Measurement of Di-Boson productions and anomalous couplings with ATLAS detector @LHC

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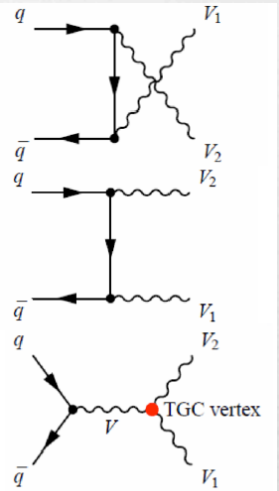
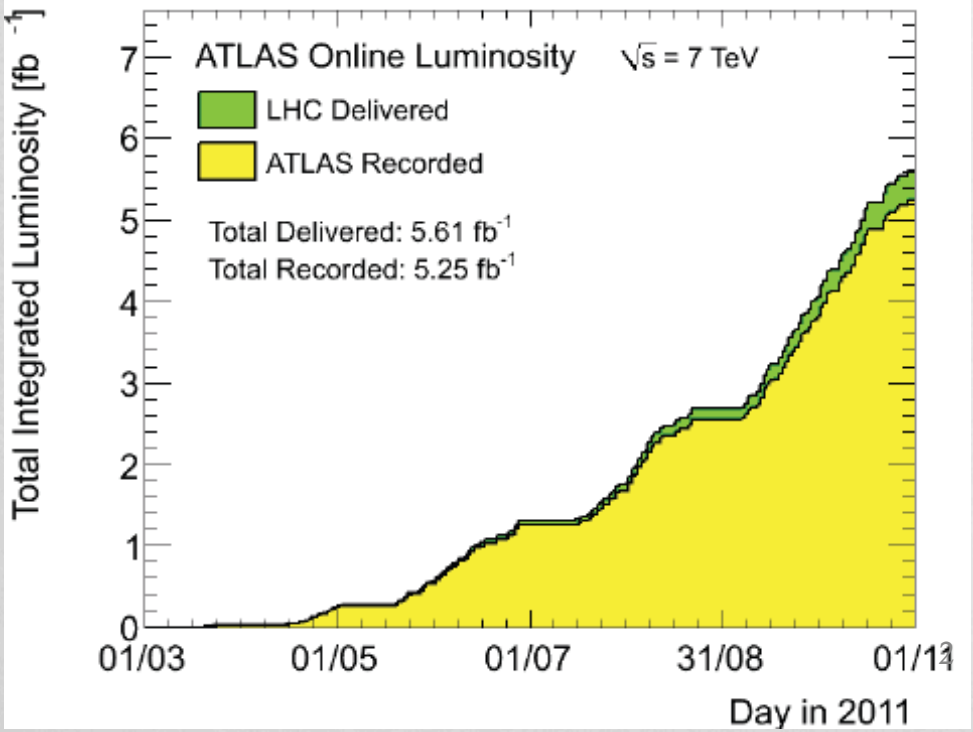
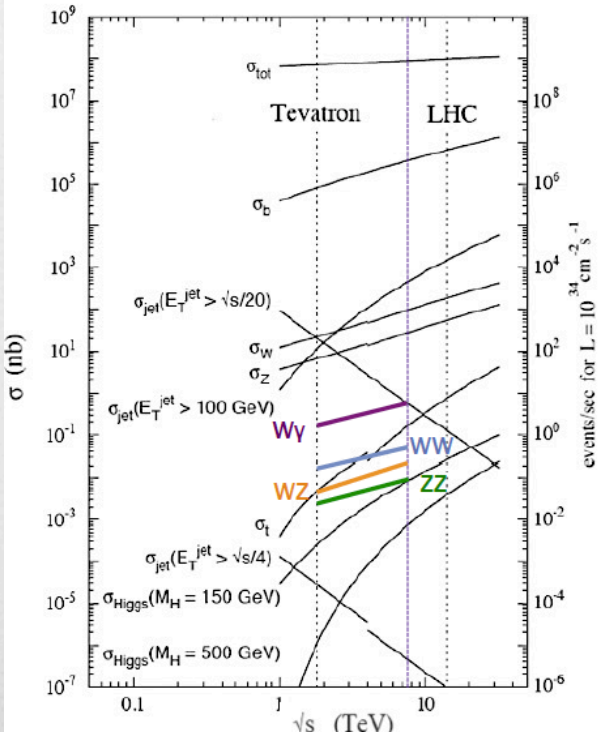
Introduction

- Motivation:
  - Important test of SM EW sector
  - Sensitive to new phenomena.
  - Irreducible background of Higgs(WW/ZZ) and relevant exotic searches
- More precise measurement with full 2011 dataset (4.7fb^{-1} in GRL)







Methods

- Cross section
  - N_{obs}: observed events passing selection
  - N_b: estimated background passing selection
  - **L:** int. luminosity
  - **Br:** the branching ratio of V→l+l/ ν
  - **A:** the fiducial acceptance
  - **C:** the eff. correction

$$\sigma_{tot} = \frac{N_{obs} - N_b}{A * C * L * Br}$$

- Anomalous Triple-gauge-coupling(aTGC) limit setting
  - Effect of new physics parameterized with effective field theory
  - Modify total production rate and event kinematics
  - Likelihood(1D or 2D) to determine the aTGCs
  - Cut-off form factor to preserve unitarity at high energy

Coupling	Parameters	Channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
ZZZ	f_{40}^Z, f_{50}^Z	ZZ
$Z\gamma Z$	f_{40}^γ, f_{50}^γ	ZZ

Forbidden in SM

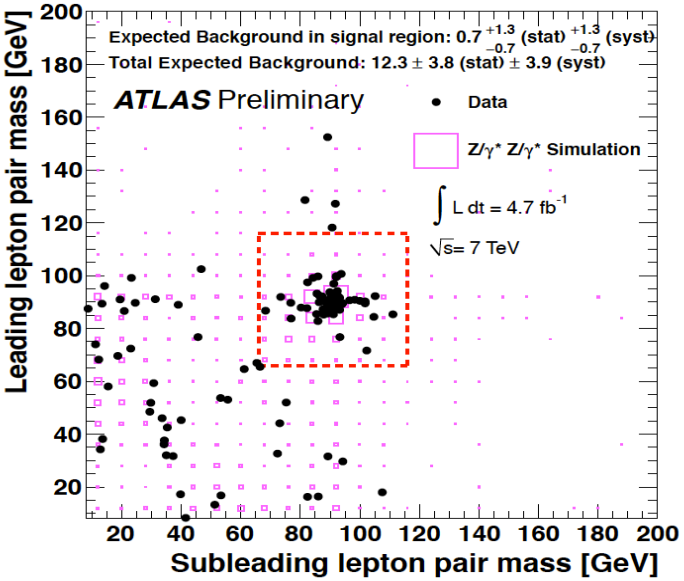
$$g_1^V = \kappa_V = 1, g_1^V = 1 + \Delta g_1^V, \kappa_V = 1 + \Delta\kappa_V$$

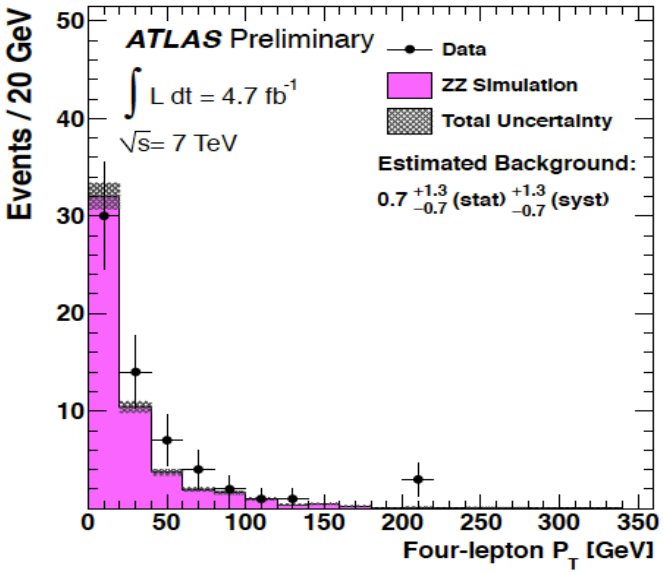
$$\alpha \rightarrow \alpha(s) \equiv \frac{\alpha}{(1 + \hat{s}/\Lambda_{FF}^2)^n}$$

