ATLAS results on the $W\gamma\gamma$ cross section and anomalous quartic gauge couplings

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IHEP
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Outline

Motivation

01 **Gauge boson coupling**
Theory

02 **TGC vs QGC**
at the LHC

03 **W$\gamma\gamma$**
at the LHC

04 **ATLAS detector**

W$\gamma\gamma$ analysis

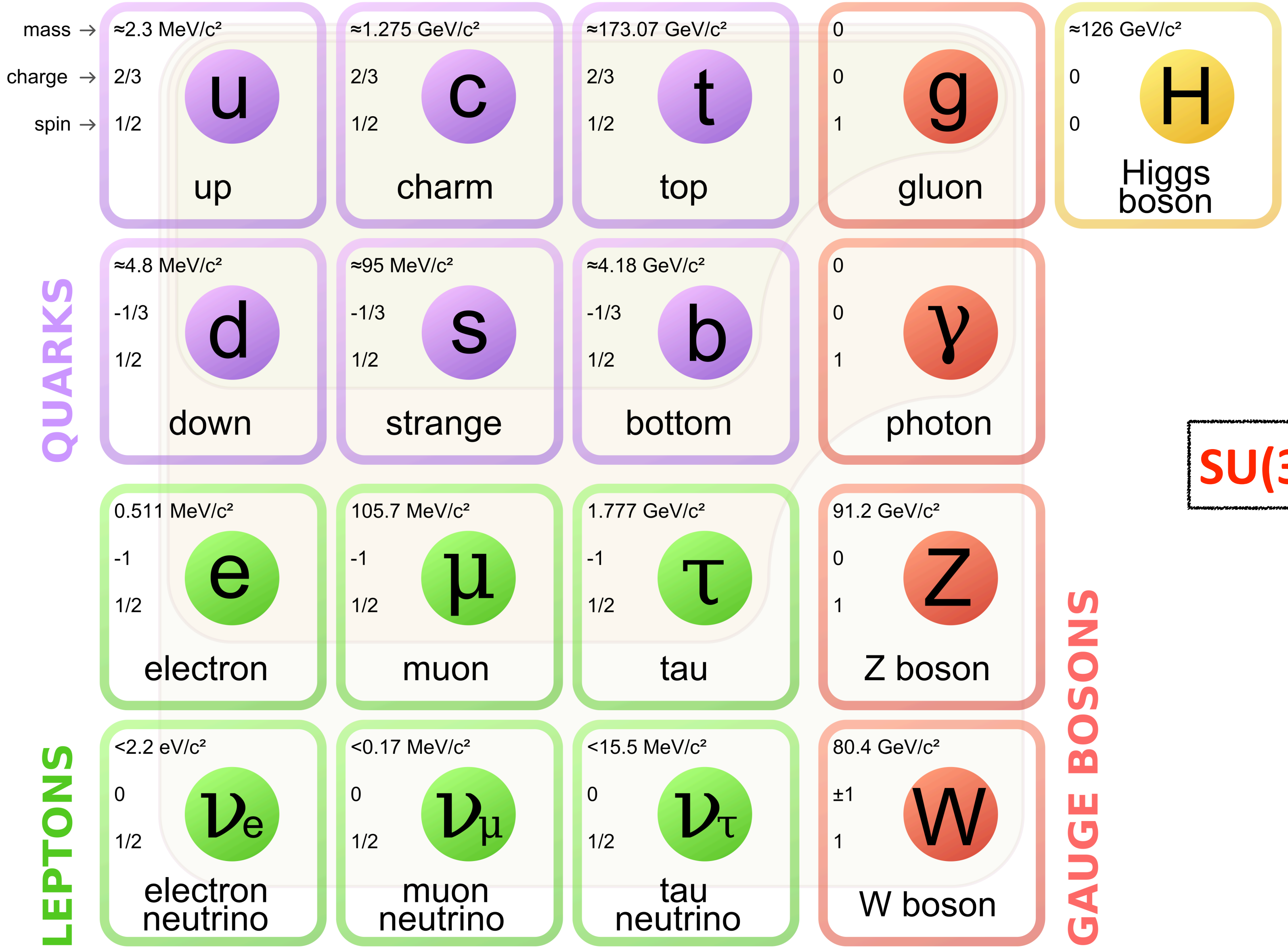
05 **Analysis review**

06 **Data analysis**

07 **Cross section**

08 **aQGC analysis**

The Standard Model



$\boxed{SU(3) \times SU(2) \times U(1)}$

Gauge boson coupling in the SM

SM EWK Gauge boson coupling:

$$-\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu}-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$SU(2)_L$ $U(1)$

TGC

QGC

- TGC:
Triple Gauge Boson coupling
- QGC:
Quartic Gauge Boson coupling

Gauge boson coupling in the SM

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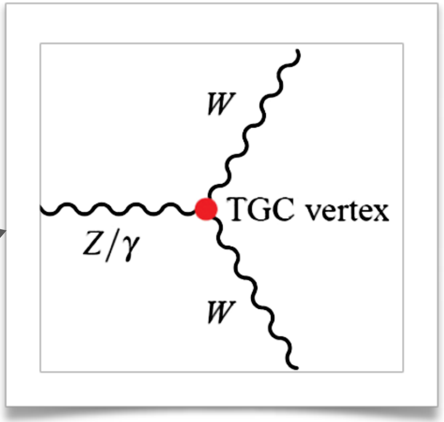
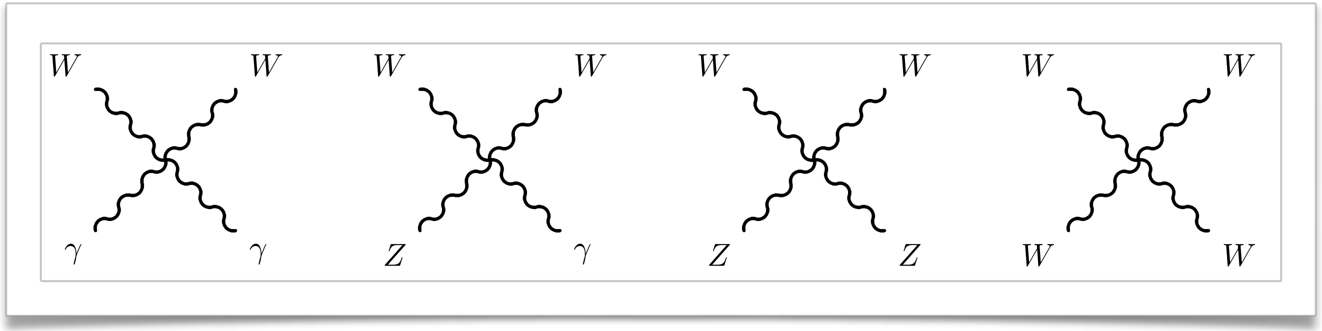
$$\underbrace{-\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu}}_{SU(2)_L} \underbrace{- \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{U(1)}$$

TGC



QGC



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Triple Gauge Boson coupling
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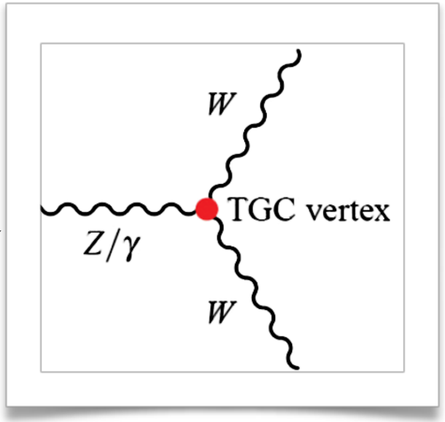
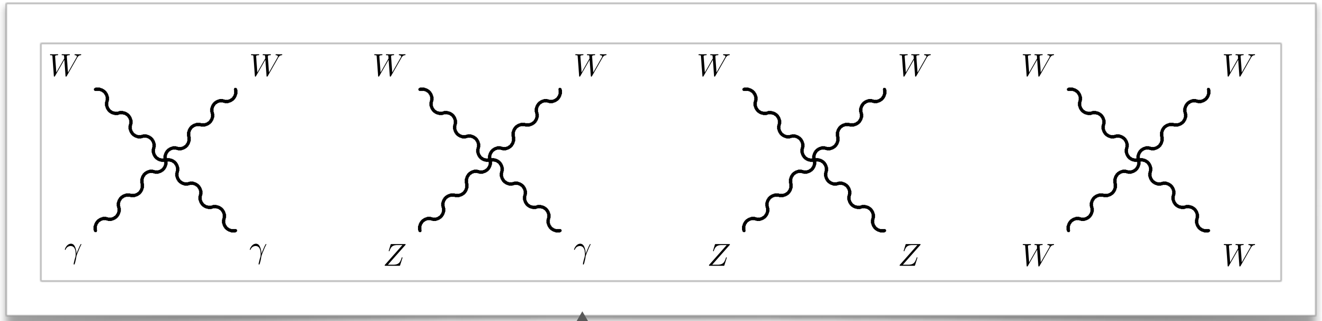
$SU(2)_L$ U(1)

