Multi Vector Boson Physics (@LHC)

UK-HEP Forum 2016

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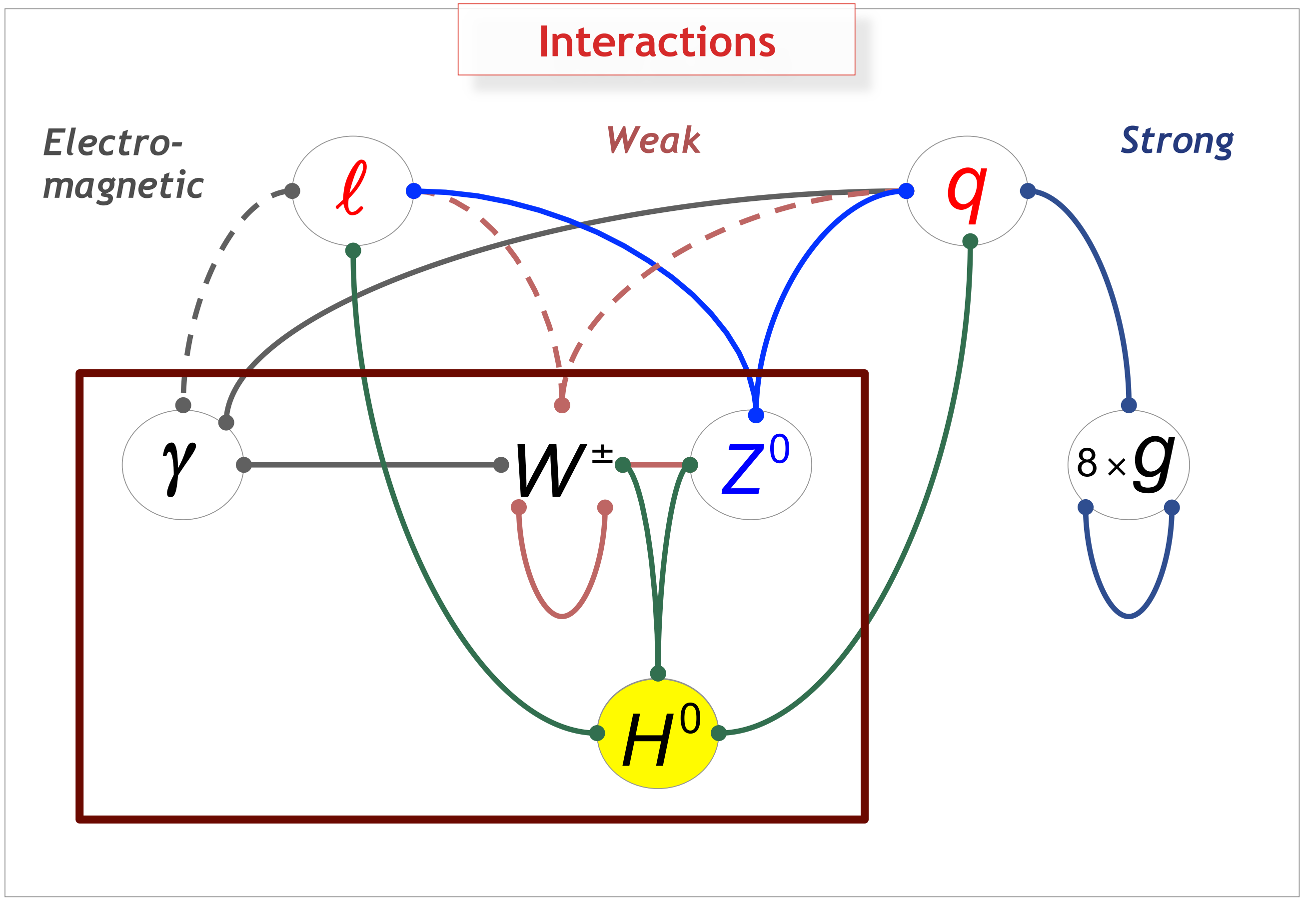


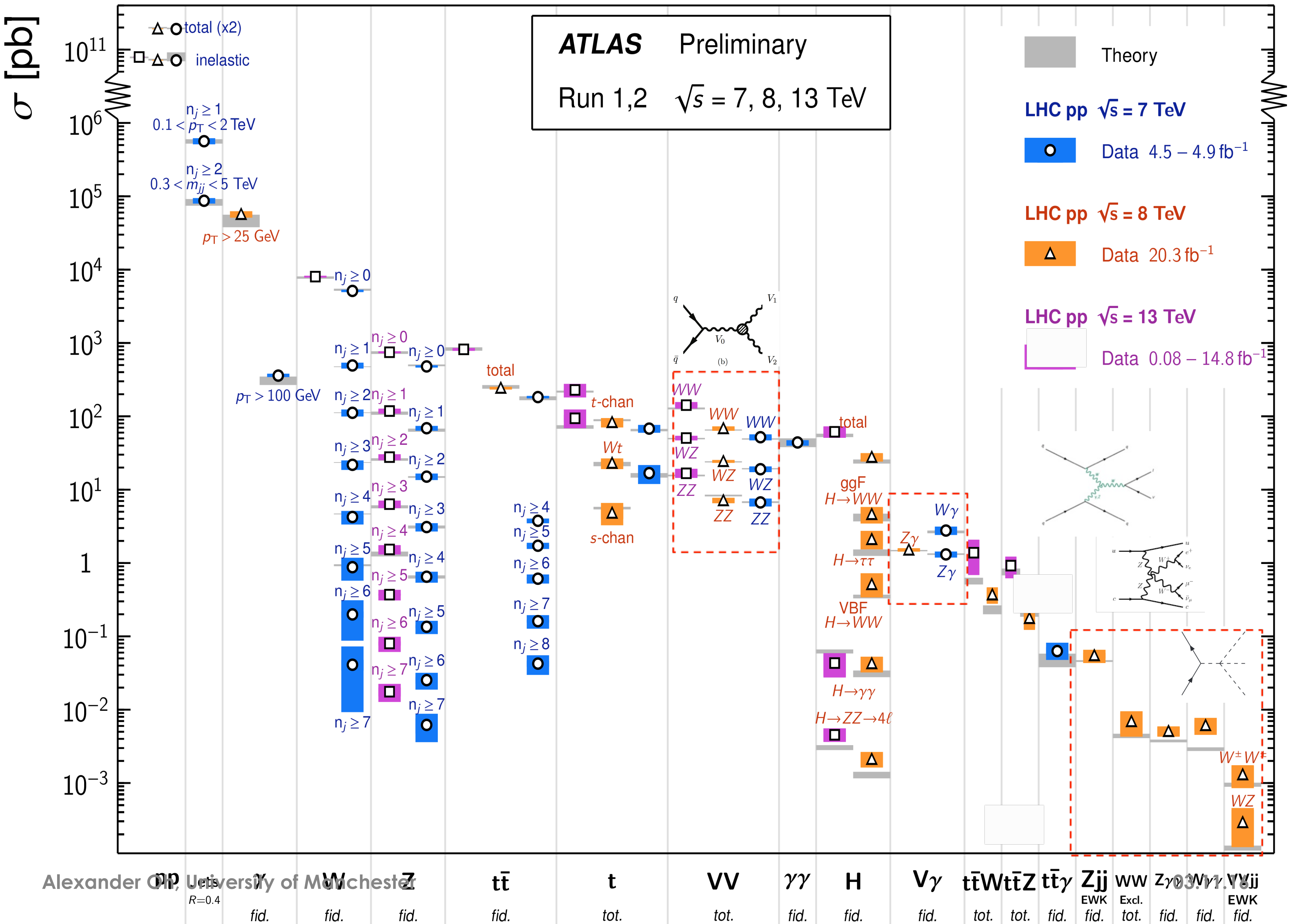
Main sources for this talk:

MBI workshop Wisconsin (Aug 2016)
https://agenda.hep.wisc.edu/event/965/other-view?view=standard

LHC SM EWK group meetings:
https://indico.cern.ch/category/3290/

Standard Model Production Cross Section Measurements

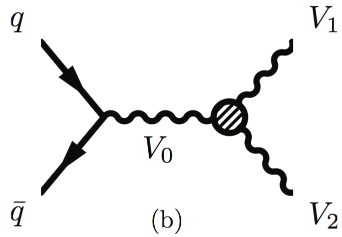
Status: August 2016

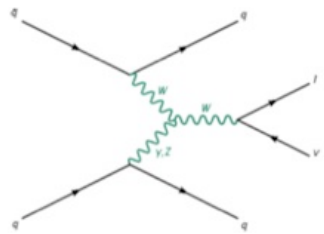


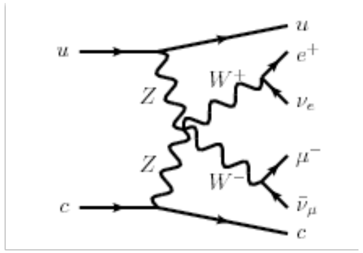
Introduction

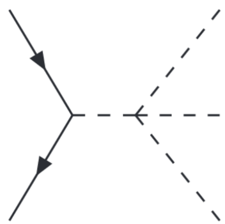
Multi-boson production is a $O(10^{-3}\text{-}10^{0})$pb process.

- **Probes the electro-weak gauge symmetry of the SM.**
  - Measure "fiducial" cross sections to minimize the dependence on theoretical predictions.
  - Determination of **Gauge Boson Couplings** provide a model independent test for "new" physics.
  - Sensitivity increases with energy reach.
- **Production Processes**
  - Inclusive di-boson
  - Vector boson fusion
  - Vector boson scattering / exclusive
  - inclusive tri-boson