ZZ→4ℓ

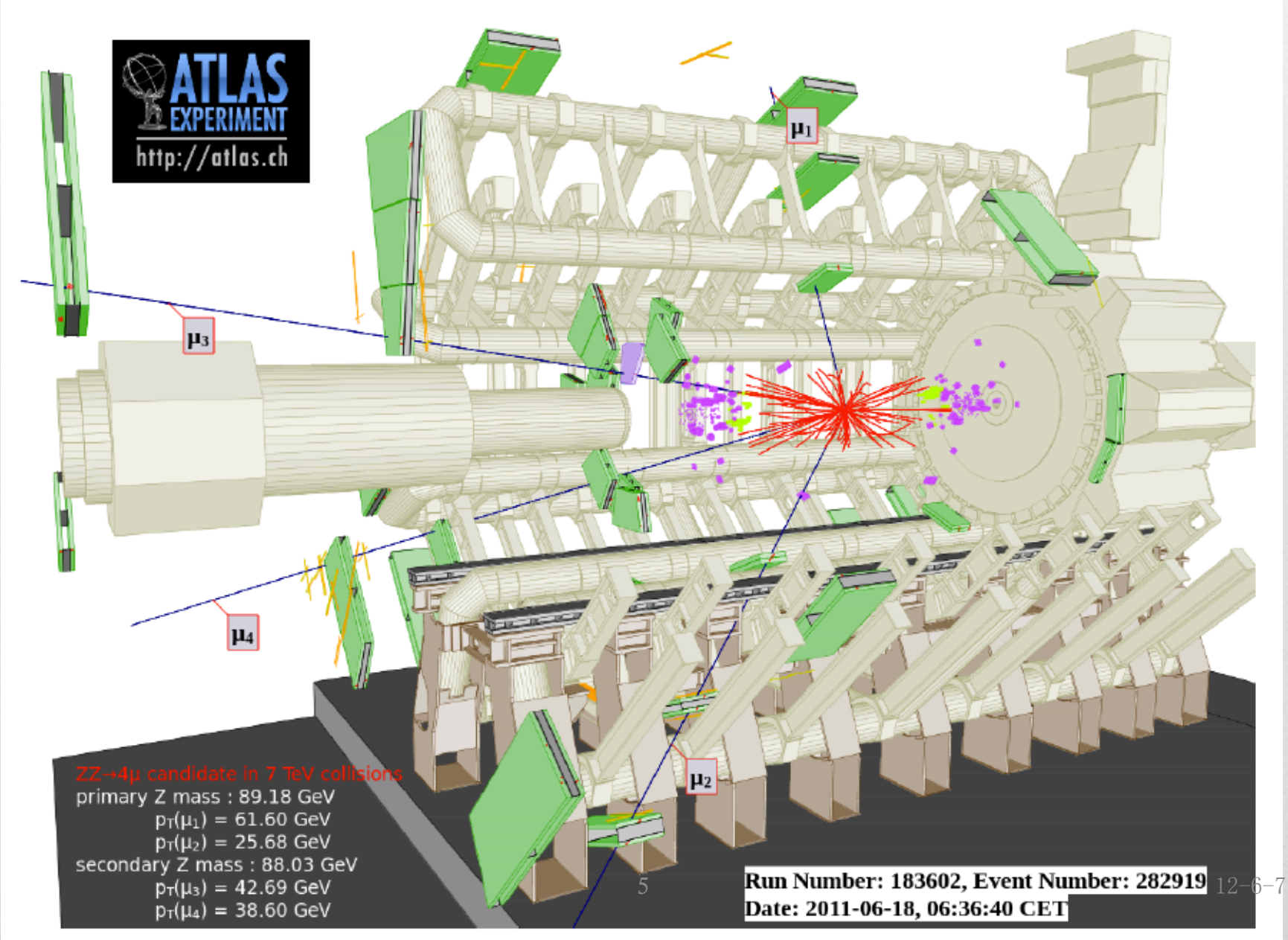
ATLAS-CONF-2012-026

- Selection:
  - 4 isolated leptons with pT > 7 GeV
  - Leading lepton pT > 25/20 GeV (e/μ)
  - 66 < M(ll) < 116 GeV for each Z lepton pair
  - Z→ τ τ not included
- Background free(<2% contamination), residual: W/Z+jet, Top, VV
- Measured cross section:
  - Total: $7.2^{+1.1}_{-0.9}(stat)^{+0.4}_{-0.3}(syst)\pm 0.3(lumi)pb$
  - SM prediction: $6.5^{+0.3}_{-0.2}pb$
  - Fiducial: $21.2^{+3.2}_{-2.7}(stat)^{+1.0}_{-0.9}(syst)\pm 0.8(lumi)fb$





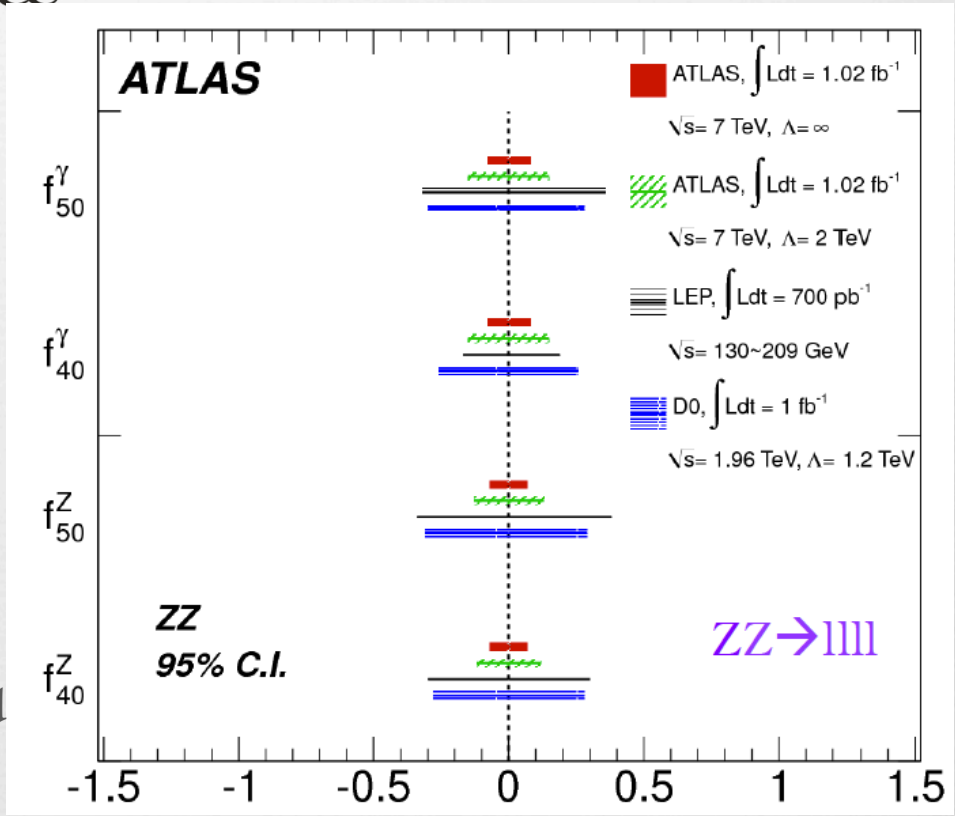
ZZ→4 μ


ATLAS EXPERIMENT
http://atlas.ch
μ1
μ2
μ3
μ4
ZZ→4μ candidate in 7 TeV collisions
primary Z mass : 89.18 GeV
pT(μ1) = 61.60 GeV
pT(μ2) = 25.68 GeV
secondary Z mass : 88.03 GeV
pT(μ3) = 42.69 GeV
pT(μ4) = 38.60 GeV
Run Number: 183602, Event Number: 282919
Date: 2011-06-18, 06:36:40 CET

Anomalous coupling from ZZ

PRL 108,041804(2012)

- ZZZ and ZZ γ neutral triple gauge boson couplings (nTGCs)
- No tree-level contribution from s-channel quark annihilation. O(10^{-4}) at one-loop level
- Signature of non-zero nTGCs: increase of ZZ cross section at high ZZ inv. Mass and high transvers momentum
- 1.02fb^{-1} anomalous nTGC limits published using the total number of observed events only.



Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
2 TeV	$[-0.15, 0.15]$	$[-0.12, 0.12]$	$[-0.15, 0.15]$	$[-0.13, 0.13]$
∞	$[-0.08, 0.08]$	$[-0.07, 0.07]$	$[-0.08, 0.08]$	$[-0.07, 0.07]$

ZZ→ℓℓνν

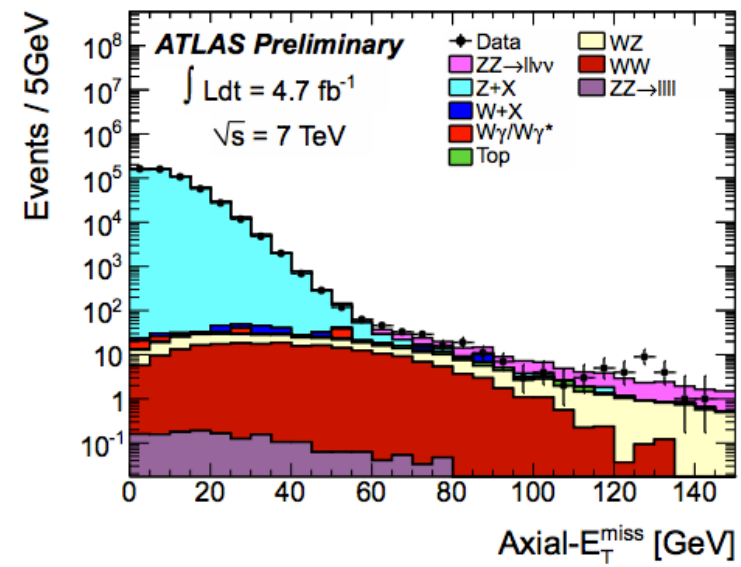
ATLAS-CONF-2012-027

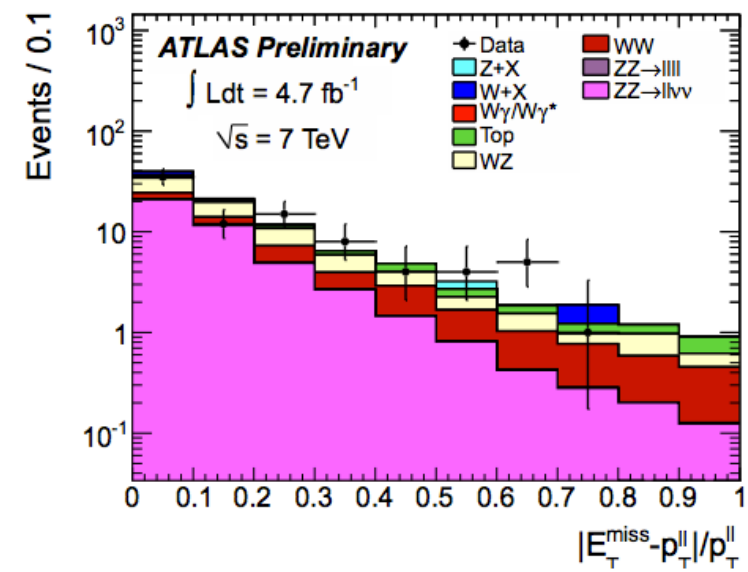
- Selection:
  - 2 isolated leptons, pT > 20 GeV
  - **Axial-E_T^{miss}>80GeV**(E_T^{miss} projection along Z p_T)
  - Jet veto : remove events with jets with pT>25 GeV
  - $|E_t^{miss} - p^Z_T| / p^Z_T < 0.6$
- Total cross section:

$$5.4^{+1.3}_{-1.2}(stat)^{+1.4}_{-1.0}(syst) \pm 0.2(lumi)\,pb$$

- SM prediction: $\sigma_{ZZ}(NLO) = 6.5^{+0.3}_{-0.2}\,pb$
- Fiducial cross section:

$$12.2^{+3.0}_{-2.8}(stat) \pm 1.9(syst) \pm 0.5(lumi)\,fb$$

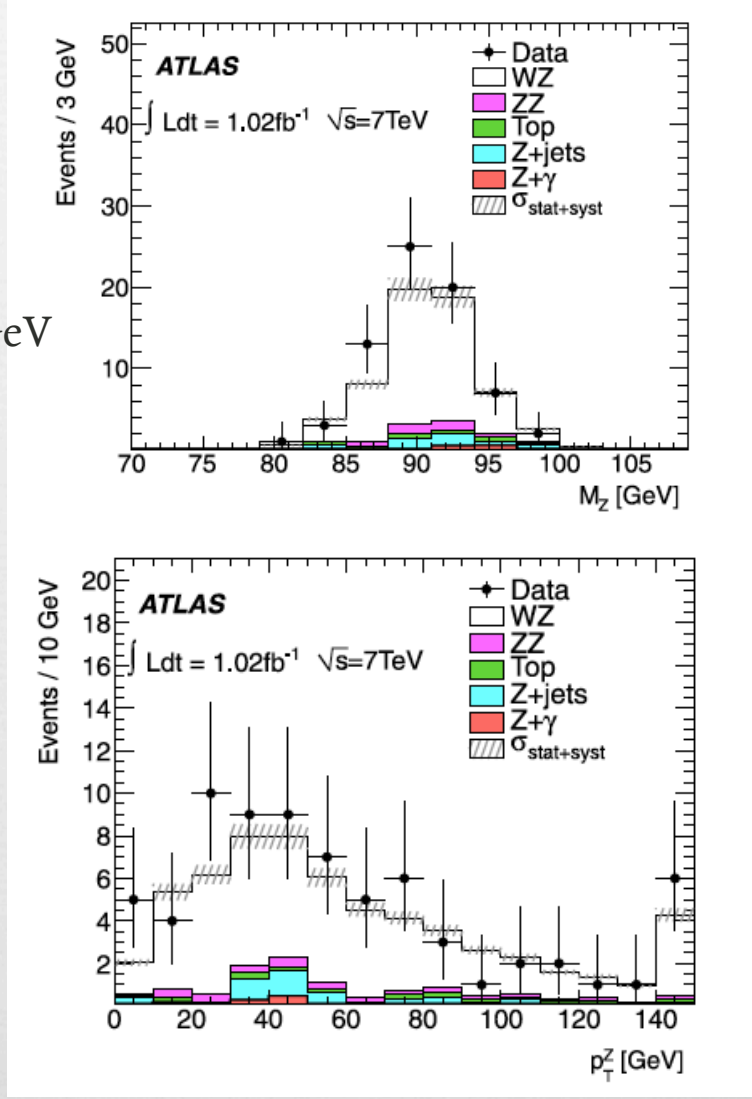




WZ→ℓνℓℓ

PLB 709(2012)341

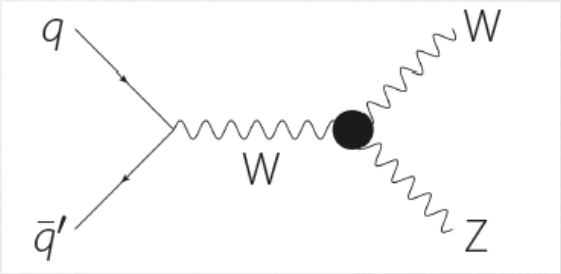
- Selections:
  - At least 3 prompt isolated leptons, pT>15GeV
  - Z: 1st and 2nd leptons, $|M_{ll}-Mz|<10GeV$
  - W: 3rd lepton, pT>20GeV, mT>20GeV, $E_T^{miss}>25GeV$
- Major backgrounds: Z+jets/ γ , ZZ, Top
  - Less background contamination than WW
- Measured cross section:
  - Total: $20.5^{+3.1}_{-2.8}(stat)\pm 1.4(syst)^{+0.9}_{-0.8}(lumi)pb$
  - SM prediction: $17.3^{+1.3}_{-0.8}pb$
  - Fiducial: $102^{+15}_{-14}(stat)\pm 7(syst)\pm 4(lumi)fb$

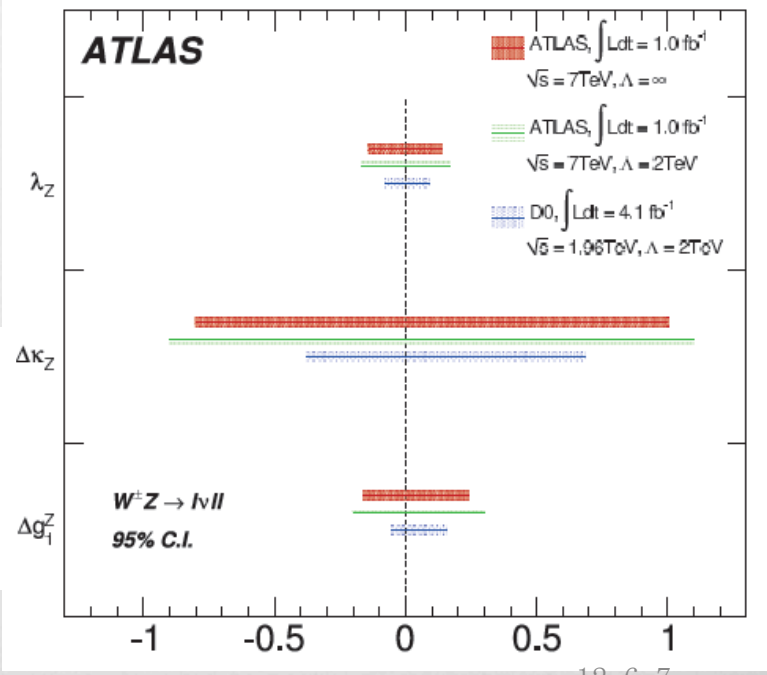


WZ constraint on aTGC

PLB 709(2012)341

- aTGC limit using measured cross section with 1.02fb^{-1} DATA with observed WZ→l ν ll events
- Frequentist approach with the profile likelihood ratio used as the test statistic
- Highest sensitivity for Δg_1^V
- Limits are set separately on each parameter with the other couplings fixed to their SM values





