Electroweak Measurements

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ATLAS

Outline

- W/Z physics
  - W charge asymmetry
  - Z A_{FB} asymmetry
    - weak mixing angle
  - VBF Z production
- Di-bosons
  - cross section measurements
  - limits on aTGC
- Conclusions

W/Z bosons, introduction

- Amongst the processes accessible at the LHC, the production and decay of W and Z bosons are of paramount importance
    - experimentally, their leptonic decays present very clean signatures
    - theoretically, we have very advanced tools at our disposal
        - NLO generators (integrated to PS in a consistent way)
        - NNLO predictions for cross sections (inclusive and differential)
- In addition to the physics measurements they allow to perform, they are also a fundamental tool to understand the performance of the detectors
    - Tag&Probe (not covered in this talk)

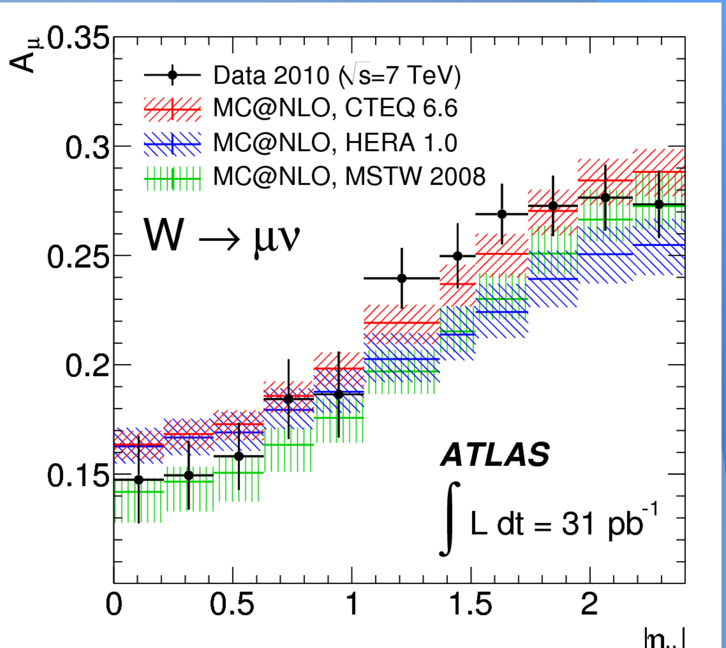
W/Z as probes

- In addition to being interesting *per se*, the study of the properties of the W and Z bosons gives insight on several parameters of the SM
- Both experiments are performing extensive studies
- Highlights given here include
  - W charge asymmetry
  - Z A_{FB}
    - weak mixing angle

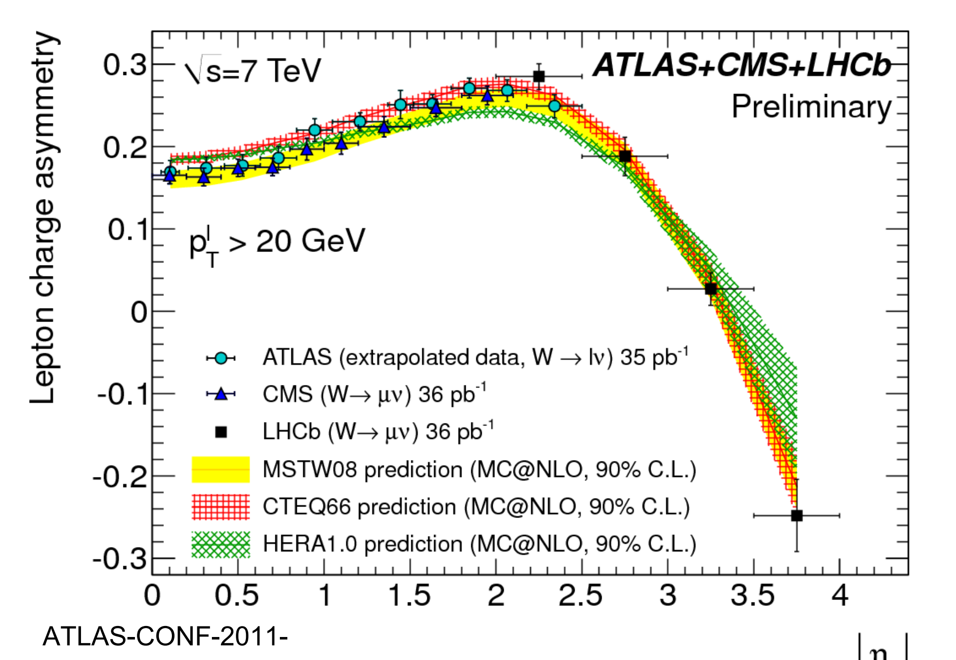
W charge asymmetry

W charge asymmetry sensitive to valence quark composition

Extrapolation to common fiducial volume allows direct comparison of ATLAS, CMS and LHCb



Phys.Lett. B701 (2011) 31-49



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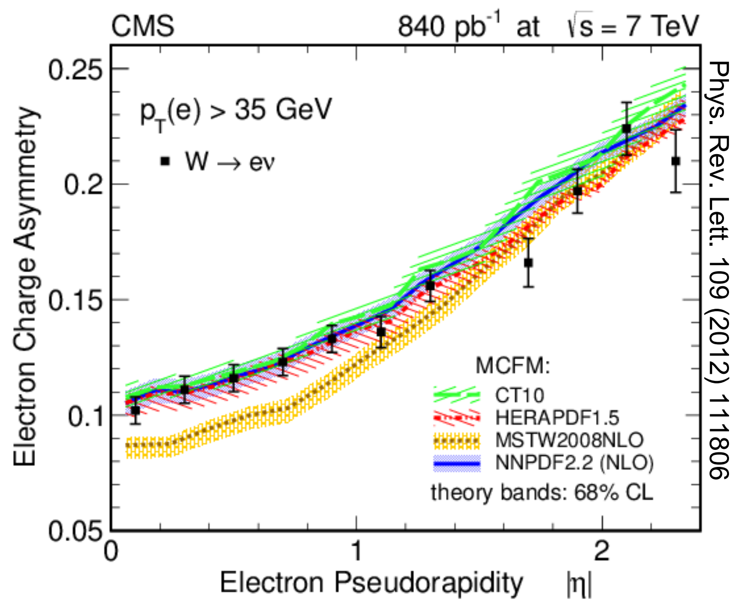


Phys. Rev. Lett. 109 (2012) 111806

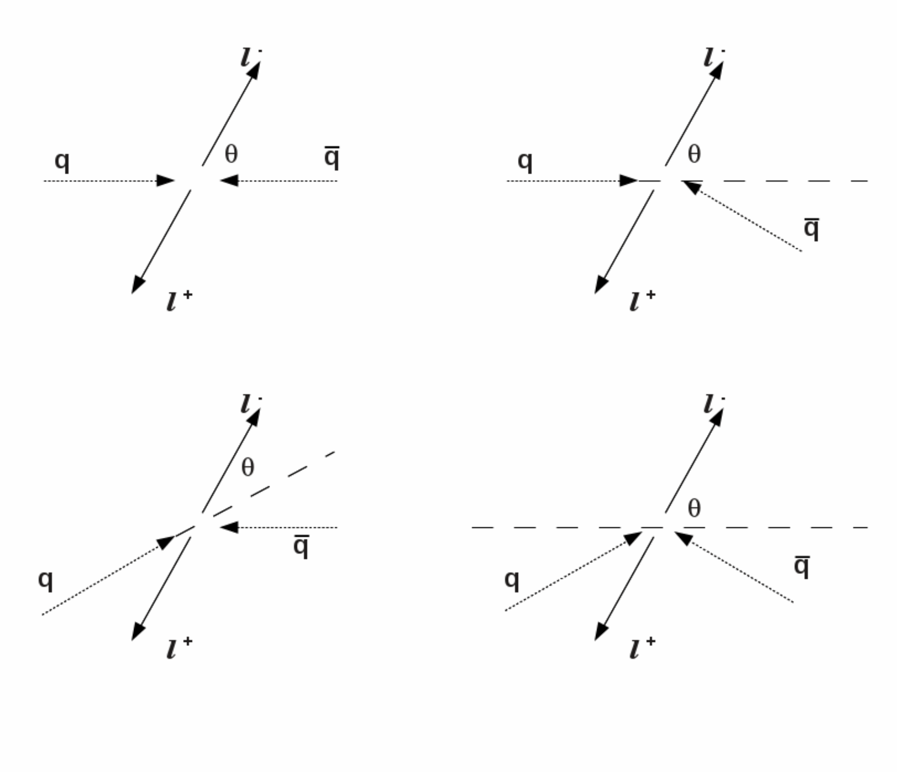
Z asymmetries

- They arise from the parity violation of EW interactions
  - As opposed to, for example, parity-conserving photon exchange
- The Z production+decay cross section gains a term proportional to the cosine of the scattering angle
- Coefficient depends on the left and right couplings, and vanishes if they are identical

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$

- This allows to define three non-vanishing observables:
  - Longitudinal polarization asymmetry, ALR
  - Unpolarized FB asymmetry
  - Polarized FB asymmetry

