Experimental Challenges in Di/Tri Boson Production

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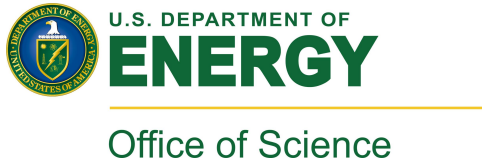
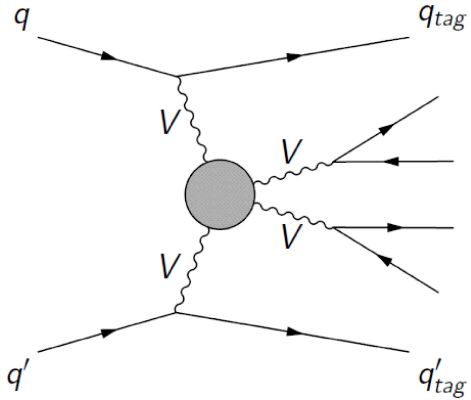
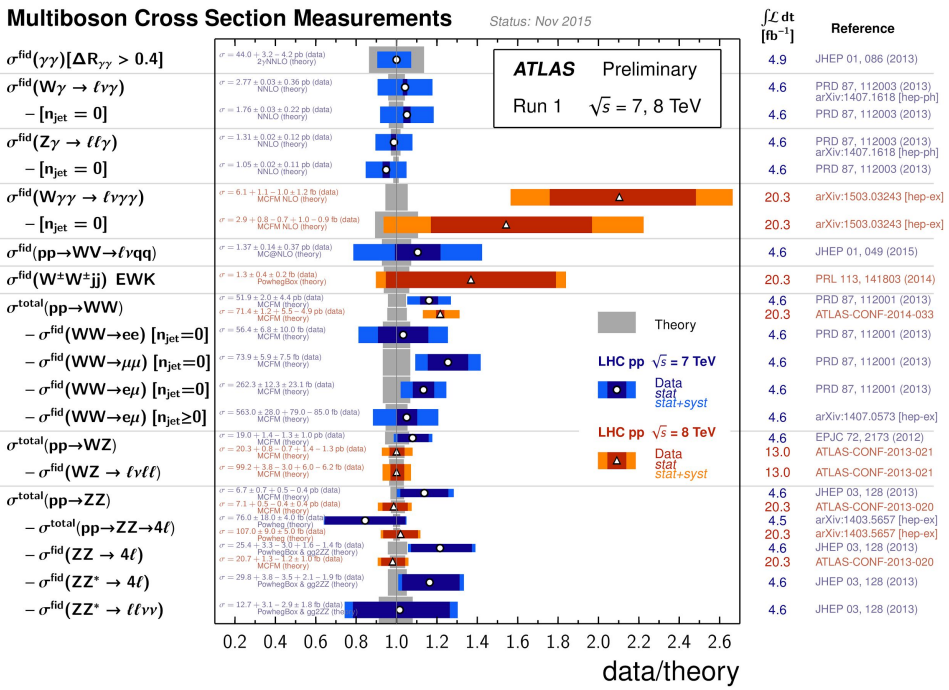




Experimental Challenges-Outline

- Lots of Challenges is Diboson and Tri-boson studies for run 2
  - Di-boson
    - Modeling
  - Vector Boson Scattering
    - Backgrounds
    - Longitudinal Fraction measurements
  - Tri-Bosons
    - Backgrounds
    - Luminosity

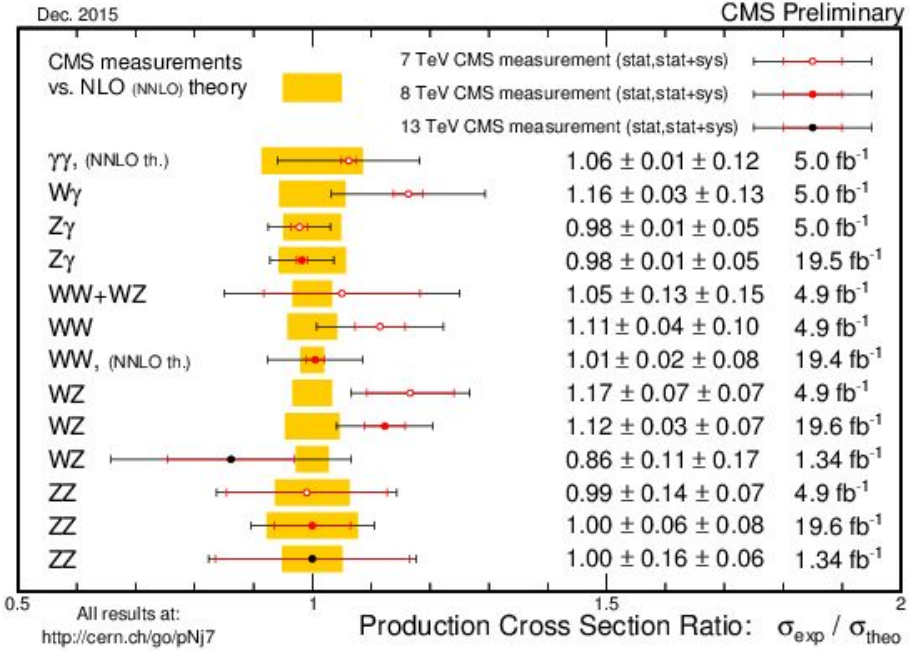
Dibosons Production at the LHC



	∫L dt [fb⁻¹]	Reference
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	4.9	JHEP 01, 086 (2013)
$\sigma^{fid}(W\gamma \to \ell\nu\gamma)$	4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$-[n_{jet} = 0]$	4.6	PRD 87, 112003 (2013)
$\sigma^{fid}(Z\gamma \to \ell\ell\gamma)$	4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$-[n_{jet} = 0]$	4.6	PRD 87, 112003 (2013)
$\sigma^{fid}(W\gamma\gamma \to \ell\nu\gamma\gamma)$	20.3	arXiv:1503.03243 [hep-ex]
$-[n_{jet} = 0]$	20.3	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(pp \to WV \to \ell\nu qq)$	4.6	JHEP 01, 049 (2015)
$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ EWK	20.3	PRL 113, 141803 (2014)
$\sigma^{total}(pp \to WW)$	4.6	PRD 87, 112001 (2013)
	20.3	ATLAS-CONF-2014-033
$-\sigma^{fid}(WW \to ee)$ $[n_{jet}=0]$	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \to \mu\mu)$ $[n_{jet}=0]$	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \to e\mu)$ $[n_{jet}=0]$	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \to e\mu)$ $[n_{jet}\geq 0]$	4.6	arXiv:1407.0573 [hep-ex]
$\sigma^{total}(pp \to WZ)$	4.6	EPJC 72, 2173 (2012)
	13.0	ATLAS-CONF-2013-021
$-\sigma^{fid}(WZ \to \ell\nu\ell\ell)$	13.0	ATLAS-CONF-2013-021
$\sigma^{total}(pp \to ZZ)$	4.6	JHEP 03, 128 (2013)
	20.3	ATLAS-CONF-2013-020
$-\sigma^{total}(pp \to ZZ \to 4\ell)$	4.5	arXiv:1403.5657 [hep-ex]
	20.3	arXiv:1403.5657 [hep-ex]
$-\sigma^{fid}(ZZ \to 4\ell)$	4.6	JHEP 03, 128 (2013)
	20.3	ATLAS-CONF-2013-020
$-\sigma^{fid}(ZZ^* \to 4\ell)$	4.6	JHEP 03, 128 (2013)
$-\sigma^{fid}(ZZ^* \to \ell\ell\nu\nu)$	4.6	JHEP 03, 128 (2013)