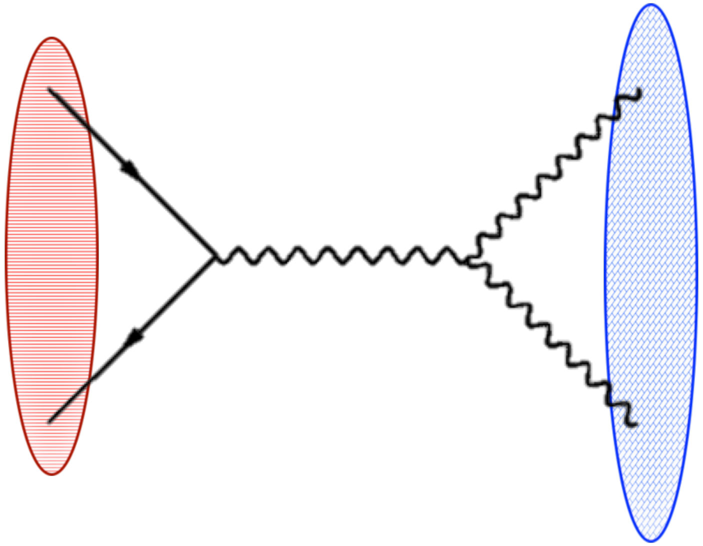






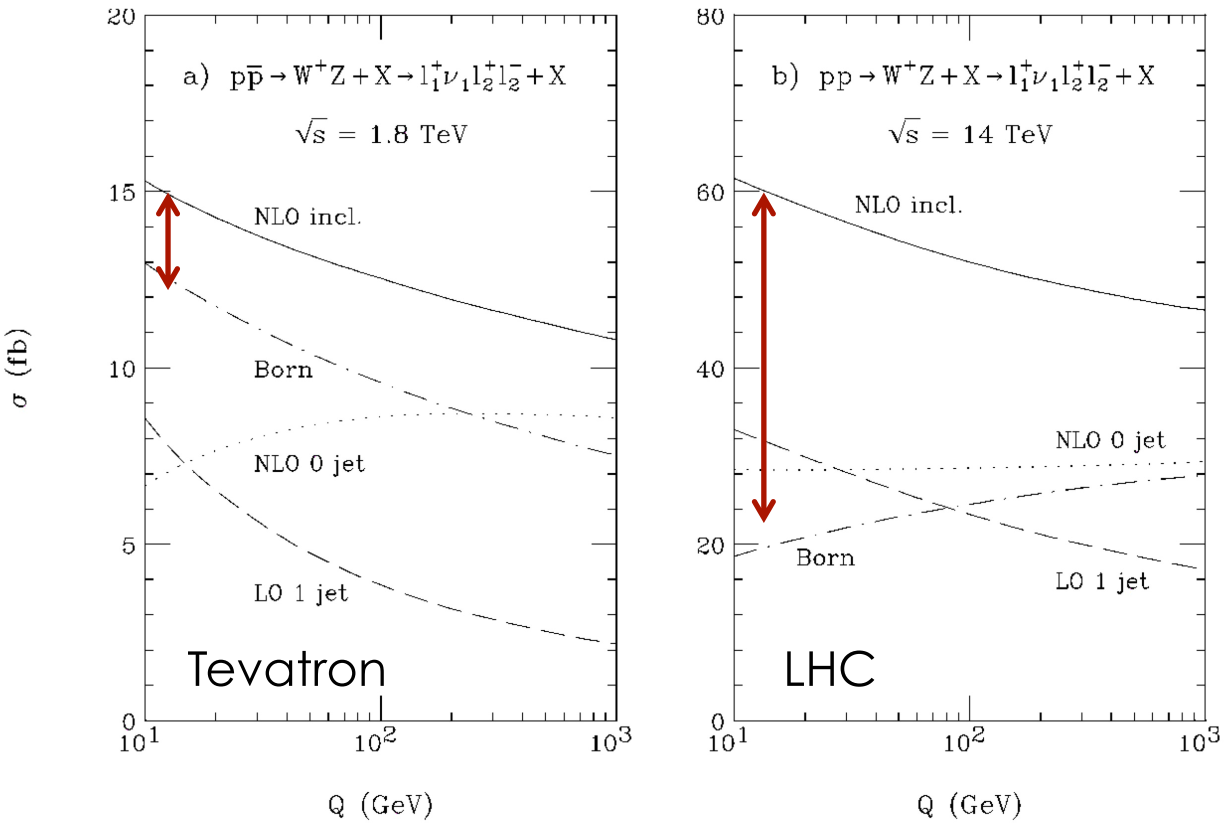
Calculations

- Pre-LHC era:
  - Initial state, LO PDF (ppbar).
  - Final state, 2 massive vector boson, little phase space for additional emissions.
  - **Higher order corrections thus small!**



Calculation

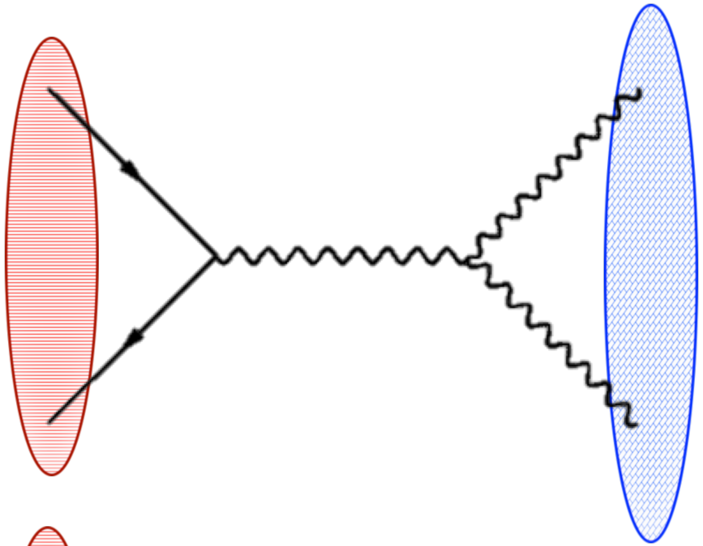
- Things look different at the LHC...

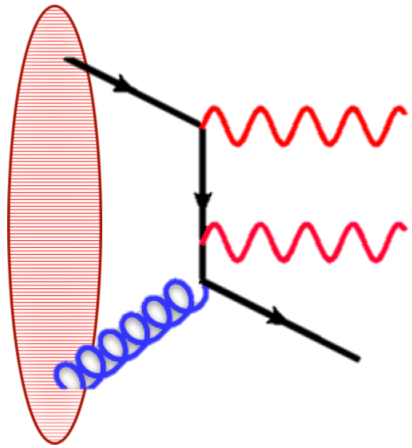


https://arxiv.org/abs/hep-ph/9503389v2

Calculations

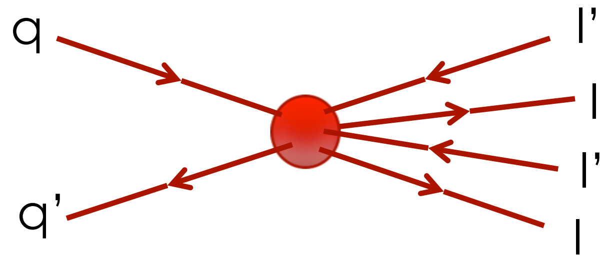
- LHC era:
  - Initial state, LO PDF disfavored (pp).
  - Final state, 2 massive vector boson, lots of phase space for additional emissions.





- **Higher order corrections are important.**
  - **gq!**

Calculations



- Treatment of the hard-process:
  - **On-shell VV' production.**
    - (+) Total cross-section.
    - (-) no treatment of decays.
  - **Narrow width approximation (production + decay at pole-mass).**
    - (+) includes physics final state (+ spin correlations)
    - (-) neglects off-shell effects
  - **(Double-)pole approximation.**
    - (+) includes off shell effects and phase space
    - (–) matrix elements include only resonant parts, no interferences
    - (+) PA only for virtual NLO corrections (HERWIG++)
  - **Full calculation.**
    - (+) includes off-shell effects, irreducible background, interferences
    - (–) complicated calculation, depends on final state

Calculations

- QCD NNLO and NLO EW available for di-boson processes:

State-of-the-art predictions:

$W\gamma/Z\gamma$ (full calculation with leptonic decays)

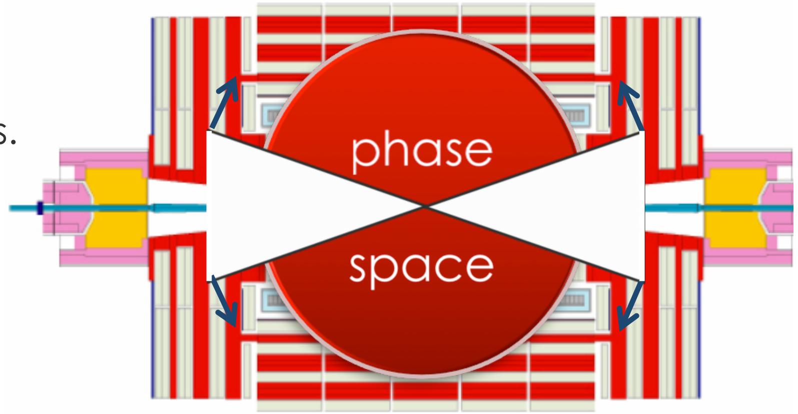
- NNLO QCD — Grazzini, Kallweit, Rathlev '14,'15
- NLO EW — Denner, Dittmaier, Hecht, Pasold '14, '15

WW, WZ, ZZ

- NNLO QCD — including leptonic decays
  - ZZ (distributions) — Cascioli et al. '14; Grazzini, Kallweit, Rathlev '15
  - WW (distributions) — Gehrmann et al. '14; Grazzini, et al. '16
  - WZ (inclusive rates) — Grazzini, et al. '16
  - $gg \to VV \to 4$ leptons — Binoth et al. '05, '06
    + NLO corrections for on-shell V's — Caola et al. '15
- NLO EW — inclusion of decays non-trivial
  - stable W/Z bosons — Bierweiler, Kasprzik, Kühn, Uccirati '12, '13; Baglio, Le, Weber '13
  - approximative inclusion in HERWIG++ (via correction factor) — Gieseke, Kasprzik, Kühn '14
  - $pp \to WW \to 4$ leptons in DPA — Billoni, Dittmaier, Jäger, Speckner '13
  - full off-shell calculation — Biedermann et al. '16

Observables

- **Total cross sections:**
  - Almost no ambiguity when comparing experiments.
  - Theory dependence on extrapolation to full phase space.
- **Fiducial cross sections:**
  - **Minimize theory uncertainties due to phase-space extrapolations.**
  - Define a "fiducial volume" mimicking the detector acceptance.
  - Definition in terms of final state truth particles after showering
    - Charged lepton and photon kinematics.
    - Neutrino transverse energy
    - Vector boson mass calculated from leptons.
  - Leptons are "redressed" with brem photons in ΔR=0.1.
  - Allows theorists to test their favorite model.

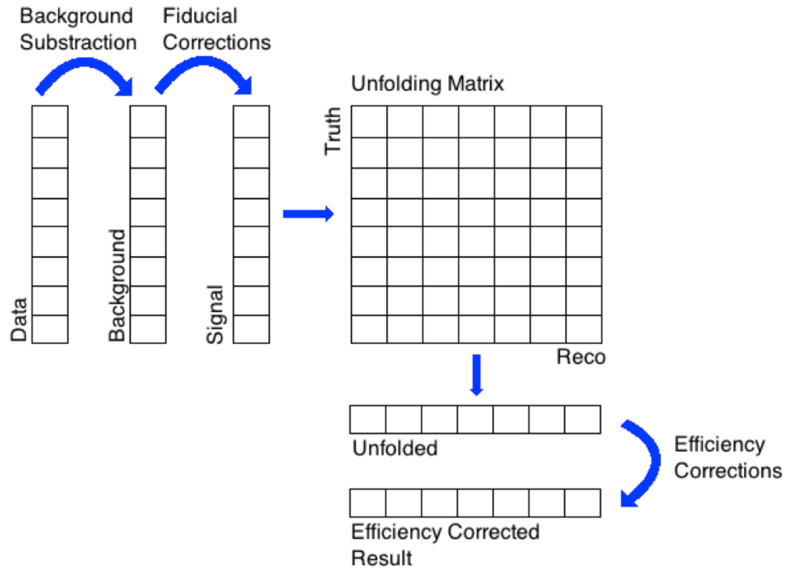


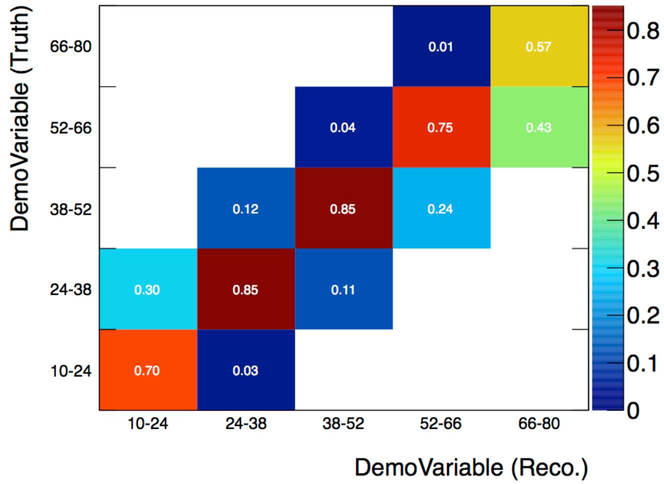
$$\sigma_{Fiducial} = \frac{N_{Obs} - N_{Bkg}}{C \times L}$$

$$C = \frac{N_{MC}^{Reco}}{N_{MC\,Truth}^{Pass\,Fiducial}}$$

Observables

- **Unfolded kinematic distributions:**
- Remove **detector effects** to allow independent interpretation of Data.
- Commonly used method
  - Bayesian iterative unfolding.
  - Unfolding within detector acceptance.
  - Normalised distributions.
- **Published Results (HEPDATA):**
  - Fractional, binned kinematic distributions.
  - Full correlation matrices.
  - Statistical and systematic uncertainties, background contributions.
- In principle can combine experiments.
  - LHC EWK WG working on conventions.