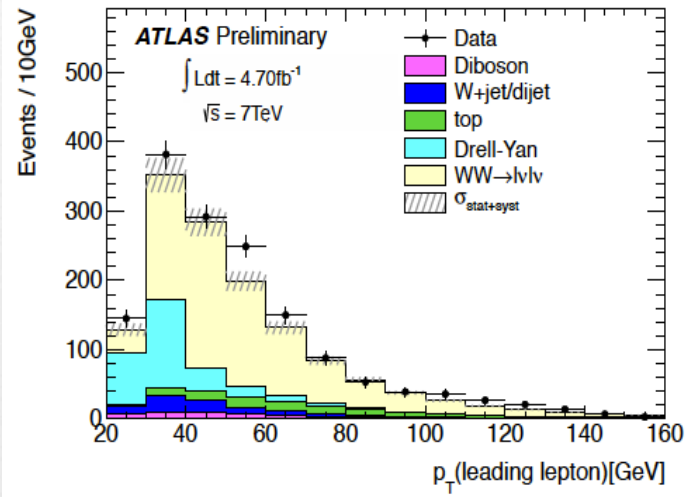
Coupling	Observed ($\Lambda = 2$ TeV)	Observed ($\Lambda = \infty$)	Expected ($\Lambda = \infty$)
Δg_1^Z	[−0.20, 0.30]	[−0.16, 0.24]	[−0.12, 0.20]
$\Delta\kappa_Z$	[−0.9, 1.1]	[−0.8, 1.0]	[−0.6, 0.8]
λ_Z	[−0.17, 0.17]	[−0.14, 0.14]	[−0.11, 0.11]

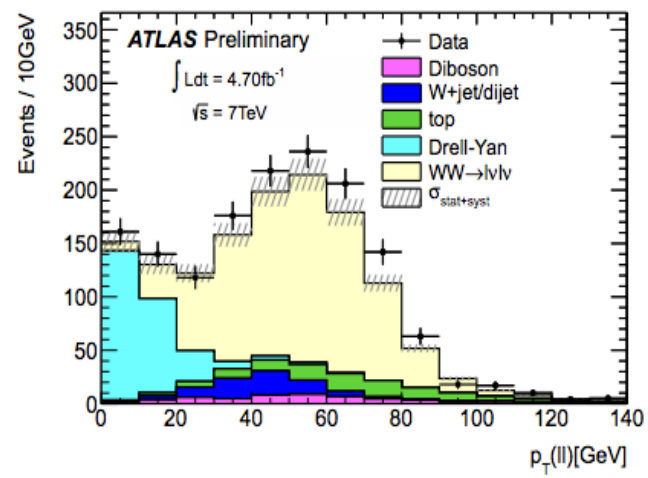
WW→$\ell\nu\,\ell\nu$

ATLAS-CONF-2012-025

- Selections:
  - Exact 2 isolated leptons, pT>25(leading),20(trailing)GeV
  - Z/ γ * rejection: M_{ll}>15GeV, $M_{ll'}$>10GeV, $|M_{ll}-Mz|$>10GeV
  - $E_{T,rel}^{miss}$>55/50/25GeV(μμ/ee/eμ)
  - pT>25/20GeV jet/b-jet Veto
- Major background: Z/ γ *, Top, W+jets
- Measured cross section: 53.4±2.1(stat)±4.5(sys)±2.1(lumi) pb
- SM NLO prediction: 45.1±2.8 pb
- Fiducial cross sections:

Channels	expected σ^{fid} (fb)	measured σ^{fid} (fb)	$\Delta\sigma_{stat}$ (fb)	$\Delta\sigma_{syst}$ (fb)	$\Delta\sigma_{lumi}$ (fb)
$e\nu e\nu$	44.9±3.7	41.4	± 6.5	± 5.7	± 1.6
$\mu\nu\mu\nu$	38.0±3.1	48.2	± 4.6	± 3.8	± 1.9
$e\nu\mu\nu$	237.4±19.4	284.9	± 12.7	± 14.1	± 11.1

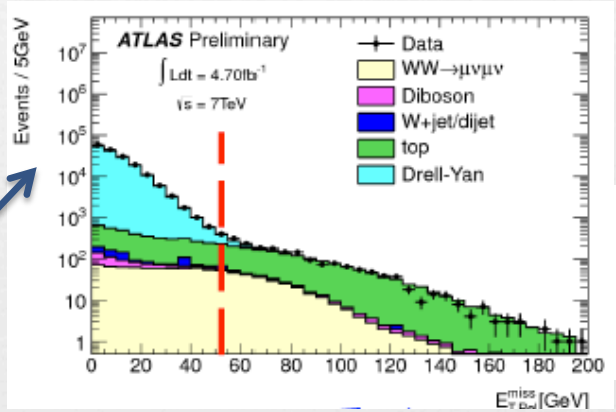




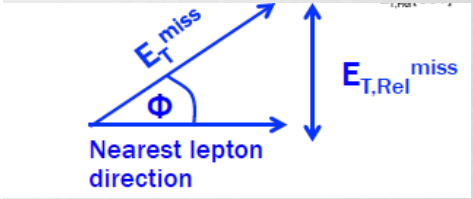
WW→$\ell\nu\,\ell\nu$ backgrounds

- Challenging task: higher signal rate than other DiBoson processes but extremely high background contamination
- ee, μμ channels at di-lepton selection:
  - Z event fraction > 99%
  - WW fraction: ~0.07%;
  - Top fraction: ~0.3%;
  - Need rejection power: ~10^4

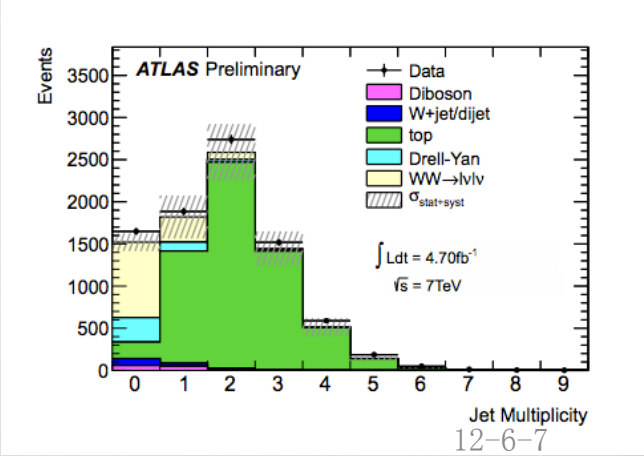
Relative E^{miss}_T in WW events against Drell-Yan(projection to nearest lepton/jet)



$E^{miss}_{T,rel}$ definition

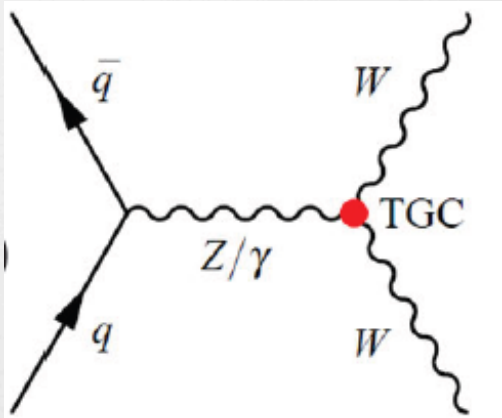


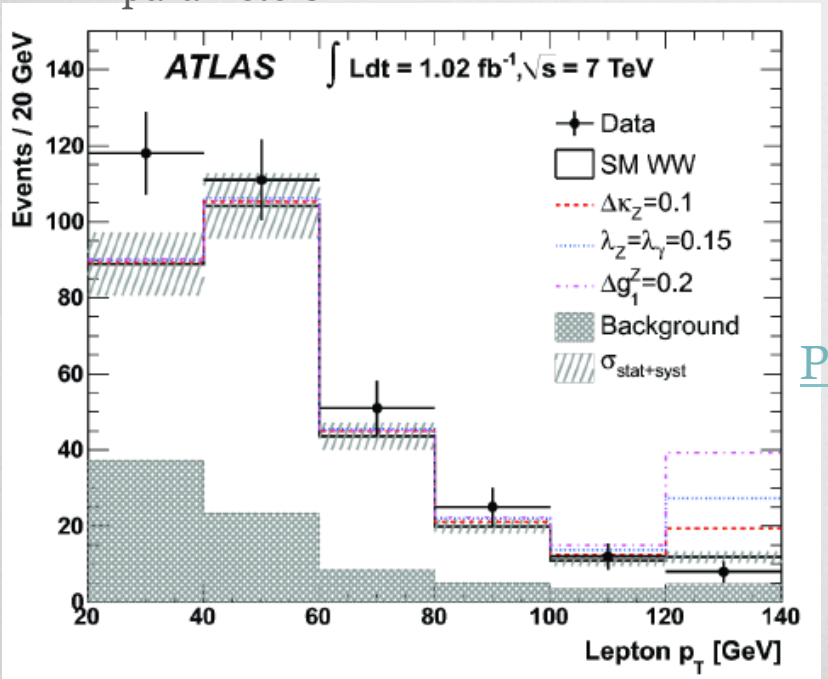
Reject multi-jet events to suppress Top rates(b-jet Veto at lower pT) Limited by JES/JER uncertainty. Using DD estimate from b-tagging control sample tech. to reduce the systematic uncertainty