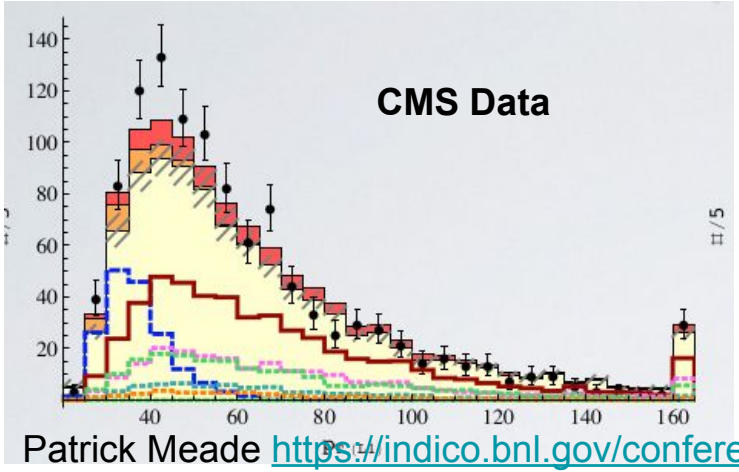
- Differentially is possible

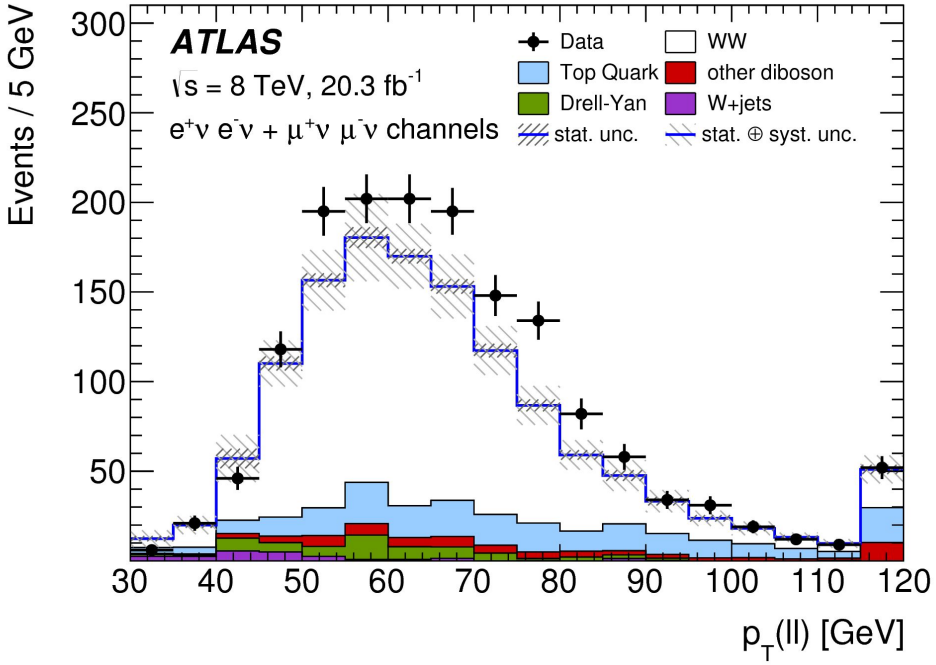
- Attempt to measure every combination of W,Z, gamma



Experimental Challenge Modeling

- Long Standing WW excess
- Seen by both CMS and ATLAS

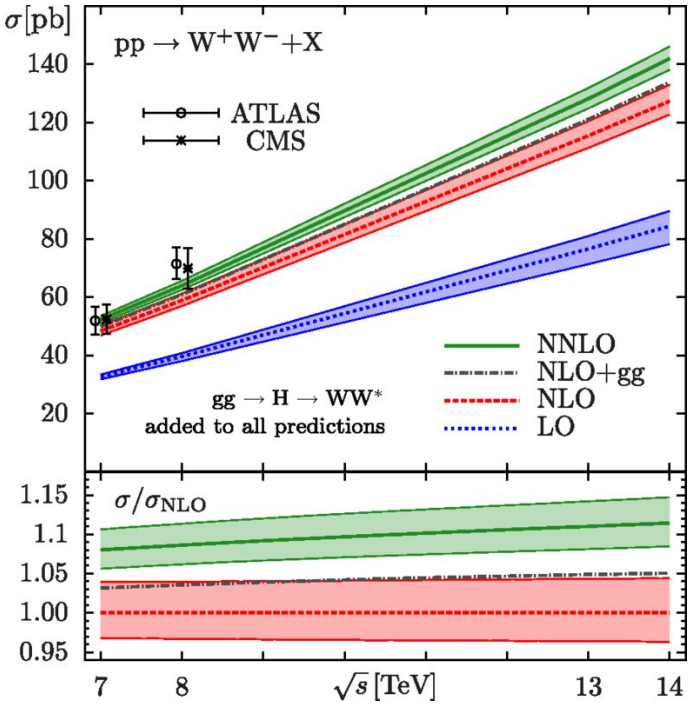




Patrick Meade https://indico.bnl.gov/conferenceDisplay.py?confId=778

WW

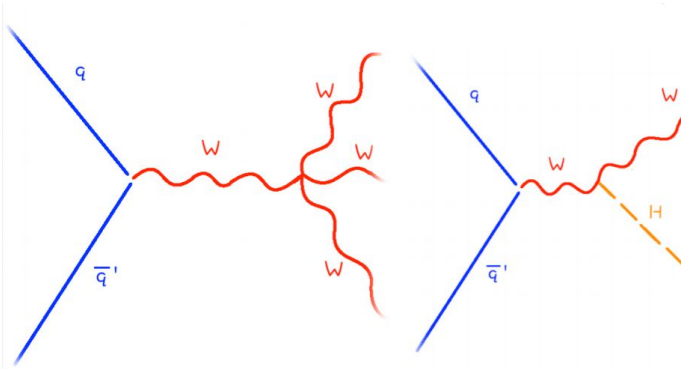
- It appears this excess is real
  - Can be explained with higher order QCD corrections
- Found a mild systematic excess
  - Could have been new physics
  - Seemed to just need better calculations
- Some Lessons
  - New physics might show up in the bulk of SM distributions
  - **In order to be confident we need excellent modeling**
- **NNLO not available for WZ**
- **LO EWK corrections becoming important**
- **My deepest thanks to the theorists working on this right now**

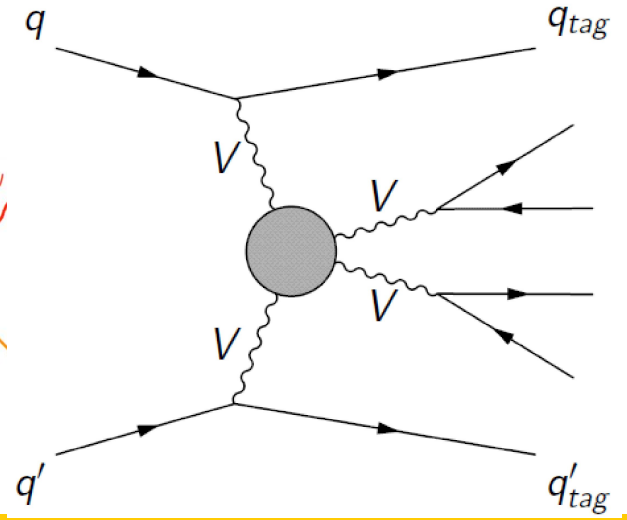


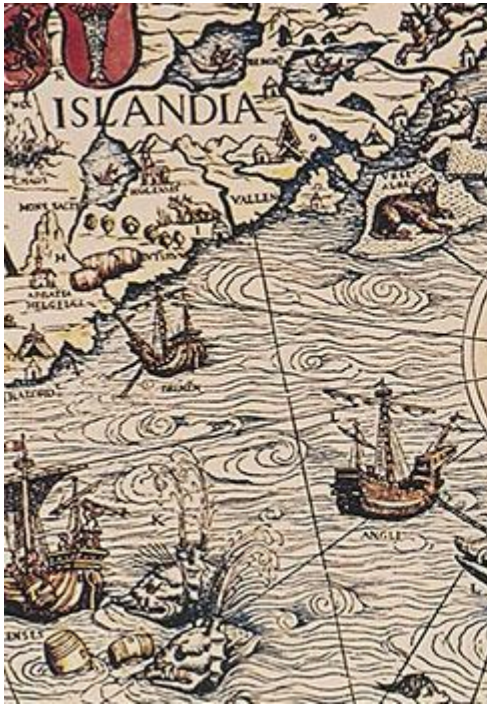
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.212001