TGC



- **Experimental signatures**
  - **Di-boson**
  - **Vector Boson Fusion (VBF)**

QGC



- TGC:
Triple Gauge Boson coupling
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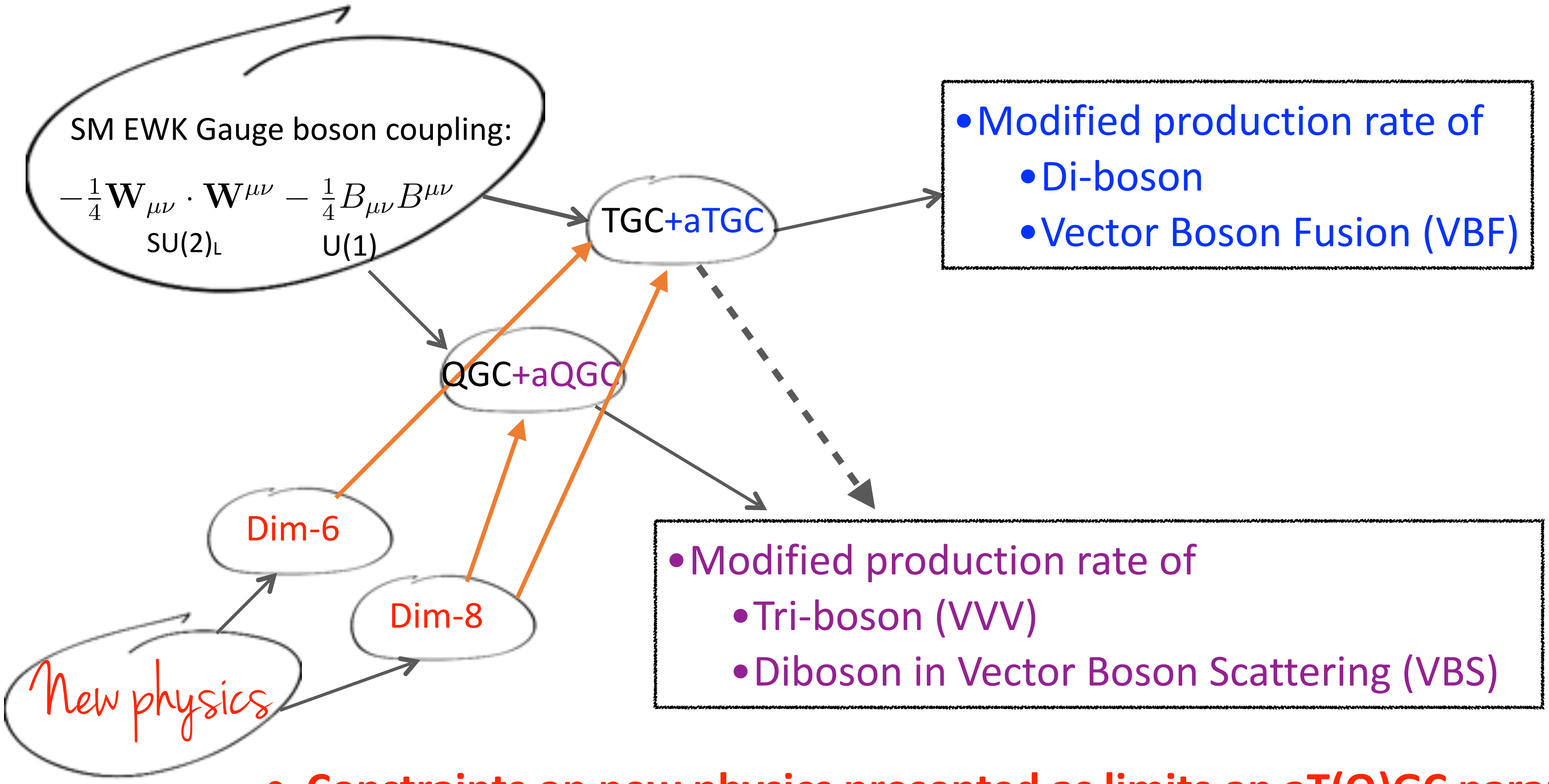
Quartic Gauge Boson coupling

- **Experimental signatures**
  - **Tri-boson (VVV)**
  - **Diboson in Vector Boson Scattering (VBS)**

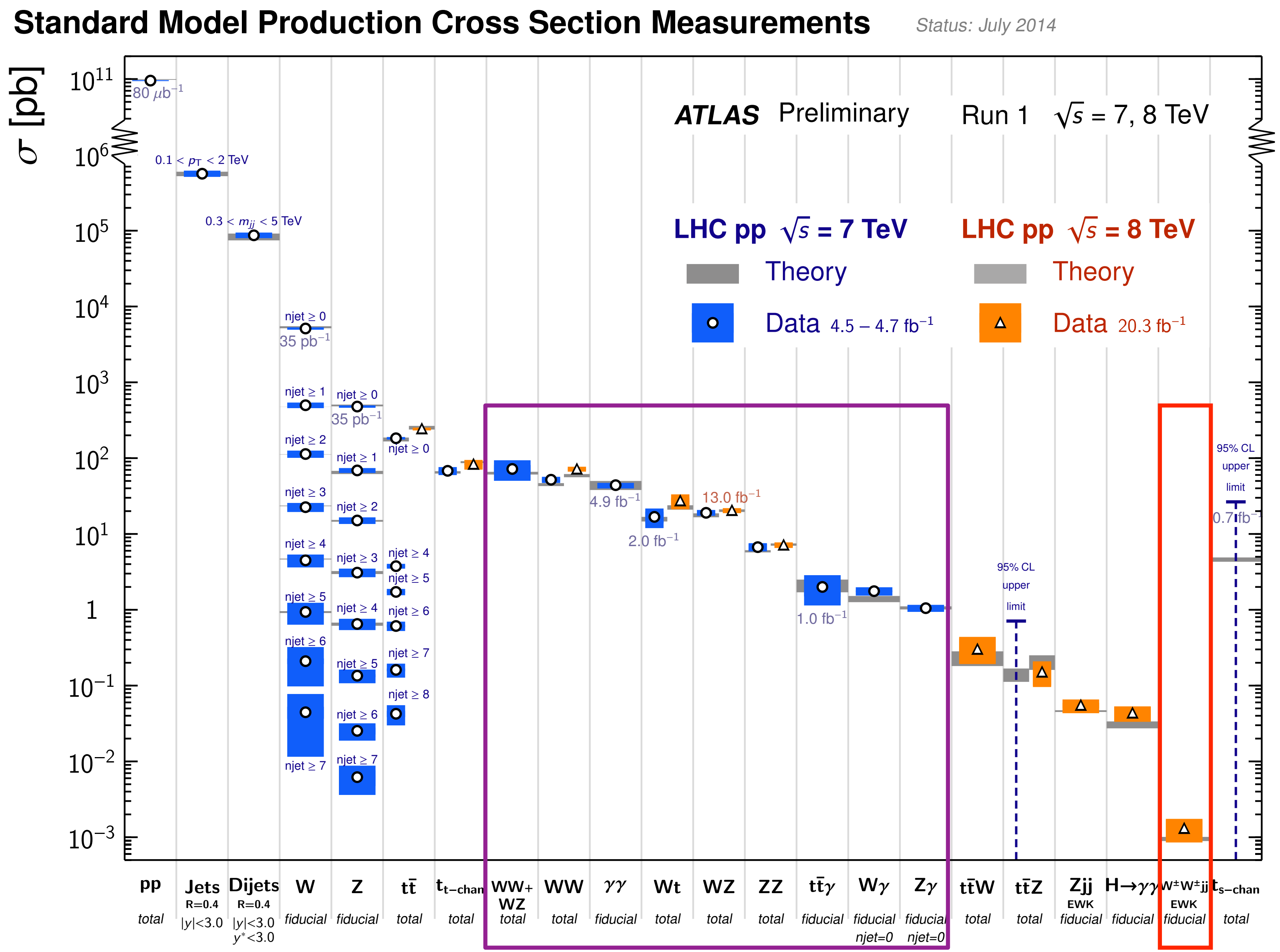
Gauge boson coupling with BSM physics



- Dim-6 (8): Dimension 6(8) operators
- aTGC: anomalous Triple Gauge Boson Coupling
- aQGC: anomalous Quartic Gauge Boson Coupling

- **Constraints on new physics presented as limits on aT(Q)GC parameters (zero in SM).**
- **Probes new physics at an energy scale that's beyond our reach.**

