Seven Slogans for the Future of LHC Electroweak Physics

Jeffrey Berryhill

May 3, 2012

Charge

- The future of electroweak physics
- Rather than forecast with higher statistics the standard suite of electroweak measurements, I will emphasize instead new observables/techniques/issues which become interesting in the 8 and 14 TeV epochs.
- Apology: relying on old MC studies, trends in recent related results, back-of-envelope estimates, and even phenomenologists
- Sloganized for your convenience.

Seven slogans

- The best QCD is electroweak

Seven slogans

- The best QCD is electroweak
- Putting nu out of business

Seven slogans

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong

Seven slogans

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong
- Size 6 is the new size 4

Seven slogans

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong
- Size 6 is the new size 4
- Some of my best friends are dijets

Seven slogans

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong
- Size 6 is the new size 4
- Some of my best friends are dijets
- You can tri it now

Seven slogans

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong
- Size 6 is the new size 4
- Some of my best friends are dijets
- You can tri it now
- Party like it’s 1989

The best QCD is electroweak

- Electroweak processes are increasingly dominating our understanding of pQCD.
  - Multi-parton matrix elements (V+jets)
  - Heavy flavor production (V+c, b, bb, etc.)
  - Parton showering (gluon splitting, ME-PS, etc.)
  - PDFs (valence and sea quarks, DPS)
  - Soft QCD (boson PT/gluon resummation)

The best QCD is electroweak

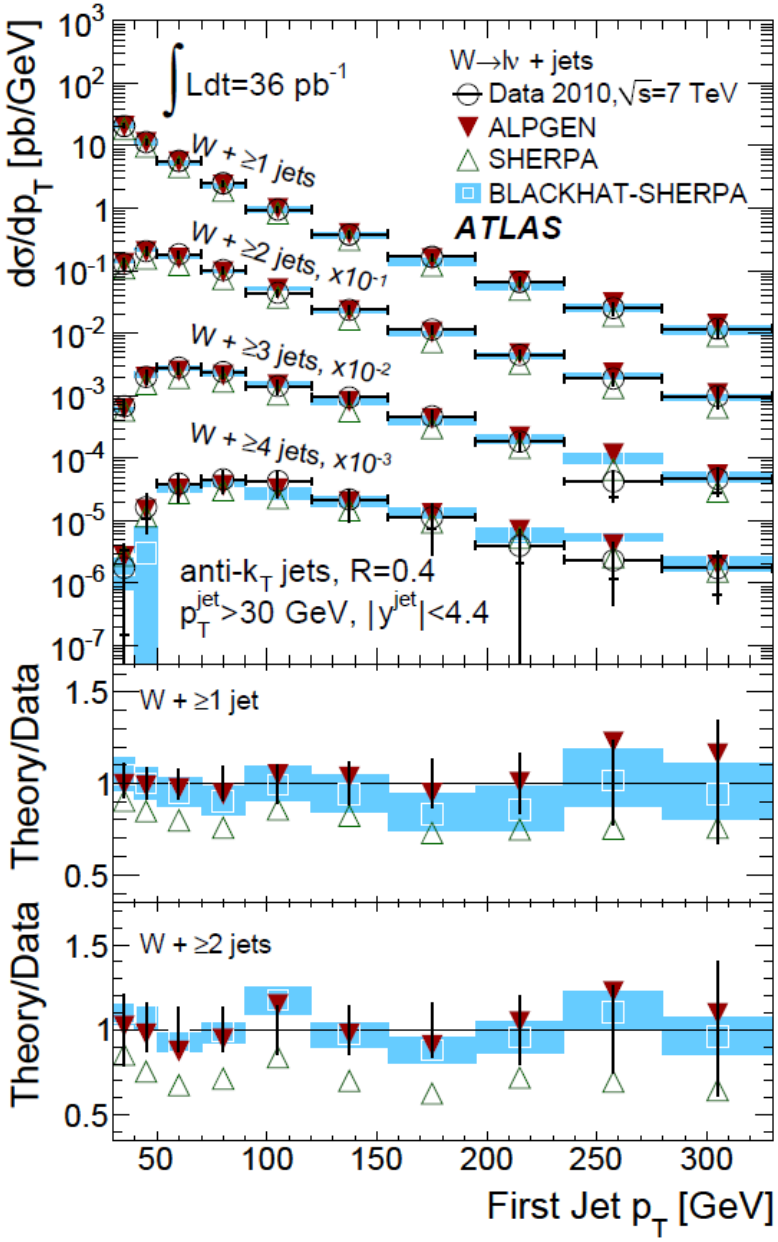
- W and Z + jets have now been tested comprehensively for N<=4, for LO and NLO predictions

- Next:
  fill in more stats at higher multiplicity

  aMC@NLO comparisons

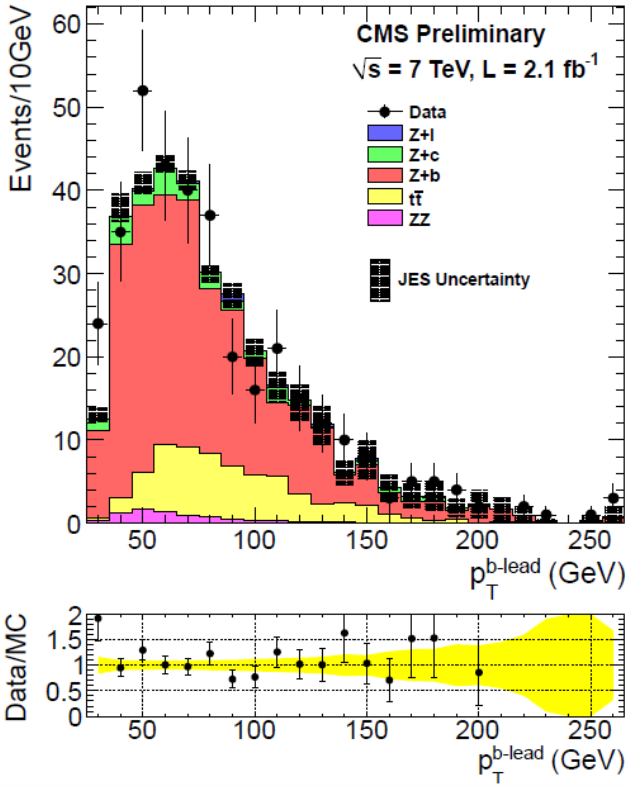
  More observables in more corners of phase space (especially those pertinent to popular searches)

  Polarization and charge asymmetry studies vs. jet observables

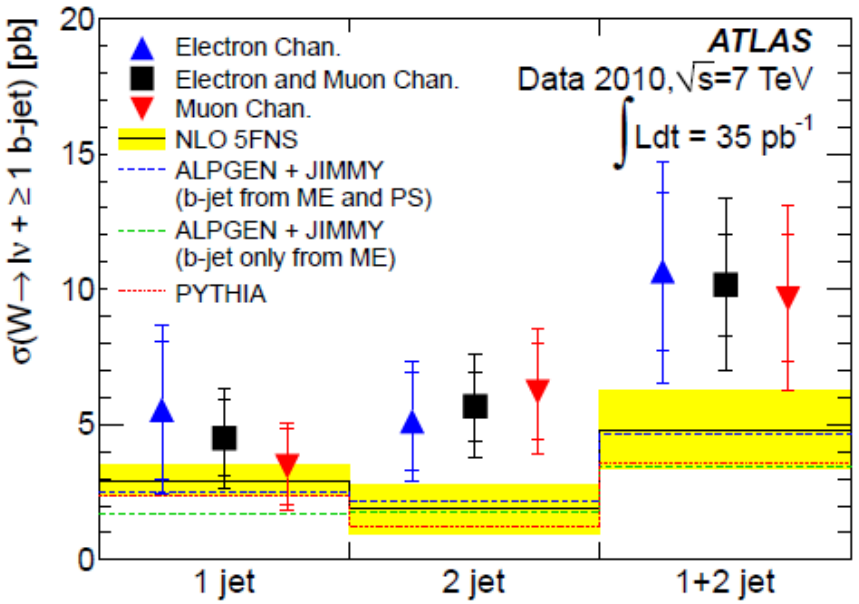


The best QCD is electroweak

- W and Z + heavy flavor will benefit from full exploitation of the 7 and 8 TeV datasets
  - Still statistics limited
  - Fully contrast fixed and variable flavor schemes