Whys Quartic Interactions

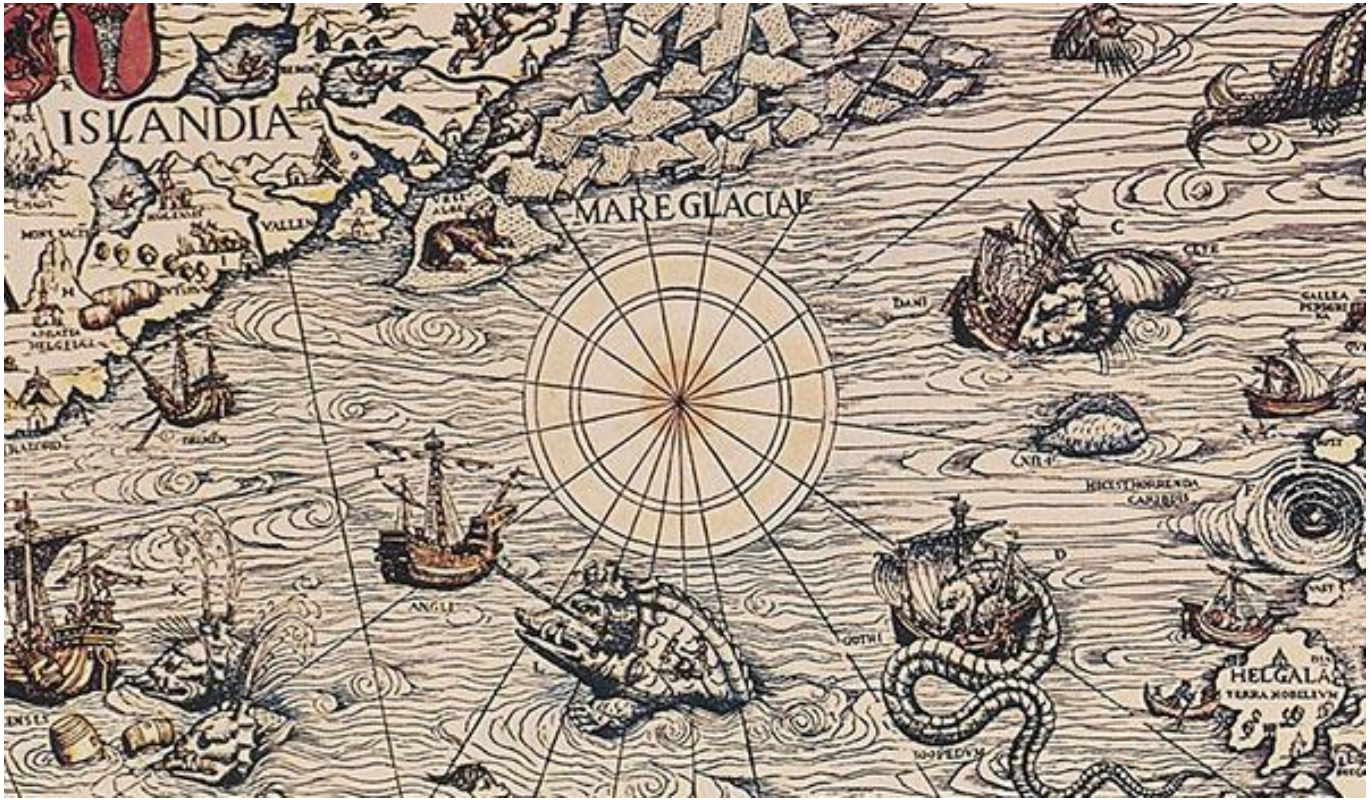
- We have never been able to do it before
- Longitudinal polarization of the W and Z directly related to electroweak symmetry breaking







Some new physics

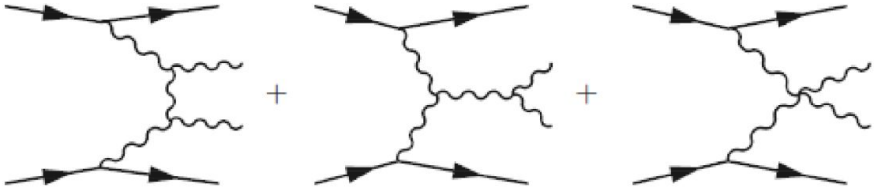


The Measurements

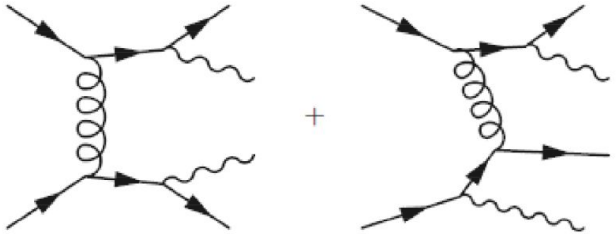
- Just at the start of exploring this interesting sector
  - VBS
    - W/Z+gamma
      - CMS-PAS-SMP-14-011
    - WZ
      - ATLAS-STDM-2014-02
    - Same Sign WW
      - SMP-13-015
      - ATLAS-STDM-2013-06
    - gamma,gamma->WW
      - FSQ-12-010
  - Tri-Boson
    - W/Zgammagamma
      - STDM-2013-05
      - SMP-15-008
    - WVgamma
      - SMP-13-009

VBS: 1st Experimental challenge finding EWK signal

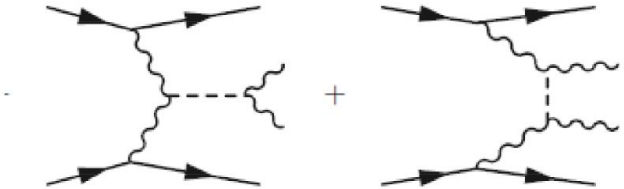
- Final State signatures with two “tag” jets come from two categories*