Z A_{FB}



$$\cos\theta^*_{CS} = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

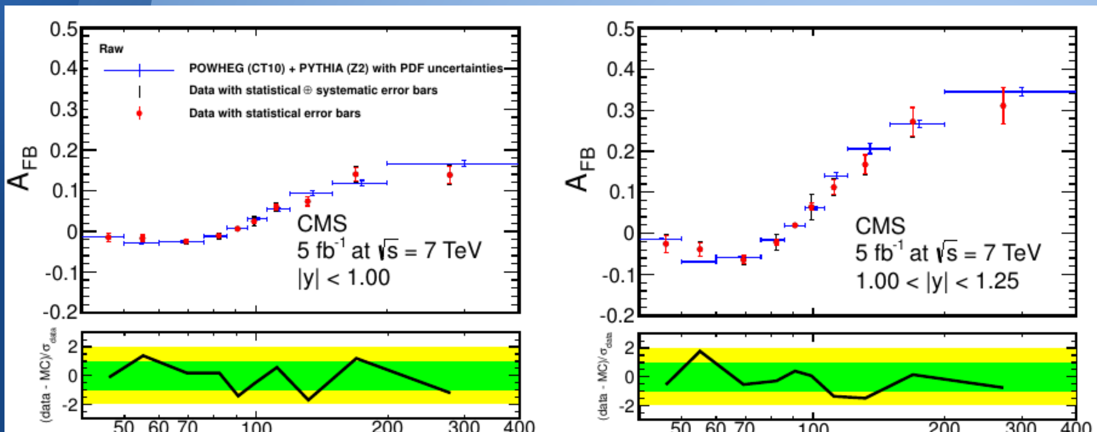
$$p_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

- An ambiguity in the definition of the scattering angle is present when the transverse momentum of the lepton pair in the lab frame is not negligible
  - Use a reference frame (Collins-Soper) which resolves this ambiguity by using a symmetric axis wrt the incoming partons

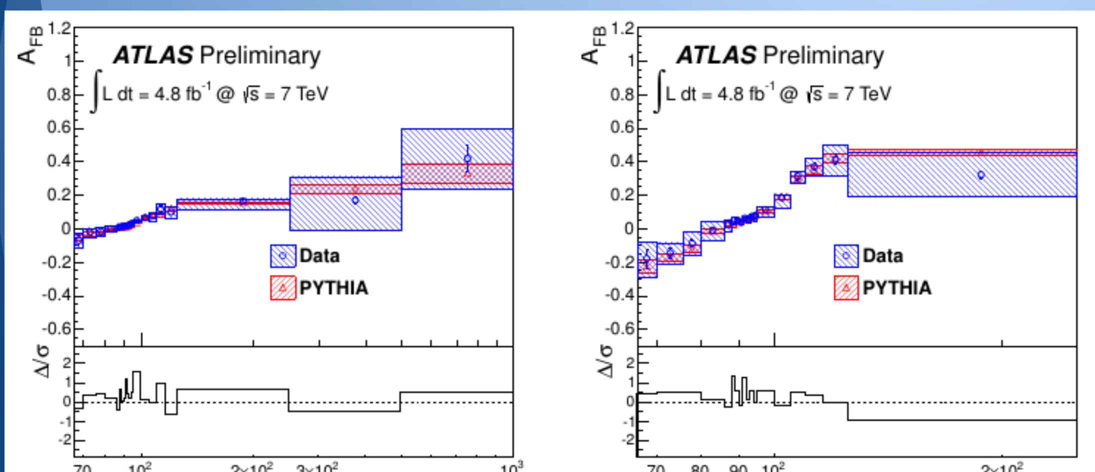
Z A_{FB}

- In pp colliders, one extra complication arises from the fact that one does not know which beam the quark belonged to
  - Result is that A_{FB} is diluted
- Dilution less important if one limits the measurement to lepton pairs with high rapidity
  - In this case, one of the partons had high x, i.e. it was most likely a quark
    - assume that the direction of flight of the Z coincides with the direction of the quark
- Note that this has a rather big effect on the measurement (see next slide)

Z A_{FB}, raw distributions



Phys. Lett. B 718 (2013) 752



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- Raw distributions allow to appreciate the effect of dilution
  - CMS: binning the measurement in bins of dilepton rapidity
  - ATLAS: using forward calorimetry to identify electrons up to $|\eta|<4.9$

Measuring the weak mixing angle

- Z A_{FB} gives direct insight on the V and A couplings
  - It is sensitive to the effective weak mixing angle
- Strategies for wma extraction are different between the two experiments
  - CMS: start from theory prediction of differential cross section, "fold in" all known effects, unbinned likelihood fit to observed cos(θ*) distribution
    - muon final state only
  - ATLAS: template fits on raw A_{FB} spectra using MC samples generated with different values of wma
    - muon, electron and forward electron final states separately, statistical combination of the results

Weak mixing angle: results

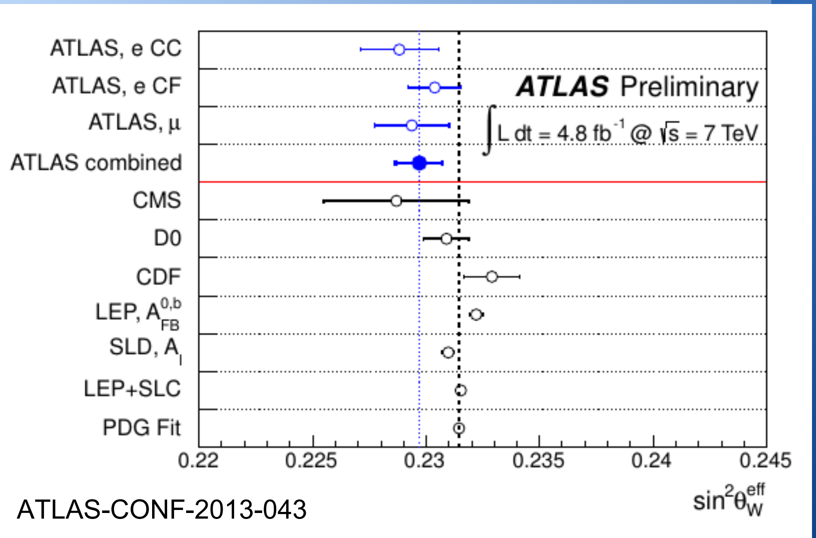
$$\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0020\,(\text{stat.}) \pm 0.0025\,(\text{syst.}).$$

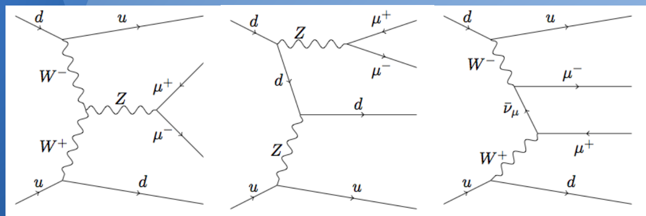
CMS: muon channel @ 1.1/fb
Phys. Rev. D 84, 112002 (2011)

$$\sin^2\theta^{\rm eff}_{\rm W\ combined} = 0.2297 \pm 0.0004(\text{stat.}) \pm 0.0009(\text{syst.})$$

ATLAS: e + forward-e + muon @ 4.7/fb
ATLAS-CONF-2013-043

- Even with only (part of) 2011 data, the result is ***dominated by systematics***
  - Mainly PDF, followed by detector-related effects (electron scale/resolution, allignment)
- ATLAS statistical precision is better than what one would expect from sqrt(N)
  - The forward electrons provide a more precise measurement, even with smaller statistics





EW Z production

- Electroweak production of Z boson, involving three diagrams
  - VBF, bremsstrahlung, multiperipheral
- Important benchmark to understand selection of forward jets and performance of additional veto on central jets
  - crucial for Higgs VBF analyses
- Signal is a Z boson plus two forward, well separated jets
  - analysis requires two good-quality, high-p_T, isolated, SFOS leptons, within 20GeV from nominal Z mass
  - two highest p_T jets within $|\eta|<4.7$ are used as tagging jets
- Main background is DY Z+2jets