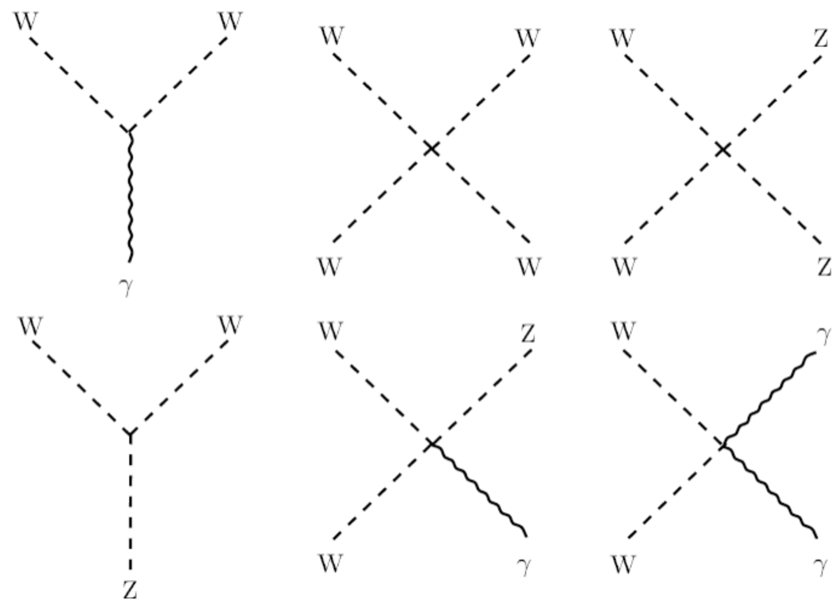


Interpretation

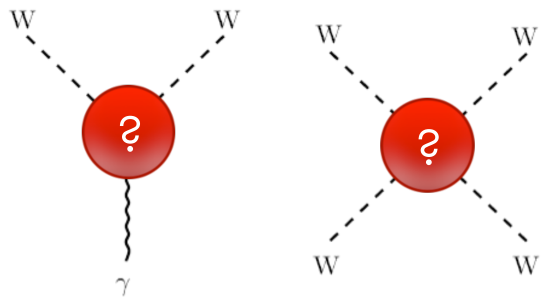
- **Beyond standard models to address**
  - Dark Matter candidate
  - CP asymmetry
  - Neutrino masses
  - Hierarchy problem
  - …
- **Effective Field Theory (EFT) approach**
  - We have the tools for precise SM calculations.
  - We have BSM extension to test against.
  - With EFT parameterize the unknown.
    - Largely model independent.

$$\mathcal{L}_{\mathrm{EW}}^{\mathrm{e},\nu_e} = \bar{\chi}_L \gamma^\mu [i\partial_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\mathbf{W}_\mu - g'\frac{Y}{2}B_\mu]\chi_L$$
$$+ \bar{e}_R \gamma^\mu [i\partial_\mu - g'\frac{Y}{2}B_\mu] e_R$$
$$- \frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}.$$

SM vector boson self-interaction term



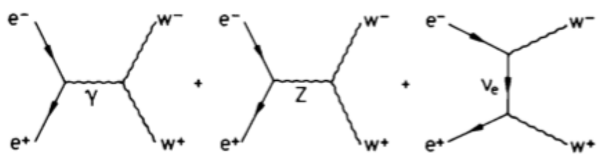
$$\mathcal{L}_{\rm EW}^{{\rm e},\nu_e} = \bar\chi_L\gamma^\mu[i\partial_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\mathbf{W}_\mu - g'\frac{Y}{2}B_\mu]\chi_L + \bar e_R\gamma^\mu[i\partial_\mu - g'\frac{Y}{2}B_\mu]e_R - \frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}.$$



Add additional interactions in the vertex*,
e.g. Hagiwara et al. Nucl. Phys. B282 1987, 253-307:

$$i\bar g_1^V\left(\mathcal{W}^+_{\mu\nu}\mathcal{W}^{-\mu} - \mathcal{W}^-_{\mu\nu}\mathcal{W}^{+\mu}\right)\mathcal{V}^\nu + i\bar\kappa_V\mathcal{W}^+_\mu\mathcal{W}^-_\nu\mathcal{V}^{\mu\nu} + i\frac{\bar\lambda_V}{M_W^2}\mathcal{V}^{\mu\nu}\mathcal{W}^{+\rho}_\nu\mathcal{W}^-_{\rho\mu},$$

but the subtle SM gauge cancellation fails



*Require: SU(2)xU(1) & EM gauge invariance, C,P

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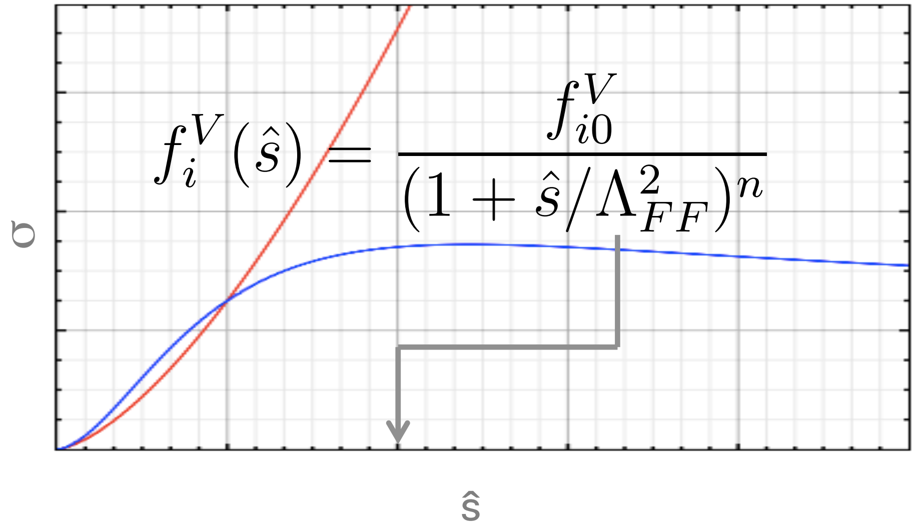
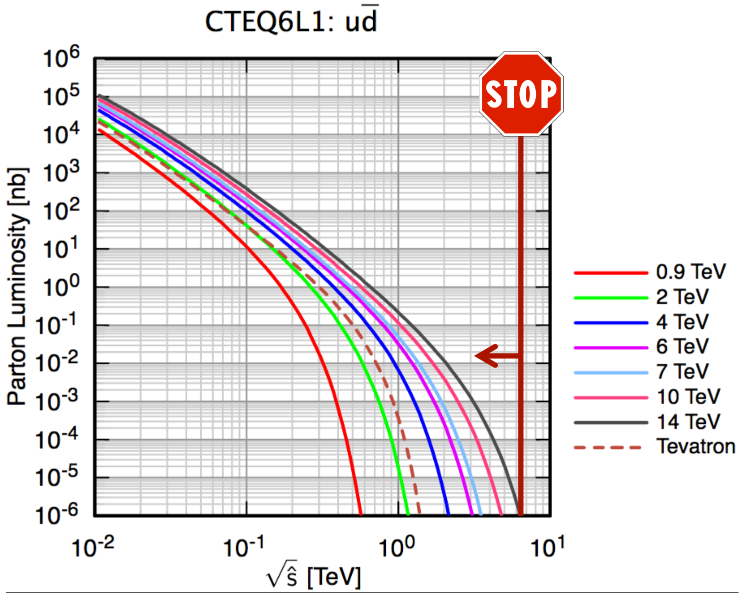
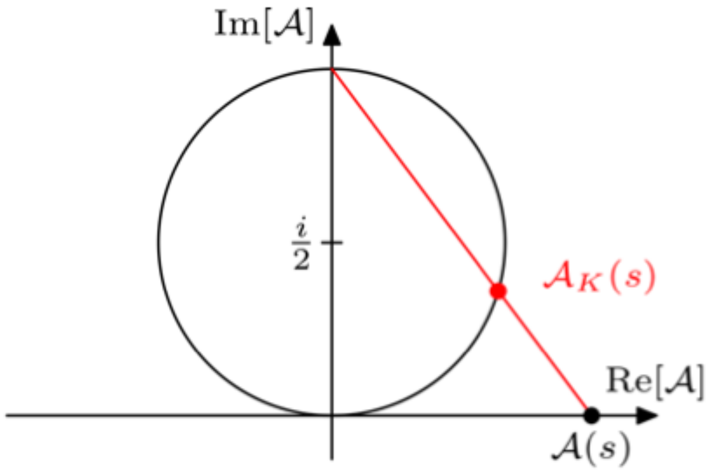
Interpretation

- Fix this by
  - Introducing form factors.
    - LEP, TeVatron, LHC
  - Project scattering amplitude.
    - k-Matrix (ATLAS)
  - Limit range of validity.
    - SM EFT
      (ATLAS, CMS).







Interpretation

- **Standard Model EFT extension (SMEFT):**
  - Wilson coefficients and operators.
  - Several complete Dim6 operator basis available.
    - Chose basis to match best the physical observables.
  - Translation between basis possible.
  - Higgs field included -> Combination with EWK.
- Being used in most recent results of aGC.

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

Higgs basis
HISZ basis
Warsaw basis
SILH' basis
…
Experiments still need to come to terms how to measure these. Discussion of "basis" vs "shifts" ongoing.

Interpretation

- Different formalism to describe anomalous couplings.