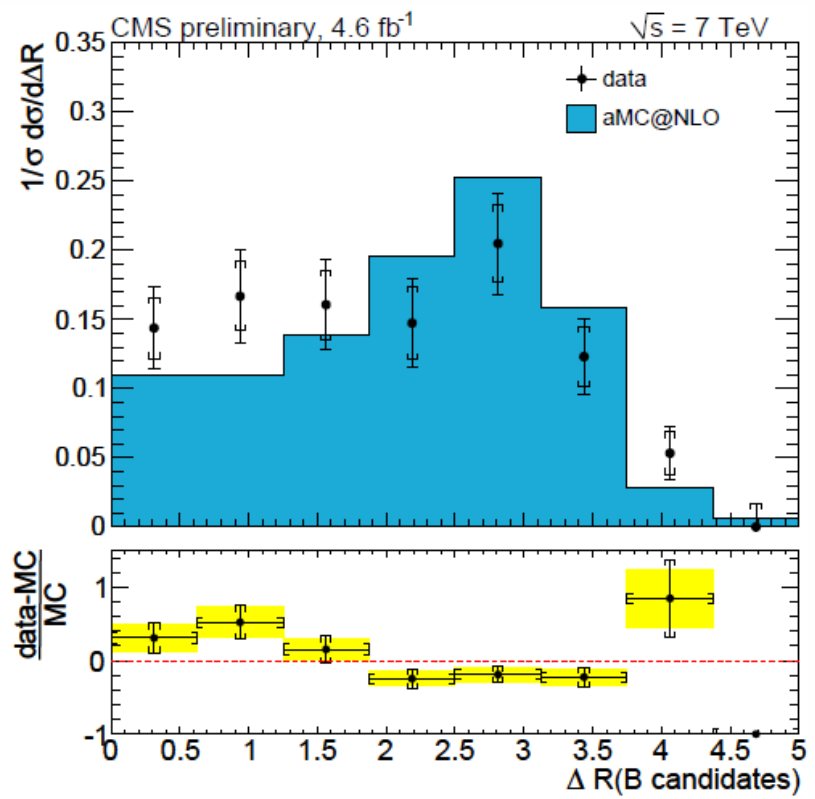
Agreement with MC in Zbb



2X disagreement in Wbb

The best QCD is electroweak

- Other aspects of parton showering and DPS can also be inferred from the V+heavy flavor data
- The population of Z+bb is now large enough (~500 events) to extract E. Berger's DPS-like events with high significance (using S' and decay planes angle).
- The recent technique of studying bb angular correlations with secondary vertices of B hadrons has been applied to the full 2011 CMS data and compared with aMC@NLO.



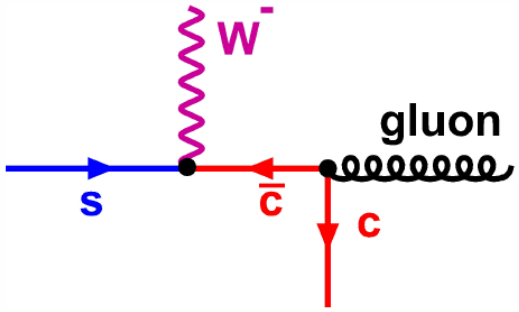
Putting nu out of business

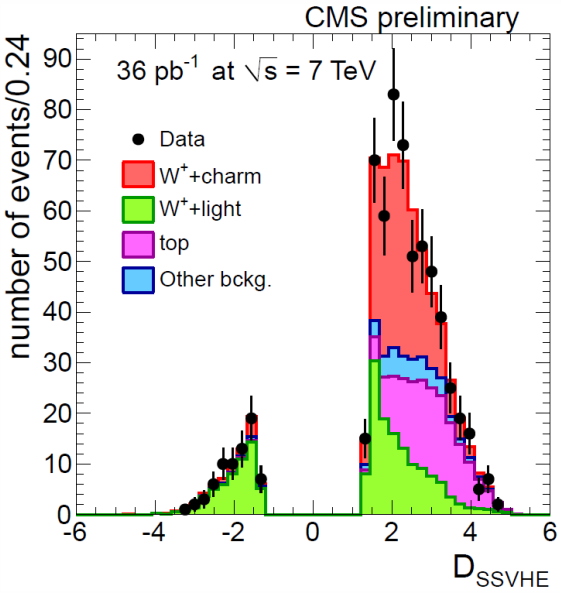
- With large samples of V and V+heavy flavor, new prospects arise for extracting the heavy flavor sea PDFs directly from LHC data

- If successful, would reduce or optionally eliminate our dependence on fixed target neutrino data.

- Ex: W+charm production

relative to W+j (Rc) and W+c/W-c ratio Rc(+/-)





$$R_c^{\pm} = 0.92 \pm 0.19\ (stat.) \pm 0.04\ (syst.)$$

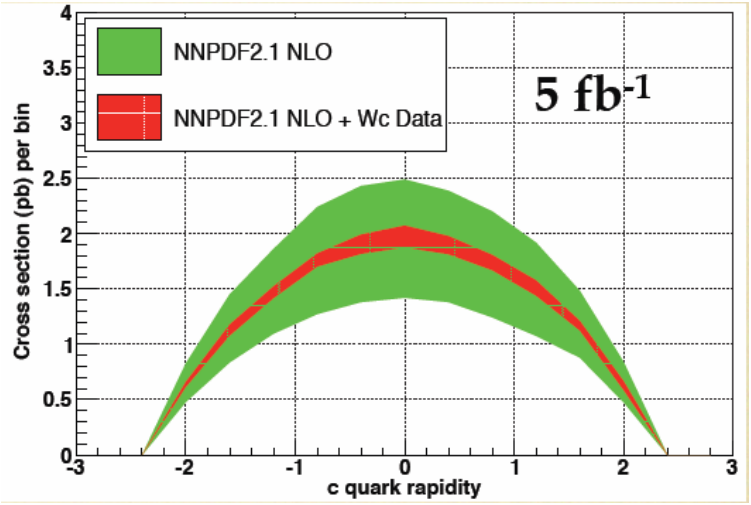
$$R_c = 0.143 \pm 0.015\ (stat.) \pm 0.024\ (syst.)$$

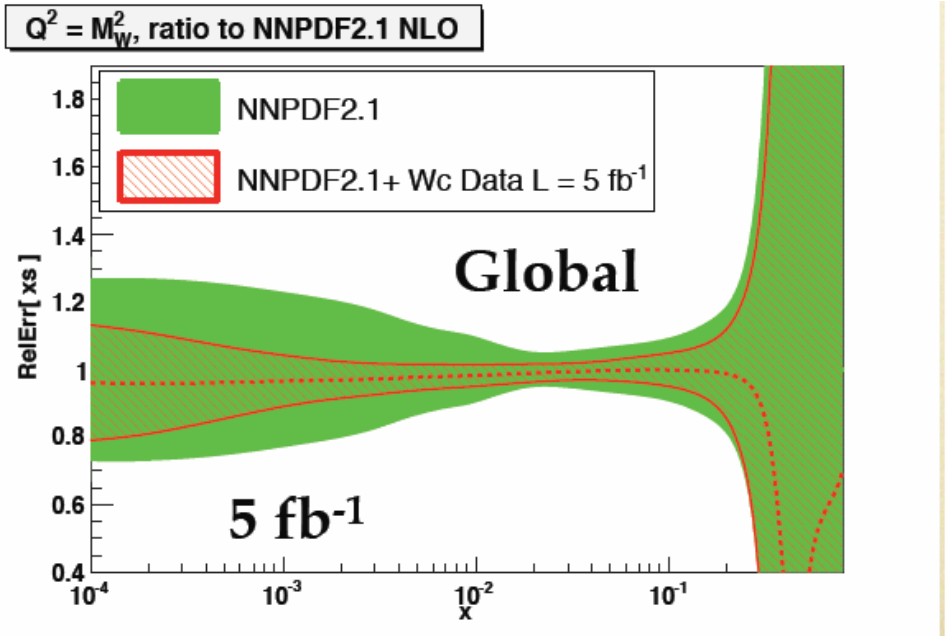
MCFM (CT10)
$0.915^{+0.006}_{-0.006}$
$0.125^{+0.013}_{-0.007}$