Probing TGC/QGC at the LHC—ATLAS



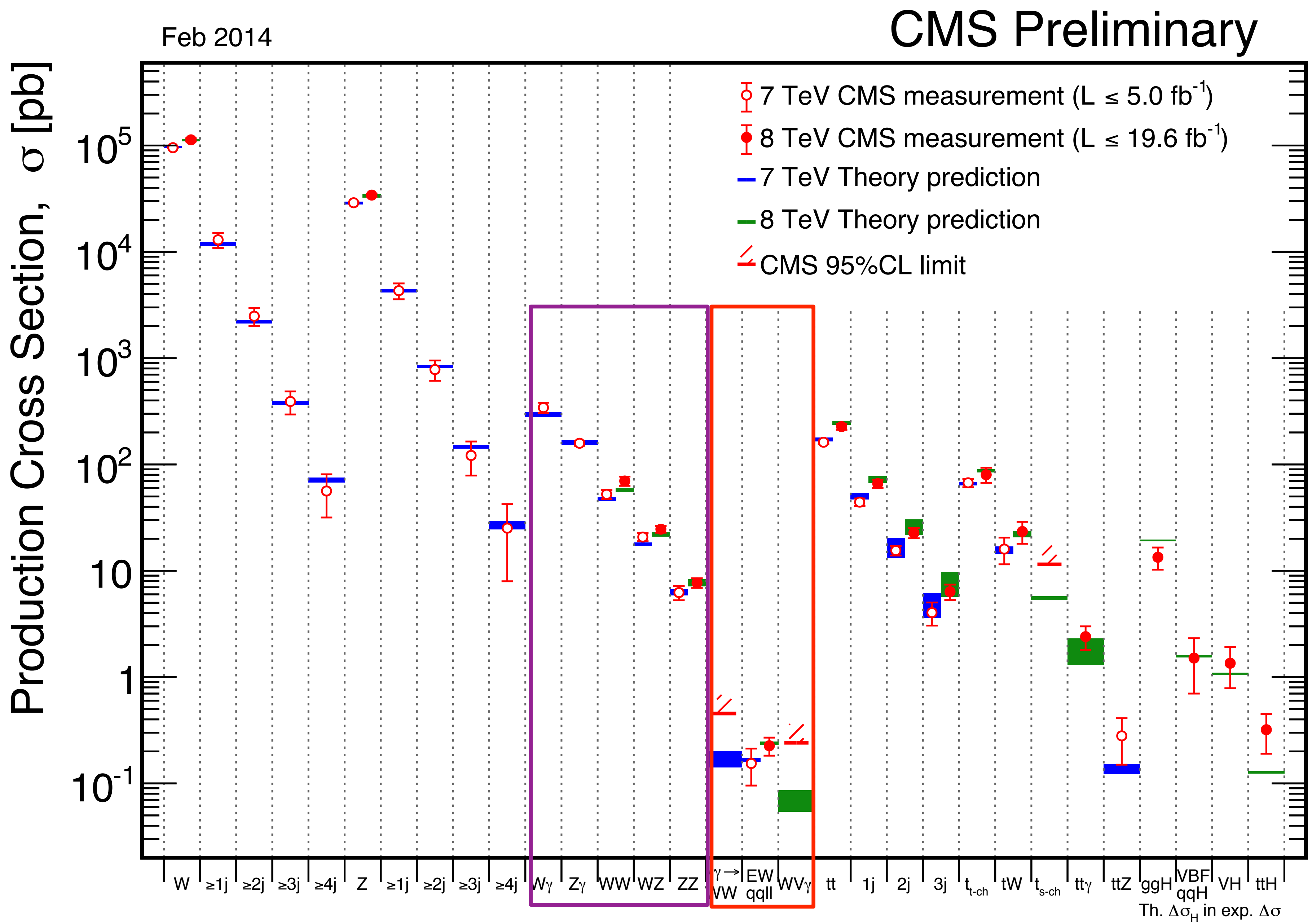
TGC

- Di-boson production well-measured.

QGC

- No VVV measurement published yet.
- Analysis published on First Evidence of Same-sign WW VBS.
  - First observation of VBS.
  - Limits on anomalous WWWW coupling.

Probing TGC/QGC at the LHC—CMS



QGC studies

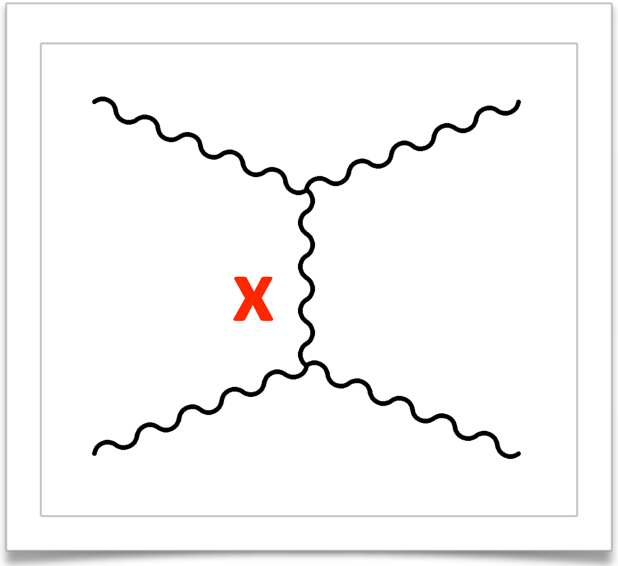
- **WVγ : σ(pp->WVγ)<241 fb ~ 3.4 times the SM prediction**
- **γγ → WW 1 s.t.d**

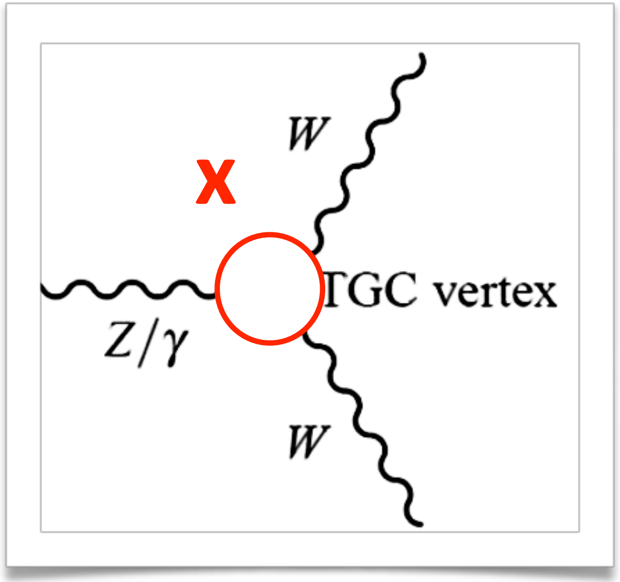
Both analyses provide limits on aQGC parameters.

not in the plot: same sign WW

Probing TGC/QGC at the LHC

- **From previous slides:** TGCs are well-understood experimentally. QGCs rarely studied.
- **EFT point of view:** exchange of heavy bosons (X) -> tree level contribution through dim-8 operators -> one loop level through dim-6 operators.





Conclusion

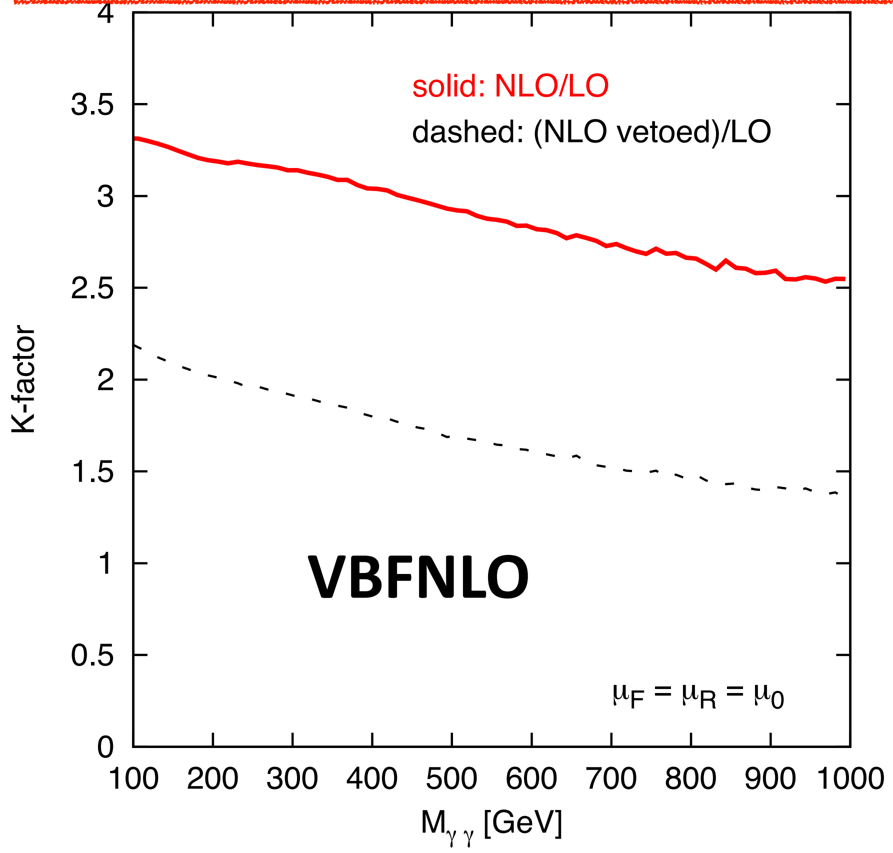
We need to perform QGC analyses (triboson and VBS) at the LHC to better understand dim-8 operators !

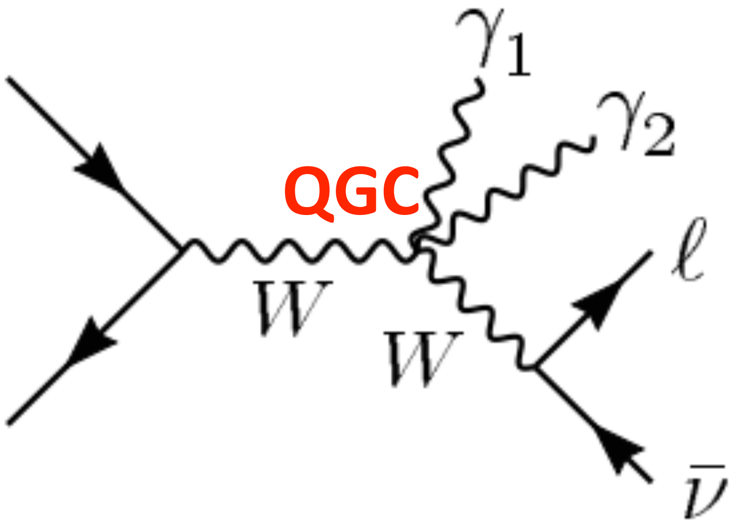
Why Wγγ?

