Muon Collider
Snowmass

B.K.Abbott, A.Apyan, B.Azartash Namin, V.Balakrishnan, J.BerryHill, S.R.Jindariani, M.P.Kawale, J.D.Nichols, M.G.Strauss, J.Stupak, M.J Swiatlowski, H.Weber

Fermilab

The UNIVERSITY of OKLAHOMA

Motivation

- Muon beam consists of large vector boson component and hence with muon collider we could probe the vector boson scattering.
- The Dimension-8 operators corresponds to quartic coupling.
- We are focussing on the vertices allowed by the Standard Model and we are looking at T1 parameter now since it is sensitive to every coupling. [Table below]
- Using muon collider, with higher luminosity and energy, we are looking at how well we can probe these coupling.
- Currently we are focusing on 3, 6 and 10 TeV center of mass energies and later study up to 30 TeV.

S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

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

Allowed by SM

The Dimension-8 operators

Potential Final States

aQGCs

	WWWW	WWZZ	WWZγ	WWγγ	N_Z	N_centralLeptons	N_forwardMuons	N_γ	missing **p**
VBS	WWνν				0	2	0	0	
		WWμμ	WWμμ	WWμμ	0	2	2	0	
		WZμν	WZμν		1	3	1	0	
			Wγμν	Wγμν	0	1	1	1	
		ZZνν			2	4	0	0	✓
			Zγνν		1	2	0	1	
				γγνν	0	0	0	2	
s-channel		WWZ	WWZ		1	4	0	0	
			WWγ	WWγ	0	2	0	1	

each row unique

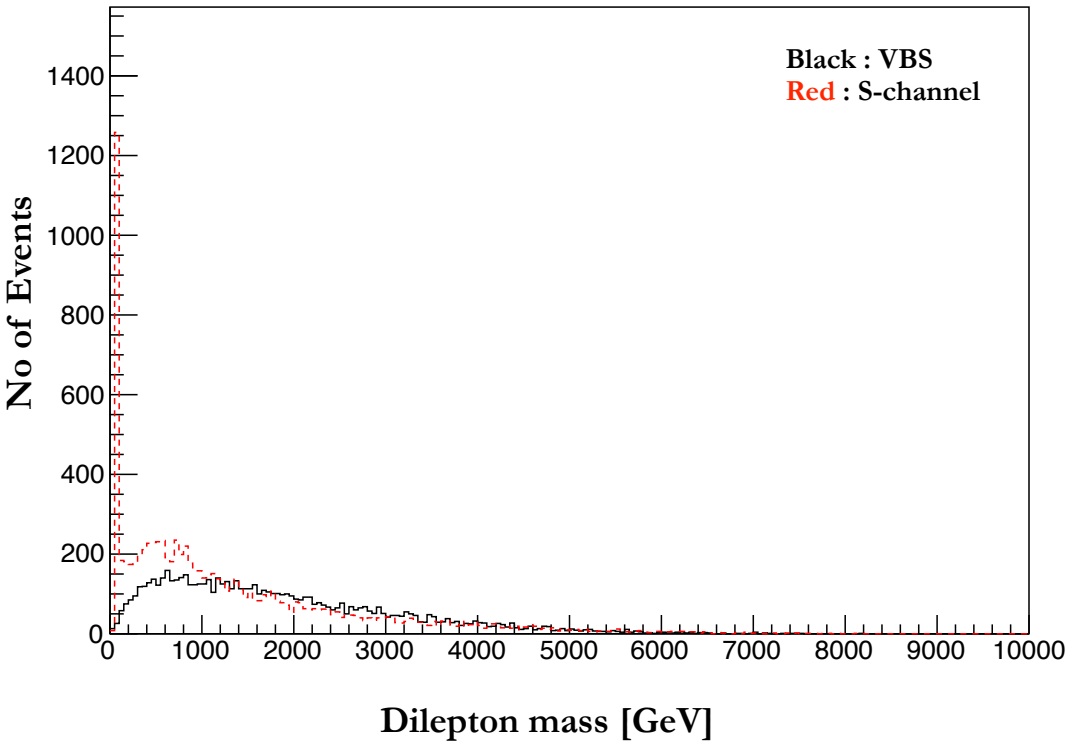
- **Example: probe WWZγ aQGC in WWμμ final state**
- **Contribution from both S-channel and VBS**
- **Not possible to distinguish these 100%**
- **But we could look at the number of forward muons in each case.**