Putting nu out of business

- Scaled up to 5 /fb, W+c/W+jets ratio constrains s quark better than NNPDF 2.1

J. Rojo, NNPDF





- R_c(+/-) could similarly constrain s-sbar asymmetry

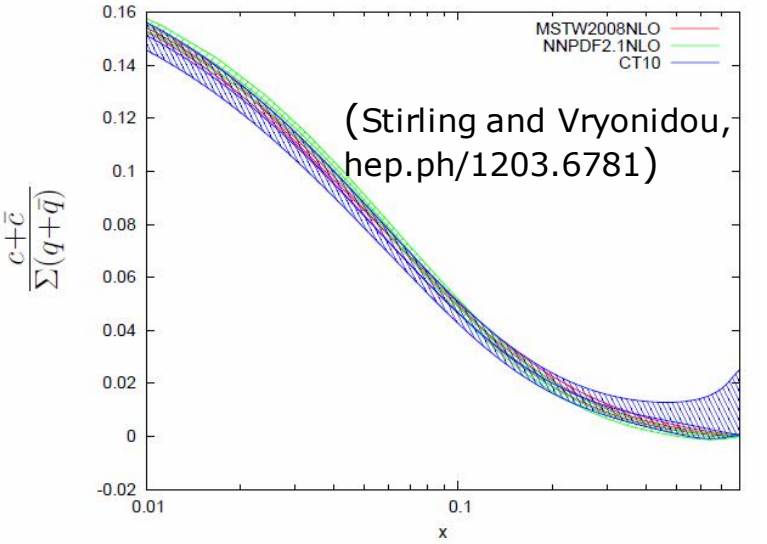
Putting nu out of business

- Other suggested V+heavy flavor PDF constraining observables

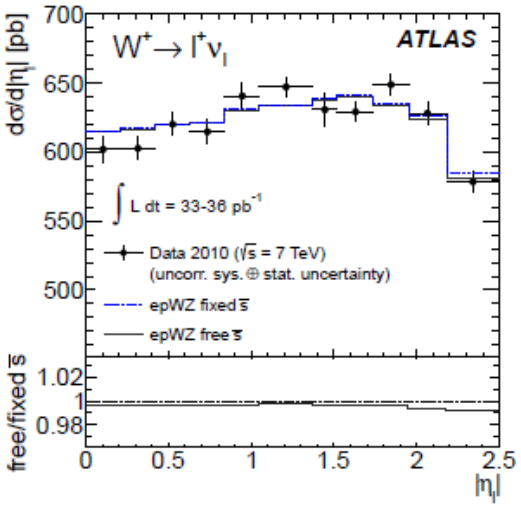
R(+/-) for all jets

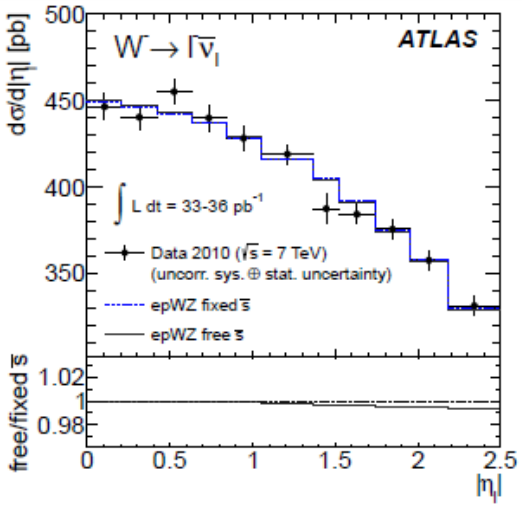
R_c and R_c(+/-) for Z+c events

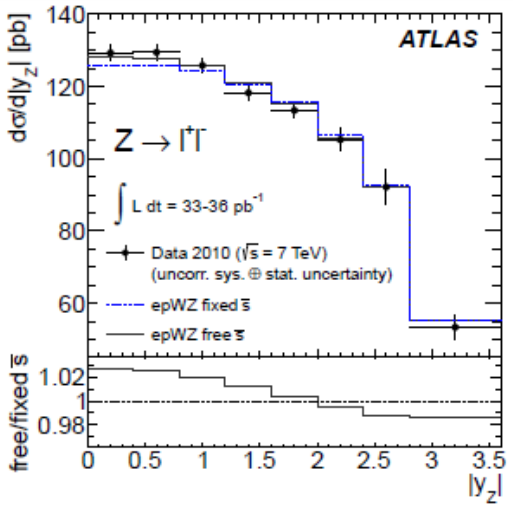
W+j/Z+j, W+c/Z+c distributions



- Inclusive W/Z differential ratio as recently proposed by ATLAS
- W is linear in s, Z is quadratic, u and d are well known,so ratio discriminates differentially…





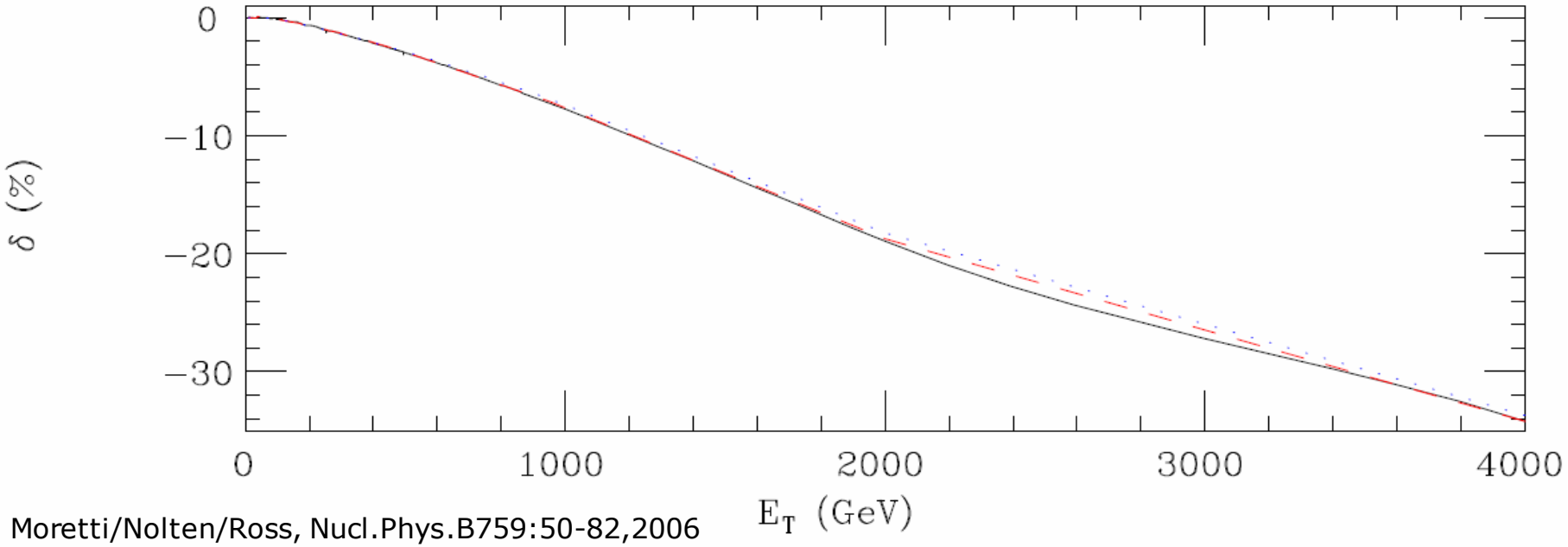


Your weak corrections are too strong

- As explained yesterday by Radja, electroweak corrections become important in certain kinematic regimes.
- At the ~TeV scale, they significantly modify production cross sections through Sudakov logs of order $\alpha_W \log^2(\mu^2/M_W^2)$
  - = 25*α_W @μ=1TeV
- This typically exceeds ~10% of LO when mu is of order 1 TeV
- We are now encountering data where the precision at the TeV scale is of order 10%
- It is important not only for nominally electroweak processes, but for nominally QCD ones as well!

Your weak corrections are too strong

- For **inclusive jet production** at 14 TeV, negative virtual contribution dominates over real emission at ~1 TeV and **cross section decreases from LO result** by ~20% at 2TeV, >30% at 4TeV

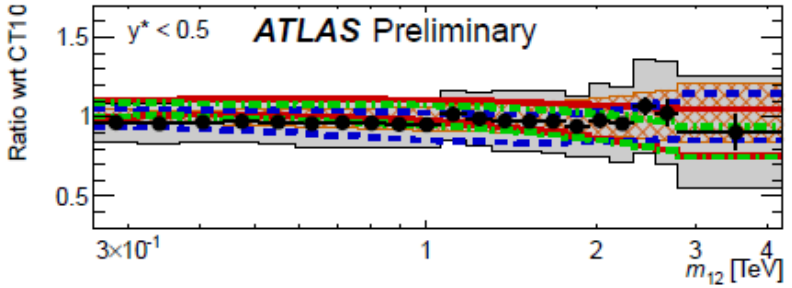


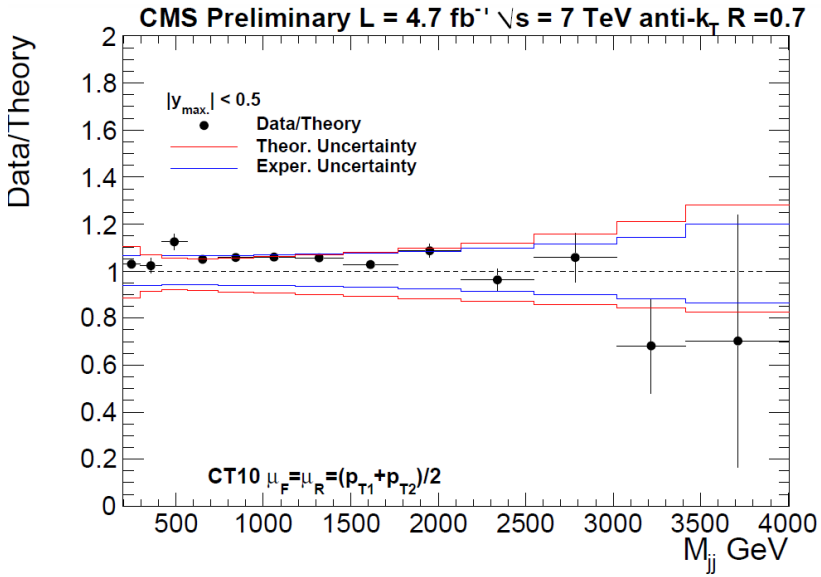
Moretti/Nolten/Ross, Nucl.Phys.B759:50-82,2006

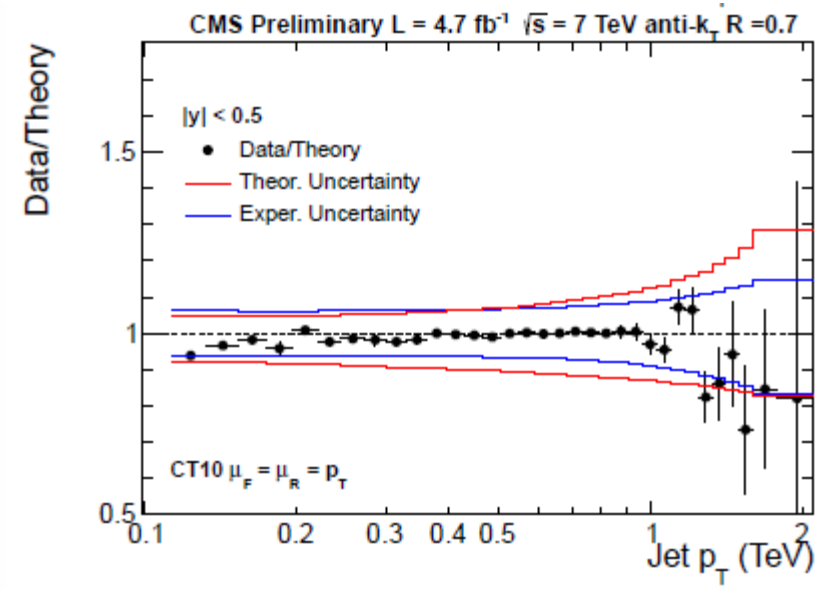
Too strong for jets?: at today's precision, yes!