- WWγγ contributes to this final state.
- Large rate compared to other VVV processes.

—> Promising first observation of VVV production!

- Important background to searches.
    - e.g.WH(γγ), SUSY searches with diphoton+MET.
- Large K-factor.





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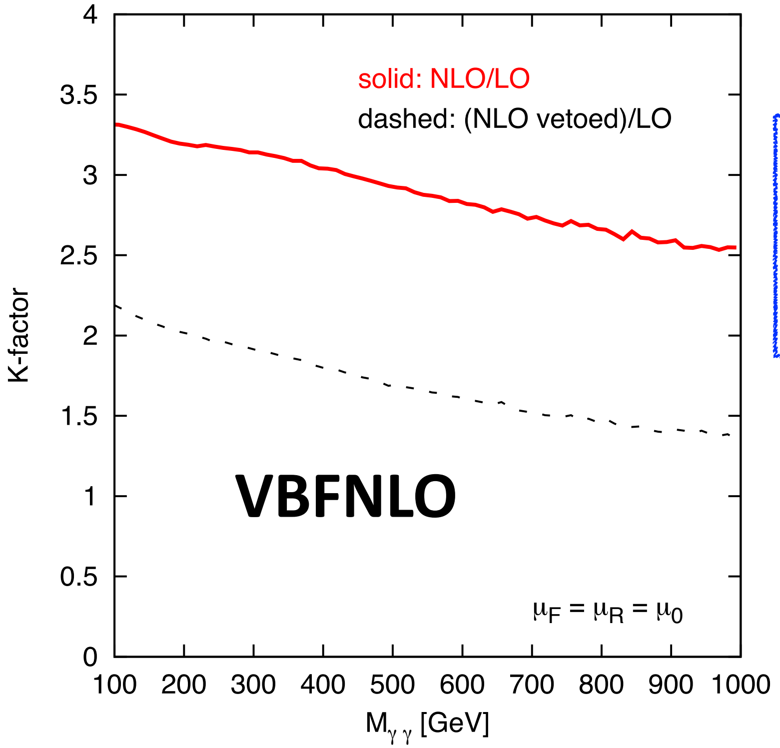
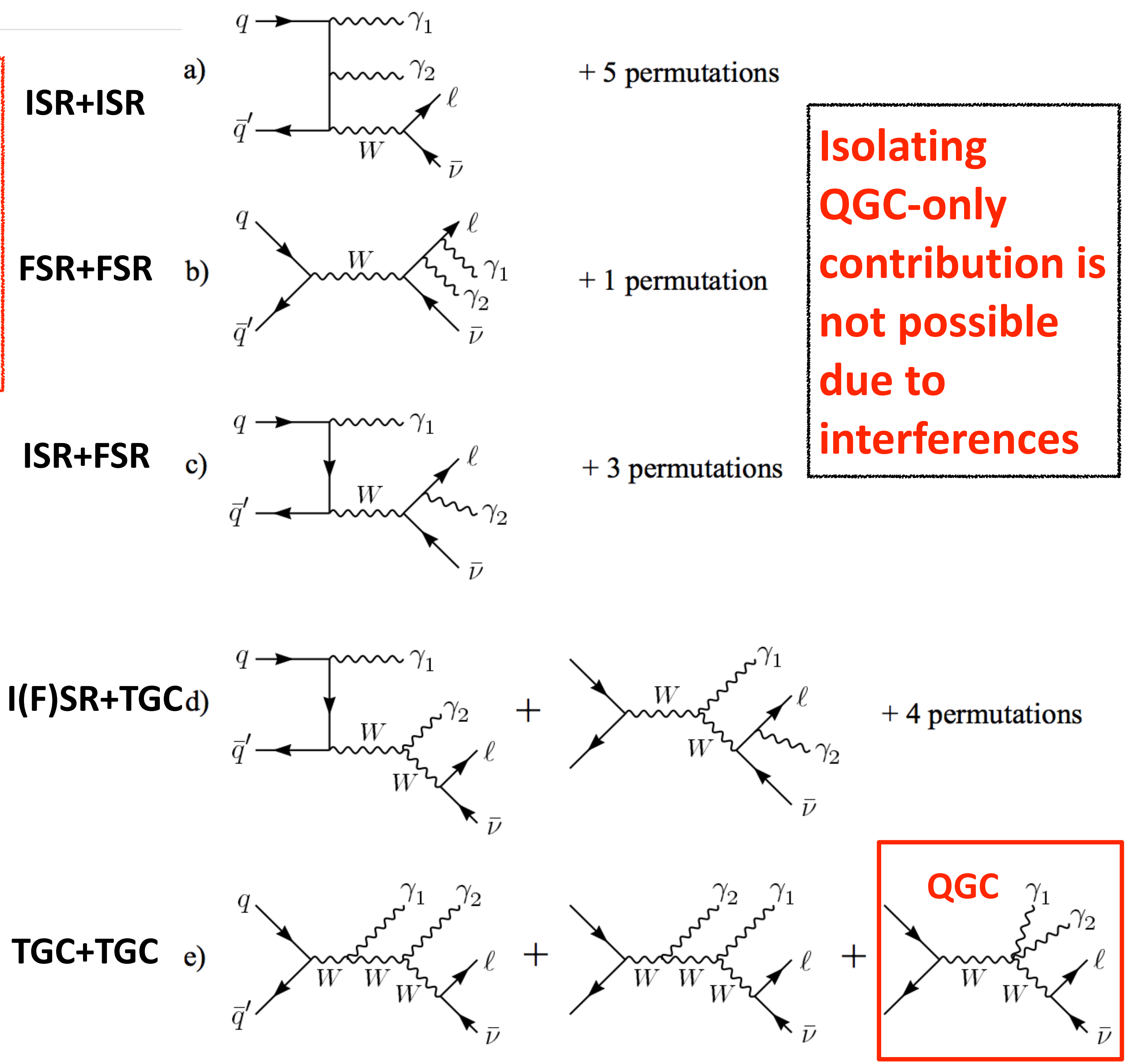