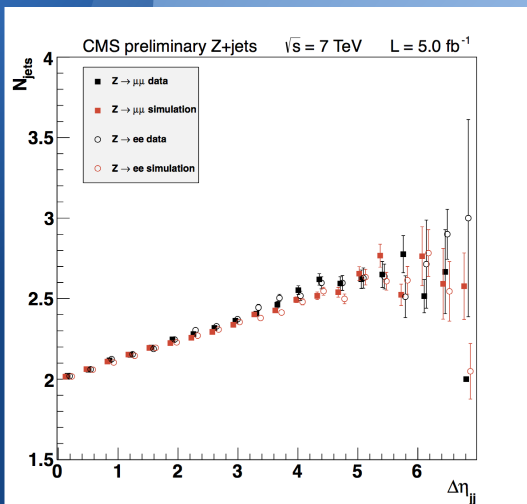
EW Z production

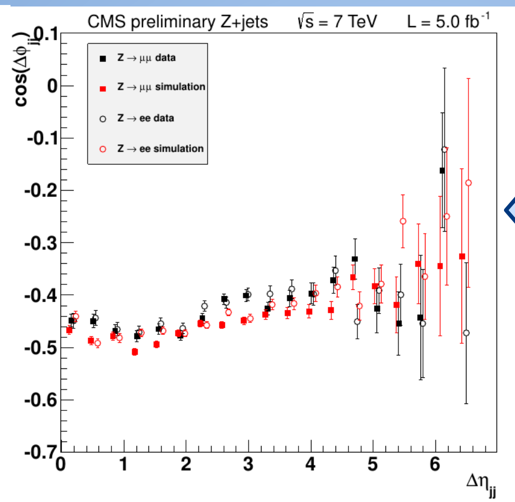
- Cross section extracted through template fit on two distributions
  - invariant mass of the tagging jets
  - neural network output (BDT)
- Neural network yields better precision on the signal fraction
- Main systematic is JES+JER
  - second largest is background modeling
- Observed cross section is in good agreement with NLO expectation (166fb)

$$\sigma^{\mathrm{EWK}}_{\mathrm{meas},\ \mu\mu+\mathrm{ee}} = 154 \pm 24(\mathrm{stat}) \pm 46(\mathrm{exp.syst.}) \pm 27(\mathrm{th.syst}) \pm 3(\mathrm{lumi})\ \mathrm{fb}$$

CMS-PAS-FSQ-12-019

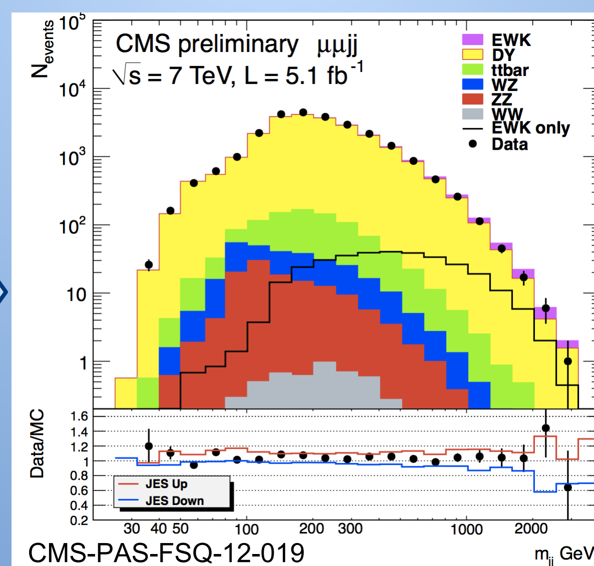
EW Z production

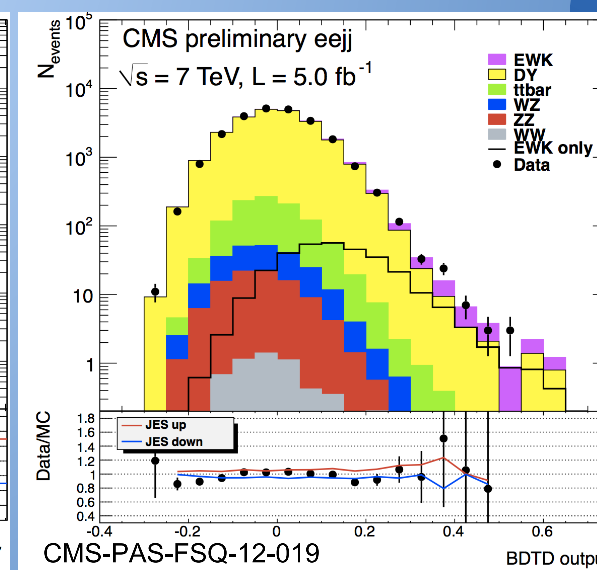




Measure detailed topology of selected events. E.g. average number of jets above 40GeV and phi separation of the two tagging jets, as a function of the eta separation of the tagging jets

m_{jj} and NN output distributions, used for signal cross section measurement. Free parameters in the template fit are the normalizations of the DY background and of the signal





Dibosons

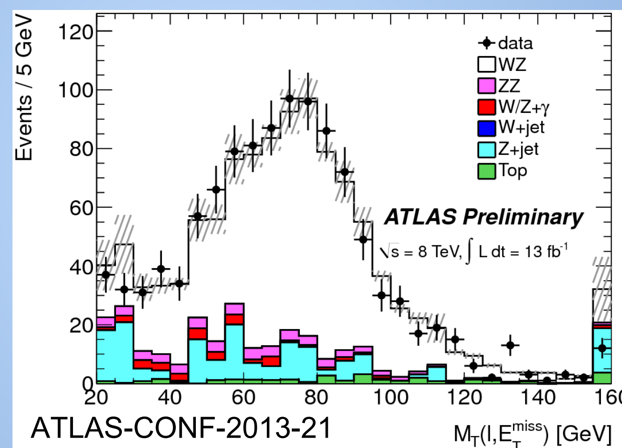
- Diboson production provides stringent tests of the electroweak sector of the SM
  - deviations from the prediction may indicate New Physics
- In addition, these processes are background to many other channels
  - e.g. Higgs decays to ZZ
- Main backgrounds are W/Z+jets, ttbar
- Uncertainties vary considerably depending on the specific analysis
  - ZZ analyses are limited by statistical uncertainty, main systematic is lepton ID and reco
  - systematics are larger in channels including a W or a photon, with main contributions coming from ID and reco, and background estimate

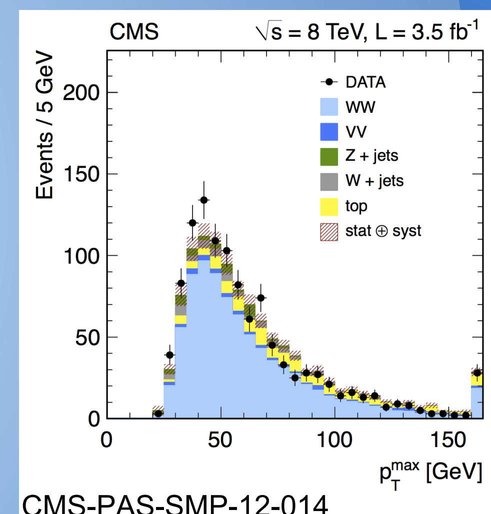
WW/WZ x-sec in leptonic decays

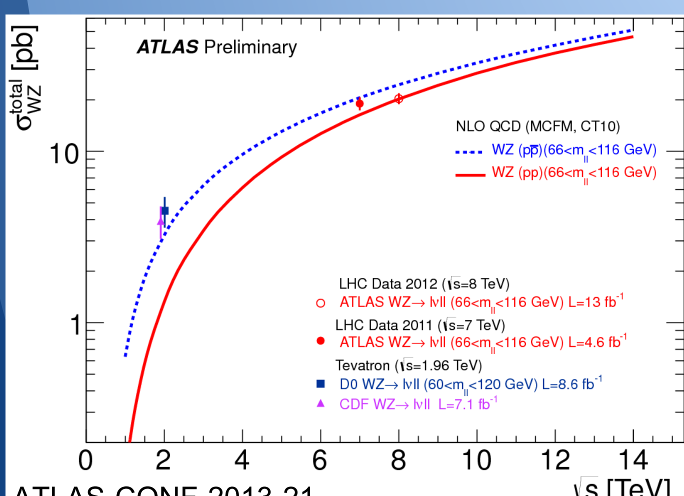
Channel	Atlas	CMS
WZ $\rightarrow \ell\nu\ \ell\ell$	4.6 fb^{-1} at 7 TeV * 13.0 fb^{-1} at 8 TeV	1.1 fb^{-1} at 7 TeV
WW $\rightarrow \ell\nu\ \ell\nu$	4.7 fb^{-1} at 7 TeV *	4.9 fb^{-1} at 7 TeV * 3.5 fb^{-1} at 8 TeV
ZZ $\rightarrow \ell\ell\ \ell'\ell'$	4.7 fb^{-1} at 7 TeV * 20.0 fb^{-1} at 8 TeV	4.9 fb^{-1} at 7 TeV * 5.3 fb^{-1} at 8 TeV

* aTGC limits

WZ and WW x-sec at ***8 TeV*** are systematically limited respectively by background and jet veto efficiency







CMS WW result slightly above expectations but still consistent

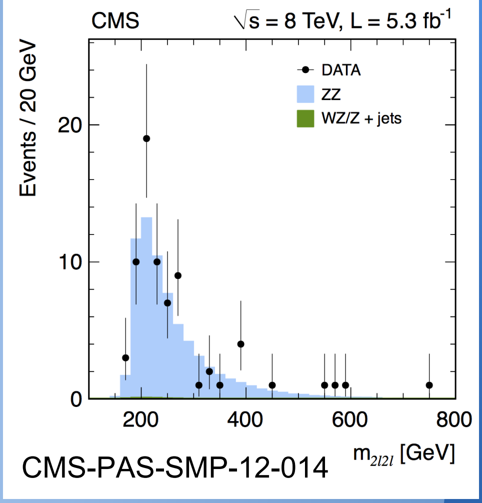
	$\sqrt{s}$	lumi	Measured σ_{total} [pb]	MCFM NLO [pb]
ATLAS	7 TeV	4.7 fb^{-1}	51.9 ± 2.0 (stat) ± 3.9 (sys) ± 2.0 (lumi)	$44.7^{+2.1}_{-1.9}$
CMS	7 TeV	4.9 fb^{-1}	52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lumi)	47.0 ± 2.0
	8 TeV	3.5 fb^{-1}	69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lumi)	$57.3^{+2.4}_{-1.6}$