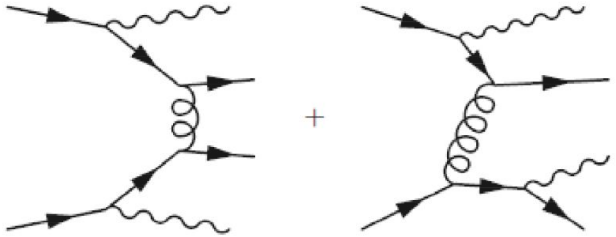


VVjj-EW



VVjj-QCD



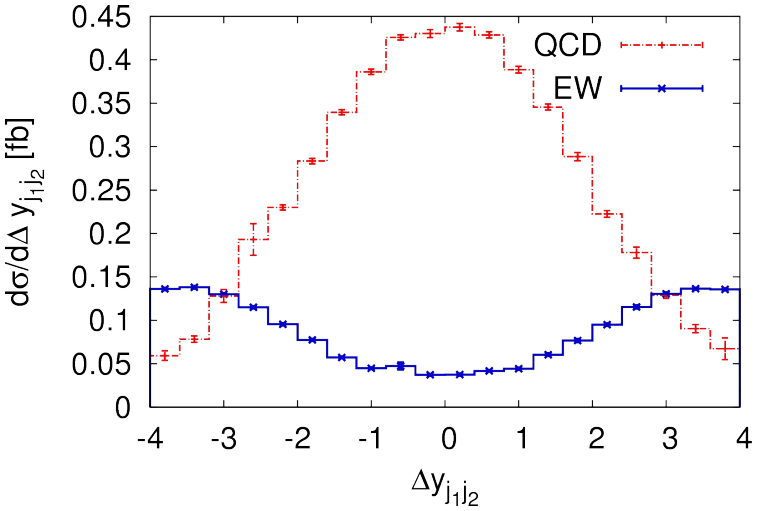


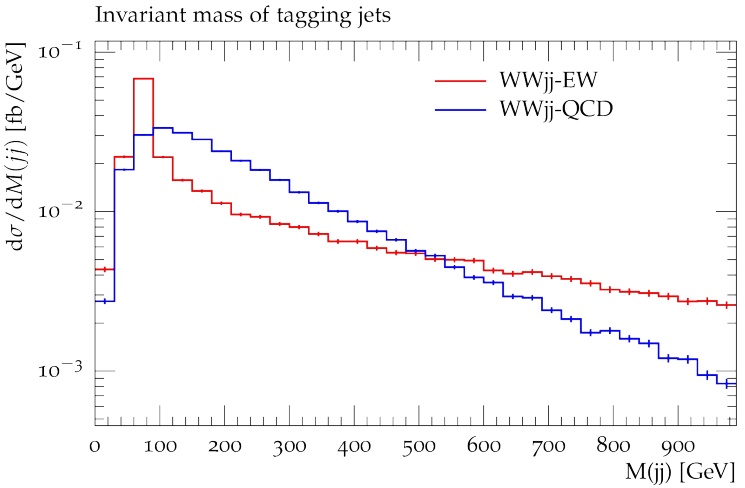
*at tree level

A few example diagrams

QCD VS. Electroweak

- Experimental Signatures
  - 2 Jets with large M(j,j)
  - 2 Jets with large rapidity separation



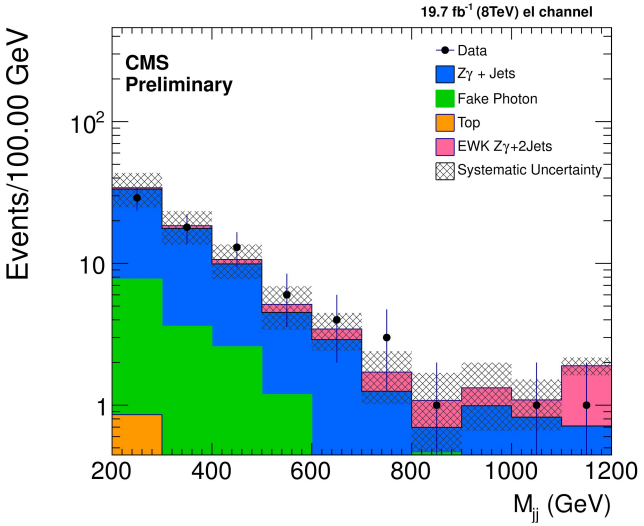


arXiv:1108.0864

Examples

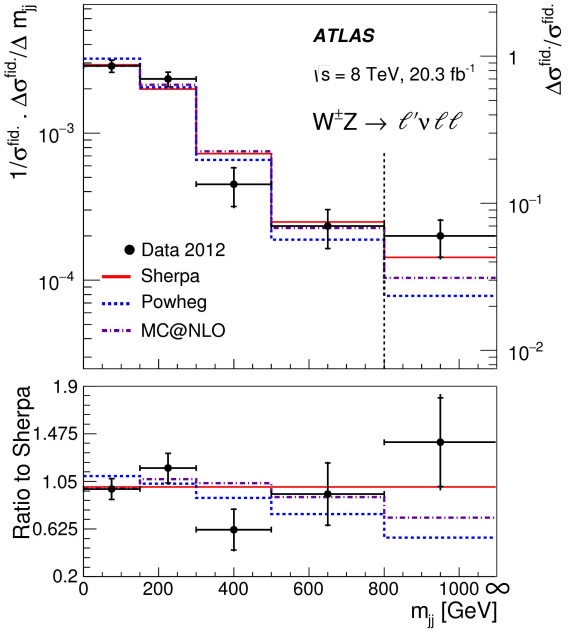
M(j,j) often (one of) the final plot for these studies