Destructive interference at LO



Isolating QGC-only contribution is not possible due to interferences

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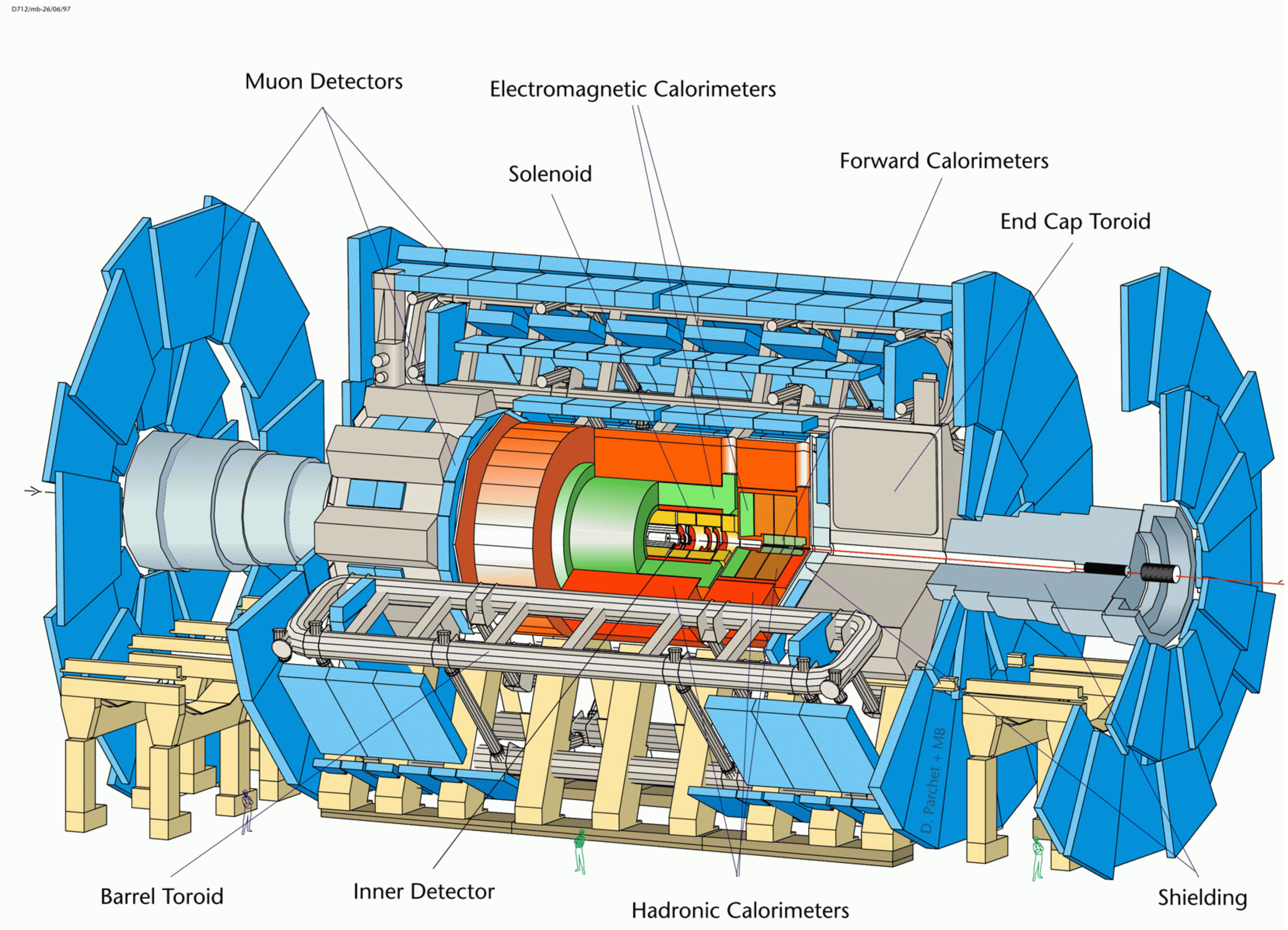
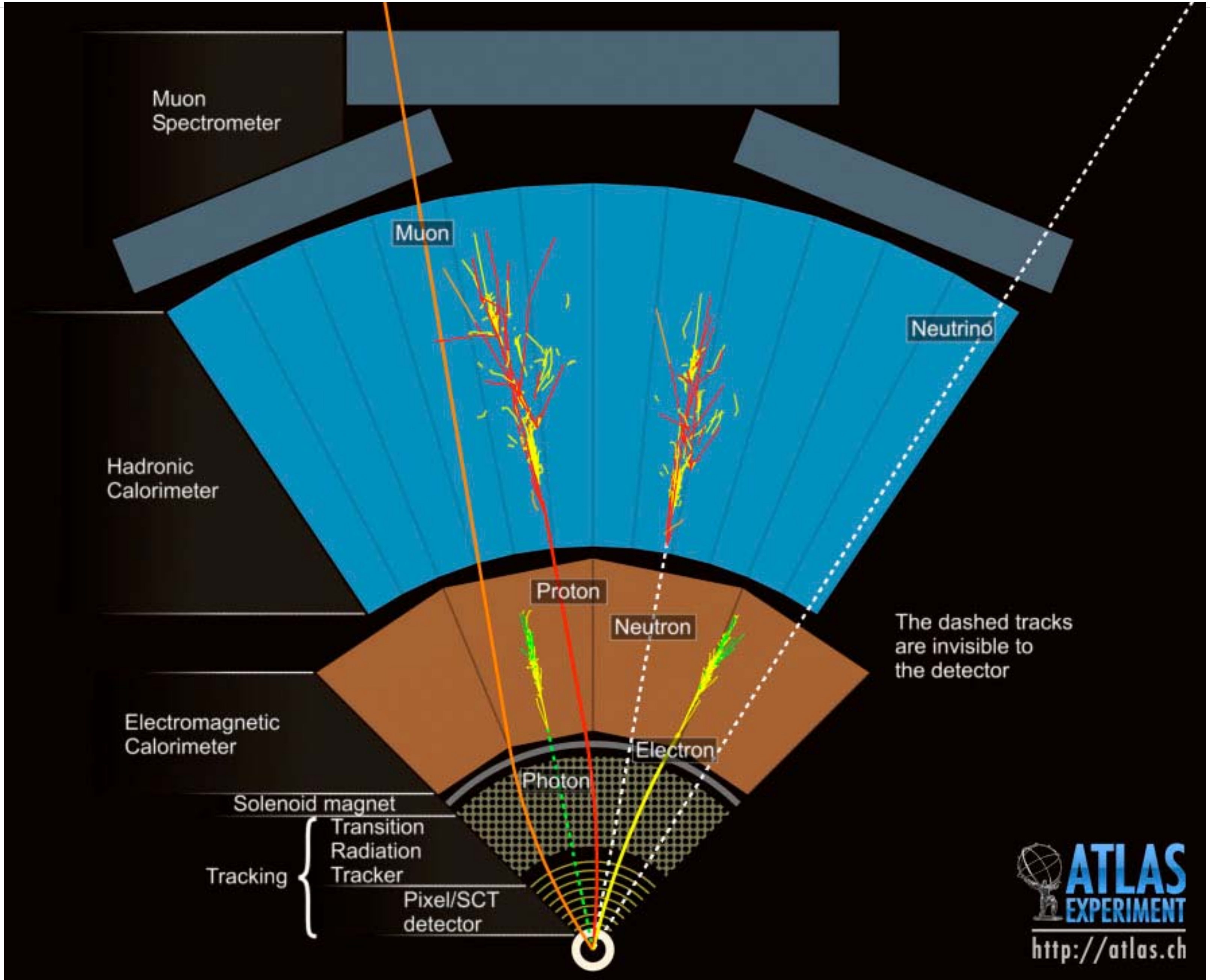
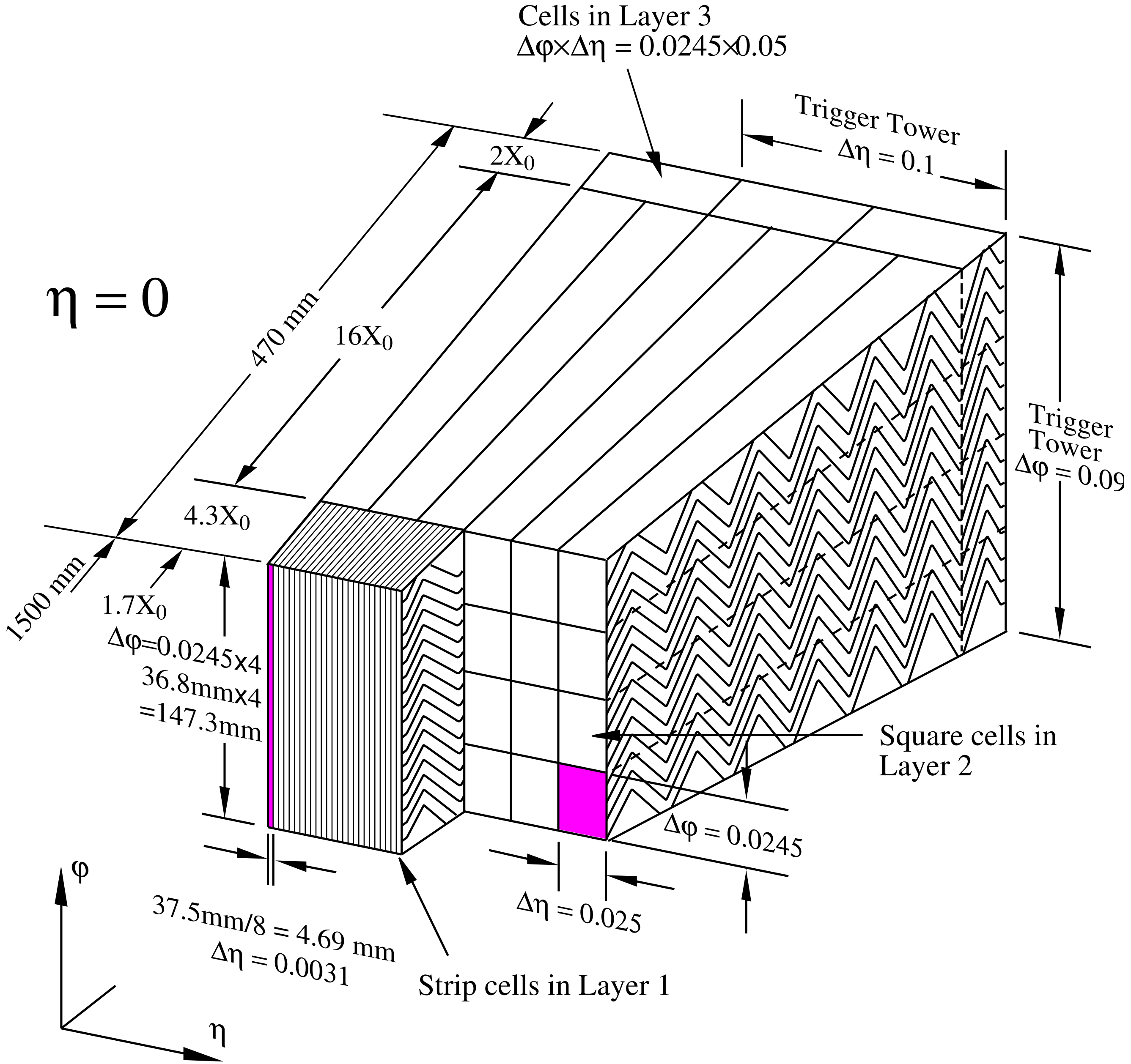
The ATLAS detector

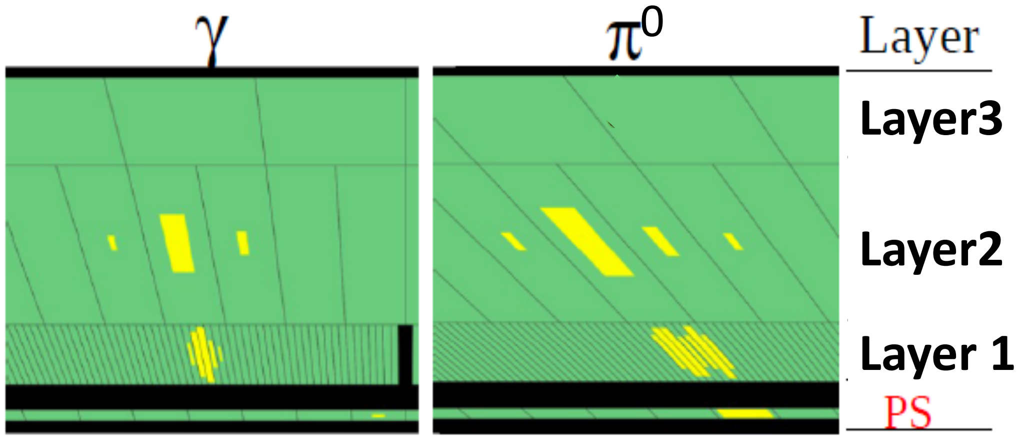


Particle detection with The ATLAS detector



The ATLAS EM calorimeter





Fine granularity in S1 for γ /π^0 separation

- ✓*Liquid argon—Pb calorimeter.*
- ✓*Intrinsically radiation hard.*
- ✓*Good photon ID.*
- ✓*Modeling of jets (control region): loose photons which fail some layer 1 cuts but passing all the other calorimeter cuts.*