ZZ x-sec in leptonic decays

ZZ events, and their fully leptonic decays, offer very clean final state

Results are still statistically limited

	√s	lumi	Measured σ_{total} [pb]	MCFM NLO [pb]	Z mass window in fiducial space
ATLAS	7 TeV	4.7 fb^{-1}	7.2 ± 1.4 (stat) ± 0.8 (sys) ± 0.4 (lumi)	6.5 ± 0.3	66 < m_{ll} <116 GeV
CMS	7 TeV	4.9 fb^{-1}	6.2 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lumi)	6.3 ± 0.4	60 < m_{ll} < 120 GeV
ATLAS	8 TeV	20.0 fb^{-1}	7.1 ± 0.4 (stat) ± 0.3 (sys) ± 0.2 (lumi)	7.2 ± 0.3	66 < m_{ll} < 116GeV
CMS	8 TeV	5.3 fb^{-1}	8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lumi)	7.7 ± 0.4	60 < m_{ll} < 120 GeV



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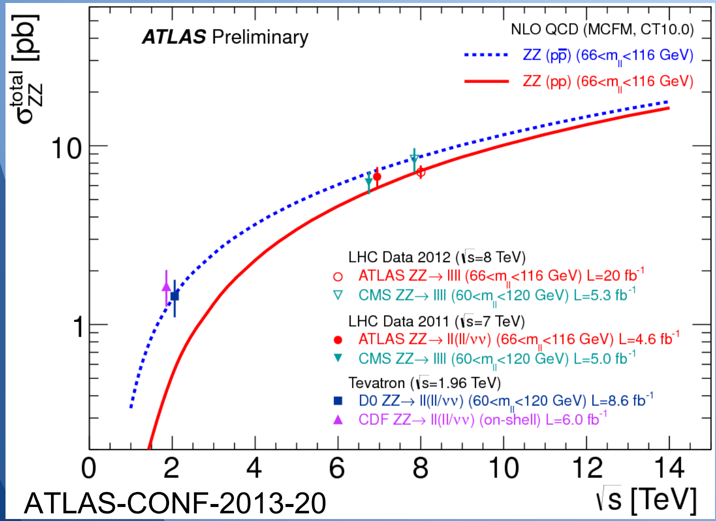

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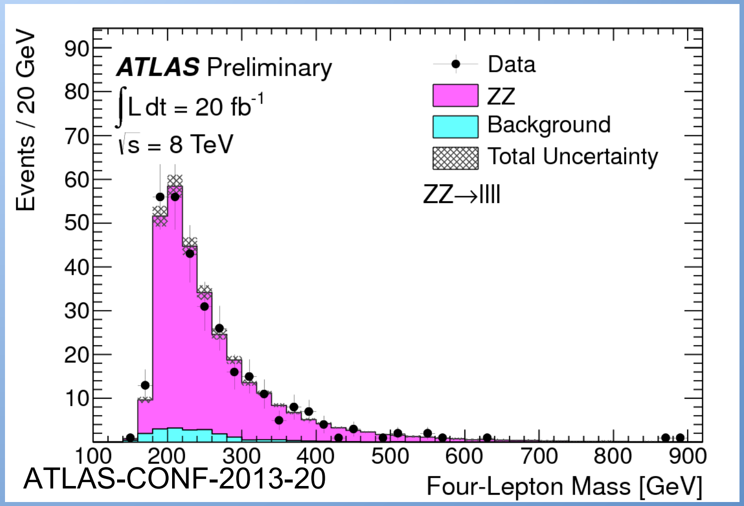

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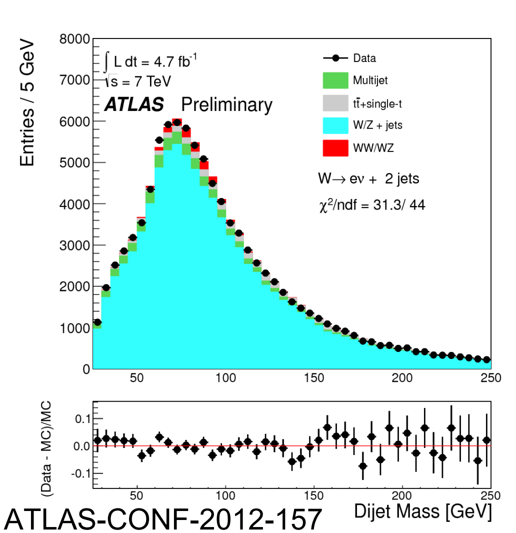
WW(WZ) x-sec in semileptonic decays



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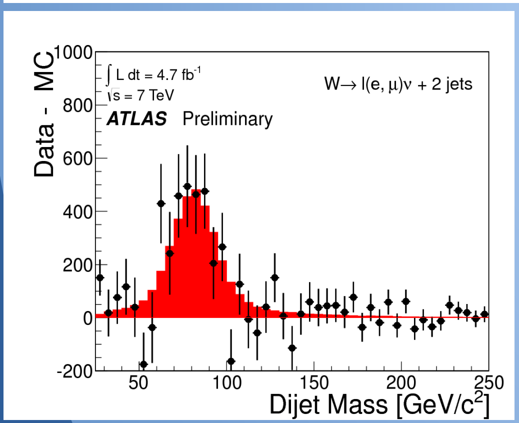


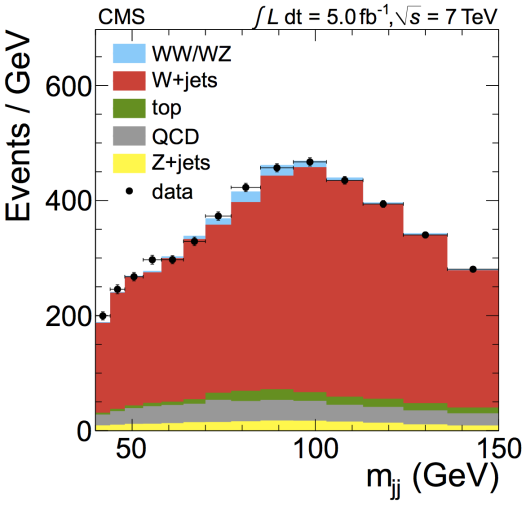
Look at events with one W decaying leptonically and a second boson (W or Z) hadronically

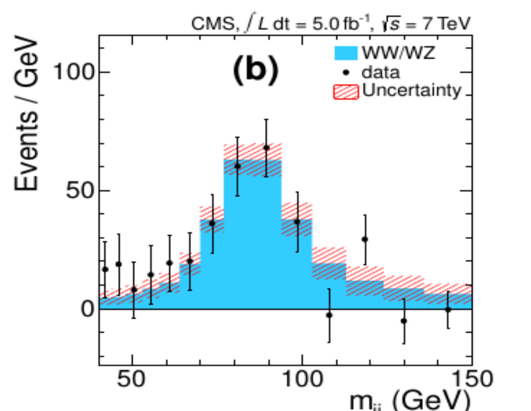
The main systematics are JES and W+jets background

Both ATLAS and CMS constraint normalization and shape of background in the fit.
CMS also constraints the JES to W mass

Measurements performed at ***7 TeV*** only

Results are in agreement with SM expectations





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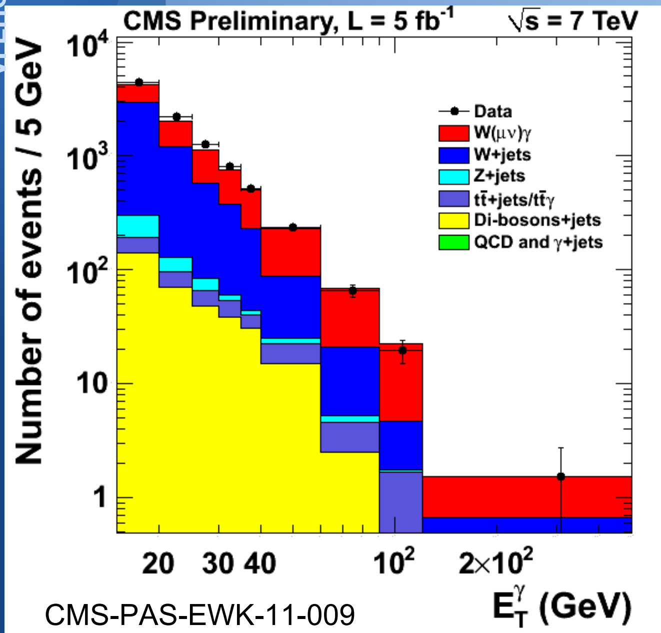
σ(WW + WZ)	measured (pb)	expected (pb)
ATLAS	72 ± 9 (stat.) ± 15 (syst.) ± 13 (MC stat.)	63.4 ± 2.6
CMS	68.9±8.7(stat.)±9.7(syst.)± 1.5 (lum.)	65.6 ± 2.2