CMS-PAS-SMP-14-011



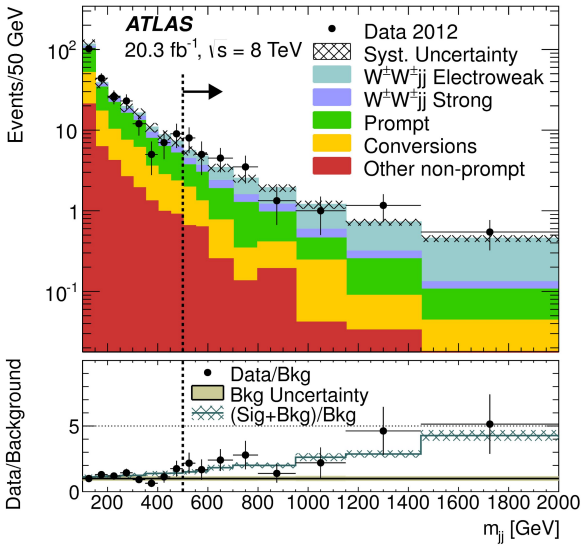
pp > Z+gamma+jj CMS

ATLAS-STDM-2014-02



pp > W+Z jj

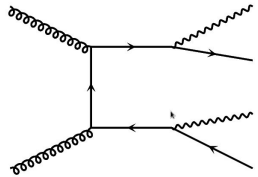
ATLAS-STDM-2013-06



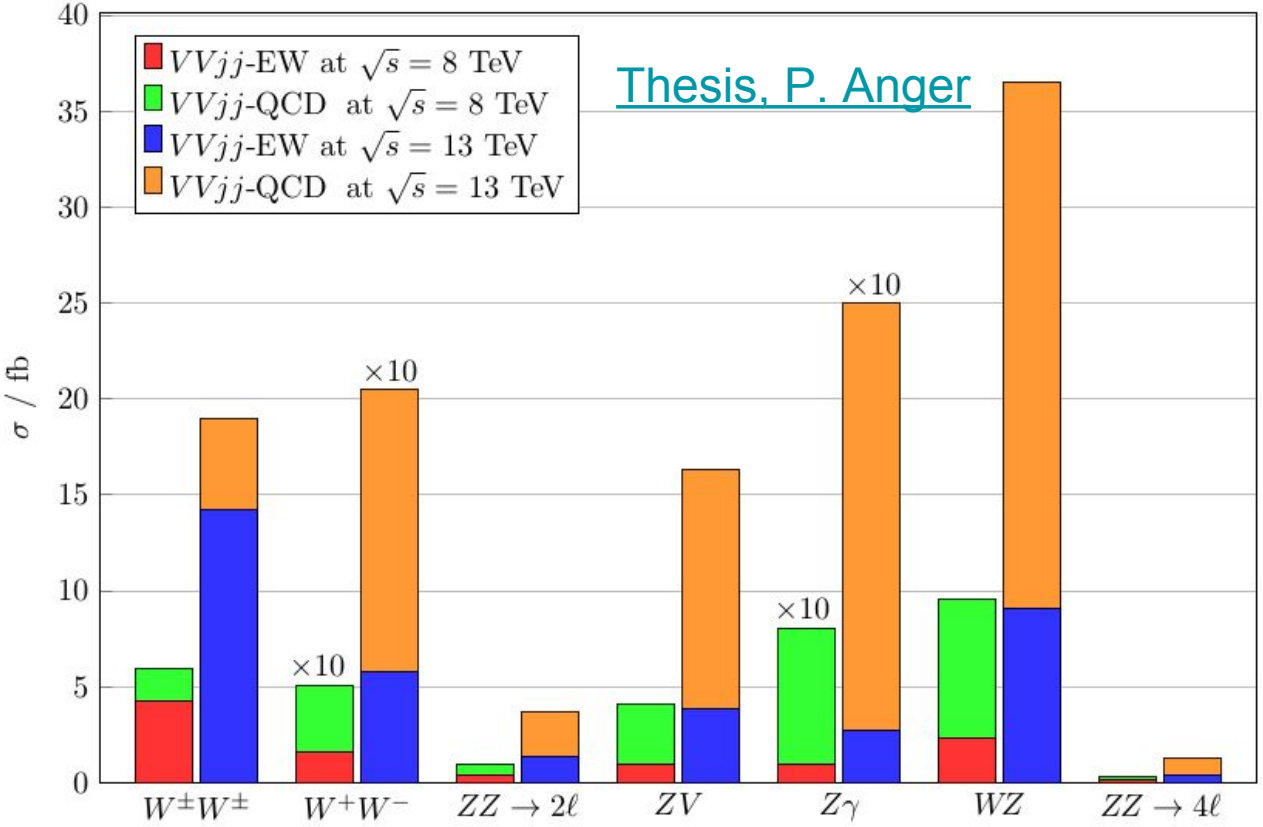
pp > W+W+ jj

Electroweak vs. Strong cross section by process

- EWK and Strong Production by channel
  - **After some analysis cuts to suppress QCD**
- Same Sign W+W+ has no gluon initial states



- Others are definitely an experimental challenge



More ways to reject Strong production

- Central jet vetos
  - The color connection between quarks in strong production gives you more radiation between the leading jets than EWK
- Quark Gluon Tagging
  - Can help mitigate some of strong production
- Lepton Centrality cuts
  - Correlated to dY(j,j) and M(j,j)
- Other ideas?
- All require good models of signal and background process
  - Good modeling of the background with 2-jets missing
    - Some NLO like WZjj available in VBFNLO, but without a shower interface tilize
  - Or complicated experimental correction schemes

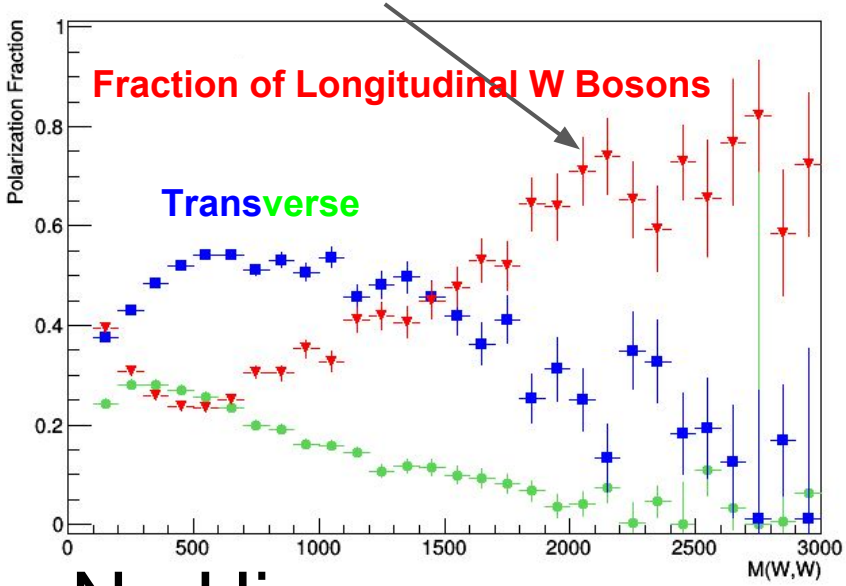
Experimental Challenge 2: Measuring Polarization

- **Aim: Measure Longitudinal scattering**
  - **How can we do it?**
- **Same Sign W^+W^+**
  - Signal is clean, small strong contribution
  - Reasonable Cross Section
  - Two neutrinos
- **WZ,ZZ,W^+W^-**
  - **All have significant strong background**
  - **WZ,ZZ can fully reconstruct event with leptonic decays**
    - **Semi-leptonic decays can be used in all channels**

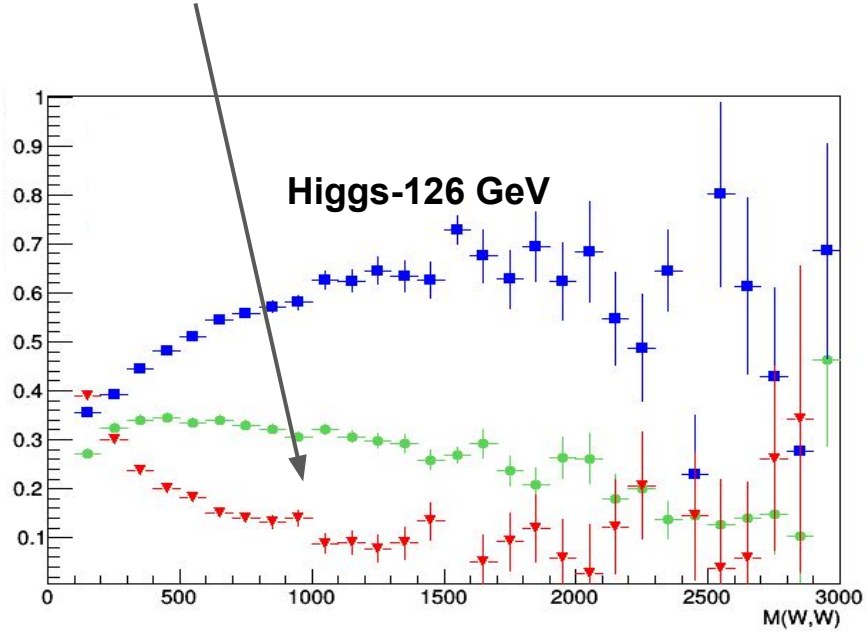
Longitudinal Scattering

Extra useful info: Link

Longitudinal bosons grow with M(WW) if there is no Higgs. Falls in normal SM.