	Limits	Unitarisation Scheme	Vertex	Process
TGC	κ, λ, g_1	FF, none	$WW(Z/\gamma)$	pp - $WZ, W\gamma, WW, Wjj$
TGC	f_4, f_5	FF, none	$ZZ(Z/\gamma)$	pp - ZZ, Zjj
TGC	h_3, h_4	FF, none	$Z\gamma\ (Z/\gamma)$	pp - $Z\gamma$
QGC	$a_{0,C}{}^{W}, f_{T,M}$	FF, none	$WW\gamma\gamma$	pp - WW (excl), $W\gamma\gamma$
QGC	$f_{T,M}$	FF, none	$\gamma\gamma Z(Z/\gamma)$	pp - $Z\gamma\gamma$
QGC	$f_{s,M}, \alpha_{4,5}$	FF, none, k-matrix	WWWW	pp - WWW,WWjj (ss)
QGC	$\alpha_{4,5}$	k-matrix	$WZW(Z/\gamma)$	pp - WZjj

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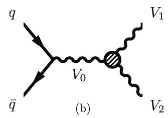
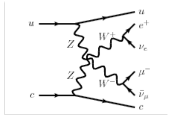
ATLAS & CMS Multi-Boson SM measurements

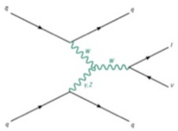
- **Inclusive Di-boson production**
  - VV channels with V=W,Z,γ
  - fully leptonic or semi-leptonic final states



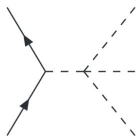
- **Vector Boson Fusion**
  - W / Z + 2 jets
  - Leptonic channels



- **Vector Boson Scattering**
  - W/Z Wjj
  - leptonic and semi-leptonic



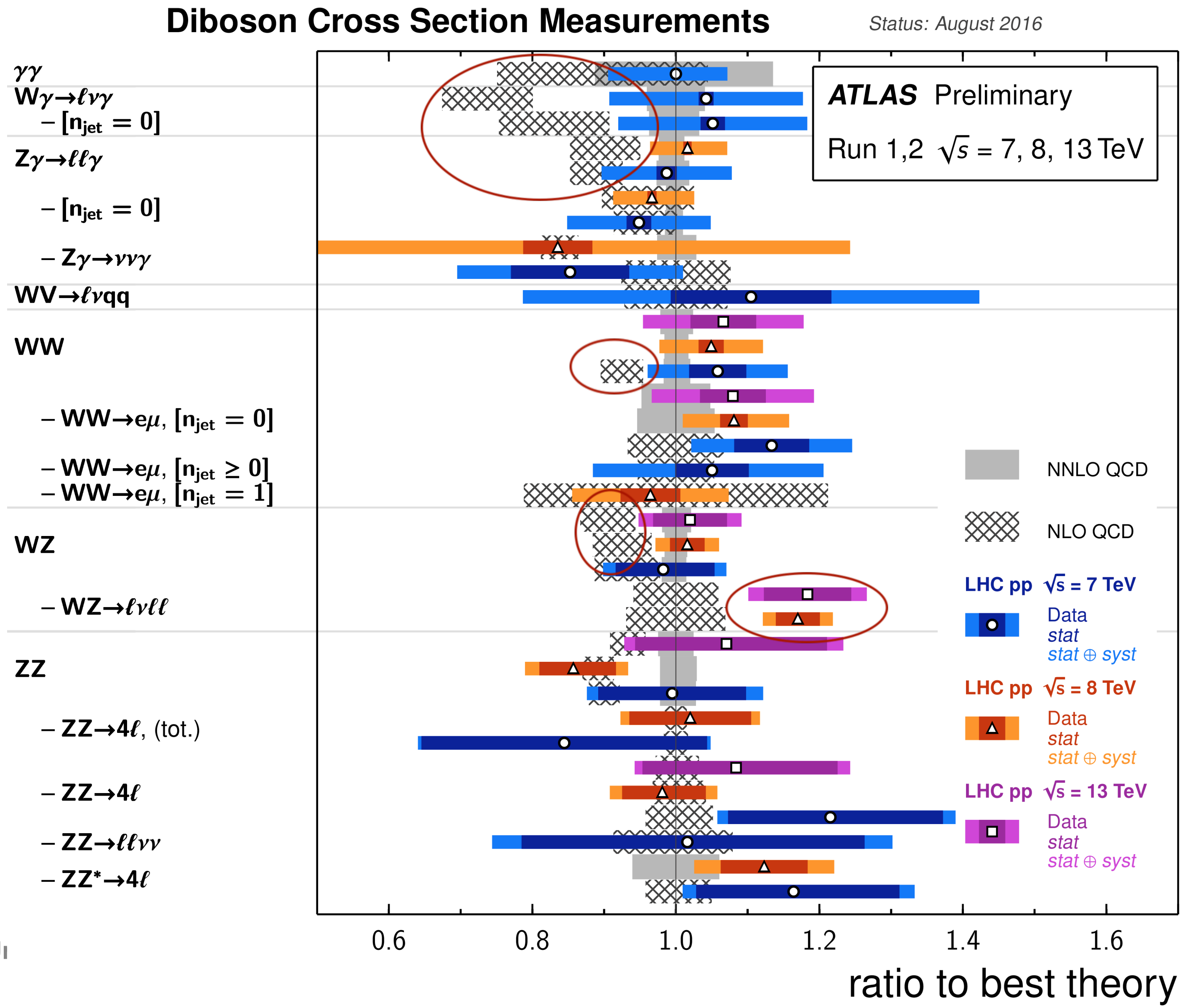
- **Tri-boson**
  - W/Z γγ : leptonic
  - WVγ : semi-leptonic
  - WWW: leptonic



Experiment	ATLAS			CMS		
Energy [TeV]	7	8	13	7	8	13
Wg	x			x		
Zg	x	x		x	x	
WW	x	x	x	x	x	x
WZ	x	x	x	x	x	x
ZZ	x	x	x	x	x	x
WV	x			x		
VBF W					x	
VBF Z		x		x	x	
VBS Wg					x	
VBS Zg					x	
VBS WW (ss)		x			x	
VBS WV		x				
VBS WZ		x				
WW excl		x		x	x	
Wgg					x	
Zgg		x			x	
WVg					x	
WWW		x				
WWV		x				