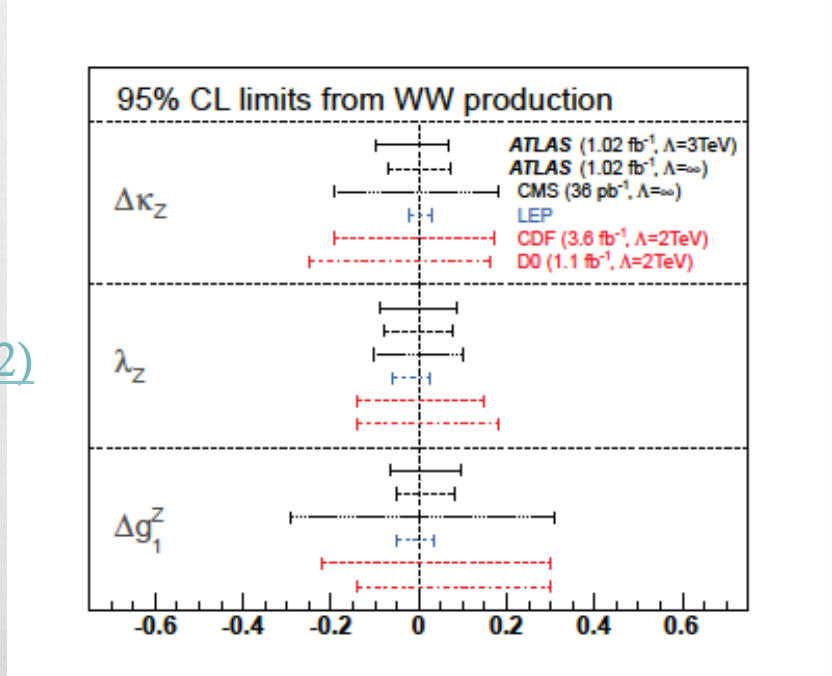
Anomalous coupling in WW

- Using leading pT spectrum which is sensitive to aTGCs. Max sensitivity at pt>120GeV.
- Sensitive to WWZ and WW γ aTGC vertices.
- Highest sensitivity for $\Delta\kappa_V$
- Binned log-likelihood limits set using LEP aTGC scenario with 3 parameters





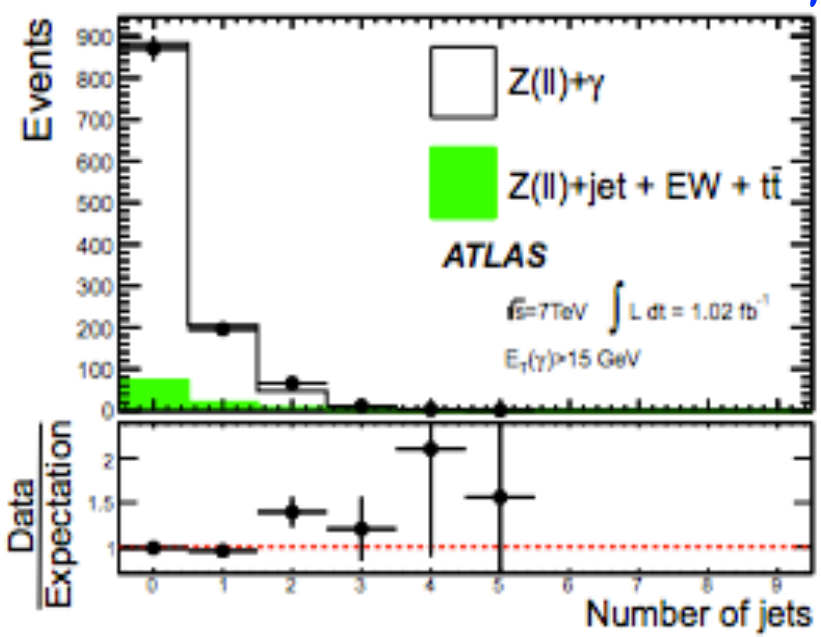
PLB 712 (2012)



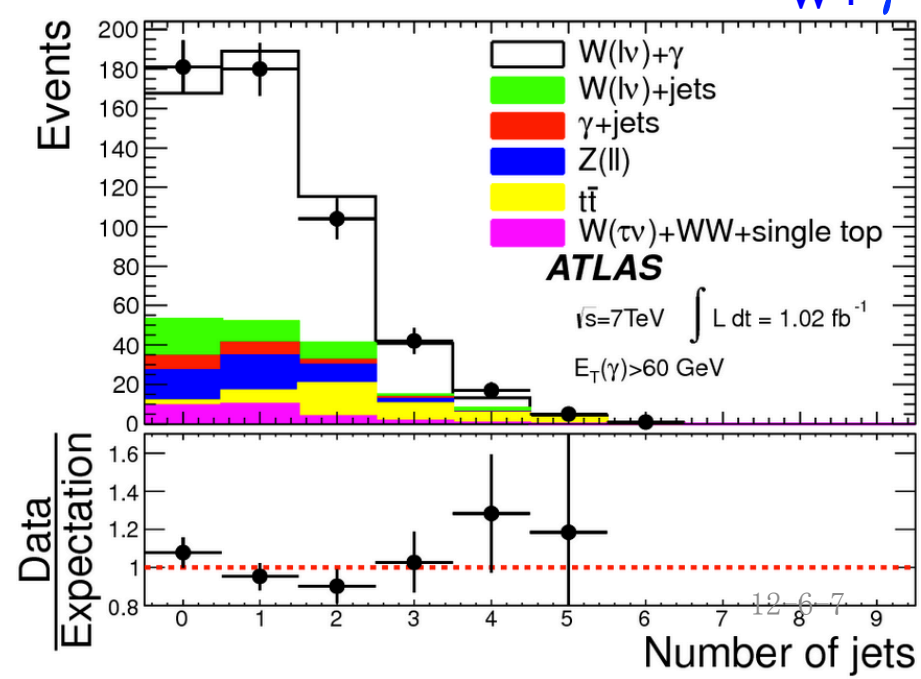
W/Z+ γ

- Selections:
  - W: 1 isolated lepton, pT > 25 GeV, E_T^{miss}>25GeV, M_T > 40 GeV
  - Z: 2 isolated leptons, pT > 25 GeV, M_{ll} > 40GeV
  - γ : ET > 15 GeV, isolated, $\Delta R(l, \gamma) > 0.7$
  - Exclusive measurement : veto of events containing jets with pT > 30GeV
- Major background: V+jets