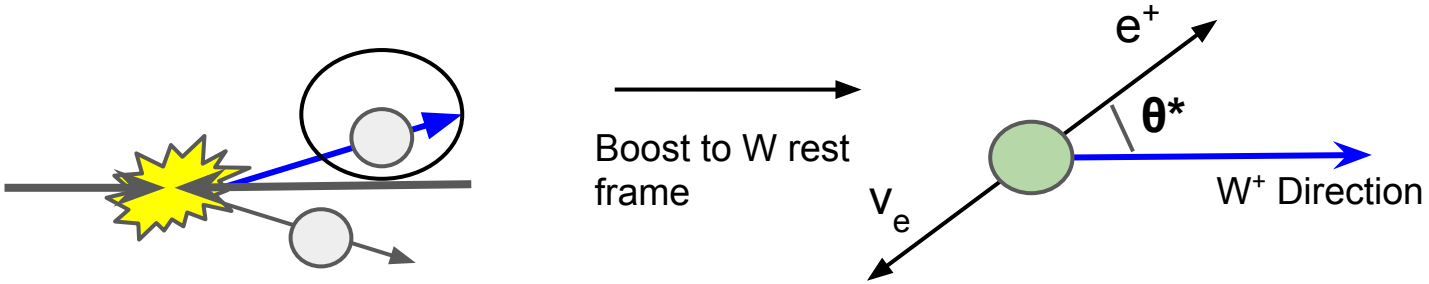
No Higgs



With Higgs

Measuring VLVL

- We've seen the first signs of VBS in W^+W^+
  - Next step is to see $V_L V_L$
    - Then can we measure $V_L V_L$ at high M(W,W)?
- Effect of polarization is on the θ* distribution

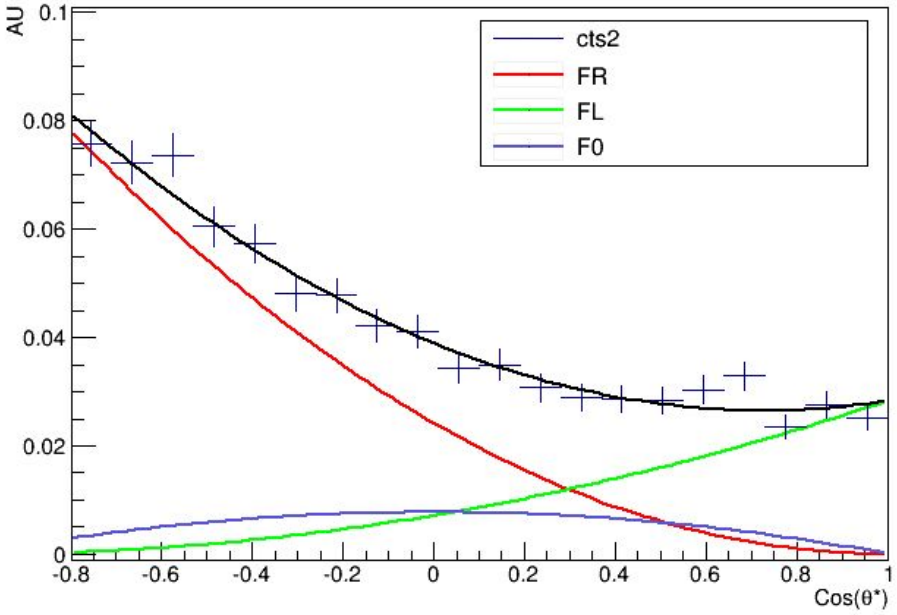


Cos(θ*) distributions - 1D

http://arxiv.org/pdf/1203.2165v2.pdf

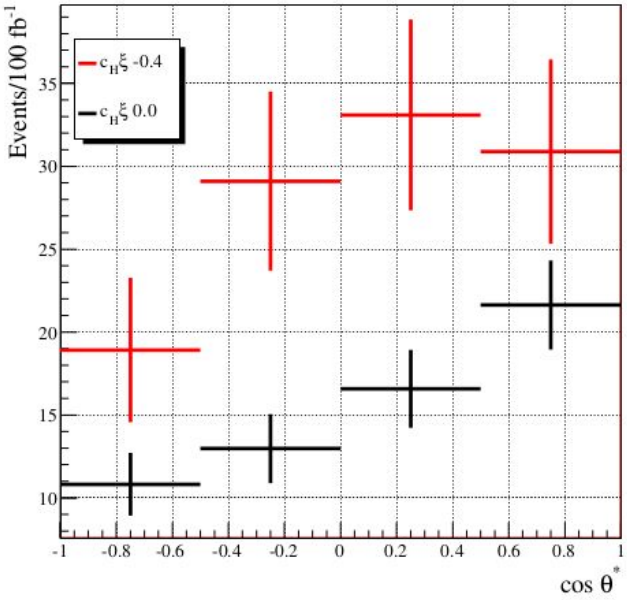
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{3D}} = \frac{3}{8}f_L(1\mp\cos\theta_{3D})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{3D})^2 + \frac{3}{4}f_0\sin^2\theta_{3D}$$

- Fits give polarization fractions
- **Can't be done directly in di-leptonic events**
  - Do we have any sensitivity with measurable quantities?
- **Possible in semi-leptonic events**



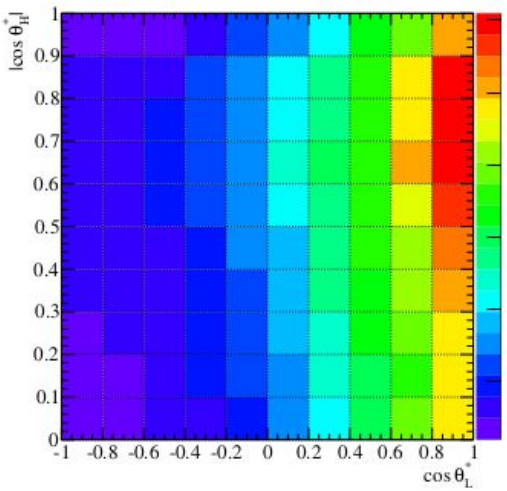
Semi-leptonic Example

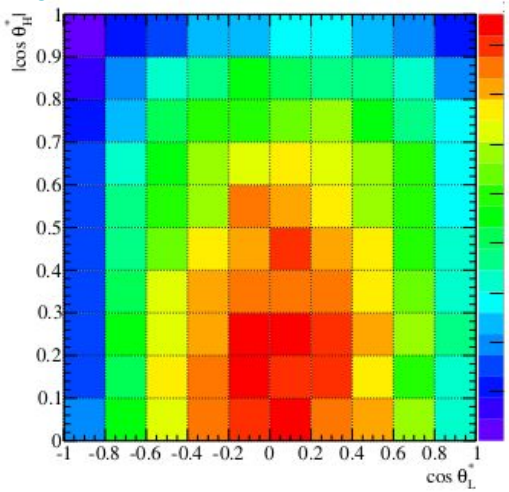
- Cos(theta*) can be directly reconstructed in semi-leptonic VV events
  - Gives the possibility of measuring LL fraction and sensitivity to new physics
  - Still have to pull the signal out in the first place (see experimental challenge 1)



http://arxiv.org/abs/0911.3656

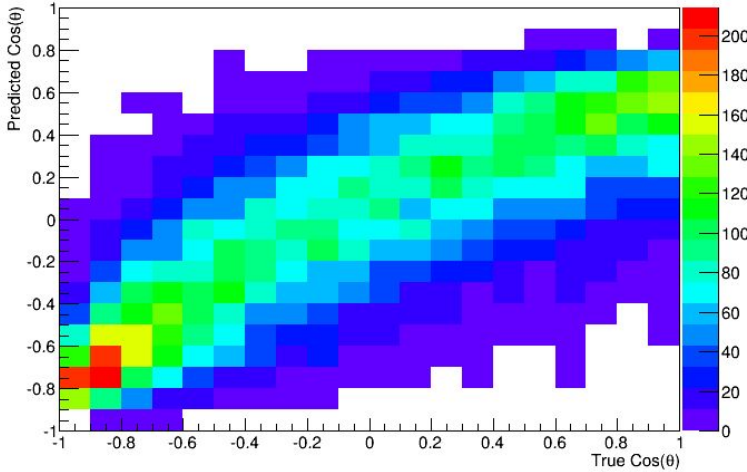
Tao Han, David Krohn, Lian-Tao Wang, Wenhan Zhu