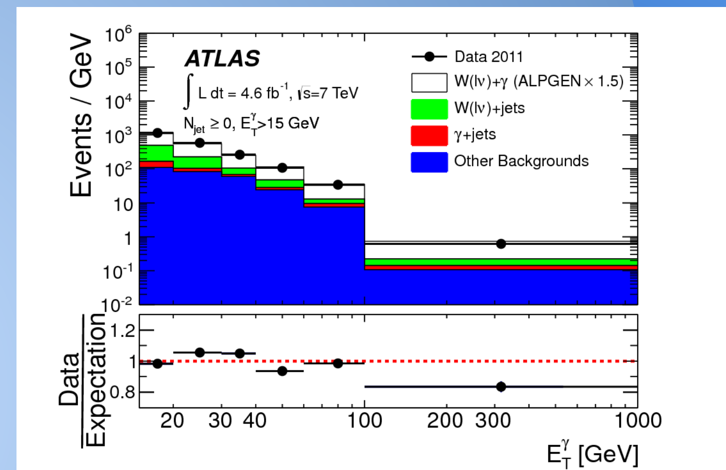
Wγ/Zγ



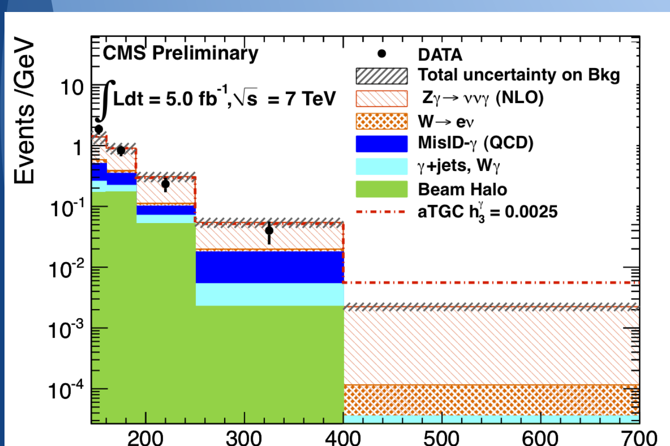
CMS-PAS-EWK-11-009

Measurements performed at ***7 TeV***

Look at events with one W or one Z decaying leptonically and an isolated photon

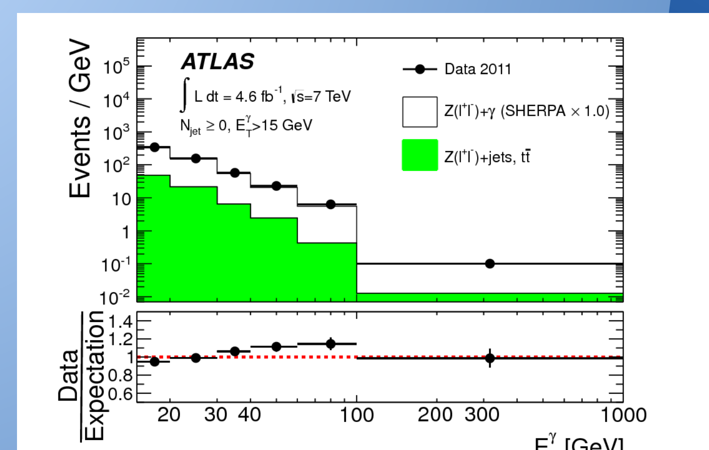


arXiv:1302.1283



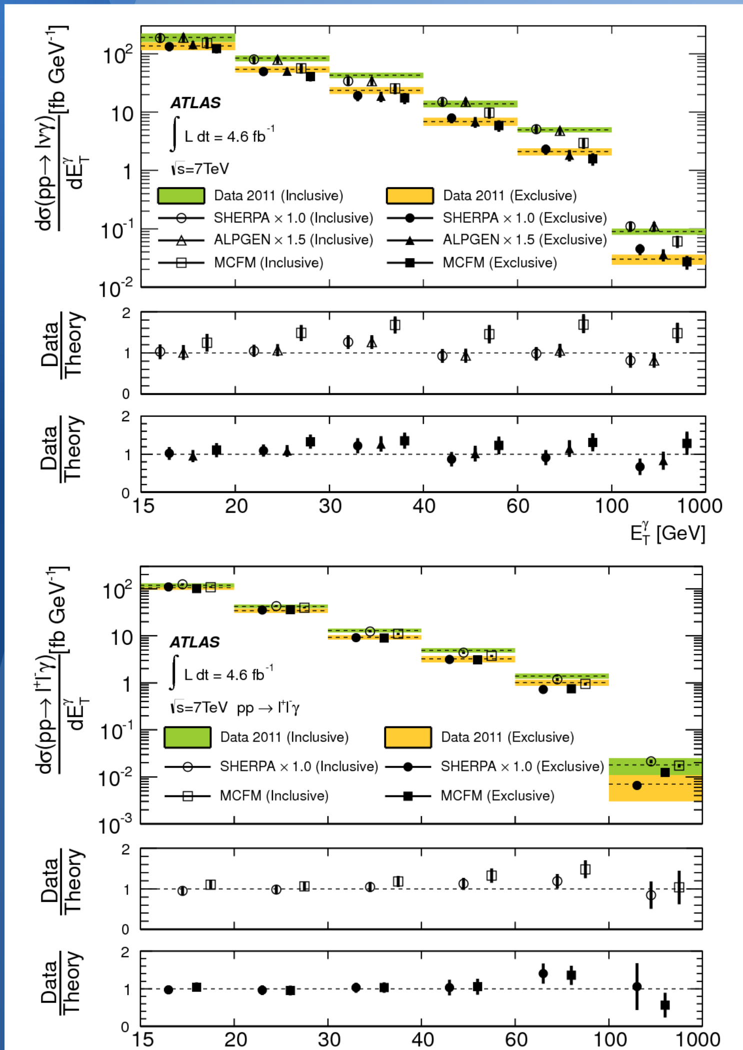
CMS-PAS-SMP-12-020

The final state with the Z decaying into neutrinos and an isolated photon is also considered



arXiv:1302.1283

Wγ/Zγ



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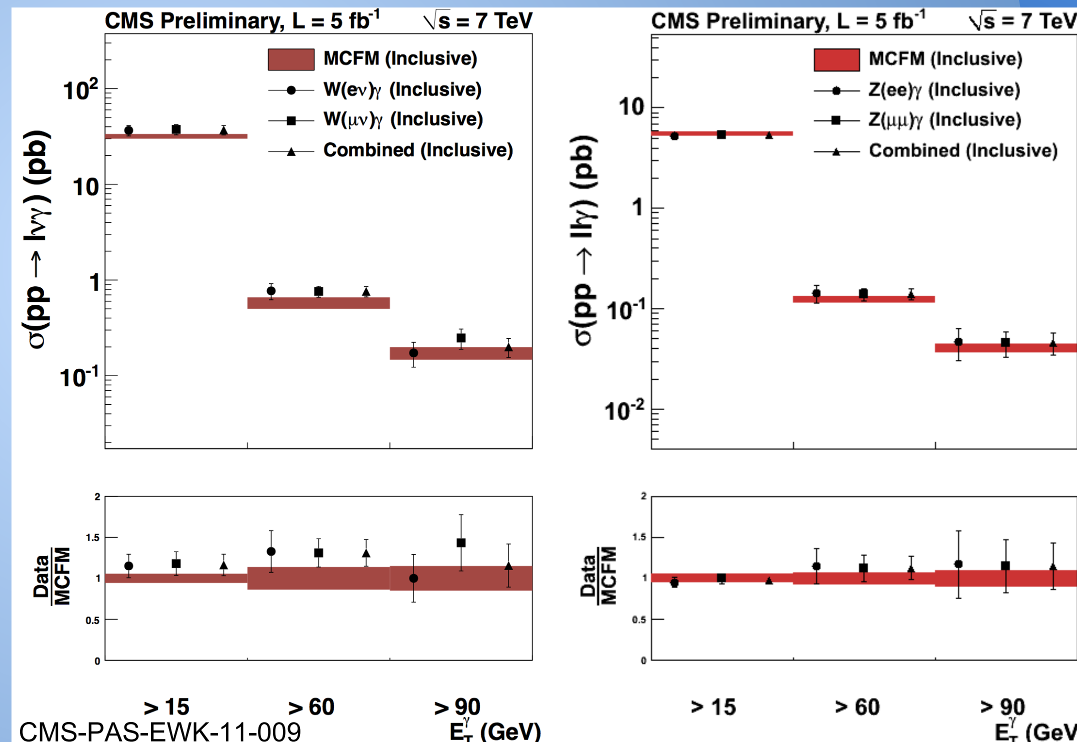
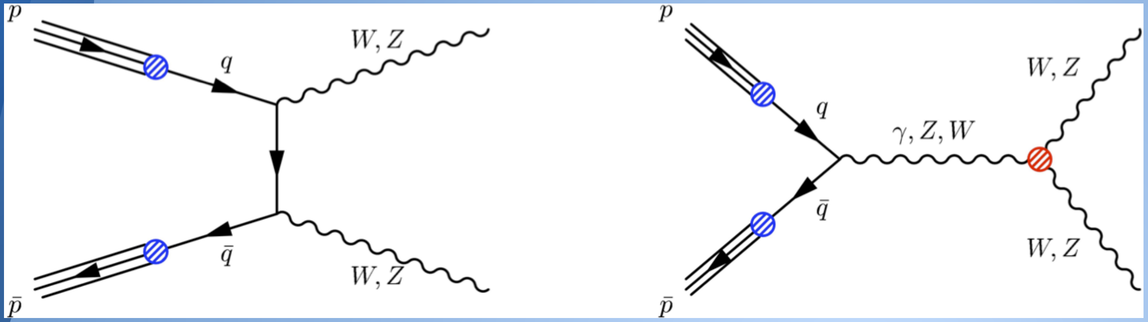