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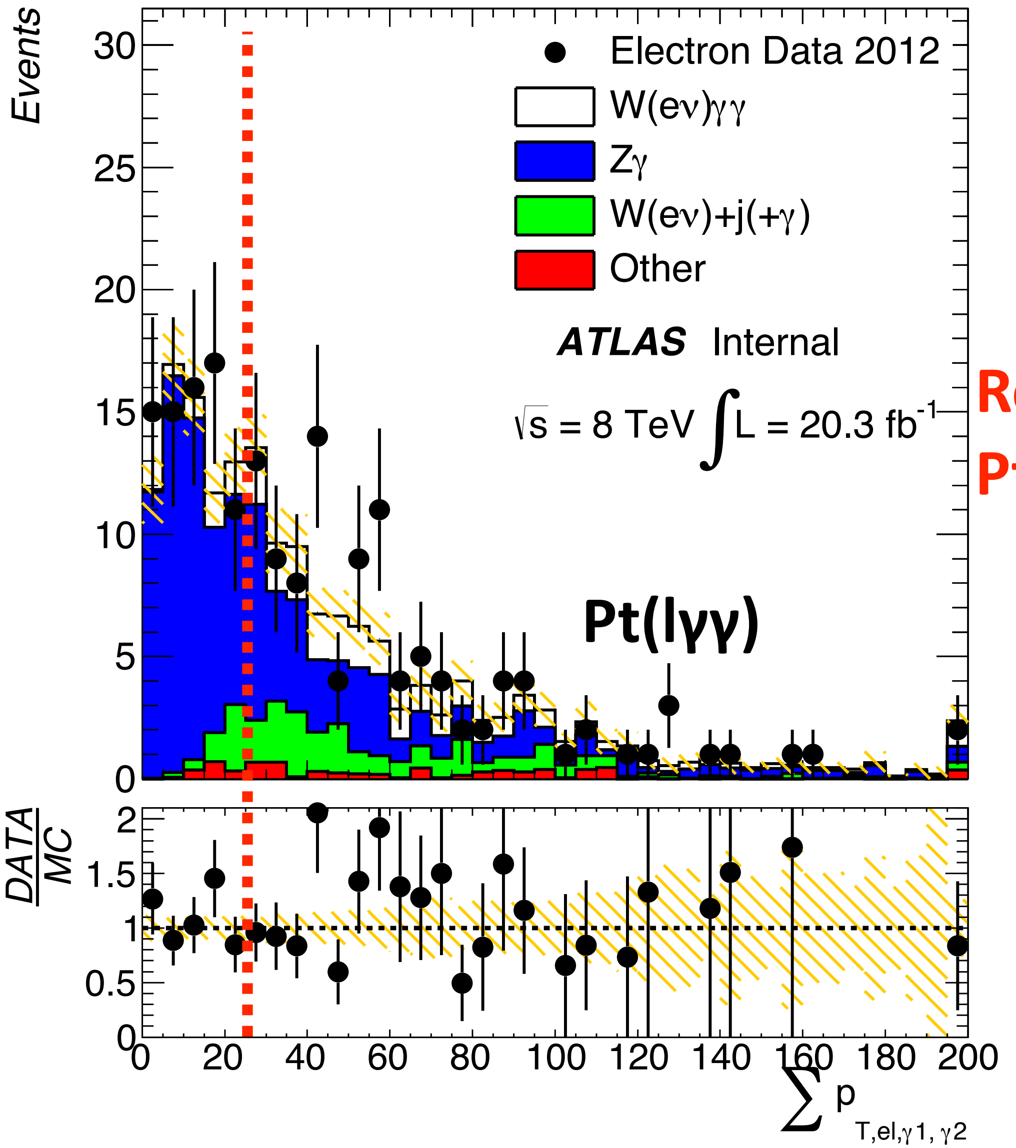
$W\gamma\gamma$ Analysis Overview

- Analysis goal: Fiducial Cross Section Measurements + aQGC limits.

- Signature : 1 lepton+ MET + 2 isolated photons.
    - Inclusive (>= 0 jets) and Exclusive (==0 jet) measurements.

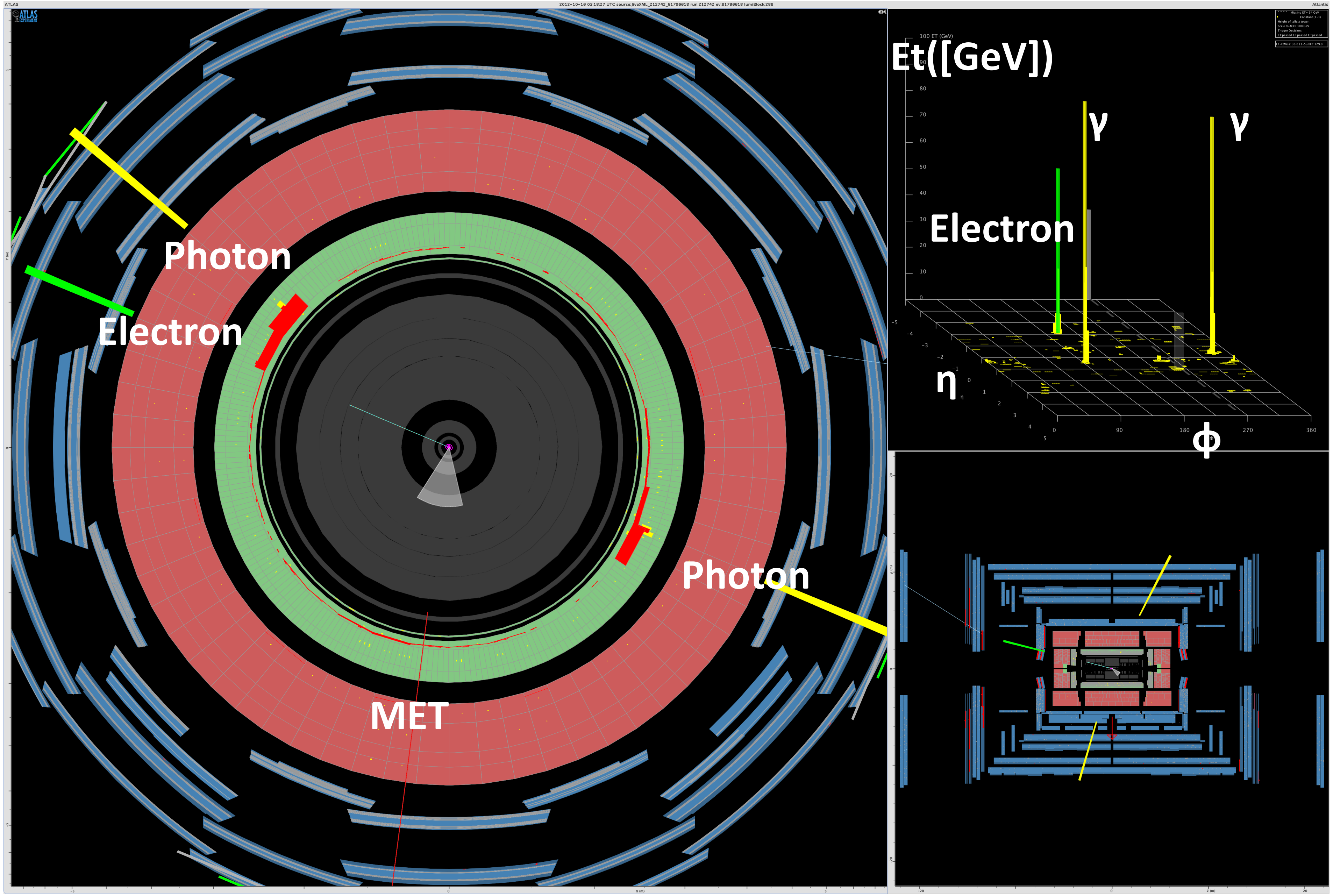
Wγγ Event selection

- Specialized triggers (three objects) extend lepton Pt range (25 GeV—>20 GeV).
- Kinematic cuts.
  - 1 lepton with pt > 20 GeV.
  - MET > 25 GeV.
  - Transverse mass of W > 40 GeV.
  - Two isolated photons with Pt > 20 GeV.
  - Jet Pt > 30 GeV.
- Zγ background suppression in the electron channel. (electron faking a photon)—M(lγ),M(lγγ) and Pt(lγγ).
  - Pt(lγγ) shows the balance of the system of selected objects.