Z+ γ



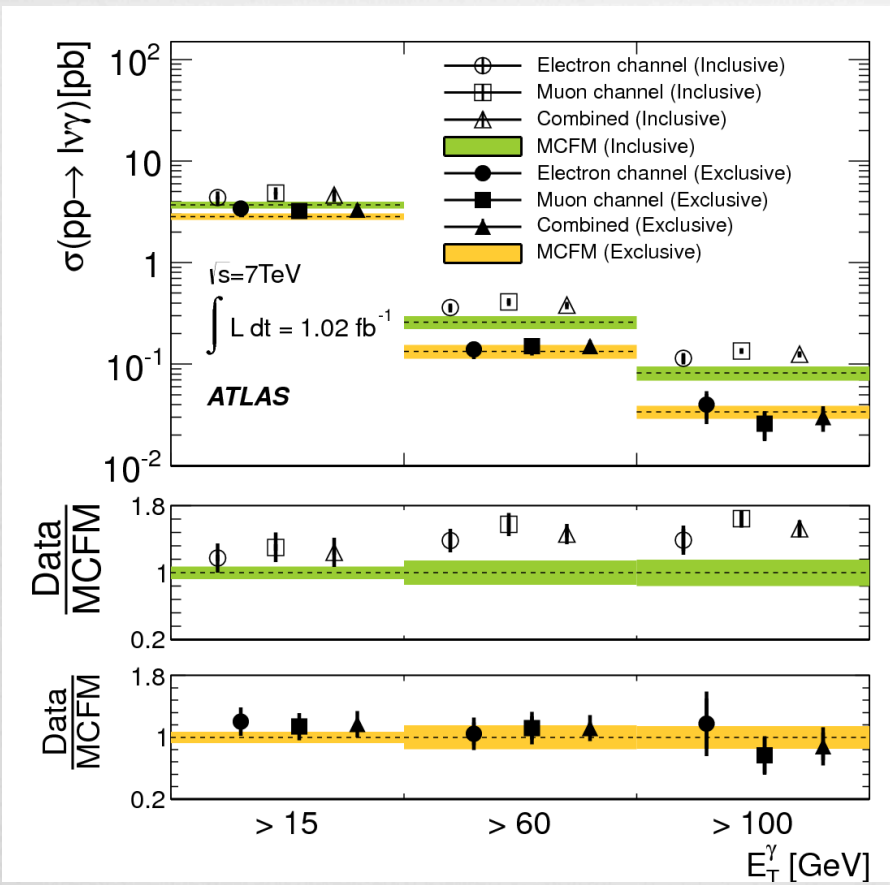
W+ γ

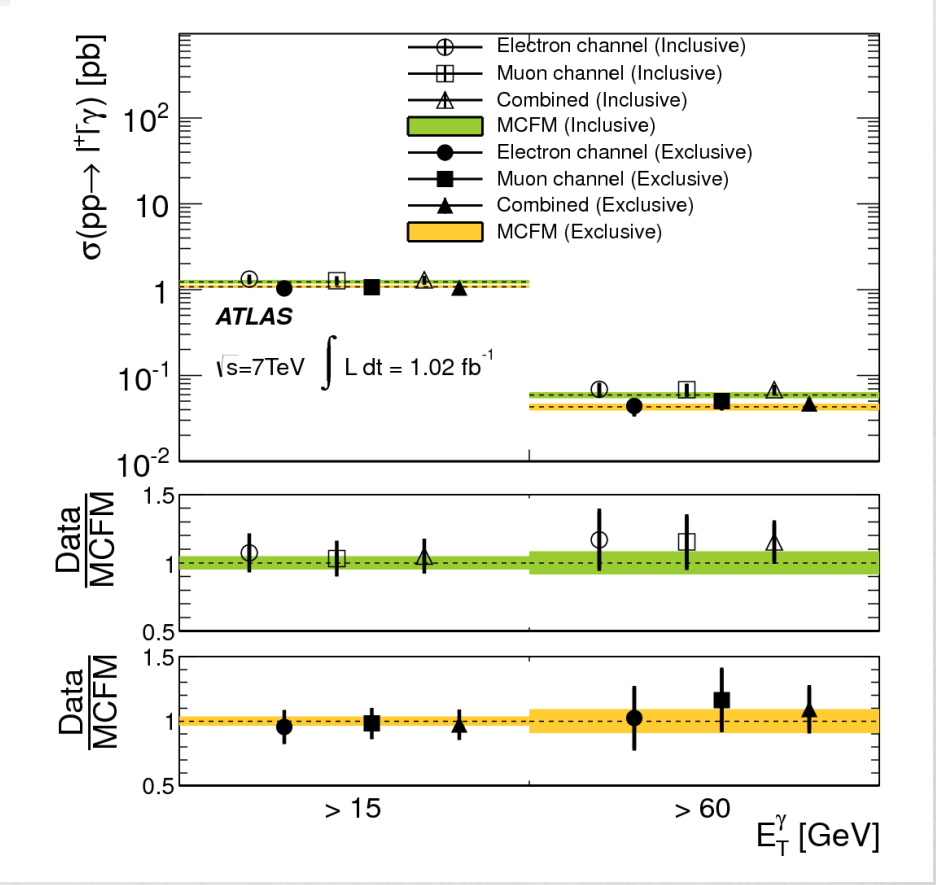


Inclusive and exclusive W/Z+ γ and aTGC

Inclusive and exclusive
cross section results for 1fb^{-1}

arxiv:1205.2531





W+ γ

Z+ γ

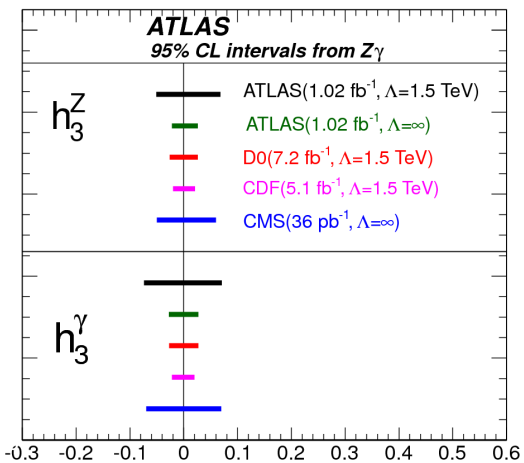
W/Z+ γ constraint on aTGC

arxiv:1205.2531

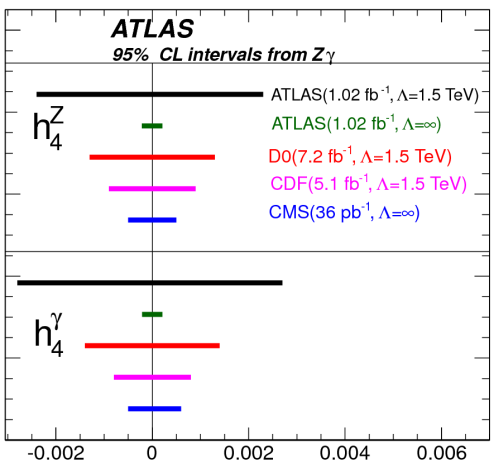
- aTGC extraction based on observed photon E_T spectrum
- Exclusive extended fiducial cross section in use:

$$W\gamma : E_T^{\gamma} > 100GeV$$

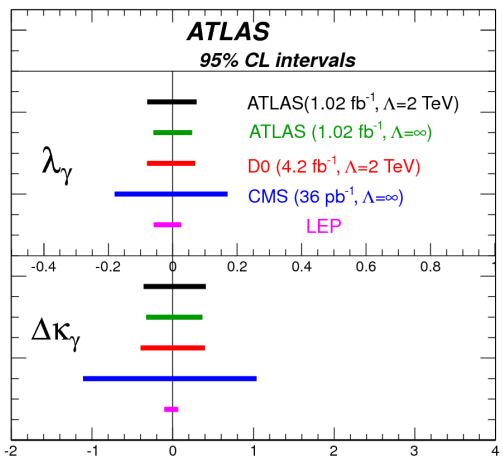
$$Z\gamma : E_T^{\gamma} > 60GeV$$



Z+ γ



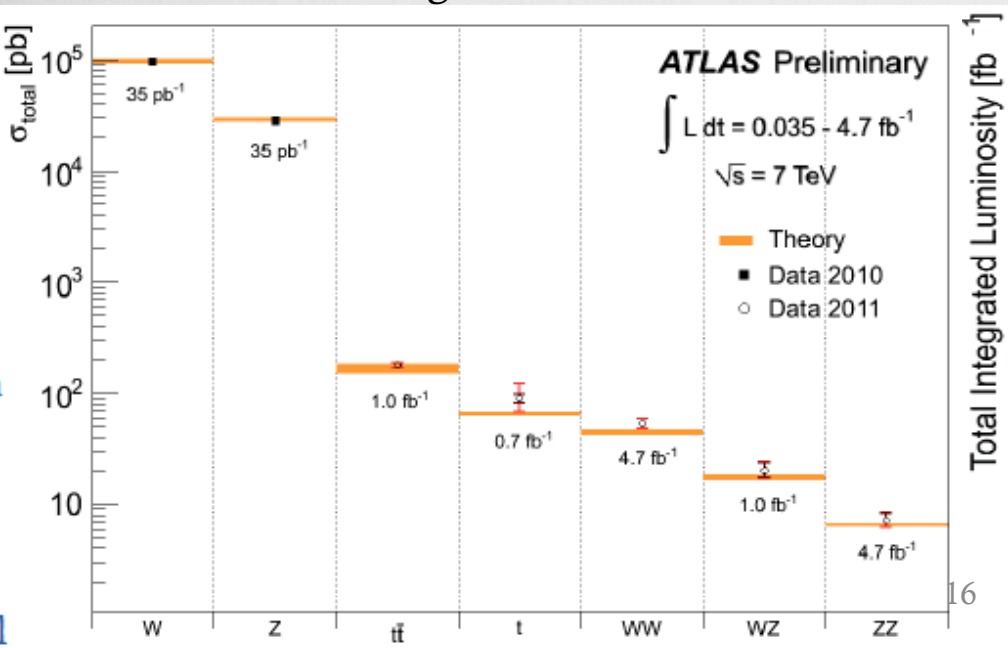
Z+ γ

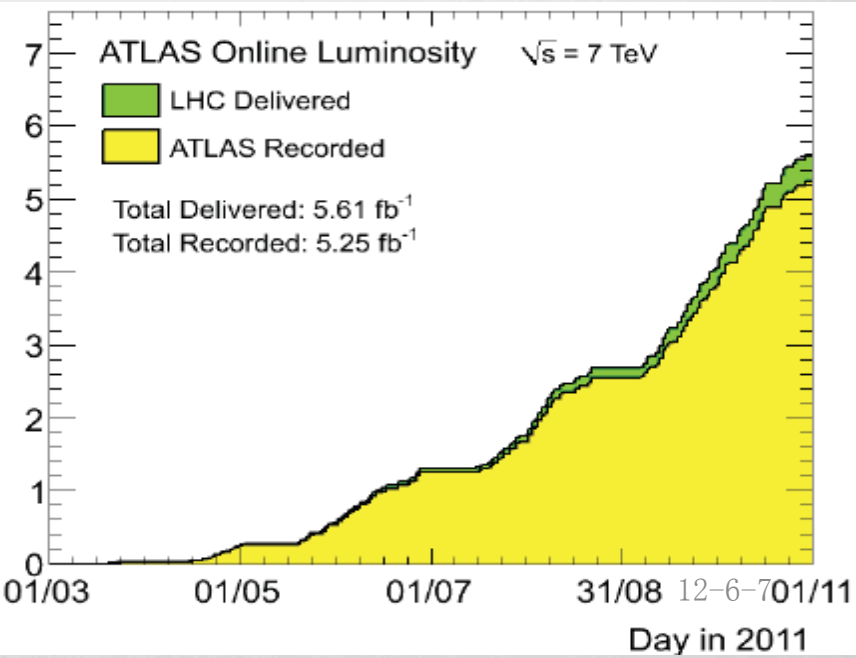


W+ γ

Summary

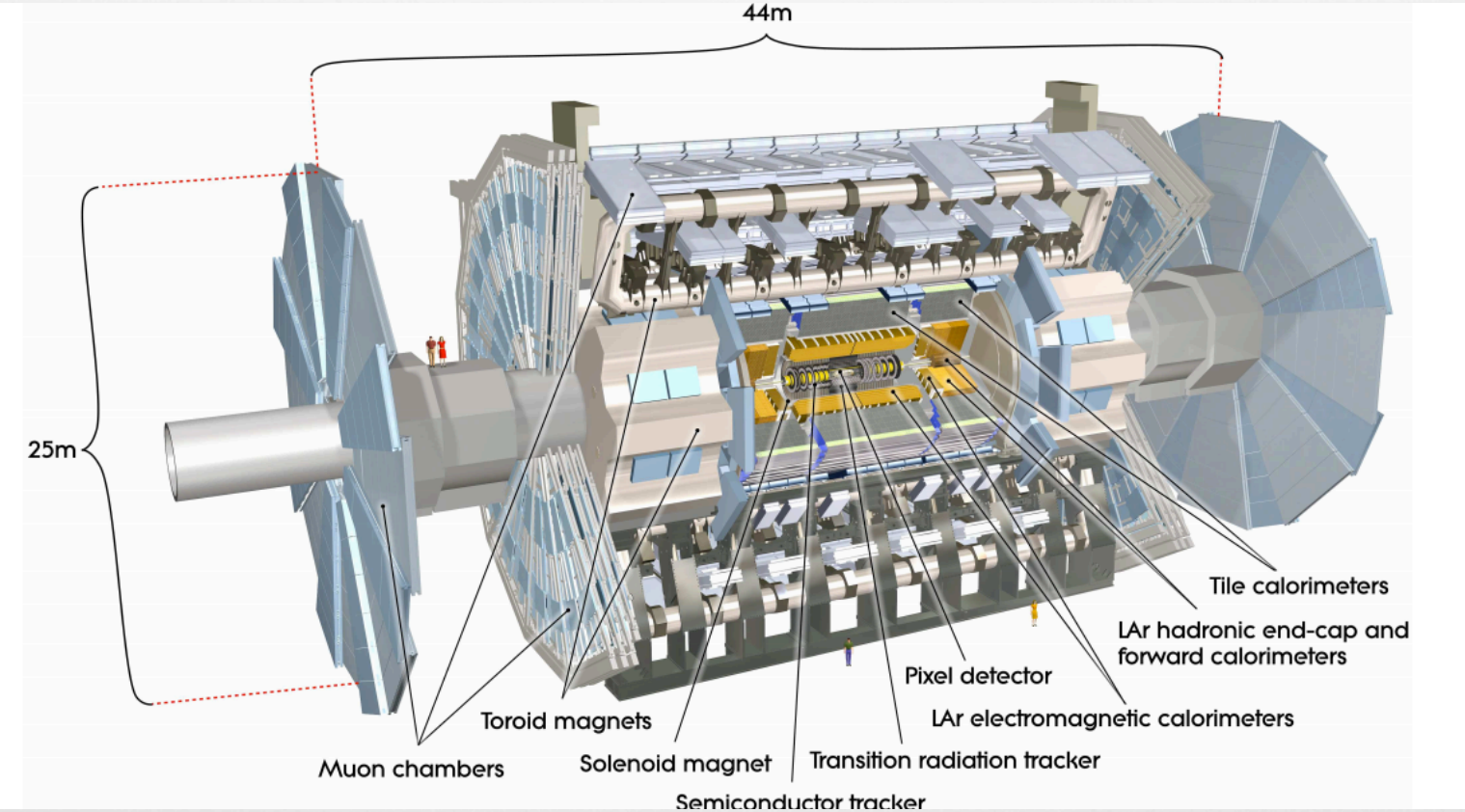
- Many thanks to LHC's smooth and fruitful data taking in 2011
- Remarkable cross sections measurement preliminarily updated with full 2011 dataset(4.7fb^{-1}).
- aTGC all successfully derived with int. Lumi up to 1fb^{-1}. Competitive with LEP and Tevatron. Working on the combination between diboson channels.
- Still working on publishing full 2011 analysis with more precise SM test while launching 8TeV taskforce meanwhile