CMS-PAS-EWK-11-009

Results are in good agreement with generator predictions
MCFM slightly lower for Wγ results both in ATLAS and CMS

aTGCs



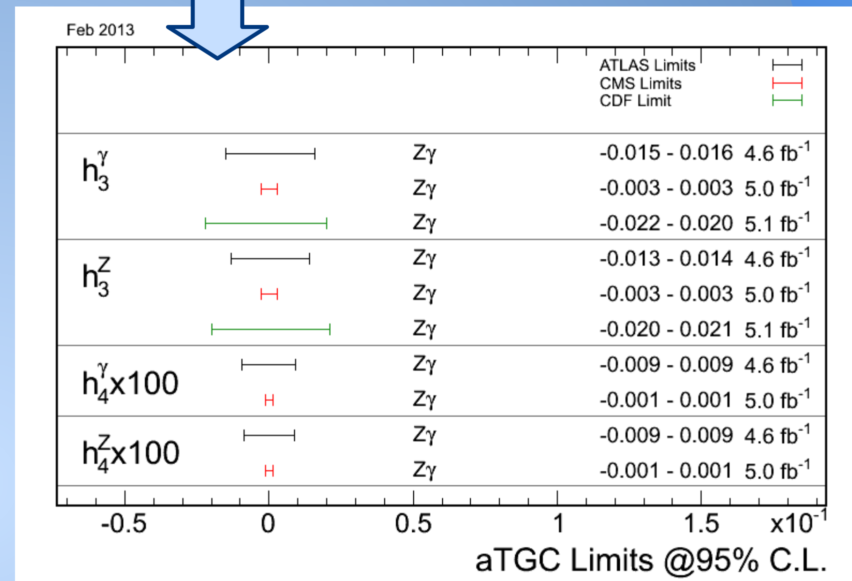
Coupling	Parameters	Channel
WWγ	λ_γ, $\Delta\kappa_\gamma$	WW,Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW,WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ

- Triple gauge couplings in SM:
    - Charged triple gauge couplings (WWZ, WW) **allowed**
    - Neutral triple gauge couplings (ZZZ, ZZγ) **forbidden**
- aTGCs modify total production rate as well as event kinematics.
- Maximum likelihood fit is done, leaving one (or two) of the aTGC parameter free.
- Form factor used in old results: $\Delta g(s) = \Delta g/(1+s/\Lambda^2)^2$ for recent we have $\Lambda=\infty$

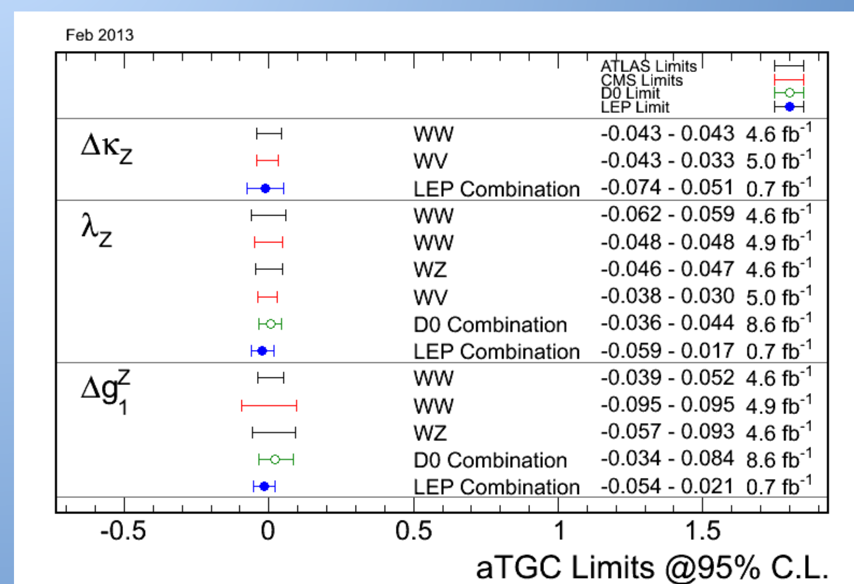
$Z\gamma \to ll\gamma$ and $Z\gamma \to \nu\nu\gamma$ combined to improve limits on neutral aTGC
CMS Limits are tighter due to 400 GeV p_T threshold of last bin in the $\nu\nu\gamma$ channel, which drives the limit

aTGCs

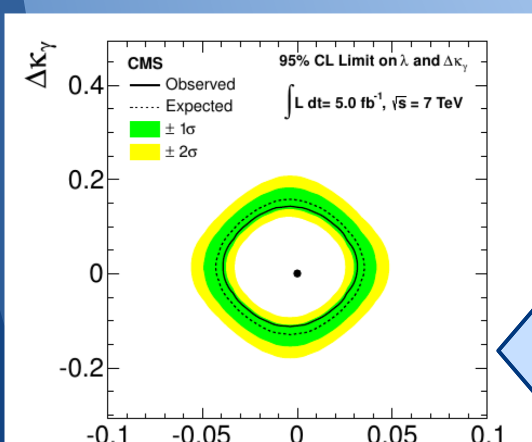
Cross section measurements described in the previous slides can be interpreted in terms of potential contributions from aTGCs



Results for charged aTGC are similar for ATLAS and CMS



CMS also published limits with $WW \to l\nu jj$ ($\Delta g_1^Z = 1$)



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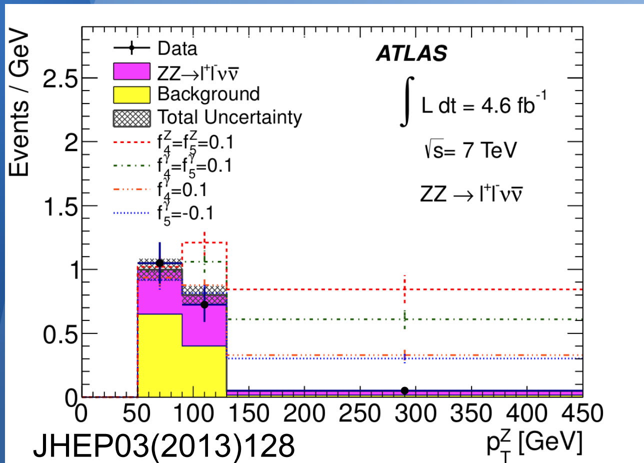
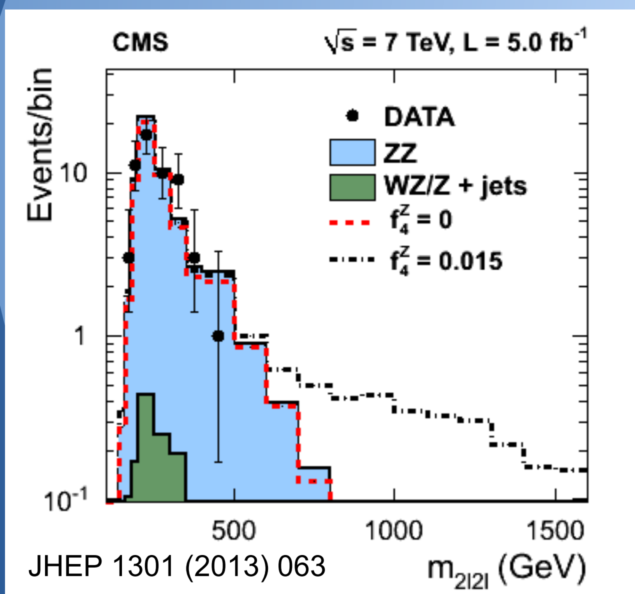
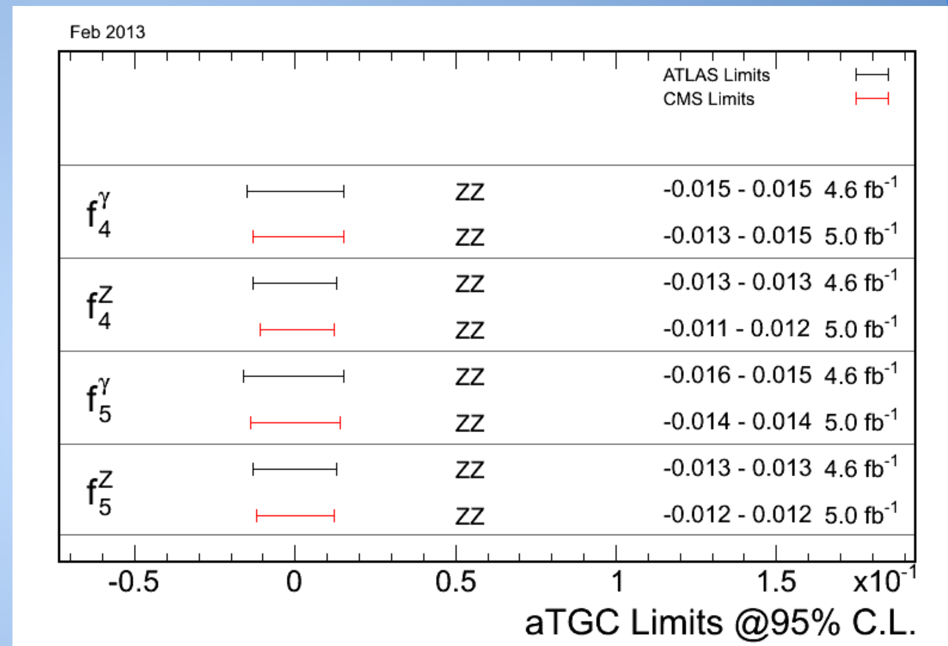
neutral aTGC from ZZ