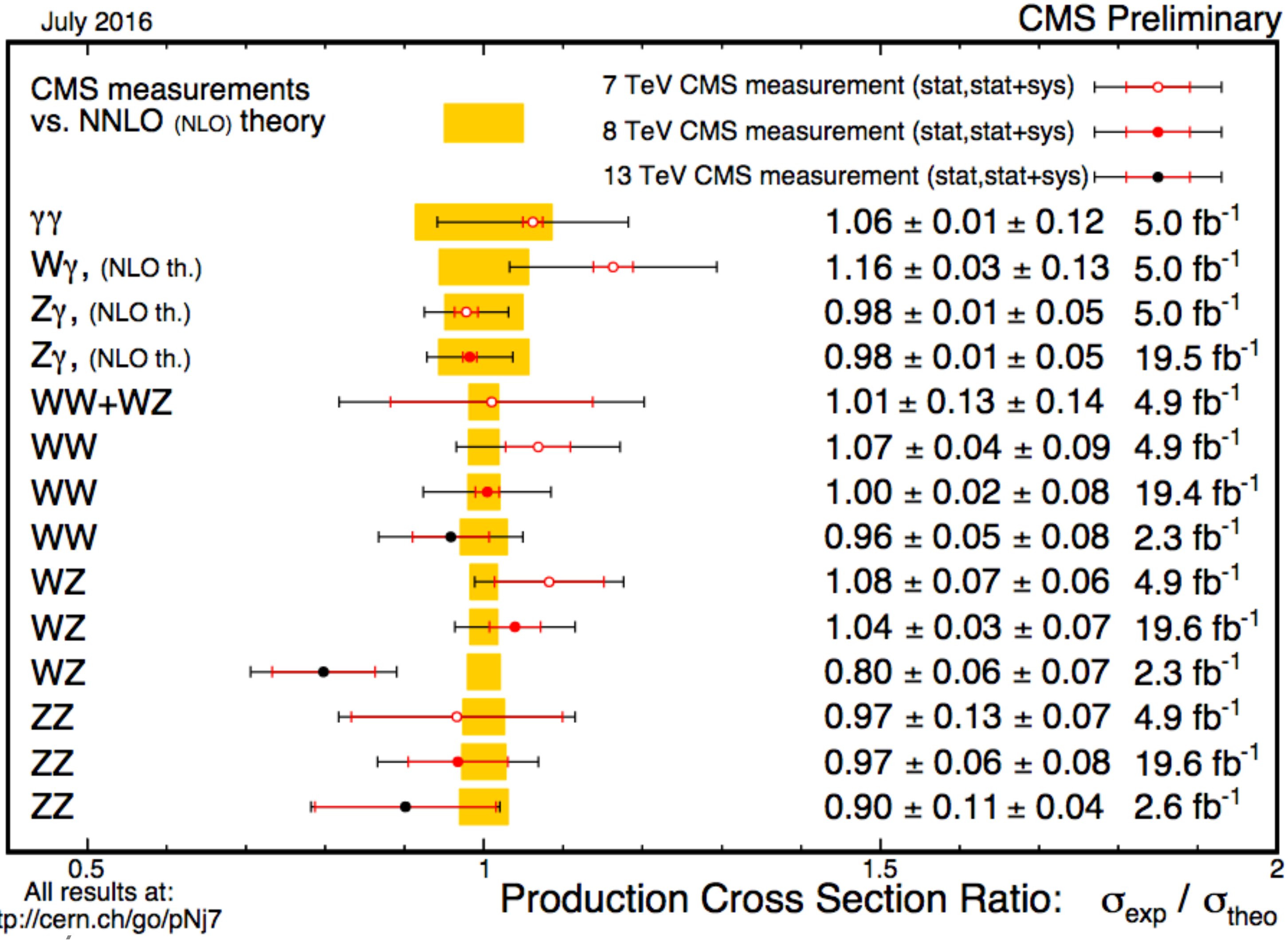
Summary Plots

- **ATLAS Di-boson**



Summary Plots

- **CMS**



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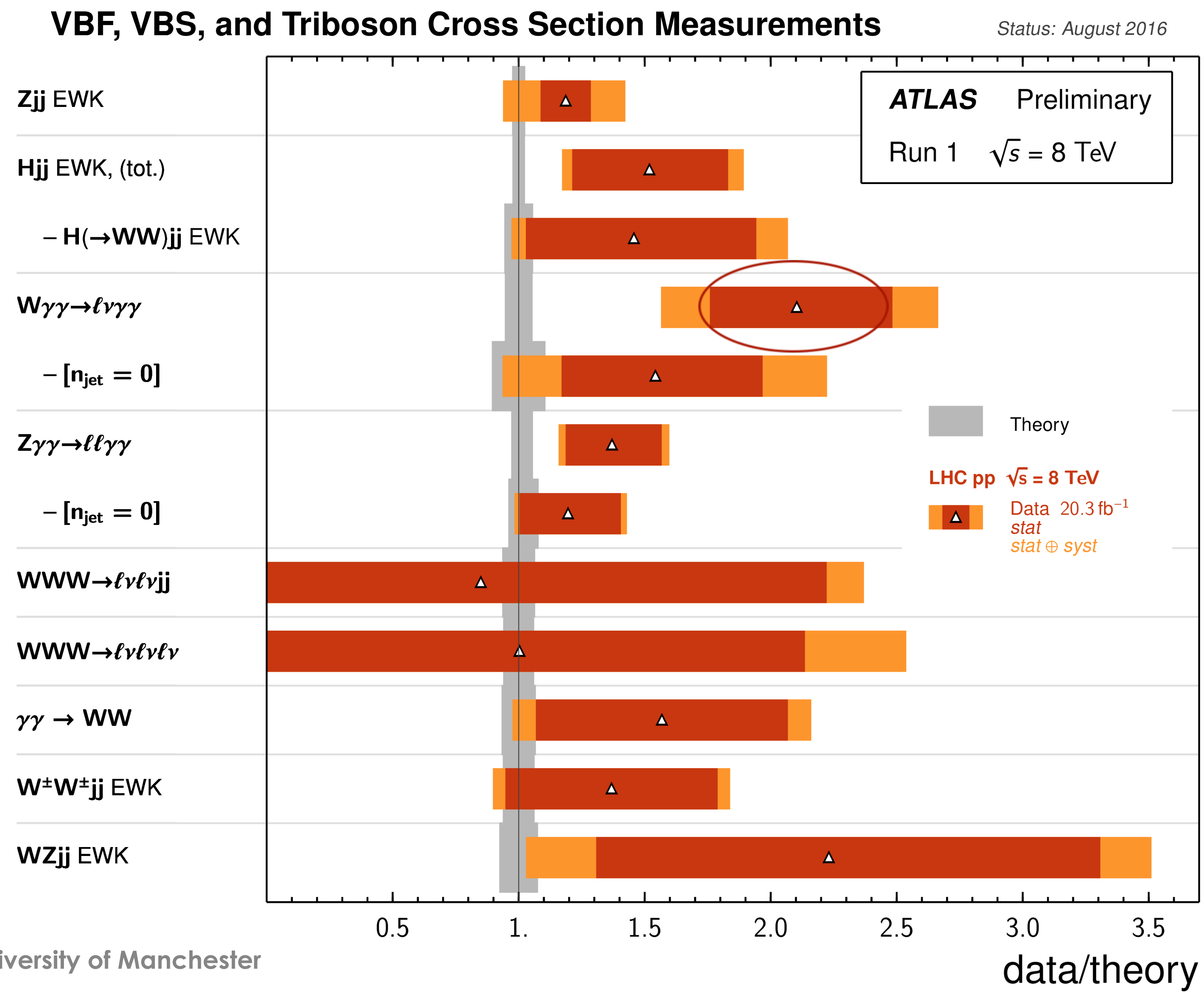
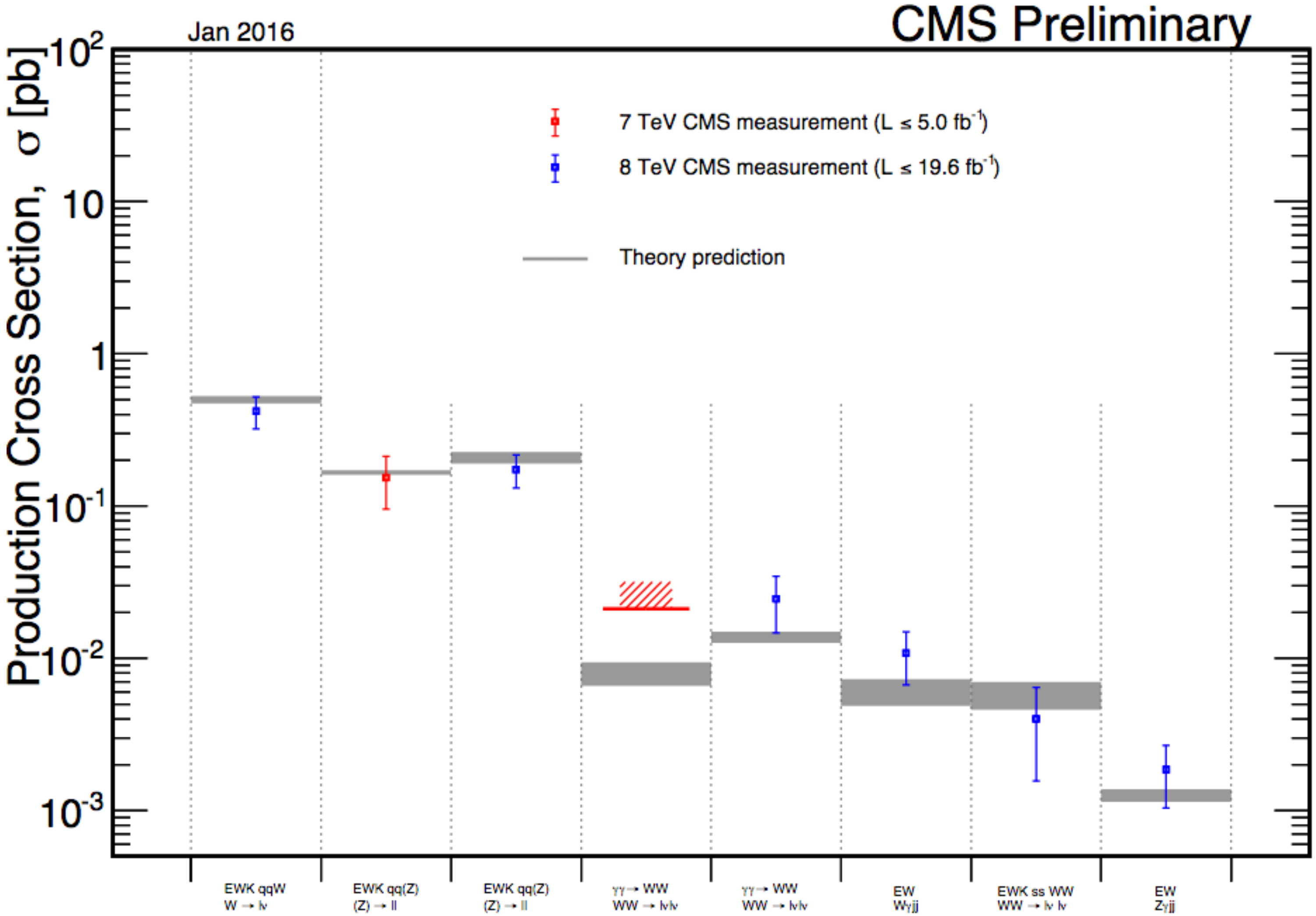
Summary Plots

ATLAS



Summary Plots

- CMS



Three recent results

- CMS WW exclusive (7TeV, 8TeV)
- ATLAS WWW (8TeV)
- ATLAS + CMS ZZ combination (7TeV)

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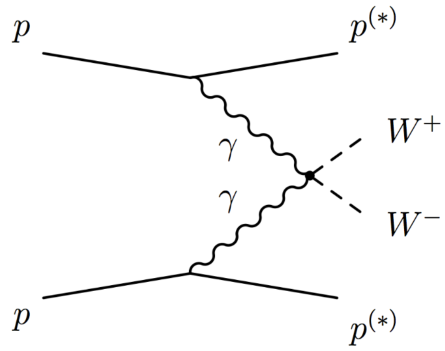
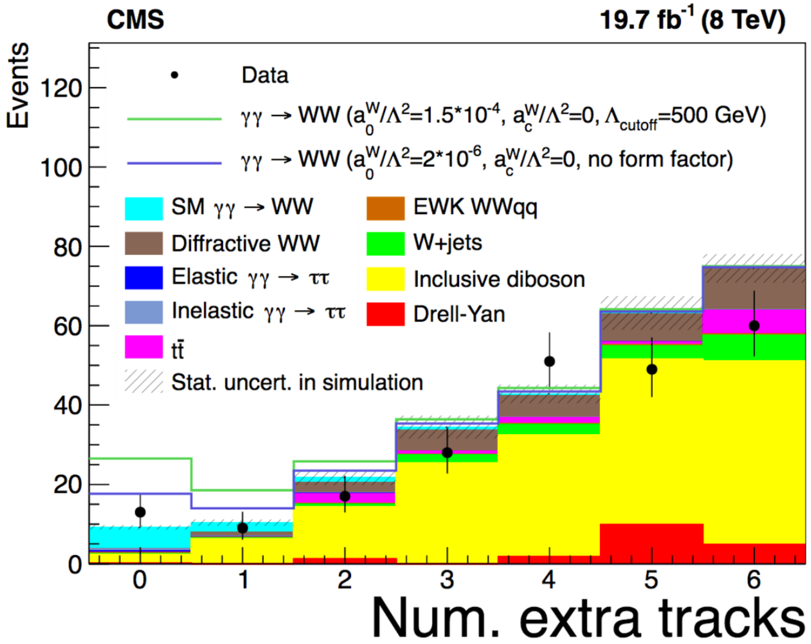
CMS excl. WW

https://arxiv.org/pdf/1604.04464v2.pdf



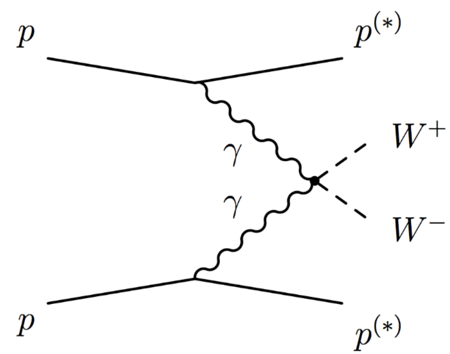
- **Exclusive WW production p(*) eμ p(*) +MET**
  - (*) protons remain intact or dissociate undetected.
- **Selection**:
  - pT(l)>20 GeV
  - pT(ll) > 30 GeV
  - |η(l)| < 2.4
  - no additional tracks!
- **Dominant background**
  - Inclusive di-boson



Selection step	Data	Exclusive $\gamma\gamma \to$ WW	Total background	Inclusive diboson	Drell-Yan	$\gamma\gamma \to \tau\tau$	Other backgrounds
Trigger and Preselection	19406	26.9±0.2	22180±1890	1546±15	7093±75	18.1±0.8	13520±1890
$m(\mu^{\pm}e^{\mp}) > 20\,\text{GeV}$	18466	26.6±0.2	21590±1850	1507±15	7065±75	18.1±0.8	13000±1850
Muon and electron identification	6541	22.5±0.2	6640±93	1306±11	4219±58	12.6±0.7	1102±72
$\mu^{\pm}e^{\mp}$ vertex with no add. tracks	24	6.7±0.2	15.2±2.5	3.7±0.7	6.5±2.3	4.3±0.5	0.7±0.1
$p_T(\mu^{\pm}e^{\mp}) > 30\,\text{GeV}$	13	5.3±0.1	3.9±0.5	2.3±0.4	0.1±0.1	0.9±0.2	0.6±0.1

CMS excl. WW

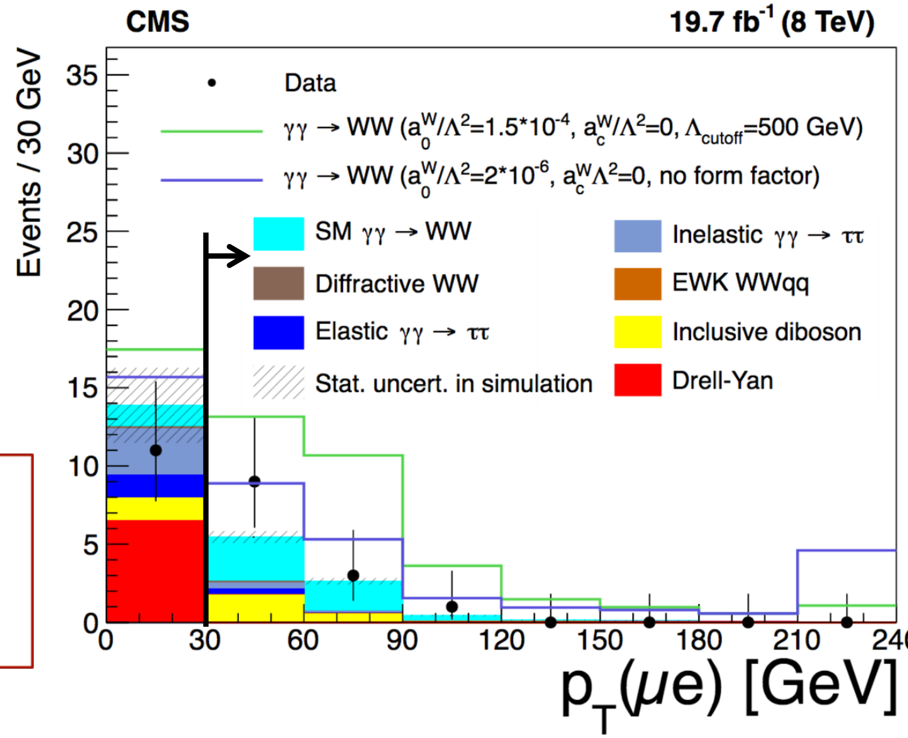
https://arxiv.org/pdf/1604.04464v2.pdf



- Observed Signal Significance: **3.4** σ (Expected 2.8 σ)
- Total cross section extracted:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) = 10.8^{+5.1}_{-4.1}\ \mathrm{fb}$$

- Expected 6.2 ±0.5 fb.