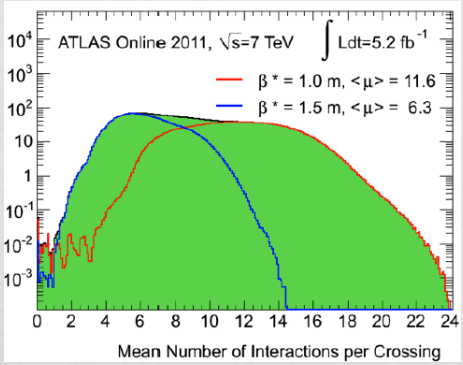


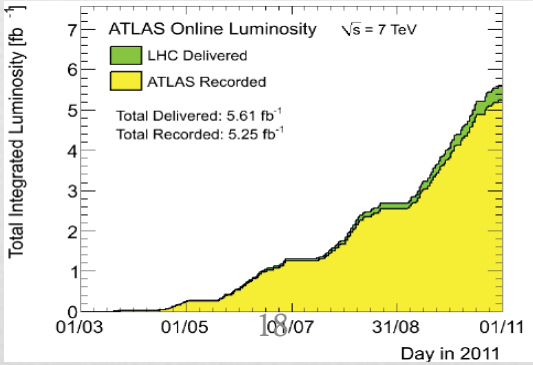


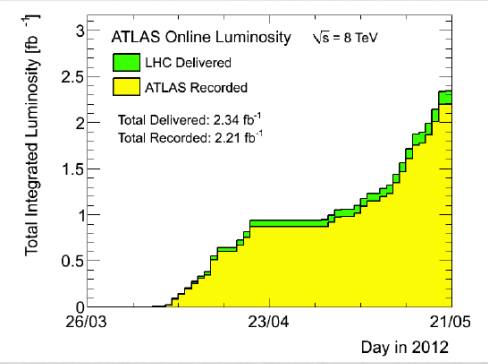
Spare

ATLAS Detector







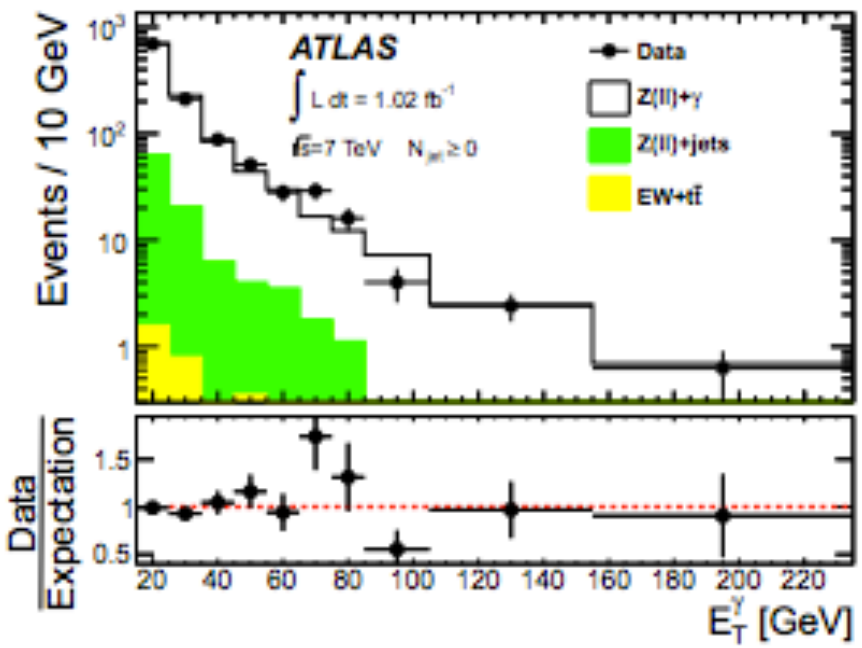


Cross section summary and observed events

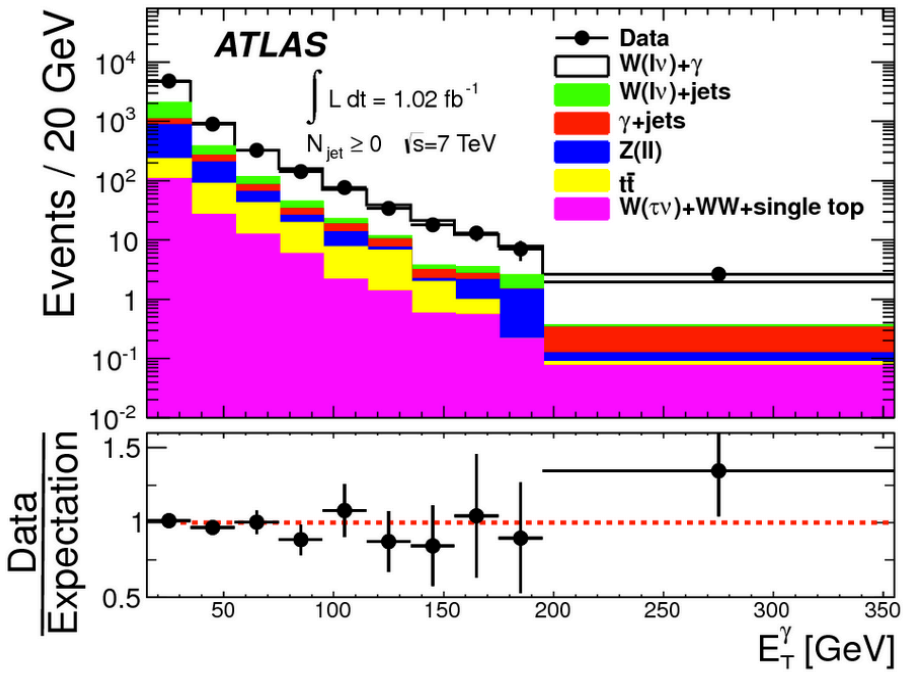
Process	$\int Ldt$	σ_{fid} (stat) (syst) (lumi)	σ_{tot} [pb] (stat) (syst) (lumi)	Reference
$W\gamma \rightarrow l\nu\gamma$	1 fb^{-1}	4.60 ± 0.11 ± 0.64 ± 0.17 pb	-	arXiv :1205.2531
$Z\gamma \rightarrow ll\gamma$	1 fb^{-1}	1.29 ± 0.05 ± 0.15 ± 0.05 pb	-	arXiv :1205.2531
$WW \rightarrow l\nu l\nu$	5 fb^{-1}	By decay channel	53.4 ± 2.1 ± 4.5 ± 2.1	ATLAS-CONF-2012-025
$WZ \rightarrow l\nu ll$	1 fb^{-1}	102 $^{+15}_{-14}$ $^{+7}_{-6}$ ± 4 fb	20.5 $^{+3.1}_{-2.8}$ $^{+1.4}_{-1.3}$ $^{+0.9}_{-0.8}$	PLB 709 (2012) 341-357
$ZZ \rightarrow llll$	5 fb^{-1}	21.2 $^{+3.2}_{-2.7}$ $^{+1.0}_{-0.9}$ ± 0.8 fb	7.2 $^{+1.1}_{-0.9}$ $^{+0.4}_{-0.3}$ ± 0.3	ATLAS-CONF-2012-026
$ZZ \rightarrow ll\nu\nu$	5 fb^{-1}	12.2 $^{+3.0}_{-2.8}$ ± 1.9 ± 0.5 fb	5.4 $^{+1.3}_{-1.2}$ $^{+1.4}_{-1.0}$ ± 0.2	ATLAS-CONF-2012-027

Process	N Observed	N Background Predicted
$WW \rightarrow l\nu l\nu$	1524	531 ± 51
$WZ \rightarrow l\nu ll$	71	12.1 ± 1.4 (stat) $^{+4.1}_{-2.0}$ (syst)
$ZZ \rightarrow llll$	62	$0.7^{+1.3}_{-0.7}$ (stat) $^{+1.3}_{-0.7}$ (syst)
$ZZ \rightarrow ll\nu\nu$	78	40.7 ± 5.6

W/Z+ γ : E_T^{γ} spectrum



Z+ γ



W+ γ

Effective Lagrangian Approach

Express model independent triple gauge couplings as parameters in effective Lagrangian:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right] \quad \text{(WW, WZ)}$$

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right] \quad \text{(ZZ)}$$

Notes on couplings:

- Couplings defined for on-shell bosons
- Charged couplings and f_5^V, h_3^V, h_4^V have CP invariance
- f_4^V, h_1^V, h_2^V do not conserve CP

In the Standard Model:

- $g_1^V = \kappa^V = 1$
  - set limits on $\Delta g = g - 1$, $\Delta\kappa = \kappa - 1$
  - g_1^γ fixed to 1 due to U(1) EM invariance
- $\lambda^V = f_4^V = f_5^V = h_3^V = h_4^V = 0$

Frequentist limits

- Compute frequentist limits by Neyman construction
  - For each hypothetical value of aTGC parameter, generate a large number of pseudo experiments
  - observed number of events drawn randomly from poisson distribution
  - Central value of nuisance parameters from Gaussian distribution
  - If > 95% of pseudo experiments have larger ratio than actual experiment did, the aTGC value is rejected at 95% CL

- Guarantees statistical coverage
- CPU intensive

Bayesian limits

- Marginalize the nuisance parameters by integrating over them with gaussian PDF

$$L_{m\arg}(\vec{x}) = \int_{-\infty}^{\infty} L(\vec{x},\vec{\beta}) \times \exp[-\frac{1}{2}\beta_i (C_{ij})^{-1}\beta_j] d^{2m}\vec{\beta}$$

- 2m-dim integral is done by the Monte Carlo method
- Interval l is computed to satisfy

$$\frac{\int_{\vec{x}\in l} L_{m\arg}(\vec{x})}{\int_{-\infty}^{\infty} L_{m\arg}(\vec{x})} = 0.95 \qquad L_{m\arg}(\vec{x}) \geq L_{m\arg}(\vec{y}) \; for \; {}^{\forall}\vec{x} \in l \; and \; {}^{\forall}\vec{y} \notin l$$

Profile likelihood ratio

Profile likelihood ratio with Gaussian constraints on nuisance parameters:

$$L_{profile}(\vec{x}) = \max_{\beta}[L(\vec{x},\vec{\beta}) \times \exp[-\frac{1}{2}\beta_i(C_{ij})^{-1}\beta_j]$$

Define profile likelihood ratio $R(\vec{x}) = \frac{L_{prof}(\vec{x})}{\max[L_{prof}(\vec{x}')]}$

Two statistical approaches using ratio:

- -ln R(x) = 1.92 gives approximate 95% limit
  - delta log-likelihood method
  - fast, but coverage not guaranteed
- Frequentist limits use R as ranking function

Methodology of Top DD estimate

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- 0-jet bin top background Estimation:

$$N_{\text{top}}^{\text{Est.}}(\ell\ell + E_T^{\text{miss}}, 0j) \simeq N_{\text{top}}^{\text{Data}}(\ell\ell + E_T^{\text{miss}}) \times \overbrace{\boxed{P_2^{\text{MC}} \times \left(\frac{P_1^{\text{Btag,data}}}{P_1^{\text{Btag,MC}}}\right)^2}}^{P_2^{\text{Exp}}}$$

$$= (N_{\text{all}}^{\text{Data}} - N^{\text{non-top}}) \times (P_1^{\text{Btag,data}})^2 \times \frac{P_2^{\text{MC}}}{(P_1^{\text{Btag,MC}})^2}$$

- P1: b-tagging control sample jet Veto survival probability
- P2: full jet veto survival probability

$$P_1^{\text{Btag}} = N_{0j}^{\text{Btag}} / N_{\text{all-jets}}^{\text{Btag}}$$

$$P_2^{\text{MC}} = N_{0j}^{\text{MC}} / N_{\text{all-jets}}^{\text{MC}}$$

- (Control sample 1)B-tagged sample:
- ✓ pure top sample, tagged with at least 1-bjet w/ the largest MV1 weight + (l^+l^-,Et_{miss})
- (Control sample 2)Multi-jet sample: (l^+l^-,Et_{miss})
- P_1 insensitive to the normalization (b-tag eff.)
- P_2 insensitive to lumi & theo. σ values
- P_2/P_1^2: reduced JES, ISR/FSR sensitivities
- MC subtractions applied to both control samples w.r.t. 4.7fb^{-1} int.Lumi. In GRL