ATLAS: $ZZ \to l^+l^-l^+l^-$ and $ZZ \to l^+l^-\nu\nu$ (limit from p_T^Z)

CMS: $ZZ \to l^+l^-l^+l^-$ (limit from m_{ZZ})

No evidence of deviations found

Conclusions

- LHC data provides a wealth of information concening the SM
  - In particular its EW sector
- Physics of the W and Z bosons plays a crucial role in the exploitation of this huge potential
  - both single- and di-boson production
- With the present statistics and with the experimental systematics under control, it becomes possible to use these analyses to probe other areas of the SM
  - PDFs
  - weak mixing angle

Discussion

wma systematics

- Differences in the experimental method are reflected in the systematics
  - precision on weak mixing angle in ATLAS is largely driven by the forward-electrons channel
    - wrt central electrons, it only has about 1/3 of the total events, but the statistical error is 2/3
    - drawback is that detector-related systematics are larger (e.g. electron energy scale)
  - CMS systematics due to FSR much larger than for ATLAS
    - could this be due to using only muons?
- In general, the measurement is dominated by systematics
  - more importantly, it is dominated by ***theory*** systematics
    - PDF
    - QCD/EW NLO

wma systematics

ATLAS

Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	9	5	9	7
MC statistics	9	5	9	4
Electron energy scale	4	6	–	4
Electron energy smearing	4	5	–	3
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

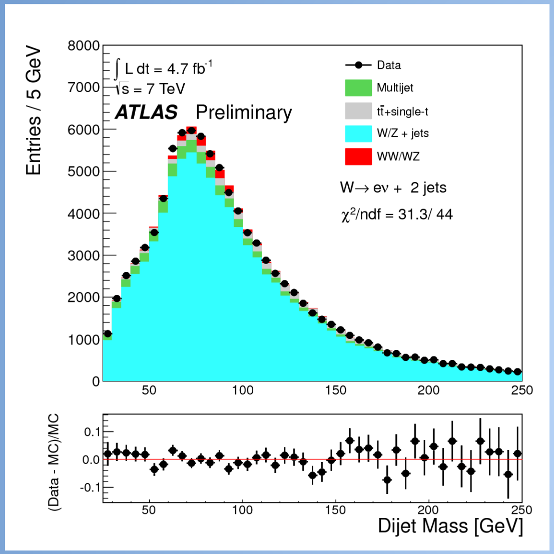
CMS

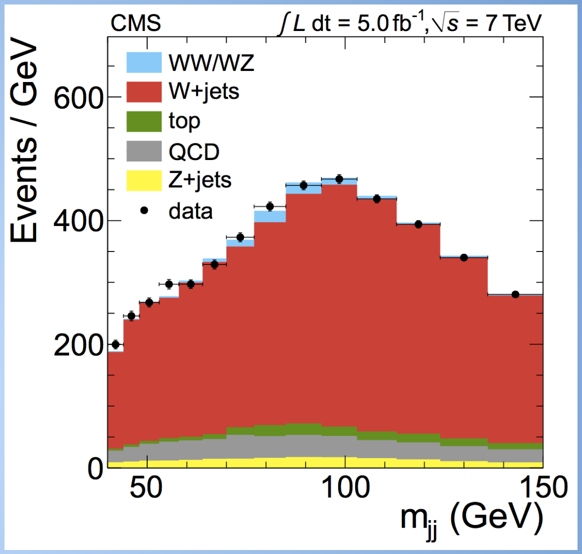
source	correction	uncertainty
PDF	-	± 0.0013
FSR	-	± 0.0011
LO model (EWK)	-	± 0.0002
LO model (QCD)	$+0.0012$	± 0.0012
resolution and alignment	$+0.0007$	± 0.0013
efficiency and acceptance	-	± 0.0003
background	-	± 0.0001
total	$+0.0019$	± 0.0025

wma systematics

- Not clear how to improve the measurement in the future
  - will the "analytical folding" procedure à la CMS be still doable with improved statistical precision?
  - template fits à la ATLAS require a generator capable of changing the effective wma value without altering the masses of the bosons
- Both measurements rely heavily on LO generator (Pythia)
  - but NLO QCD has a large effect, so one should probably move to NLO generators
  - with improved statistics, NLO EW will also become relevant
  - **how to define the quark-lepton angle in an NLO world?**

W+jets background systematicys on WW measurement





The shape of the W+jets bkg is taken from MC with ME+PS (LO)

- uncertainty is modeled changing ren/fac scale and matching parameters
- scale variations in LO MC are known to be very large compared to data
- problem is not the rate but shape and exclusivity of the selection
- uncertainty will be smaller using NLO ME+PS generators?

aTGC and aQGC

Results on aTGC are still dominated by statistical errors

- current constraints on charged aTGCs < 10%
  - already improved over LEP on several parameters
- expected to reach few % at 8 TeV

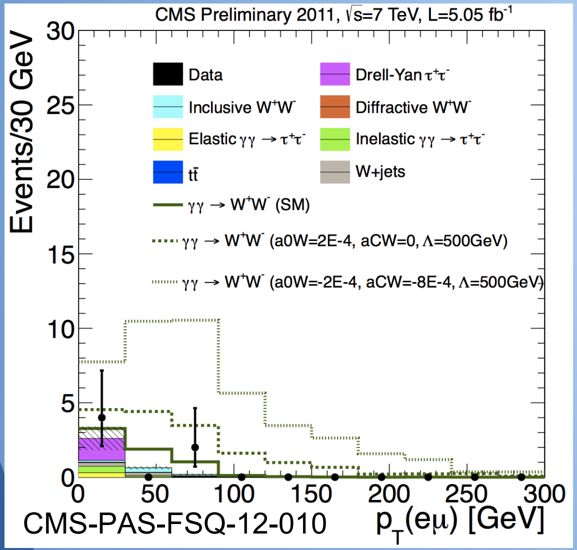
Perspectives on aQGC

- can be measured from
  - tri-bosons final states
  - Vector Boson Scattering
- SM cross-sections are ~2 order of magnitude lower than dibosons
- Theoretical interpretation of anomalies is much more difficult
  - quartic couplings expected also from aTGC
  - unitarity is violated quite soon → add form factor

$\gamma\gamma \to WW$

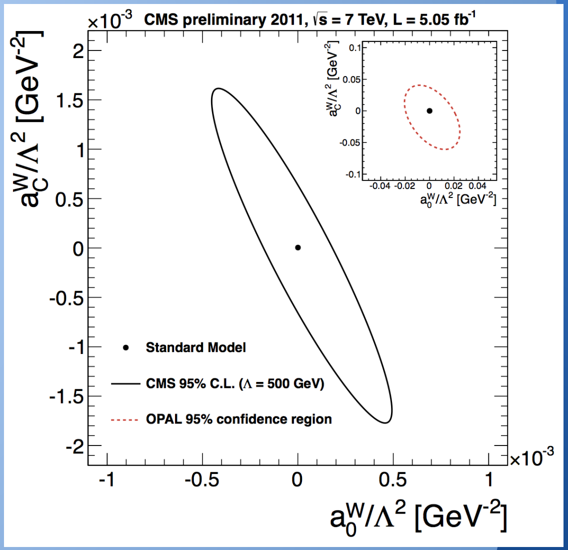
Search for eμ events with no additional tracks

- aQGC enhance x-sec at high p_T(eμ)
- results on 5 fb^{-1} of 7 TeV data
  - 2 events with p_T(eμ) > 30 GeV compatible with SM



no events with p_T (eμ) > 100 GeV

Limits on aQGC with Λ=500 GeV about 2 order of magnitude better than LEP



Without form factor the limit is much smaller, but dominated by the high energy $\gamma\gamma$ region ~ 1 TeV that is above the unitarity bound