- ATLAS dijet and CMS inclusive jet/dijet data/theory comparisons with 5 fb^{-1}
- Theory and exper. syst. error for ~2(4) TeV jets(dijets) is now 25-30%
- This is comparable to the possible size of electroweak corrections

(~ -20%)

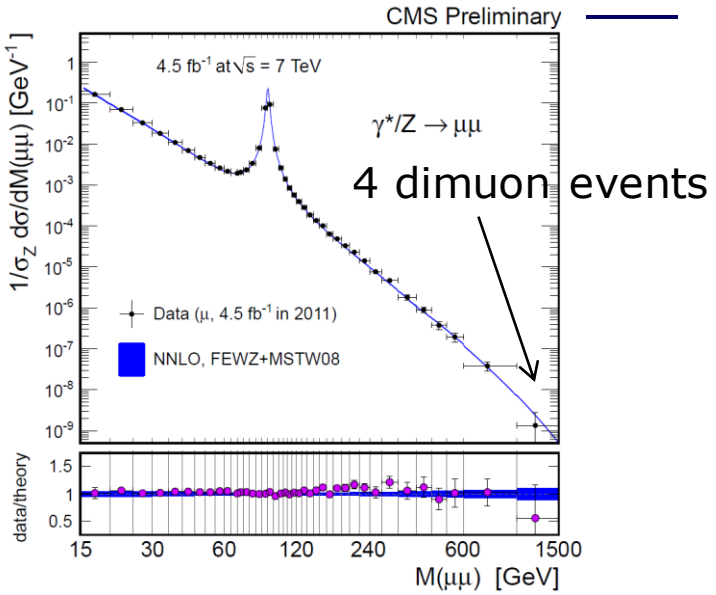


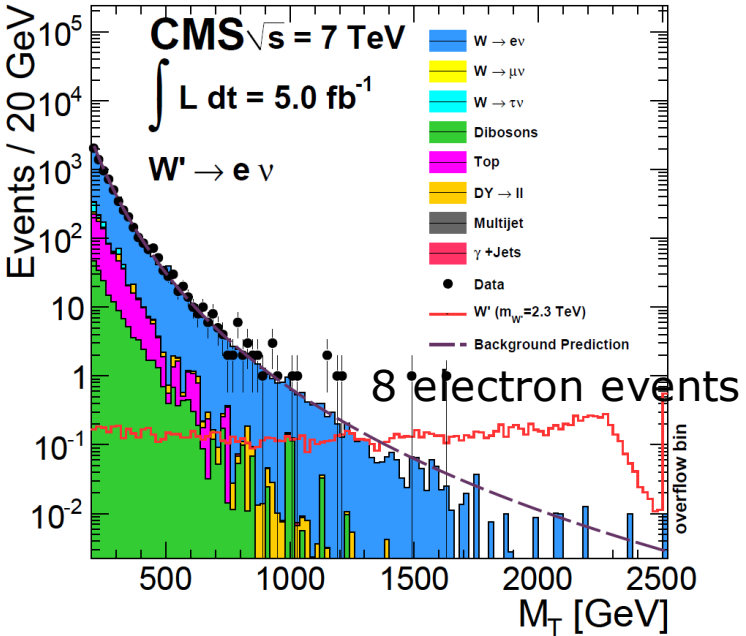




Too strong for W,Z?: Perhaps soon.

- Recent CMS Drell-Yan cross section data have 8 candidates above 1 TeV.
- Stat. precision >1 TeV will improve to <15% by end of 2012.
- CMS W' search has accumulated 14 events above 1 TeV, <10% precision in 2012
- Most everything we could measure in 2010 (jets, photons, W, Z) will enter the "Sudakov zone" in 2012.



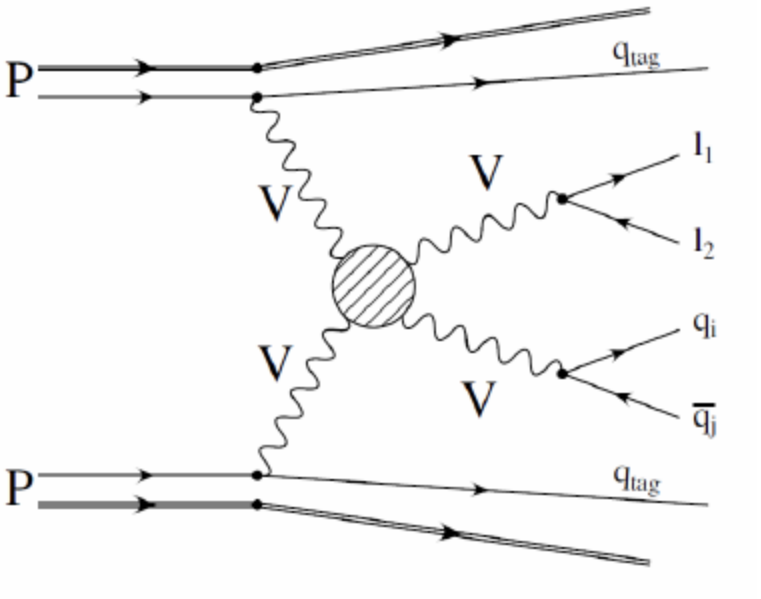


Size 6 is the new size 4

- Up until recently, the vanguard of electroweak interaction studies considered <=**4-body final states**
  - Single bosons decaying to two fermions
  - Dibosons leading to 3 or 4 final state particles

- At LHC, the study of **EWSB and its relation to vector-boson scattering** has trained our focus on vector boson fusion electroweak processes with up to **6-body final states** at leading order.

- A major goal of LHC electroweak studies at 8 and 14 TeV will be to understand as many aspects of this process (and its backgrounds) as possible



Is VV-scattering in reach?

Public studies by CMS/ATLAS last done years ago for TDRs.

For resonant VBF production scenarios, 10's of /fb@14 TeV required. Non-resonant, 100's of /fb.

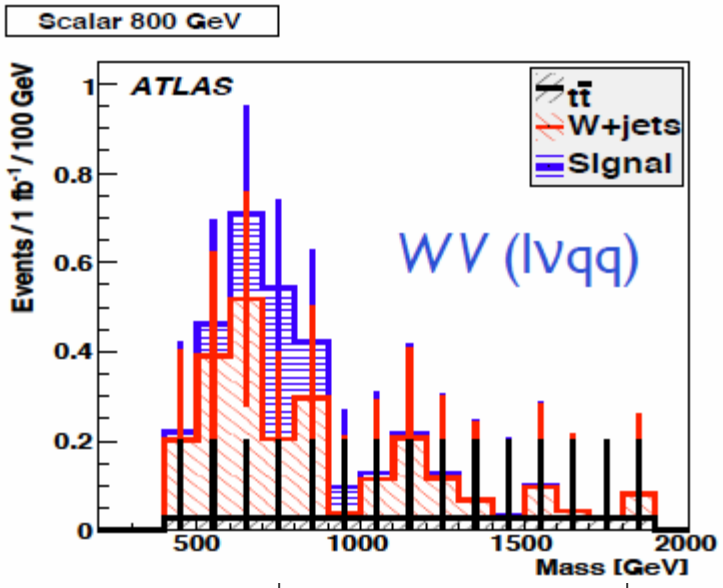
Process	Cross section (fb)		Luminosity (fb^{-1})		Significance for 100 fb^{-1}
	signal	background	for 3σ	for 5σ	
$WW/WZ \to \ell\nu\ jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_jZ_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_jZ_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

ATLAS 2008 Physics TDR CERN-OPEN-2008-02

Is VV-scattering in reach?

Public studies by CMS/ATLAS last done years ago for TDRs.

For resonant VBF production scenarios, 10's of /fb@14 TeV required. Non-resonant, 100's of /fb.