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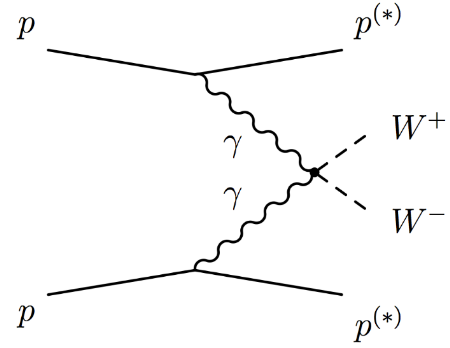
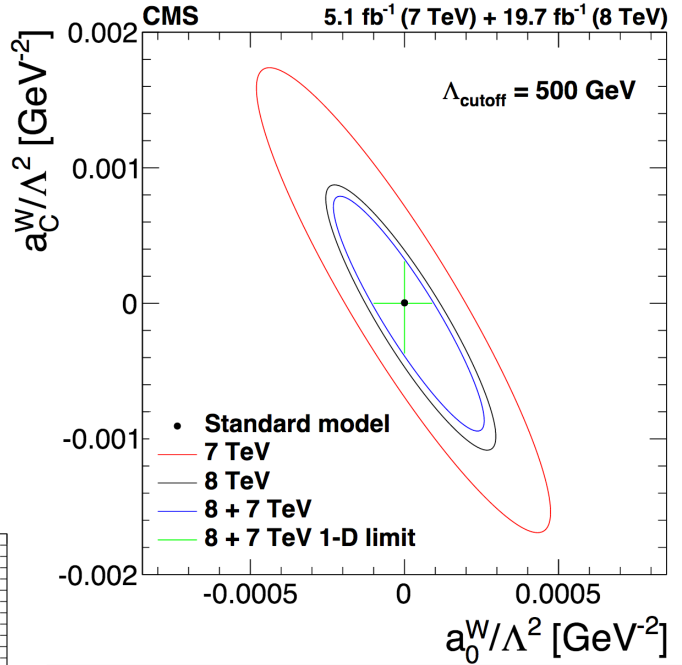
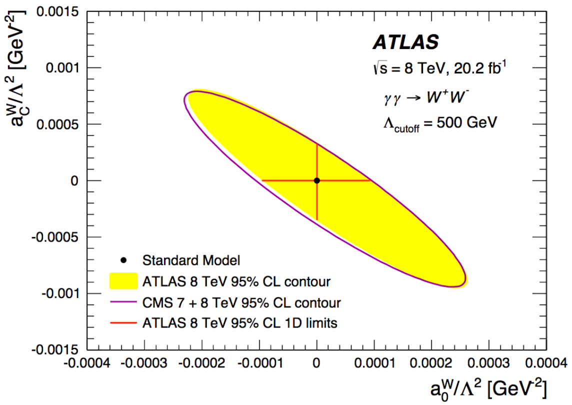
CMS excl. WW

https://arxiv.org/pdf/1604.04464v2.pdf



- Combine 7TeV and 8TeV to extract aQGC limits.
  - With and w/o form factor.
  - Dim6 ($a^W_{0/c}$) and Dim8 (fM,0-4)operators.
  - Comparable to ATLAS 8TeV limits. [link]

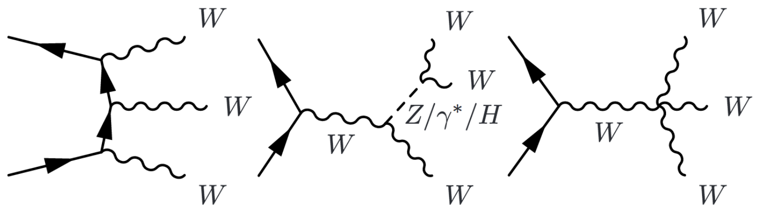




ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- Three heavy vector boson final state search.
- leptonic and semi-leptonic channels.
- Set limits on
  - Production cross section.
  - anomalous couplings.



$$W^{\pm}W^{\pm}W^{\mp} \rightarrow \begin{matrix} \ell^{\pm}\nu\ell^{\pm}\nu\ell^{\mp}\nu \\ \ell^{\pm}\nu\ell^{\pm}\nu jj \end{matrix}$$

ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- **Leptonic selection**

- Increase MET with #SFOS.
- SFOS mass outside Z peak.
- Δϕ (MET,3l) requirement.

$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
Preselection	Exactly three charged leptons with $p_T > 20$ GeV		
E_T^{miss}	-	$E_T^{miss} > 45$ GeV	$E_T^{miss} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	-	
Angle between trilepton and $\vec{p}_T^{miss}$	$\lvert\phi^{3\ell} - \phi^{\vec{p}_T^{miss}}\rvert > 2.5$		
Z boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$m_Z - m_{SFOS} > 35$ GeV or $m_{SFOS} - m_Z > 25$ GeV	$\lvert m_{SFOS} - m_Z\rvert > 20$ GeV
Jet veto	At most one jet with $p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$		
b-jet veto	No identified b−jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$		

ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- **Semi-leptonic selection**

- Two same sign leptons.
- Z-veto on di-electrons.
- Two resolved jets, mjj compatible with W.

$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Lepton	Exactly two same-charge leptons with $p_{\mathrm{T}} > 30$ GeV		
Jets	At least two jets with $p_{\mathrm{T}}(1) > 30$ GeV, $p_{\mathrm{T}}(2) > 20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV		-
m_{jj}	65 GeV $< m_{jj} <$ 105 GeV		
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$		
Z boson veto	$m_{ee} < 70$ GeV or $m_{ee} > 110$ GeV	-	
Third-lepton veto	No third lepton with $p_{\mathrm{T}} > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified $b-$jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

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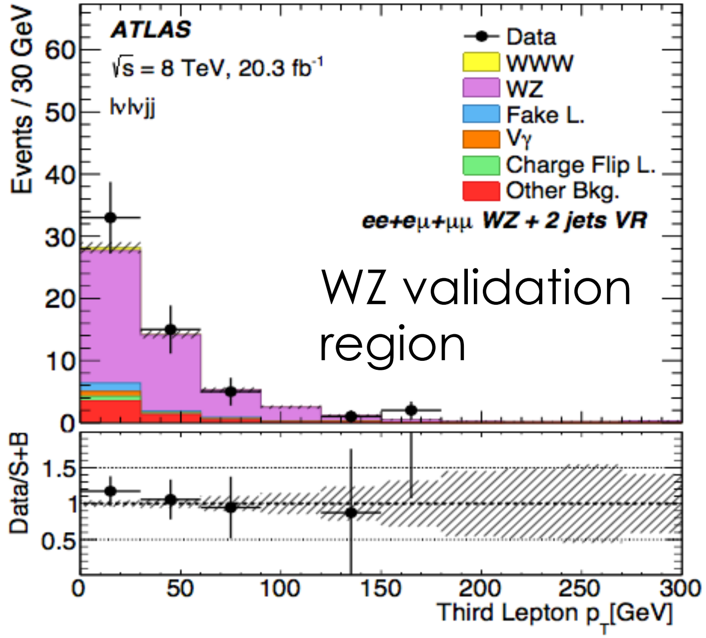
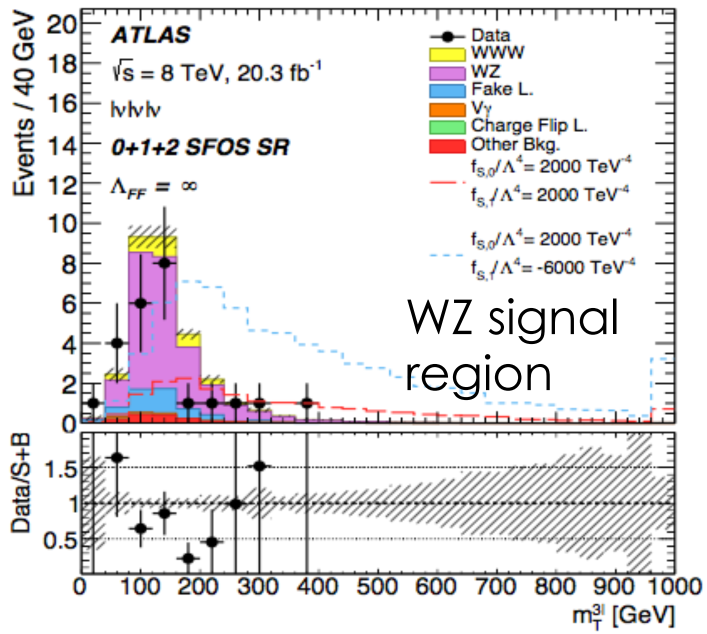
ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- **Main Background** from WZ+jets, followed by Vγ+jets, and other non-prompt backgrounds.
  - WZ estimated from Powheg + Pythia8.
  - Normalization from WZ validation region (1.08 for lvlvlv) or VBFNLO calculation (1.04 for lvlvjj).
- **Signal significance**
  observed 0.96σ
  expected 1.05σ

  most sensitive 0-SFOS channel.

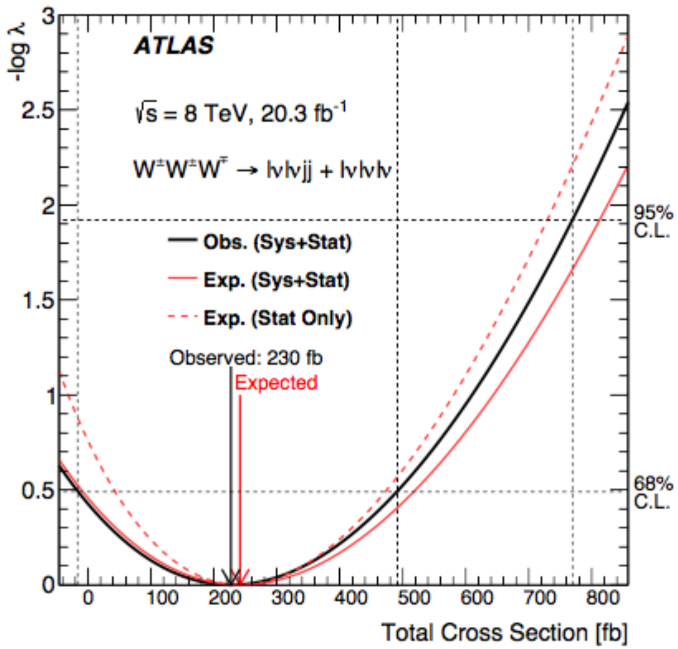




ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- **Signal cross section compatible with expectation.**
  - Fiducial
  - Total
- **Need more data for observation of WWW production.**

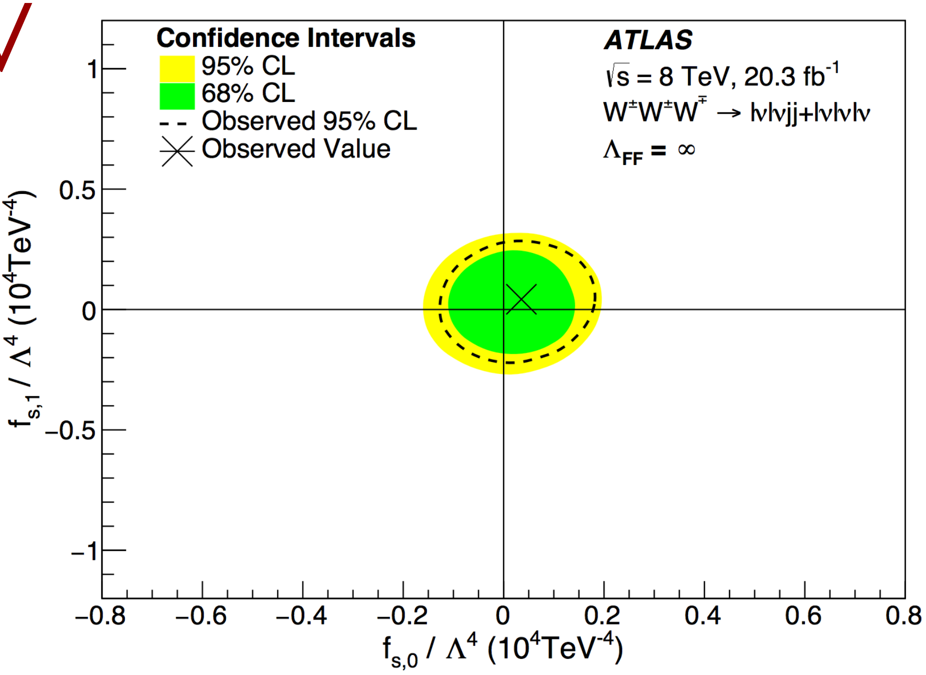


		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.306 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.011 (scale)	$0.26\ ^{+0.42}_{-0.35}$ (stat.) $^{+0.20}_{-0.21}$ (syst.)
Total		241.5 ± 0.1 (stat.) ± 10.3 (PDF) ± 6.3 (scale)	230 ± 200 (stat.) $^{+150}_{-160}$ (syst.)