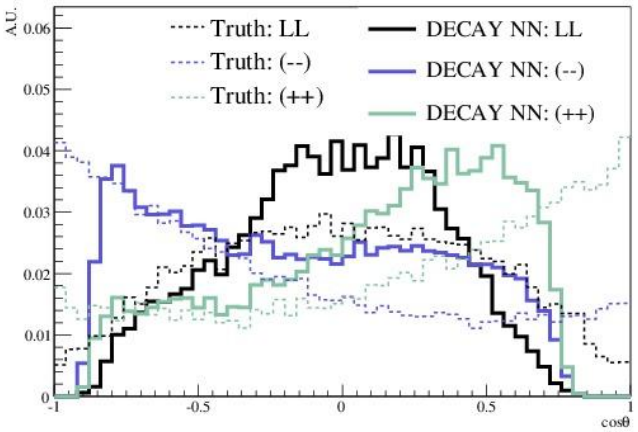




Approximate Cos(theta*) in ssWW

- Deep learning with regression has been used to approximate Cos(theta*) of the two bosons in a di-lepton decay
  - Cleaner signal
  - Worse resolution on cos(theta*)
  - Far from perfect, but certainly usable

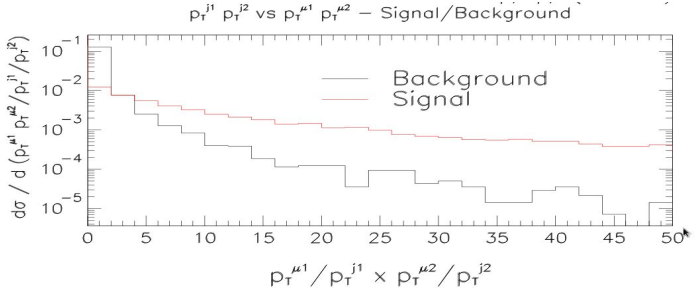




arXiv:1510.01691

J Searcy, L Huang, M-A Pleier, J Zhu

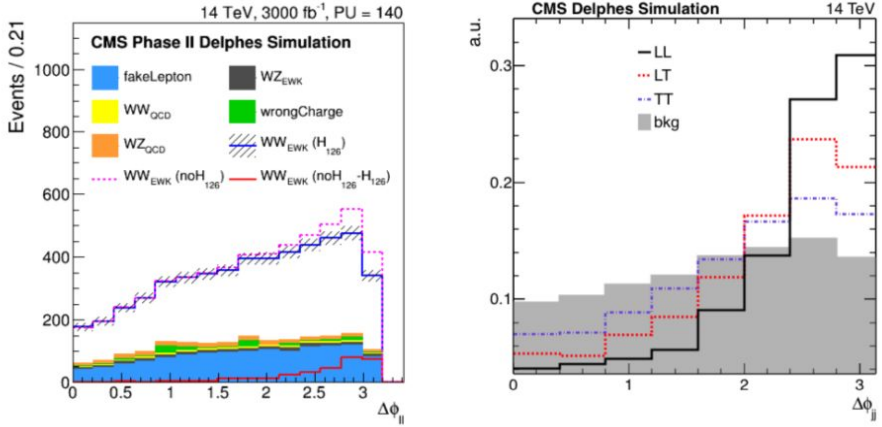
Non-Cos(theta*) techniques in ssWW

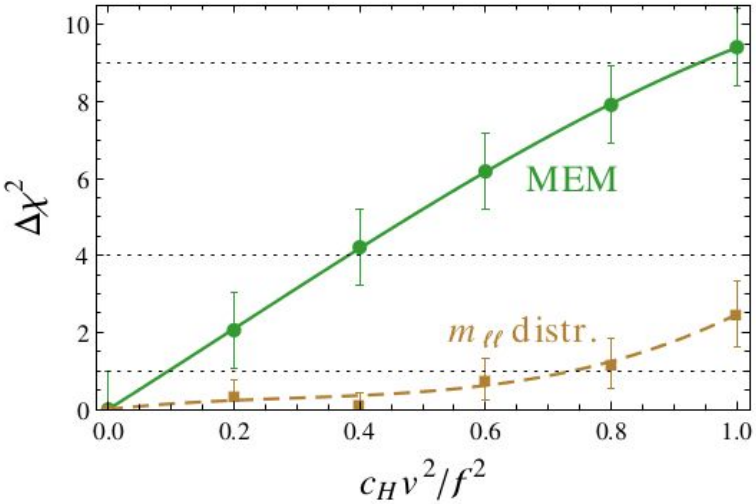


K. Doroba, J. Kalinowski, J. Kuczmarski, S. Pokorski, J. Rosiek, M. Szleper, S. Tkaczyk

- Lots of other methods tried in ssWW
  - All have advantages and disadvantages
- No “golden” proposal yet on the best way to extract the longitudinal fraction

Matrix element analysis



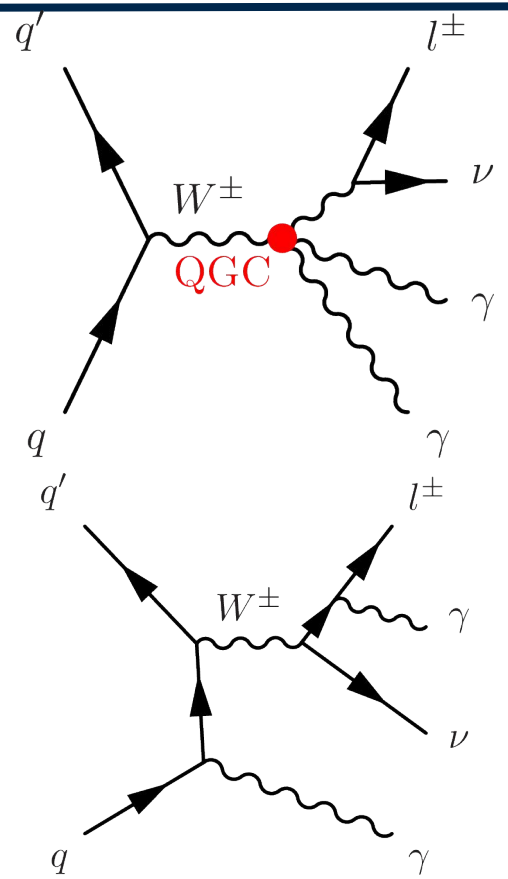


CMS Phase 2 Proposal

http://arxiv.org/abs/1212.3598

Tri-boson production

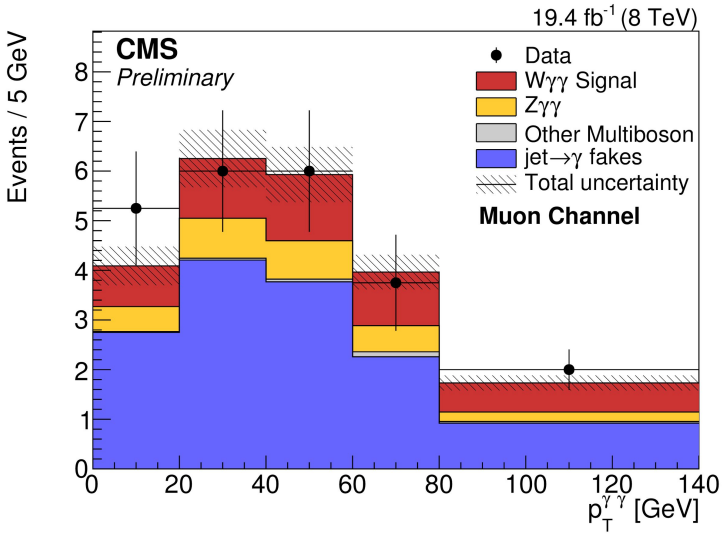
- Quartic couplings can also be probed with tri-boson production
- Currently probing events with at least 1 gamma
  - Also has some less exciting diagrams
    - FSR of the final state lepton
    - Tend to be reduced by ΔR(l,γ) cut
    - **ΔR(l,γ) > 0.7** ATLAS; **ΔR(l,γ) > 0.4** CMS
- Tri-heavy bosons will need more data to measure