Process				osity (fb^{-1}) for 5σ	Significance for 100 fb^{-1}
$WW/WZ \to \ell\nu\ jj$, $m = 500$ GeV				235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV				60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV				230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV				90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV				55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV				160	3.9 ± 1.2
$W_jZ_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_jZ_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

ATLAS 2008 Physics TDR CERN-OPEN-2008-02

A staged program for VV scattering

It requires understanding a lot of EWK and QCD!

V+jets and tt

understanding of central jet veto or jet counting veto
confidence in V+4 jets @NLO. >4?

VV+jets

confidence in VV+jets @NLO

V+VBF dijets

measure VBF-like production of single W or Z.

VV+VBF dijets

part of Higgs search in several channels already.

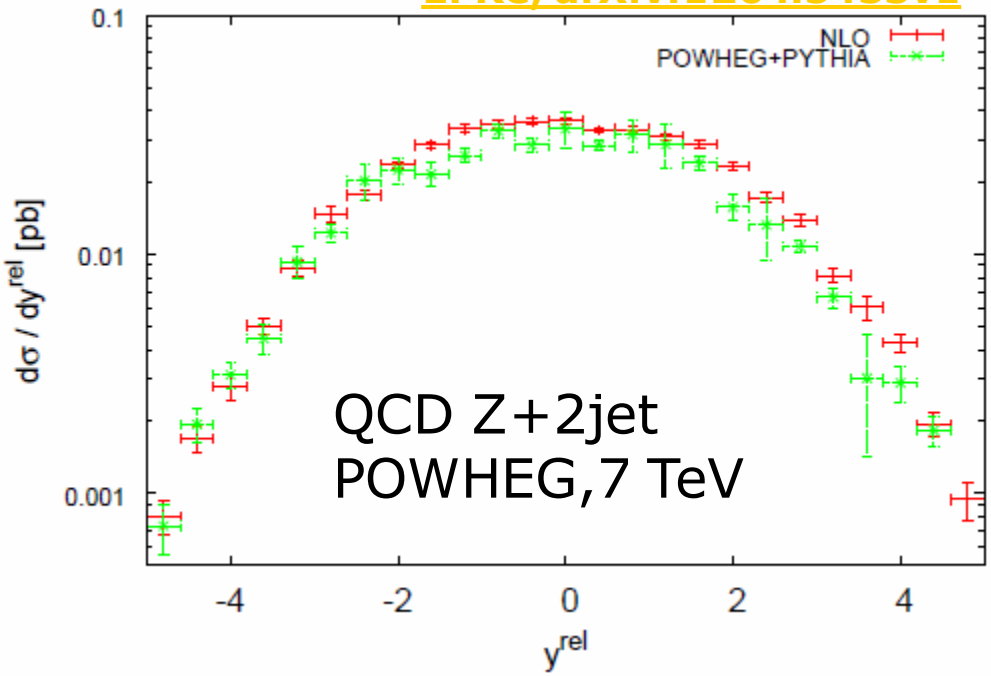
V+VBF dijets

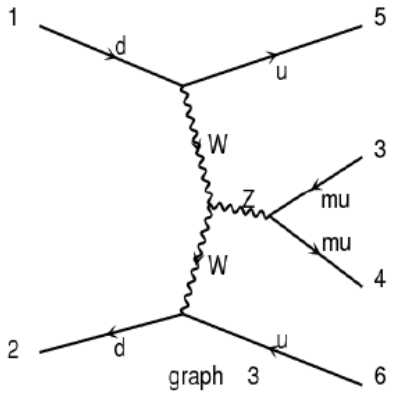
Z+VBF dijets an important background for Higgs to tautau

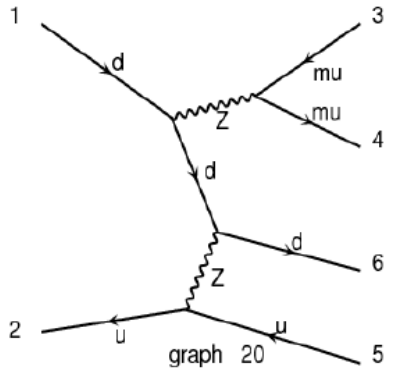
Hundreds of ee, mumu candidates observable in 2011 data

Study needed of discriminating QCD, EWK, and their interference in this topology

E. Re, arXiv:1204.5433v1





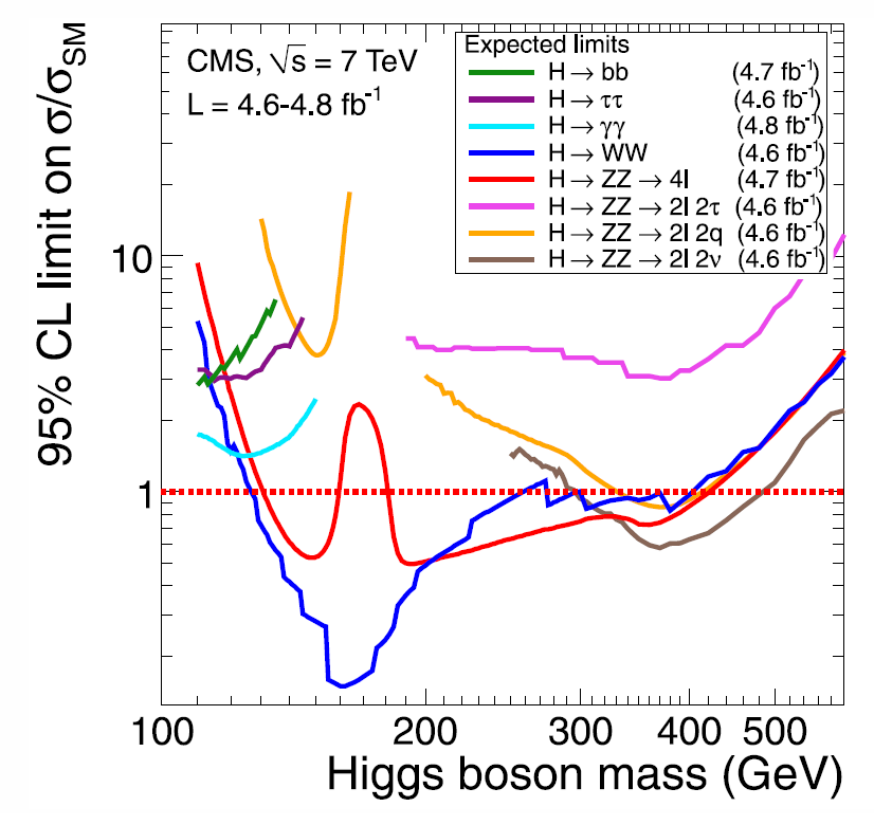


Some of my best friends are dijets

In multi-boson production (but not top!), channels with one or more hadronically decaying V have been historically overlooked in favor of more sensitive all-leptonic ones.

With the LHC, the focus on massive or high-PT diboson production is a game-changer for "semi-leptonic" diboson production.

Near 400 GeV diboson mass or 200 GeV boson PT, the V+2jet background is depleted to the point that the V to dijet BR equalizes or wins out over charged leptons.



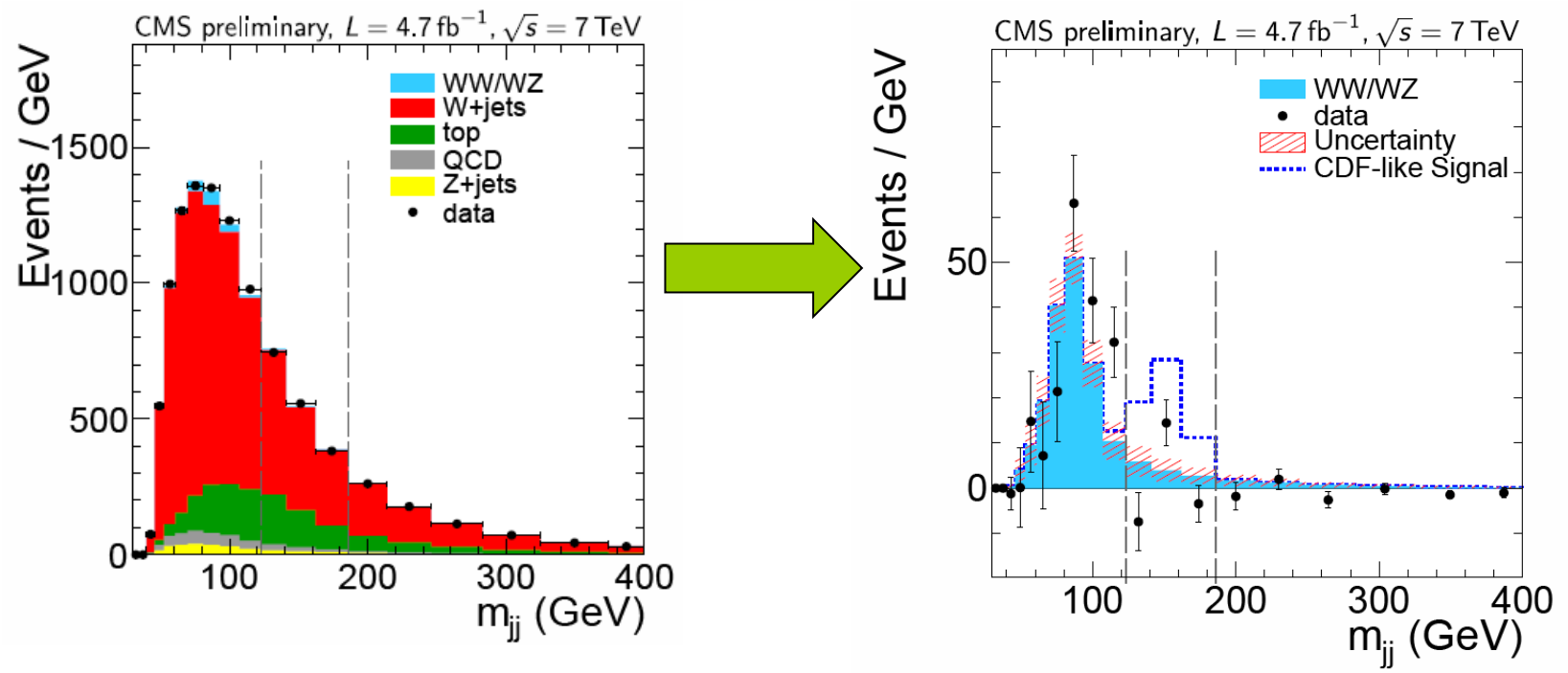
ZZ4l limit = ZZ2l2q at 400 GeV
But ZZ2l2nu is better still!
Can the same be achieved for WW?