ATLAS WWW, 8 TeV

https://arxiv.org/pdf/1610.05088v1.pdf

- **Limit on anomalous QGC.**
  - Only dim8 operators -> pure aQGC.
  - Limits for dipole FF and w/o.
  - O(100) more stringent limits then ssWW analysis (CMS).
  - Comparison to ATLAS ssWW not possible due to different unitarisation scheme (k-matrix).



Λ_{FF} [TeV]	Expected CI [$\times 10^4$ TeV^{-4}] $f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$	Observed CI [$\times 10^4$ TeV^{-4}] $f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$
0.5	[−0.81, 0.89]	[−1.00, 1.29]	[−0.77, 0.85]	[−1.01, 1.22]
1	[−0.37, 0.42]	[−0.52, 0.62]	[−0.31, 0.39]	[−0.48, 0.58]
2	[−0.24, 0.26]	[−0.33, 0.40]	[−0.19, 0.24]	[−0.29, 0.37]
3	[−0.19, 0.22]	[−0.29, 0.36]	[−0.16, 0.21]	[−0.25, 0.32]
∞	[−0.16, 0.19]	[−0.25, 0.31]	[−0.13, 0.18]	[−0.21, 0.27]

ZZ combination for 7 TeV

- **Measurements of aTGC parameters have been performed by ATLAS and CMS in many diboson channels.**
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC
  - Limits on neutral (charged) aTGCs are (close to) world best limits.
  - Combination of results at 8 and 13 TeV will be an important result.

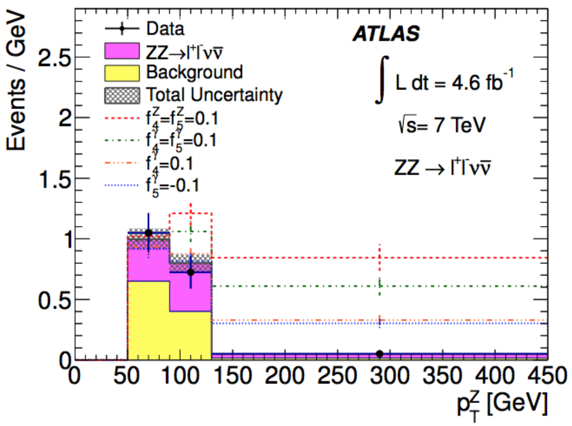
- **Why 7 TeV**
  - Define and test framework for the combination of upcoming results.
  - Ensure the framework is well tested thus we perform the combination of public results with similar sensitivity from both experiments -> ZZ @ 7TeV as benchmark channel.

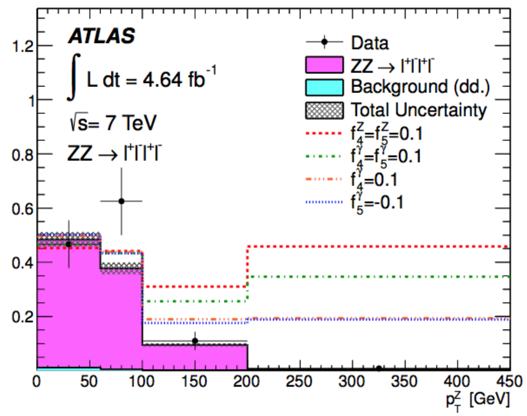
ZZ combination

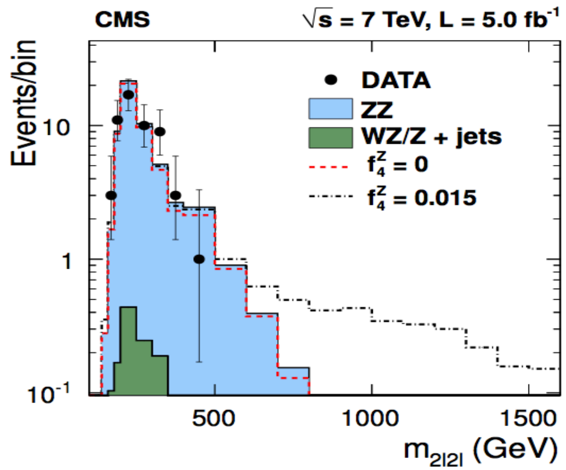
- Identified many technical differences in the way how the aTGC limits were set in ATLAS and CMS

Combined limits

- Channels: ZZ->4l and ZZ->2l2nu (ATLAS) and ZZ->4l (CMS)
- Signal: Sherpa MC with ME weights (ATLAS) and pol2 fit on expected yields (CMS)
- Combined fit on ATLAS Pt(Z) distribution and CMS M(ZZ) distribution
- deltaNLL and F-C criteria for limits
- lnN nuisance shape; nuisance summation: $N\_i = N\_i(S)\prod_k (1+\sigma_k^i \tau_k)$







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Uncertainties

uncertainty	ATLAS: 4l [p_TZ]	ATLAS: 2l2nu [p_TZ]	CMS: 4l [MZZ]
N_bins	4	3	5 (x3 channels)
Luminosity	3.9%	3.9%	2.2%
Stat on signal	Shape	-	-
	-	Shape	-
Stat on bkg data-driven	Shape)	-	-
	-	Shape	-
Stat on bkg MC	-	Shape	-
Reco uncertainty	Normalisation	Normalisation	-
Syst on bkg data-driven	Shape	Shape	-
Syst on bkg MC	-	Normalisation	-
Total bkg uncertainty	-	-	Per channel, normalisation
Signal other (stat+fit+reco)	-	-	13.42% (normalisation
Signal theory (PDF+scale)	Normalisation	Normalisation	Normalisation

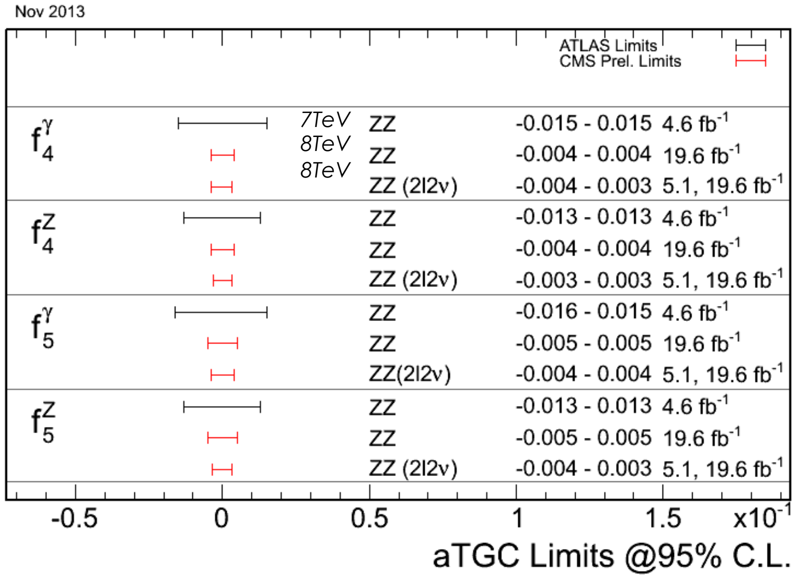
Uncertainties in the same row are treated as correlated!

Results

Combination yields ~20% improvement compared to single results.

Paving the way towards 8 TeV and run-2 combinations.

Public results



1D deltaNLL limit	**f_5^γ**		**f_5^Z**	
	CMS code	ATLAS code	CMS code	ATLAS code
Combined expected	[-0.0125, 0.0120]	[-0.0126, 0.0119]	[-0.0105, 0.0103]	[-0.0105, 0.0103]
Combined observed	[-0.0108, 0.0103]	[-0.0108, 0.0103]	[-0.00906, 0.00886]	[-0.00902, 0.00885]

1D deltaNLL limit	**f_4^γ**		**f_4^Z**	
	CMS code	ATLAS code	CMS code	ATLAS code
Combined (expected)	[-0.0119, 0.0123]	[-0.0120, 0.0123]	[-0.0102, 0.0104]	[-0.0102, 0.0104]
Combined (observed)	[-0.0102, 0.0108]	[-0.0102, 0.0108]	[-0.00871, 0.00909]	[-0.00870, 0.00907]