Require Pt(lγγ) > 30GeV

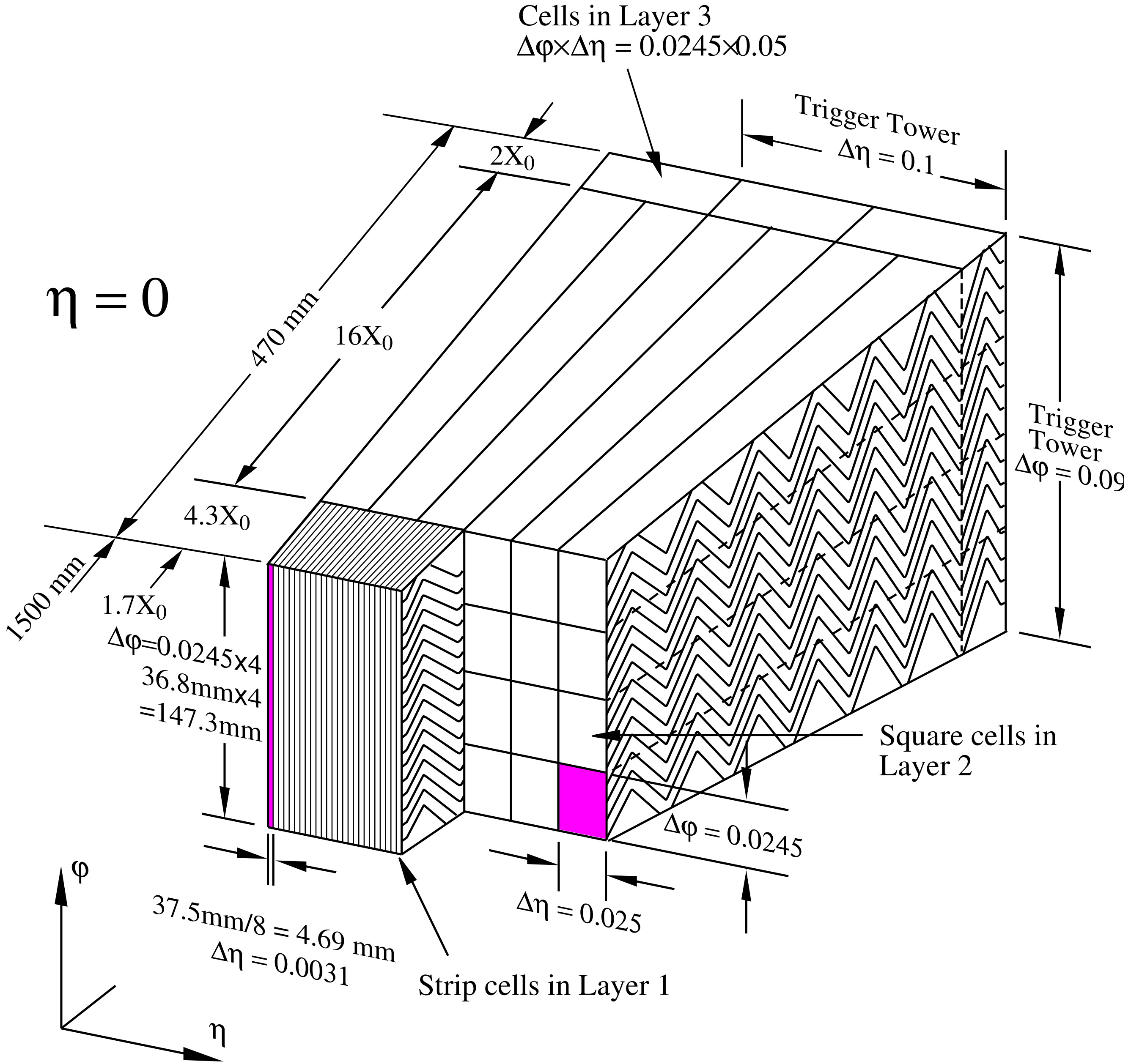
W(eν)γγ event in ATLAS

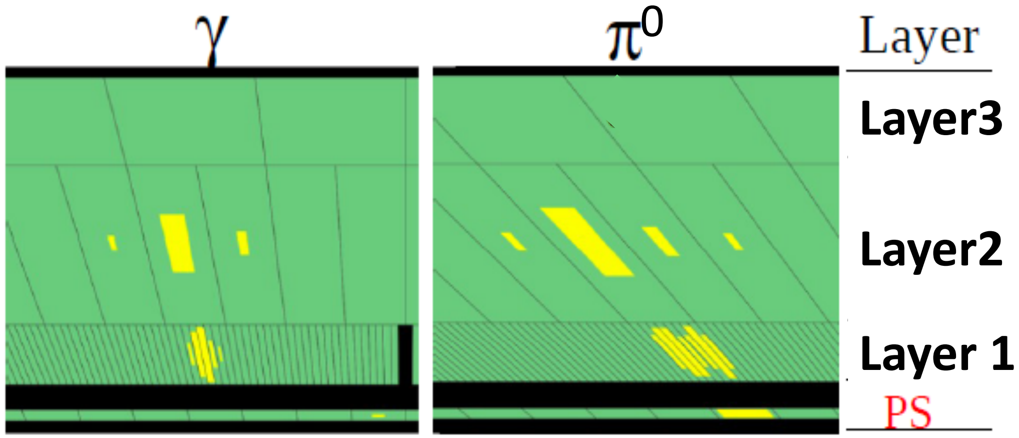


Wγγ Background components

Processes	Fake signature	Baseline Method
Wγ+jets,W+jets, Zγ+jets(missing one lep in reco)	jet faking γ	• 2D isolation template fit (Data-Driven)
QCD (γ+jets,γγ+jets)	jet faking lepton	• 2D sideband (ABCD method) (Data-Driven)
Zγ+jets	lep faking γ	• Highly suppressed by Pt(lγγ),M(lγγ),M(lγ)cuts • Estimated from sherpa MC

The ATLAS EM calorimeter





Fine granularity in S1 for γ / π^0 separation

- ✓ ***Liquid argon—Pb calorimeter.***
- ✓ ***Intrinsically radiation hard.***
- ✓ ***Good photon ID.***
- ✓ ***Modeling of jets (control region): loose photons which fail some layer 1 cuts but passing all the other calorimeter cuts.***

2D template fit for jet->γ

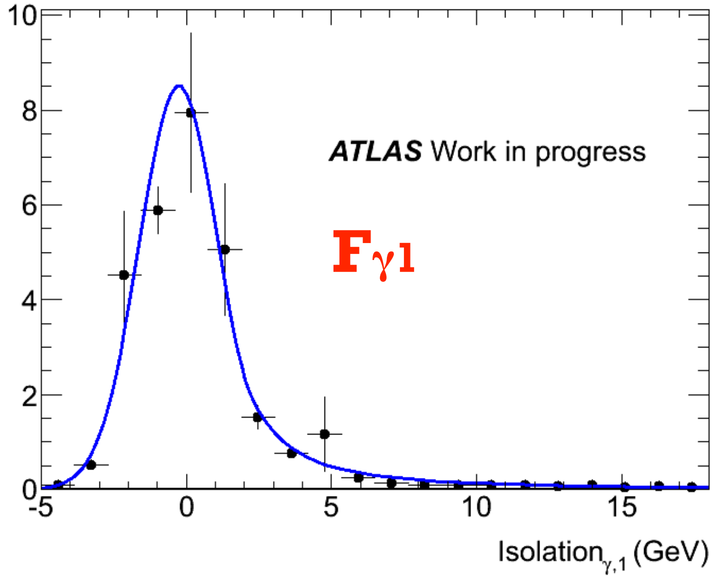
3 categories: γj,jγ,jj (sorted by Pt).

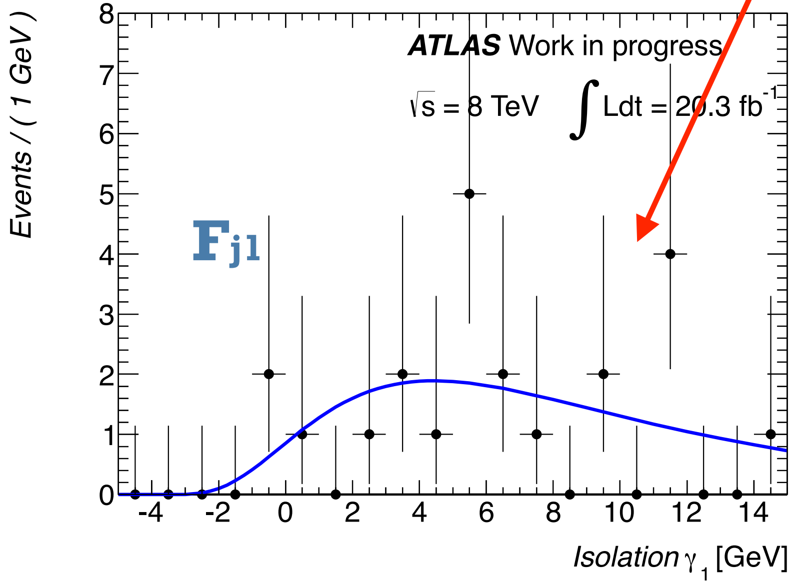
Idea :
isolation templates for real γ from MC and for jets from control regions in data.

