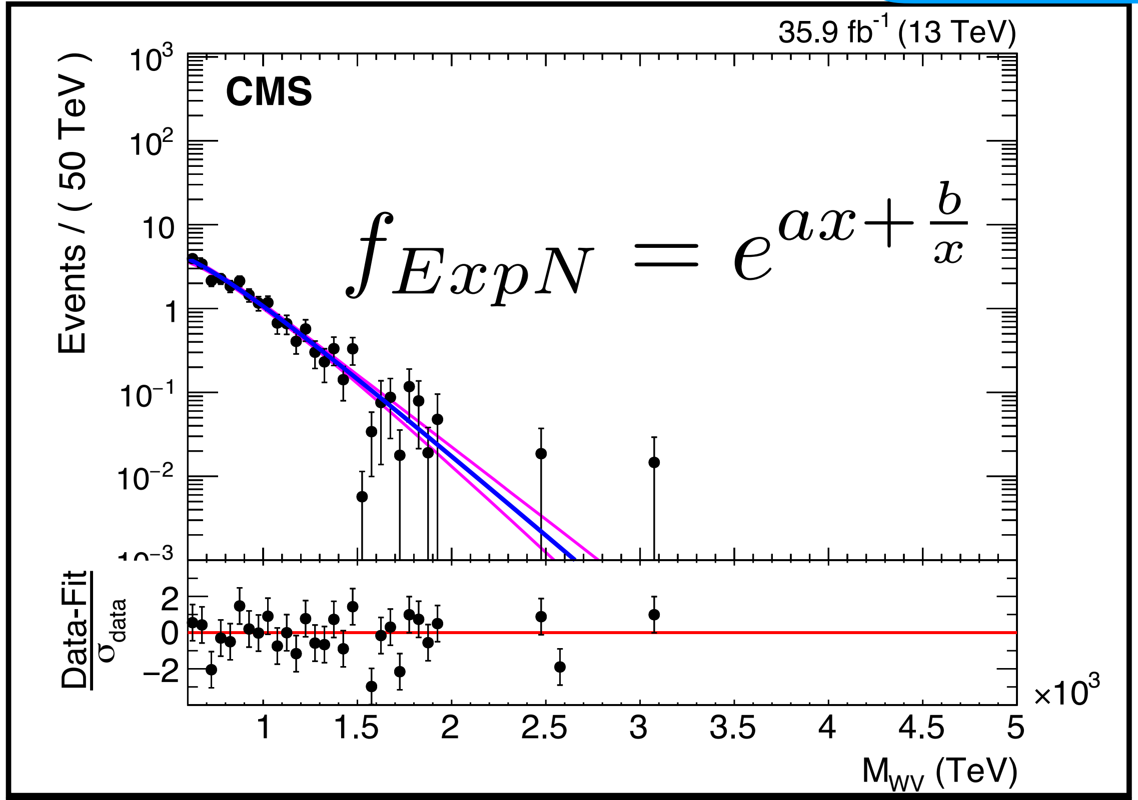
- Signal extraction was done using invariant mass of WV/ZV system ($M_{WV/ZV}$).

Thank You...