Backup

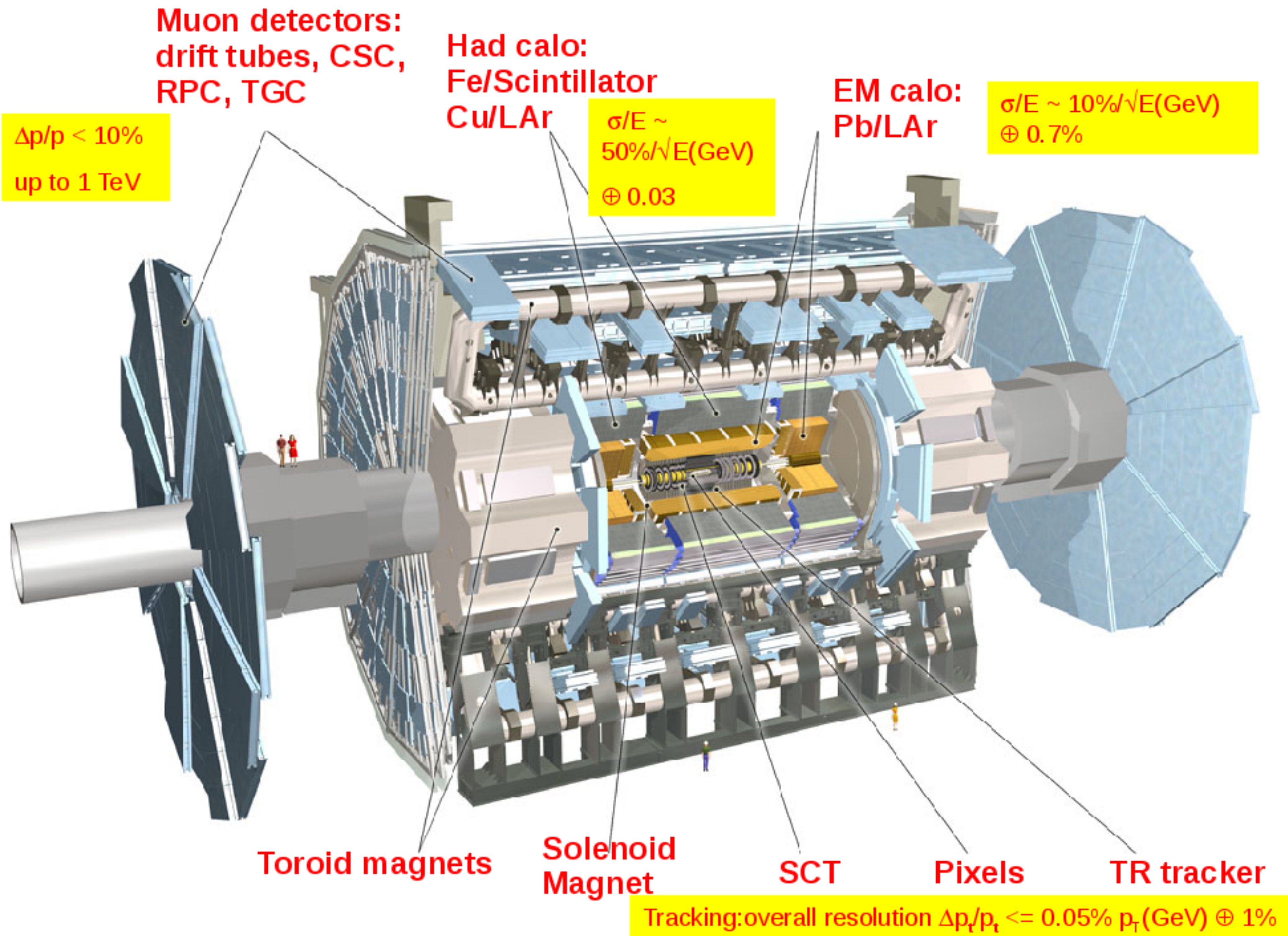
SM and the wma

- SM only needs three input parameters
  - All other observables can be predicted from these
- The most common prescription uses the Z mass, the fine structure constant and the Fermi constant
  - In this context, wma and the W mass can be calculated (given some value of m_t and m_H)
- At tree level, all is nice and simple
  - The problem arises when incorporating higher orders
  - Depending on where one decides to “hide” HO contributions in the formulas, one ends up having different predictions for the calculated quantities, with different dependence on m_t
- A striking consequence of this is that the PDG lists not one, but ***FIVE*** different possible values of the weak mixing angle

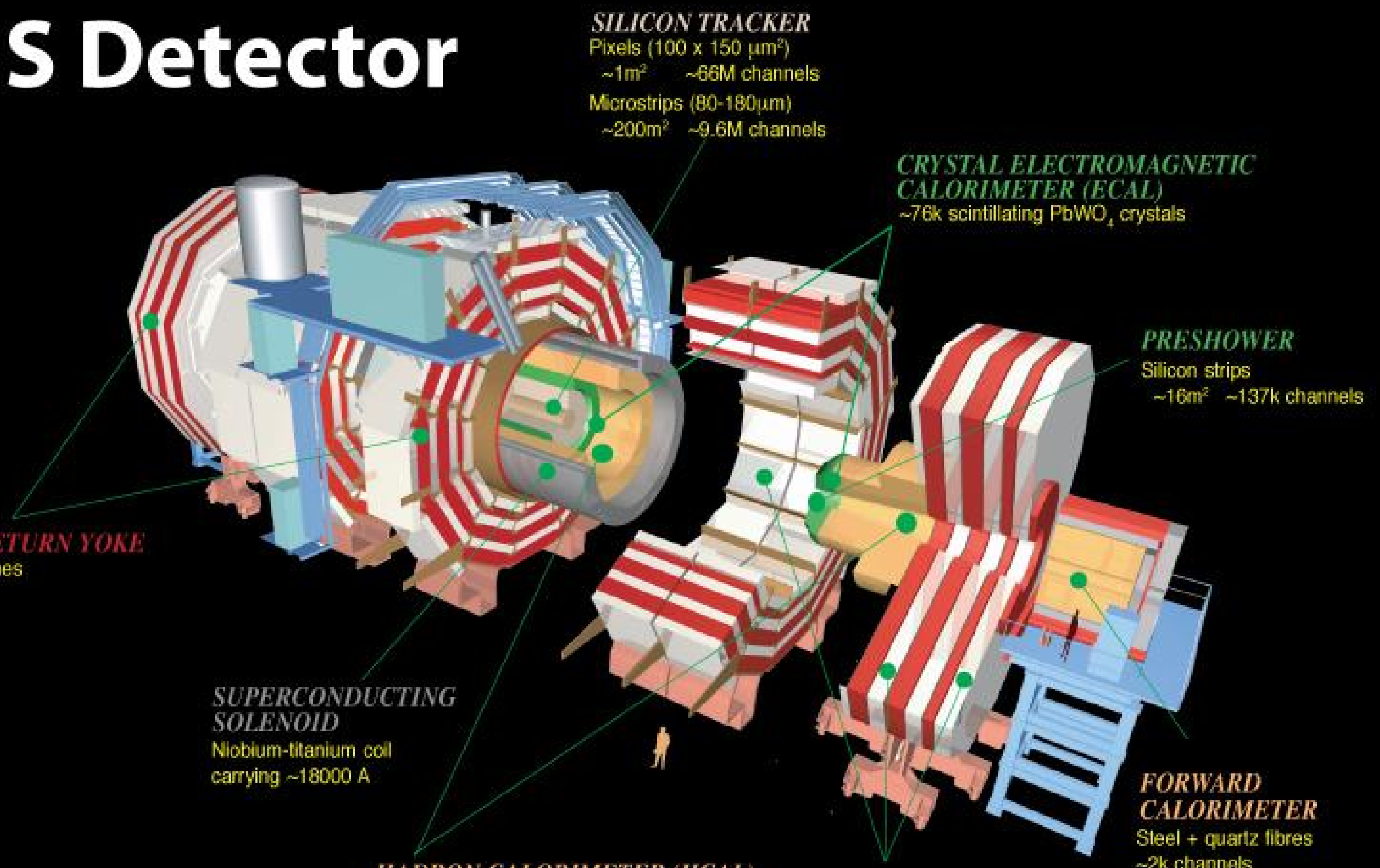
SM and the wma

- The most relevant normalization scheme for Z-A_{FB} measurements is the Effective one, since it is directly related to the coupling of Z to fermions
- Bulk of EW corrections is absorbed into *effective* couplings
- One then defines an *effective* weak mixing angle in such a way that the new couplings are proportional to the tree-level ones
    - The predictions for the asymmetries stay formally identical to the tree-level expressions, modulo using the effective angle [illegible]

Scheme	Notation	Value
On-shell	s_W^2	0.2233
NOV	$s_{M_Z}^2$	0.2311
$\overline{\text{MS}}$	$\hat{s}_Z^2$	0.2313
$\overline{\text{MS}}$ ND	$\hat{s}_{\text{ND}}^2$	0.2315
Effective angle	$\bar{s}_f^2$	0.2316


Muon detectors: drift tubes, CSC, RPC, TGC
Δp/p < 10% up to 1 TeV
Had calo: Fe/Scintillator Cu/LAr
σ/E ~ 50%/√E(GeV) ⊕ 0.03
EM calo: Pb/LAr
σ/E ~ 10%/√E(GeV) ⊕ 0.7%
Toroid magnets
Solenoid Magnet
SCT
Pixels
TR tracker
Tracking:overall resolution Δp_t/p_t <= 0.05% p_T(GeV) ⊕ 1%

CMS Detector



Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T