Some of my best friends are dijets

In response to the CDF W+2jet anomaly, CMS has examined W+2j dijet mass

Even recoiling against only a hypothetical 150 GeV dijet, good sensitivity is obtained and a significant SM diboson signal is evident

Technicolor and Z' models consistent with CDF have been excluded.
This only gets better at higher boson PT or exotic parent mass.



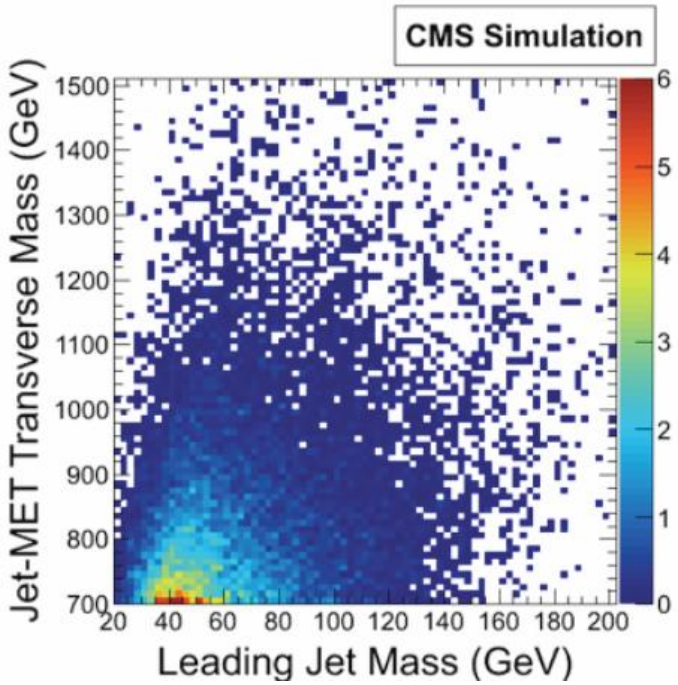
Some of my best friends are dijets

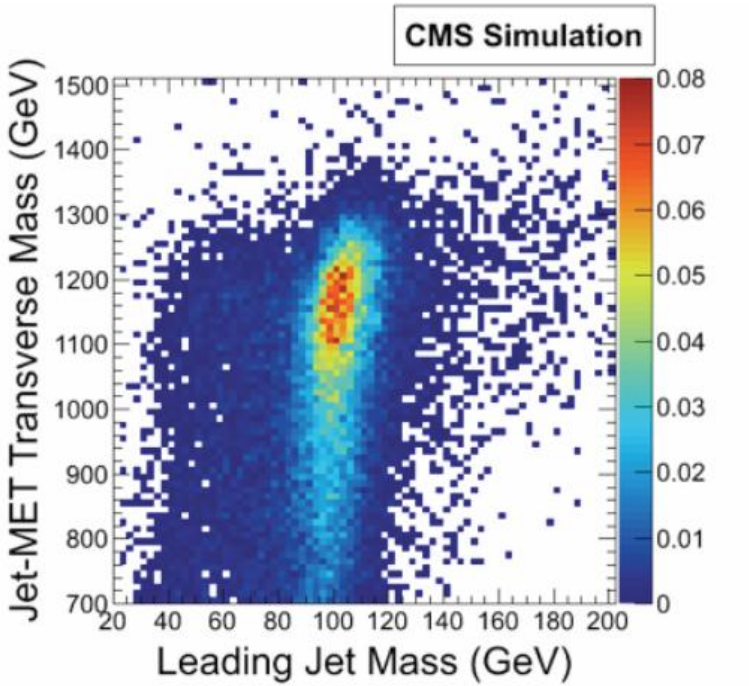
Takeaway trend:

As part of VV scattering and anomalous diboson production studies, Semileptonic VV topologies will start to play a leading or equal role with leptonic.

Possible problem: Boosted dijets merge

Solution: See yesterday's session on jet substructure

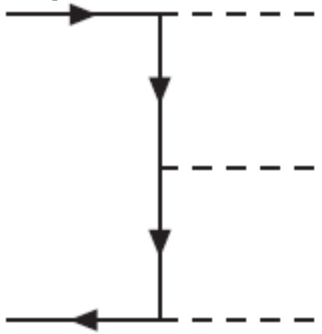




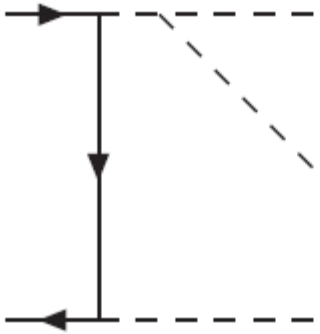
You can tri it now

- Another window to quartic couplings/VV scattering is **triboson production.**
- Handfuls of these events start appearing in CMS/ATLAS with 20 fb^{-1} @8TeV.
- $W\gamma\gamma$, $WW\gamma$, $WZ\gamma$, WWW have reasonable sigma*BR*A
- Interpretation is difficult due to complex interplay of many amplitudes with Vqq, VVV, VVVV couplings.

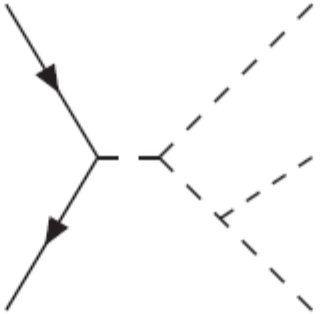
Triple emission



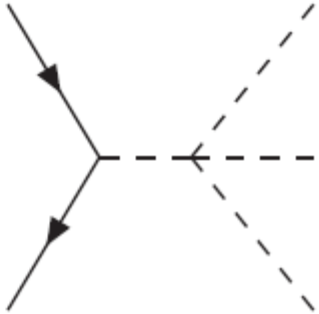
Diboson + ISR



Diboson + FSR



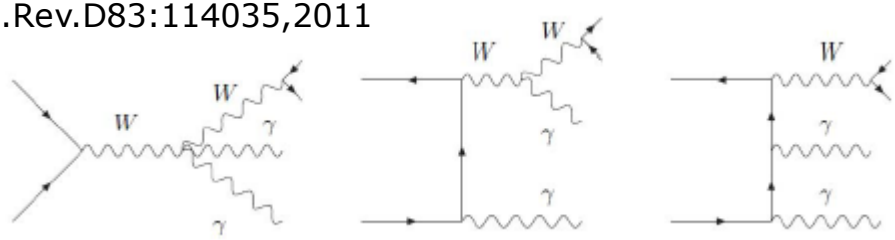
Quartic



Tri it: are Wγγ or VVγ observable?

- All of Wγγ, WWγ, WZγ, should be observable in 2012 (20 fb-1 @8TeV).

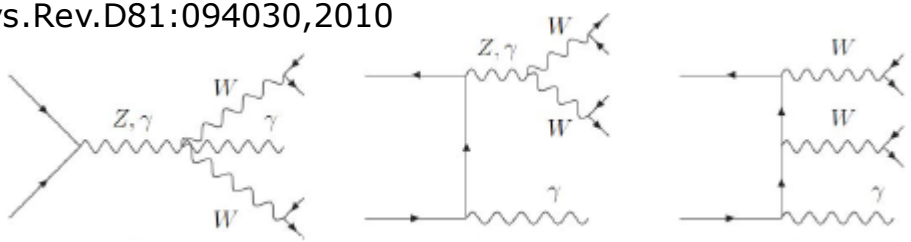
Phys.Rev.D83:114035,2011



- ~160 Wγγ candidates/expt (VBFNLO)

PT(γ) > 20 GeV
For WWγγ quartic.
Observable now!