Fermilab The UNIVERSITY of OKLAHOMA

- Example: probe WWZγ aQGC in WW+Z/μμ final states.
- Ideally, we would have:
  - A SM sample with all SM μμ→WW+Z/μμ processes.
- For interpretation:
  - A set of unphysical "signal" (BSM - SM ≈ signal) samples for μμ→WW+Z/μμ which only include interference+quadratic terms (with various Λ_{NP}).
- For optimization:
  - A set of BSM samples for μμ→WW+Z/μμ which include SM+interference+quadratic terms (with various Λ_{NP}).
- All of the above should have sufficient stats in s-channel and VBS, to permit studies in both topologies.
  - But cross sections have non-trivial $s^{1/2}$ dependence, mixed sample may not adequately populate both topologies.
    - For S-channel : σ decreases with $s^{1/2}$, E(vertex) = $s^{1/2}$
    - For VBS : σ increases with $s^{1/2}$, E(vertex) < $s^{1/2}$
- We have produced these samples using madgraph.

WWZγ Vertex

All OSSF lepton pairs, reconstructed from leptons with pT>5 GeV and |eta|<2

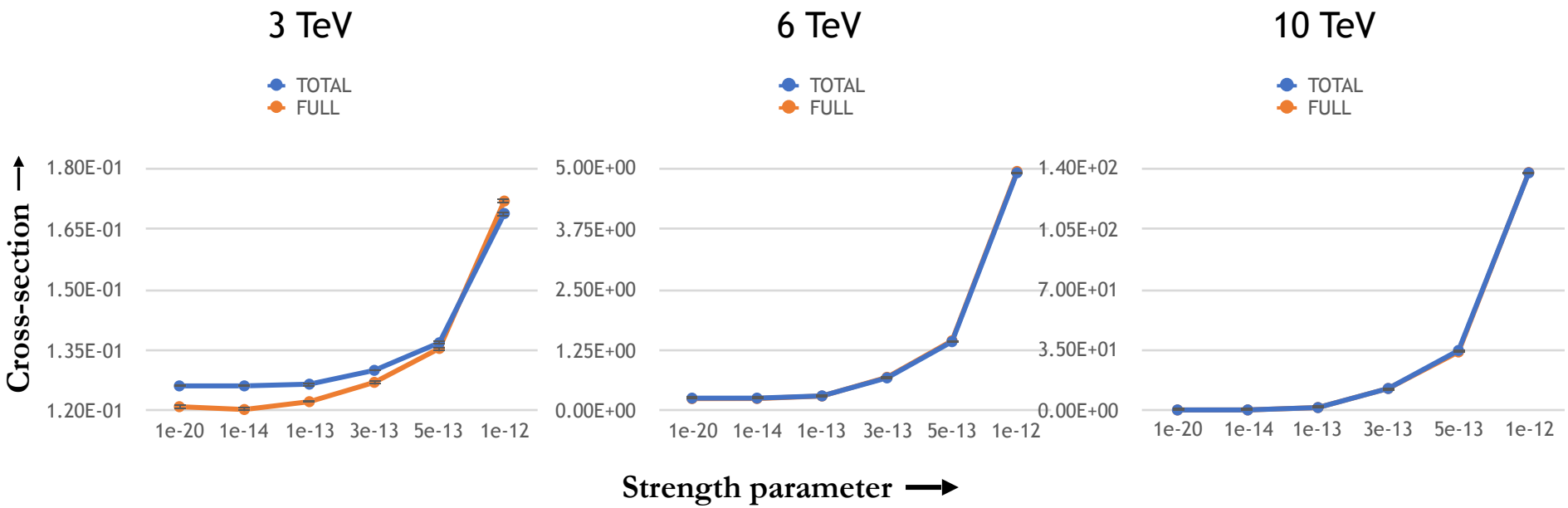


Fermilab

The UNIVERSITY of OKLAHOMA

WWWW Vertex : Cross-section results for T1 parameter

- Number of events = 5000
- Total = SM, INT & QUAD cross-section calculated separately and added.
- Full = Includes SM, INT & QUAD cross-section.