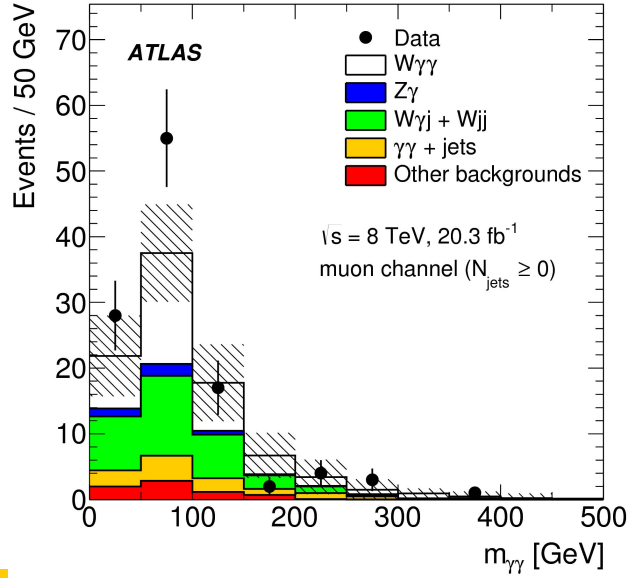
W+gamma+gamma

- Another good example of Modeling

NLO MCFM

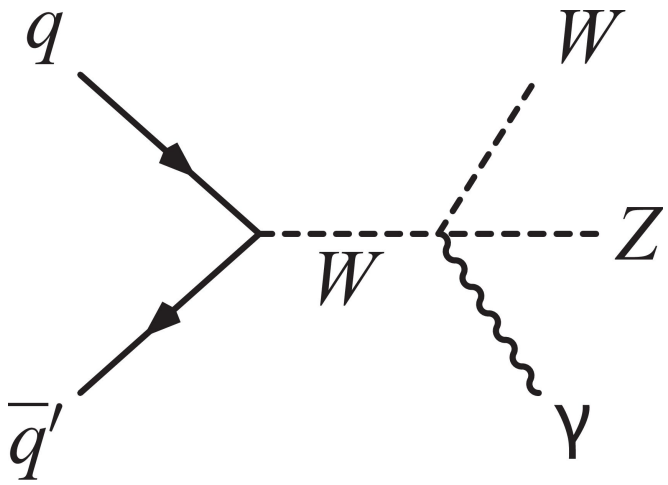


LO Sherpa

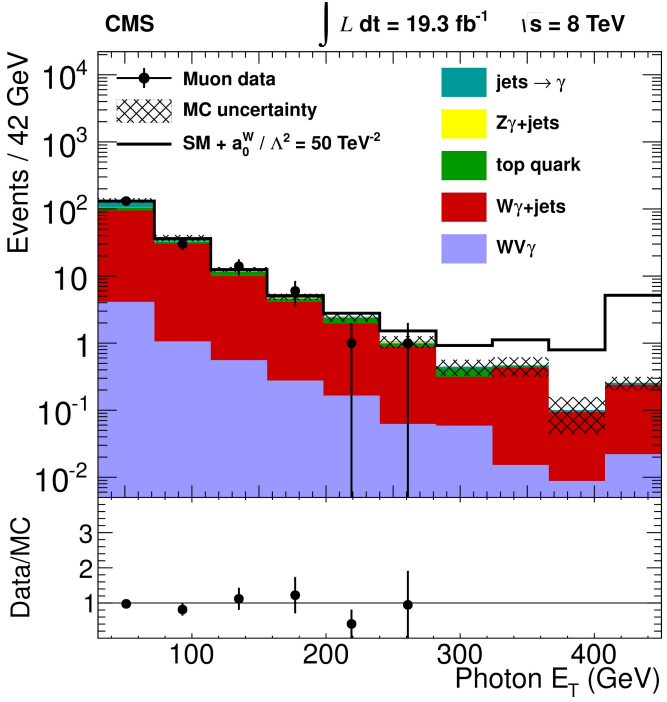


Tri-bosons 1 photon

- Two heavy bosons + 1 photon still in search mode



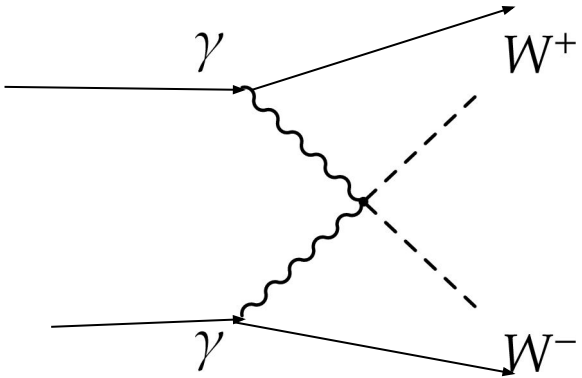
Semi-leptonic decays are used to boost signal

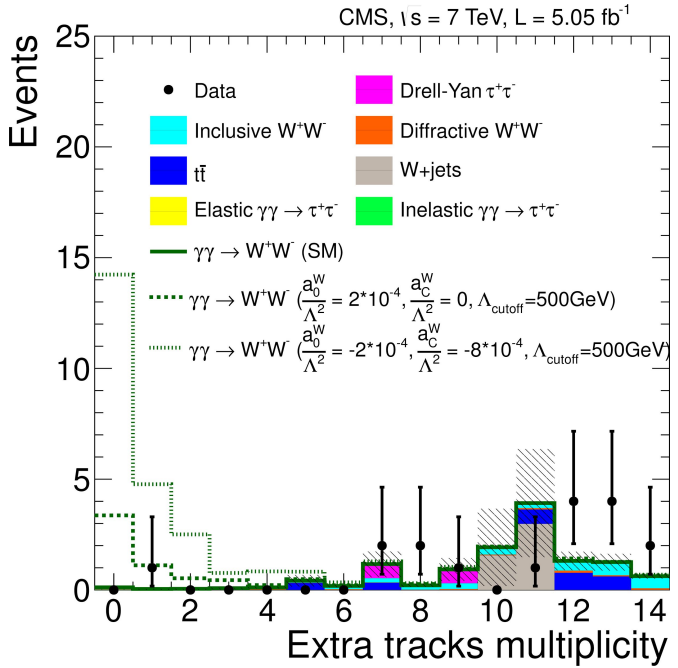


- Three heavy bosons aren't available yet

Exclusive WW production

- You can also get VBS with jets so far forward they go directly down the beam pipe
  - Signature of two leptons with no additional tracks except from the two leptons in a dileptonic W decay
  - Also is search mode
- **Experimental Challenge:** Dealing with tracks from higher pile-up and underlying event at higher energies





Summary

- Reach of the LHC is giving us access to processes never studied before
  - Caught the first glimpse of them in run 1
  - Have some challenges ahead of us to understand these processes
    - Signal and Background Modeling essential for understanding what we measure
      - Also important for good background measurements
    - Finding small signals with lots of background
      - Need good methods of Strong Production rejection
      - May need MVA tools to extract interesting parameters like polarization fractions
    - Extracting the Longitudinal scattering fraction
      - Have to deal with large backgrounds or missing decay information
  - Tri-boson cross sections have started, more will become available with more luminosity