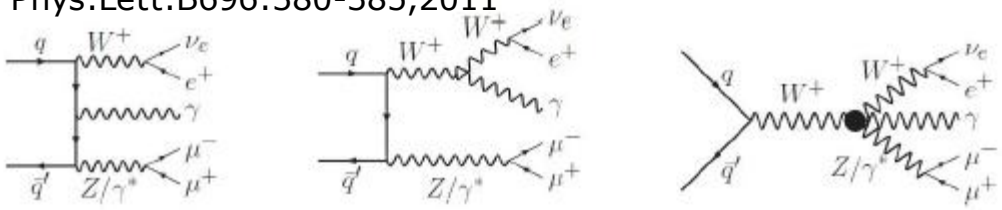
Phys.Rev.D81:094030,2010



- ~30 WWγ candidates (VBFNLO)

PT(γ) > 20 GeV
For WWZγ or WWγγ quartics

Phys.Lett.B696:380-385,2011



- ~10 WZγ candidates (VBFNLO)

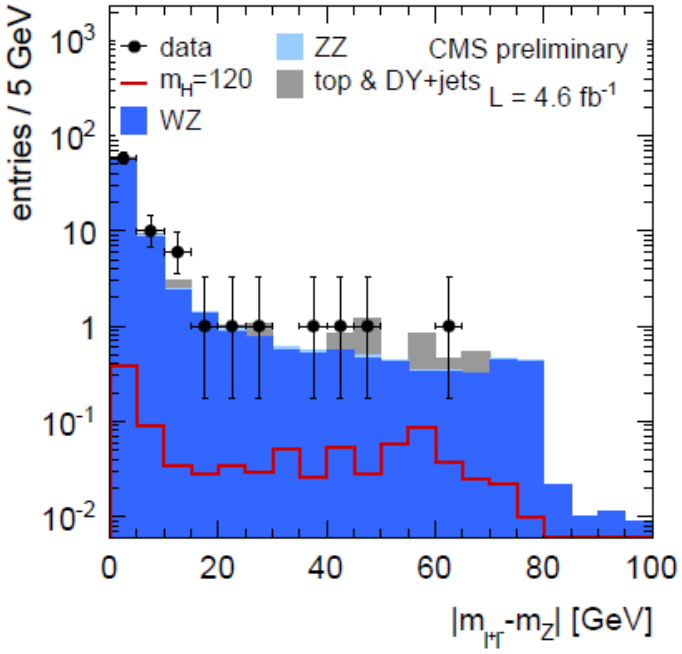
PT(γ) > 20 GeV
WWZγ or WWγγ

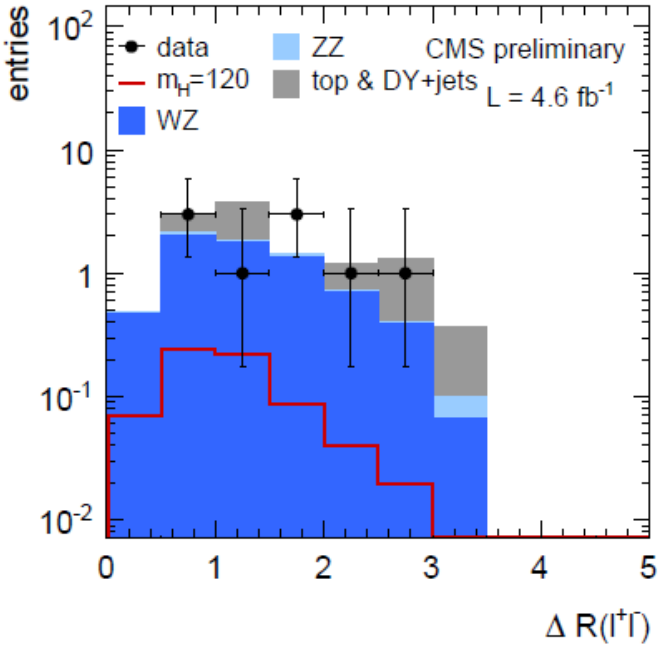
- To do: these are predominantly ISR/FSR. Can (anomalous) quartic be better isolated kinematically with high statistics?

Tri it: is WWW observable?

Three lepton + MET mode:
VBFNLO Sigma(WWW) = 80 fb, Sigma(WWW→3l) = 0.9 fb
~20 candidates maximum in 20fb^{-1} @8TeV (no acceptance/eff cuts).

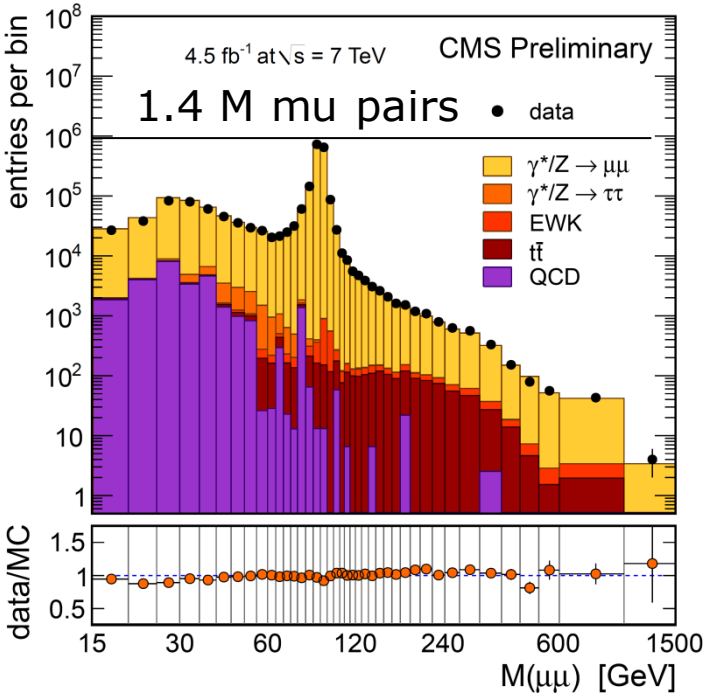
BUT backgrounds are large, so this will likely wait for 14 TeV:
Extrapolating from **CMS PAS HIG-11-034 (WH, H → WW):**
After Z and top vetoes,
35 WZ candidates, 20 tt candidates minimum.

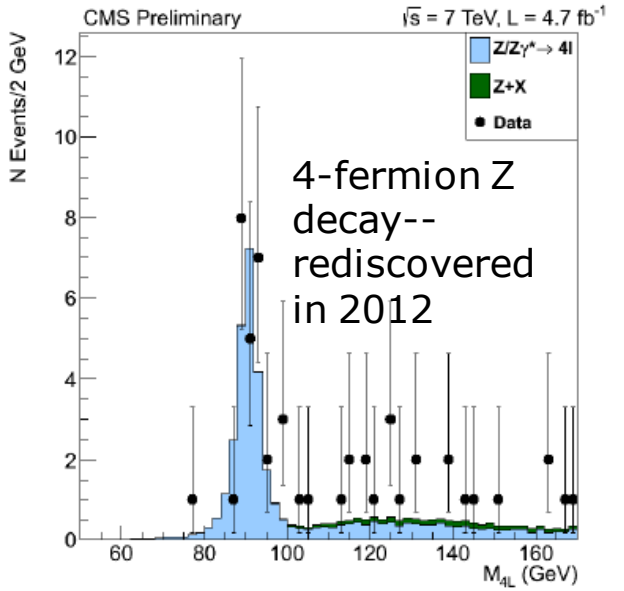




Party like it's 1989

- The LEP 1 data consist of 17 million Z decays.
- In 2011, CMS+ATLAS collected ~6 million ee or μμ Z decays (120k taus).
- In 2012, this will be closer to **28 million (550k taus).**
- With 100 fb^{-1} at 14 TeV, **250 million (5M taus)**.
- The production mechanism is very different and dilutes EWK effects
- But a clever exploitation of 10M-100M Z's could start to rival the LEP+SLD asymmetry measurements





Party like it's 1989: $\sin^2\theta_W$

CERN-PH-EP-2011-159

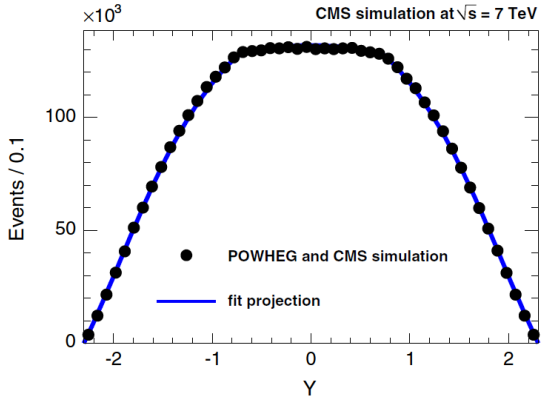
- $\sin^2\theta_W$ recently extracted from CMS mumu data via a multidimensional MLH fit.