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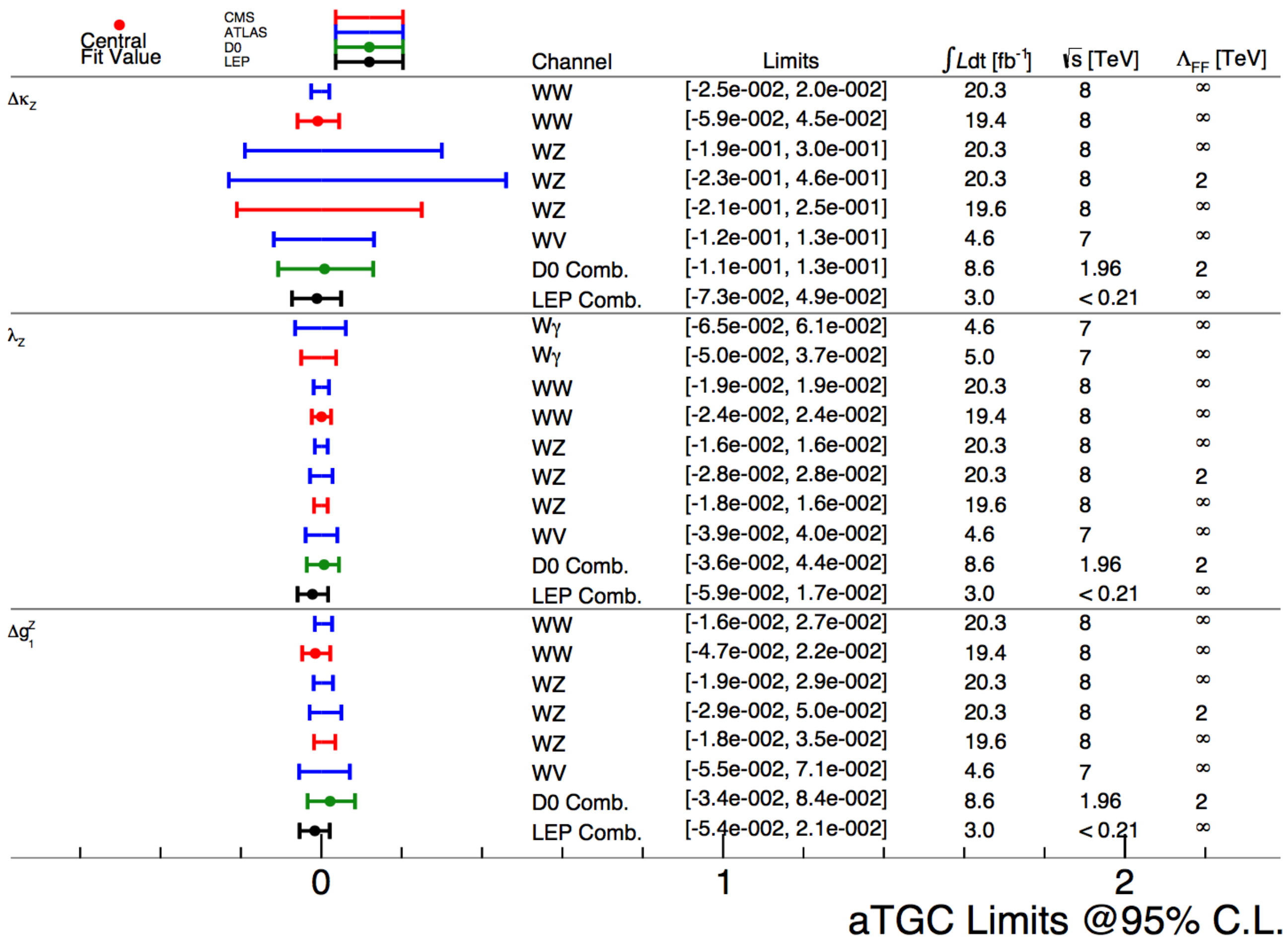
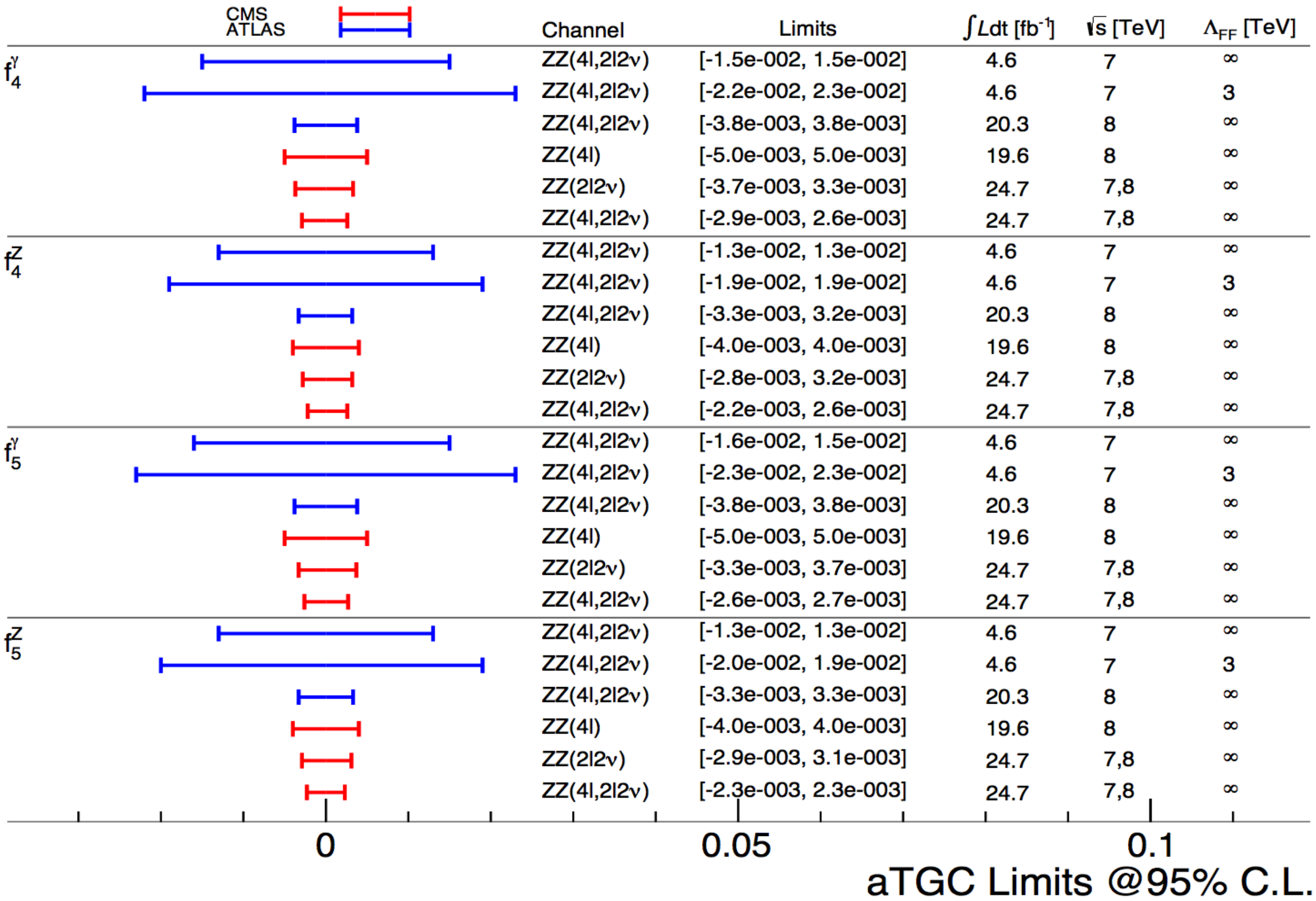
aGC Summary Plots

- Charged aTGC: LHC provides best limits



aGC Summary Plots

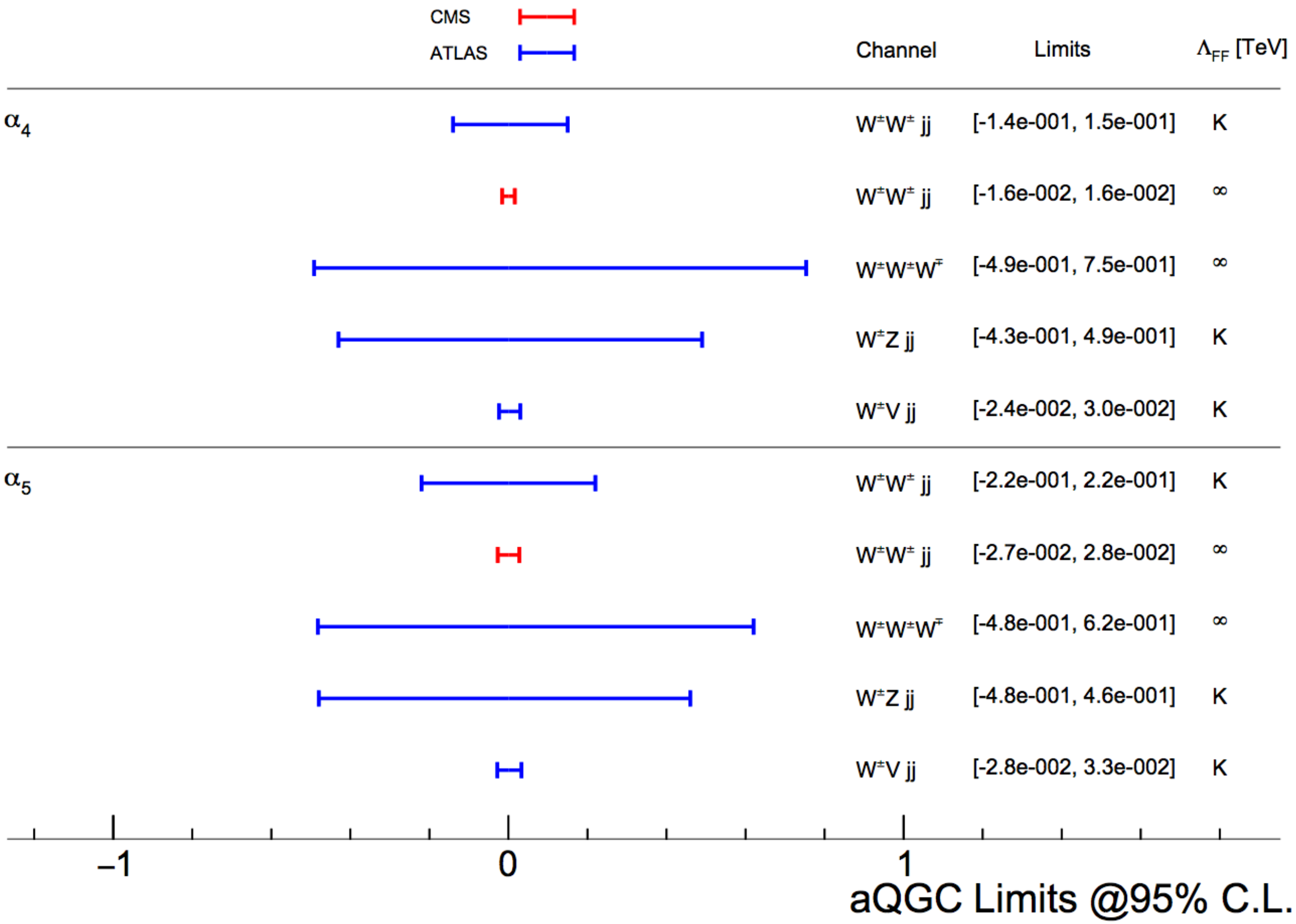
- Neutral aTGC: CMS and ATLAS comparable.



	Channel	Limits	∫Ldt [fb⁻¹]	√s [TeV]	Λ_{FF} [TeV]
f_4^γ	ZZ(4l,2l2ν)	[-1.5e-002, 1.5e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.2e-002, 2.3e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.8e-003, 3.8e-003]	20.3	8	∞
	ZZ(4l)	[-5.0e-003, 5.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-3.7e-003, 3.3e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.9e-003, 2.6e-003]	24.7	7,8	∞
f_4^Z	ZZ(4l,2l2ν)	[-1.3e-002, 1.3e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-1.9e-002, 1.9e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.3e-003, 3.2e-003]	20.3	8	∞
	ZZ(4l)	[-4.0e-003, 4.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-2.8e-003, 3.2e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.2e-003, 2.6e-003]	24.7	7,8	∞
f_5^γ	ZZ(4l,2l2ν)	[-1.6e-002, 1.5e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.3e-002, 2.3e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.8e-003, 3.8e-003]	20.3	8	∞
	ZZ(4l)	[-5.0e-003, 5.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-3.3e-003, 3.7e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.6e-003, 2.7e-003]	24.7	7,8	∞
f_5^Z	ZZ(4l,2l2ν)	[-1.3e-002, 1.3e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.0e-002, 1.9e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.3e-003, 3.3e-003]	20.3	8	∞
	ZZ(4l)	[-4.0e-003, 4.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-2.9e-003, 3.1e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.3e-003, 2.3e-003]	24.7	7,8	∞

aGC Summary Plots

- Quartic aGC: CMS and ATLAS charter new territory!



Wrap-up

- (1,2,3,…)-boson final states probe the EWK gauge structure of the SM.
- Precision calculation at NNLO(QCD) and NLO(EWK) are necessary and are becoming available.
- Fiducial cross sections and unfolded kinematic distributions of MBI processes will be the legacy of LHC to EWK physics.
- EFT and anomalous gauge couplings are useful tools to compare and combine experiments/channels.
- Still many multi-boson final states to be discovered.
- Combination of EWK & Higgs to gain sensitivity.
- Exploit cross-section ratio measurements.