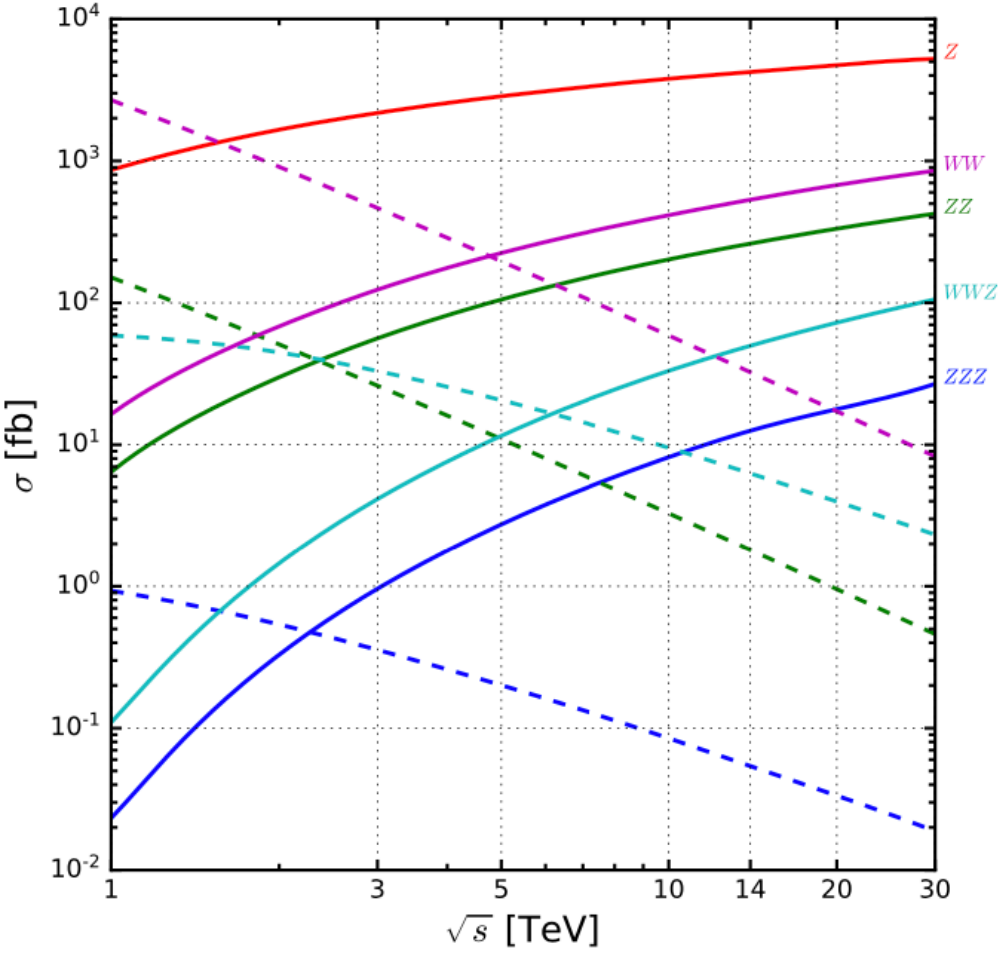


Fermilab The UNIVERSITY of OKLAHOMA

Future Plans

- **Finalize the center of mass of energy to generate the samples: 3, 6, 10 or 30 TeV?**
- **Leptonic vs hadronic decay modes.**
- **VBS vs S-channel**
- **How the muonic acceptance effect our ability to tag VBS events?**
- **Cross checking the results from WHIZARD**

Backup



Solid = VBF , Dashed = S-channel

Fermilab

The UNIVERSITY of OKLAHOMA

WWZγ Vertex

- **Z mass distribution for 10k events: s-channel (WWZ(->μμ)) and VBF (WWμμ) generated at 10 TeV**
- **Full signal -> (SM + Int + Quad).**
- **VBF:**
  generate mu+ mu- > mu+ mu- W+ W- QED=2 QCD=0 T0=0 M0=0 M1=0 M2=0 M3=0 M4=0 M5=0 M6=0 M7=0 T1=1 T2=0 T5=0 T6=0 T7=0 $ z a h
- **S-channel:**
  generate mu+ mu- > Z > mu+ mu- W+ W- QED=2 T0=0 M0=0 M1=0 M2=0 M3=0 M4=0 M5=0 M6=0 M7=0 T1=1 T2=0 T5=0 T6=0 T7=0
- **add process**
  generate mu+ mu- > a > mu+ mu- W+ W- QED=2 T0=0 M0=0 M1=0 M2=0 M3=0 M4=0 M5=0 M6=0 M7=0 T1=1 T2=0 T5=0 T6=0 T7=0 $ z
- **$ - gauge invariant**
  $ z a h forbids z, a, h in s-channel