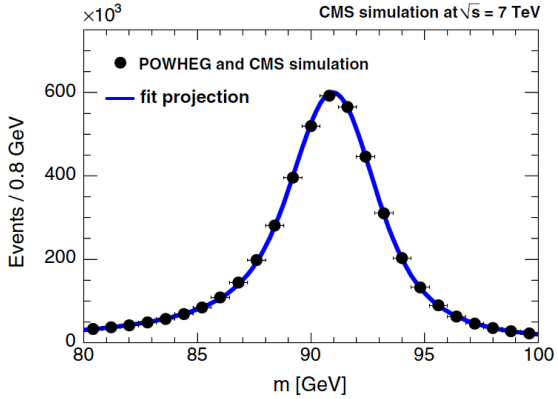
$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0020\,(\text{stat.}) \pm 0.0025\,(\text{syst.})$$

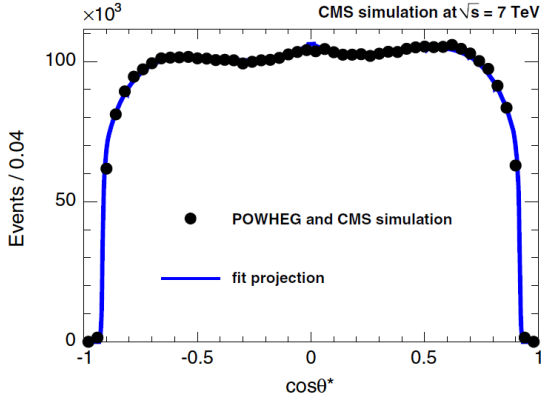
- Leverage per event is poor due to weak correlation of $\cos\theta^*$ polar axis with true quark direction

- To reduce stat error to world average precision = 0.00016, need ~50 fb^{-1} @14TeV

- PDFs, NLO effects, alignment effects dominate but can hopefully be reduced with more data

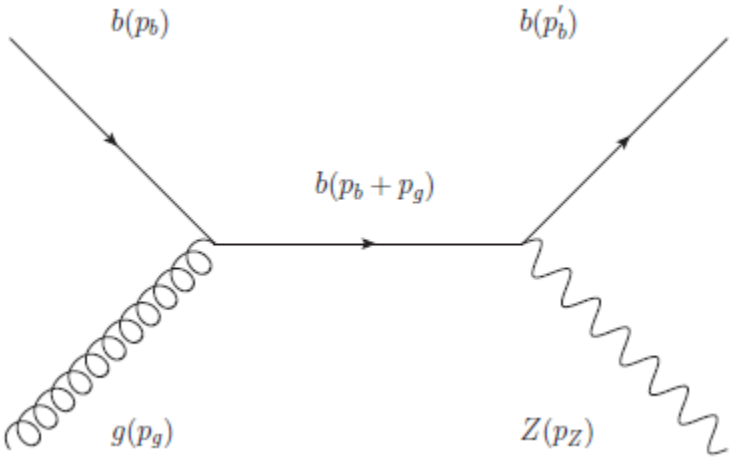




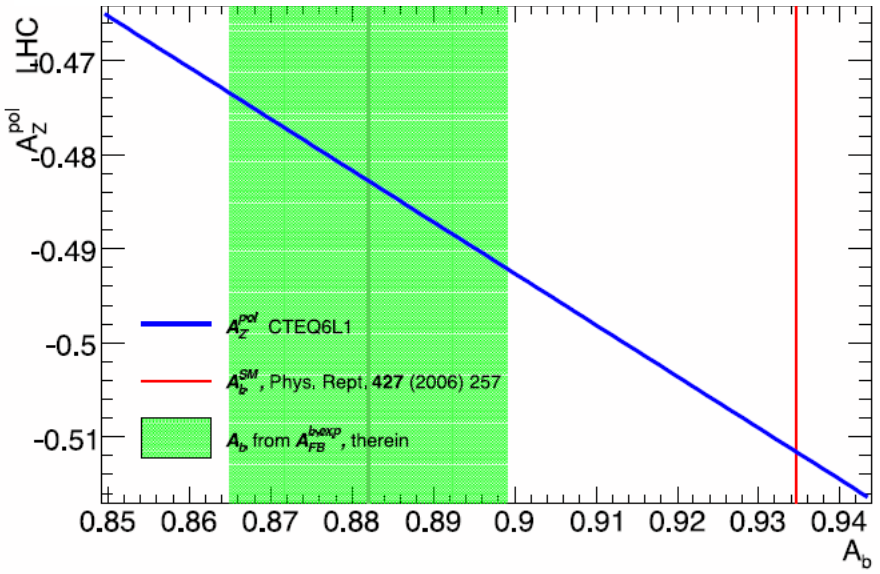


Party like it's 1989: $A_{b,c}^0$?

- Z+b and Z+bb production have been observed by CMS
- Multiply-differential angular analysis (a la weak mixing angle) can define a Z polarization asymmetry Apol
- It was recently argued that NLO, scale, and PDF effects are < 1% in relating Apol to Ab (*Beccaria et al., hep-ph/1204.5315*).
- Could resolve a long-standing outlier in the electroweak precision data?
- Could also work for Z+c?



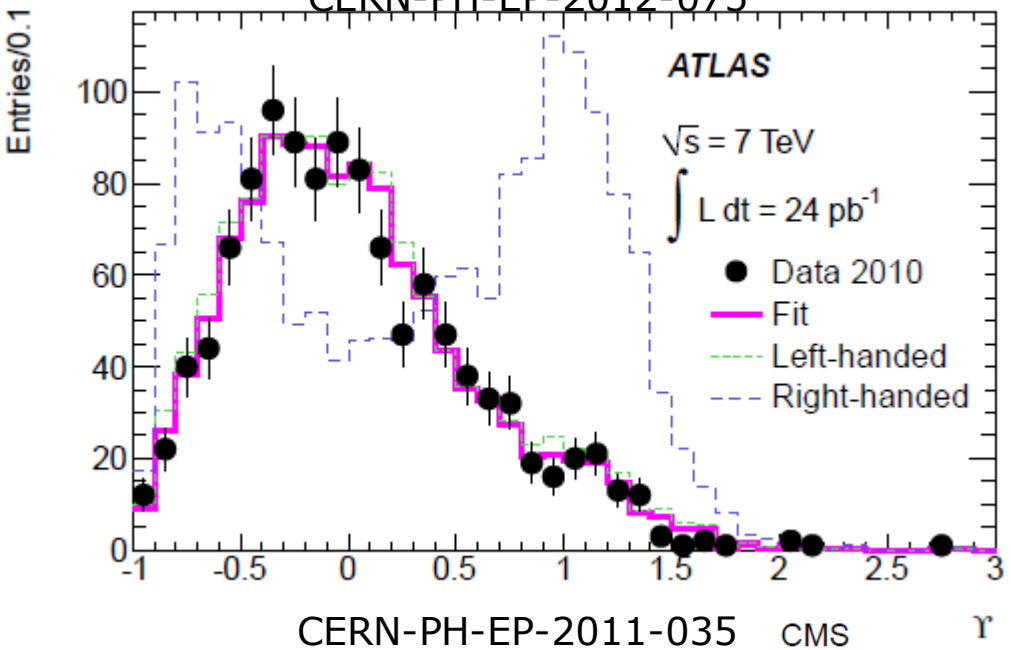
$$A_Z \equiv \frac{\sigma(Z_R)-\sigma(Z_L)}{\sigma(Z_R)+\sigma(Z_L)} = \frac{(g_{Zb}^R)^2-(g_{Zb}^L)^2}{(g_{Zb}^R)^2+(g_{Zb}^L)^2} C_{pol}$$



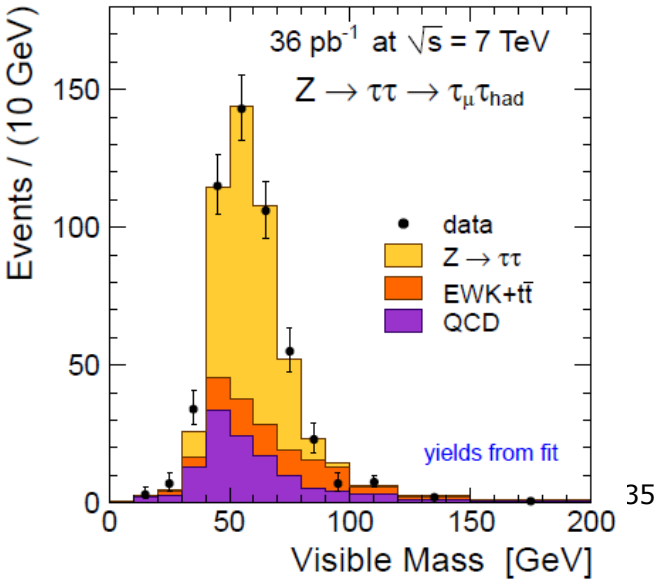
Party like it's 1989: tau polarization

- Tau polarization effects largely ignored by hadron colliders to date, but was an essential ingredient of LEP+SLD asymmetry measurements
- ATLAS has recently observed ~100% tau polarization in hadronic taus from W's
- With ½ million tau pair candidates in 2012, tau polarization could be extracted from Z events, on-shell and off.
- Could approach LEP-like sensitivity in 14 TeV era.

CERN-PH-EP-2012-075



CERN-PH-EP-2011-035 CMS



Metaconclusions

- LHC electroweak boson production shall continue to be an **excellent laboratory for pQCD and PDFs**.

- The **program to understand VV scattering** shall realize its potential only starting with the 14 TeV run, but the tools to understand it can be trained up today.

- The chief limitation to the LHC electroweak program is not instrumental, but rather **our human will and creativity** to conduct it.