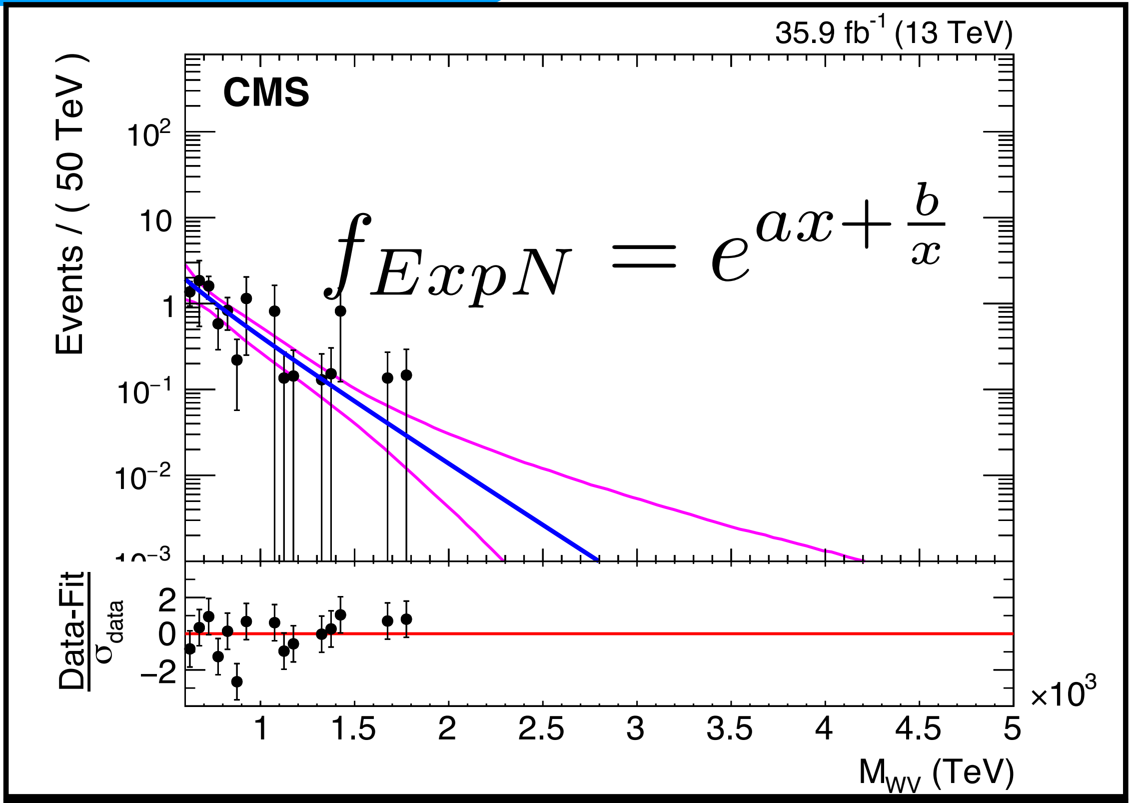
Parametric Function For Each Background

Side-band

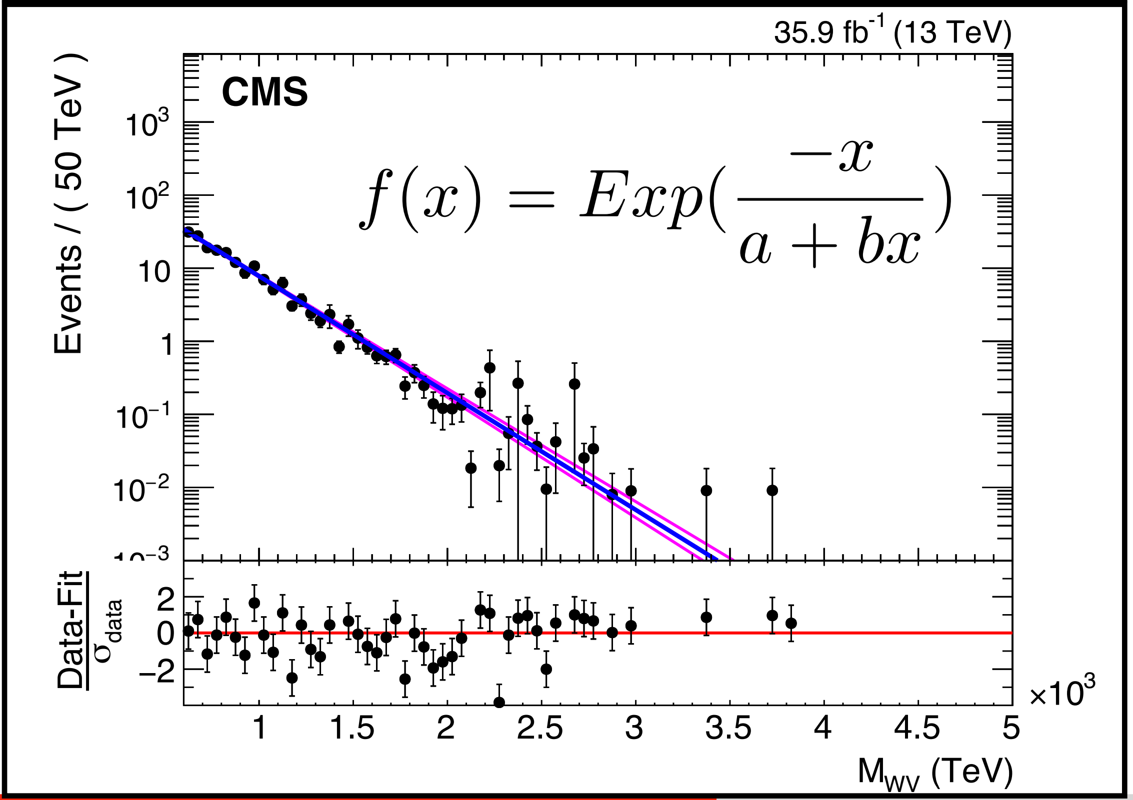
Diboson



Single Top



V+jet



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