WWWW Vertex

- **Generated samples for the WWWW vertex using the following commands for 3, 6 and 10 TeV using MadGraph.**
- **1) SM: Did not load the aQGC model.**

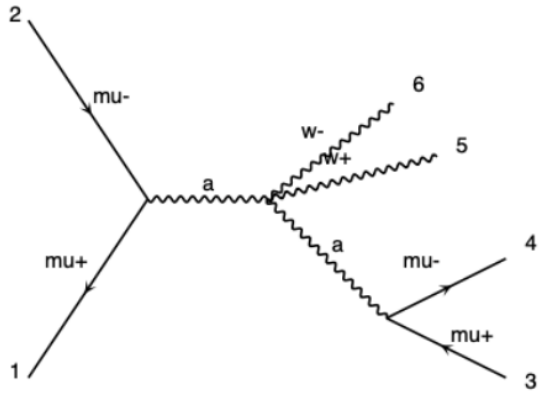
  generate mu+ mu- > w+ w- vm~ vm
- **2) INT+QUAD:**

  generate mu+ mu- > w+ w- vm~ vm QED=2 QCD=0 T1^2==1 S0=0 S1=0 M0=0 M1=0 M6=0 M7=0 T0=0 T2=0

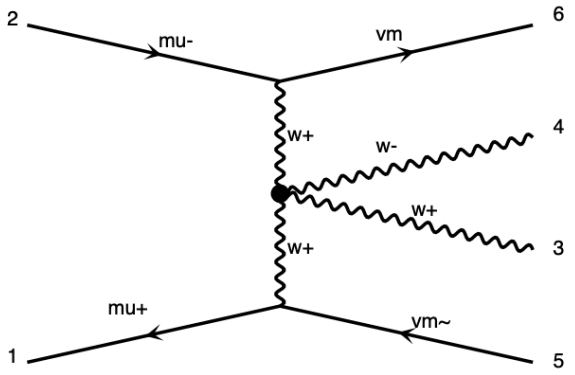
  add process mu+ mu- > w+ w- vm~ vm QED=2 QCD=0 T1^2==2 S0=0 S1=0 M0=0 M1=0 M6=0 M7=0 T0=0 T2=0
- **3) FULL :**

  generate mu+ mu- > w+ w- vm~ vm T1=1 S0=0 S1=0 M0=0 M1=0 M6=0 M7=0 T0=0 T2=0
- **The parameters used in the commands above are those corresponding to the WWWW vertex.**

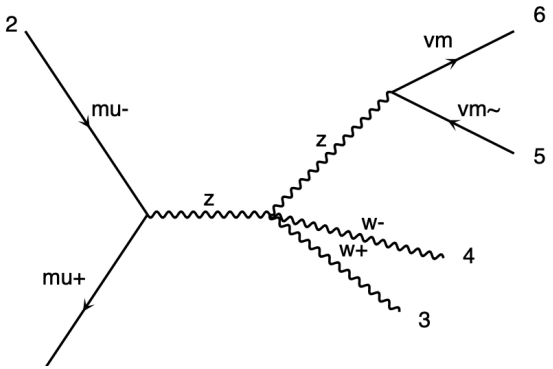
Feynman Diagrams



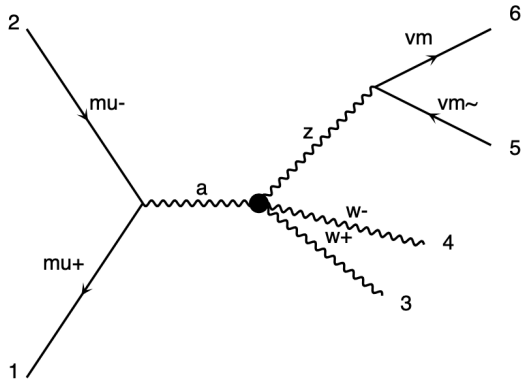
WWγγ



WWWW



WWZZ



WWZγ

Fermilab

The UNIVERSITY of OKLAHOMA