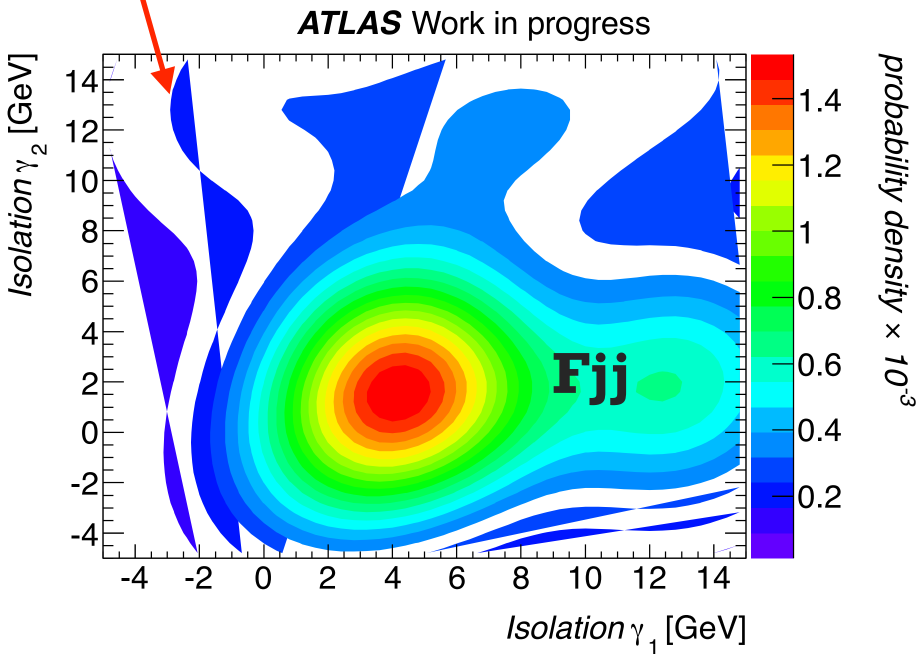
01

jets (control region): loose photons which fail some 1st layer cuts but passing all the other calorimeter cuts.

Isolation templates: $F_{\gamma 1}$(MC), F_{j1} (data) and Fjj(data).







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2D function:

W*F (total)=

$$W_{\gamma\gamma} * F_{\gamma 1} F_{\gamma 2} + W_{\gamma j} * F_{\gamma 1} F_{j2} + W_{j\gamma} * F_{j1} F_{\gamma 2} + W_{jj} * F_{jj}$$

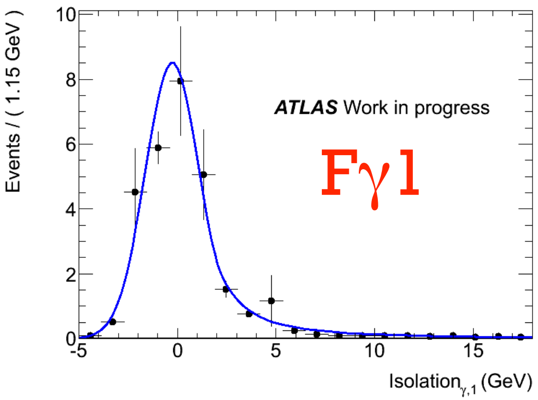
W's : normalizations determined with a maximum likelihood fit.

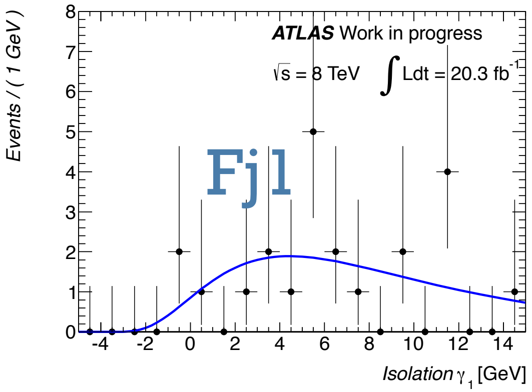
Projection of the fitted 2D function onto the isolation of the leading pt photon.

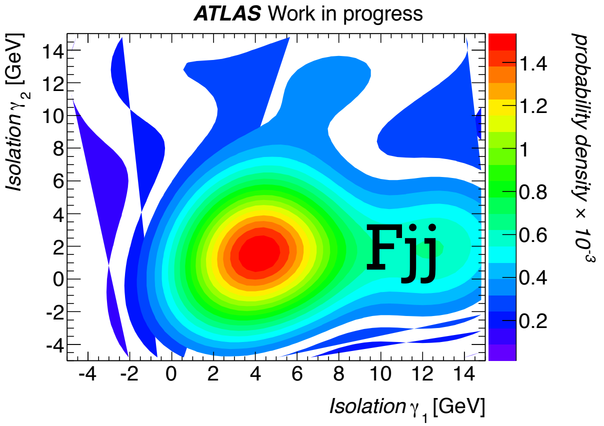
01

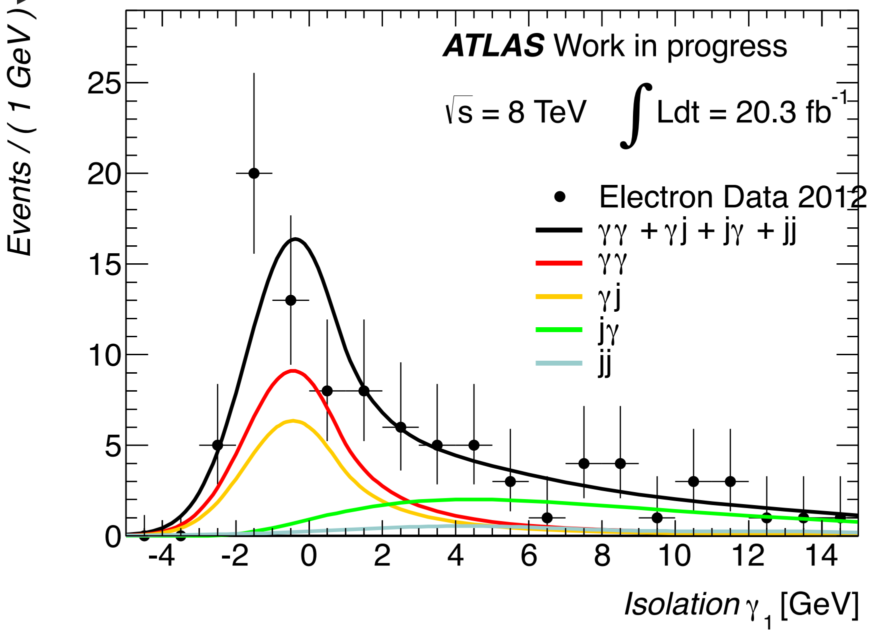
02

Isolation templates: $F_{\gamma 1}$(MC), F_{j1} (data) and Fjj(data).









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$W_{\gamma\gamma}$*Fγ1Fγ2+Wγj*Fγ1Fj2 +Wjγ*Fj1Fγ2+Wjj*Fjj

W's : normalizations determined with a maximum likelihood fit.

Results !

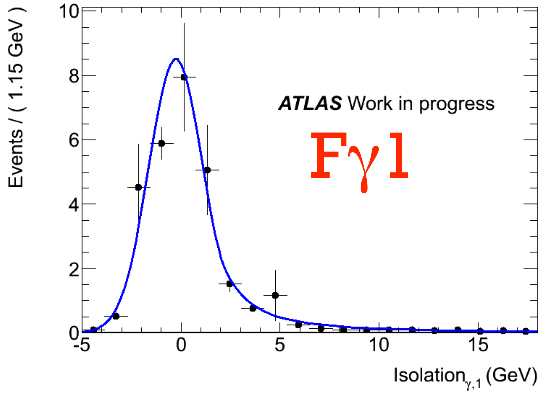
	Electron channel	Muon channel
γ-jet	8 ± 3 (stat.) ± 3 (syst.)	16 ± 6 (stat.) ± 5 (syst.)
jet-γ	6 ± 3 (stat.) ± 4 (syst.)	9 ± 4 (stat.) ± 4 (syst.)
jet-jet	1 ± 2 (stat.) ± 1 (syst.)	5 ± 2 (stat.) ± 1 (syst.)
total fake γ	15 ± 5 (stat.) ± 5 (syst.)	30 ± 8 (stat.) ± 7 (syst.)

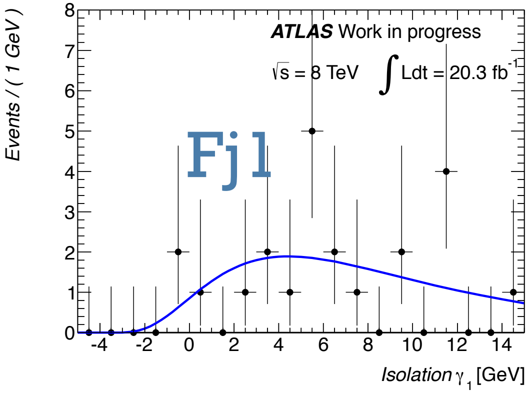
01

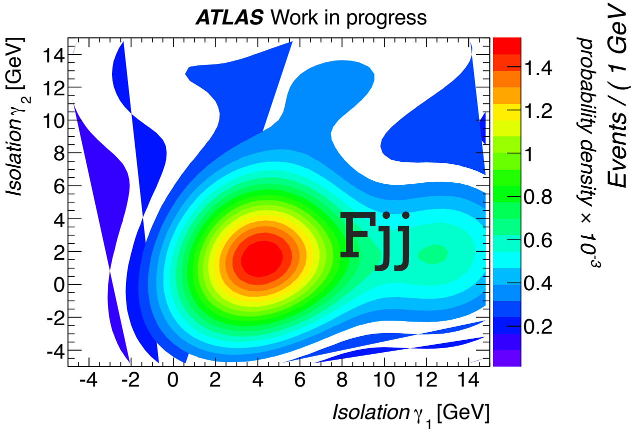
Isolation templates : Fγ1(MC), Fj1 (data) and Fjj(data).

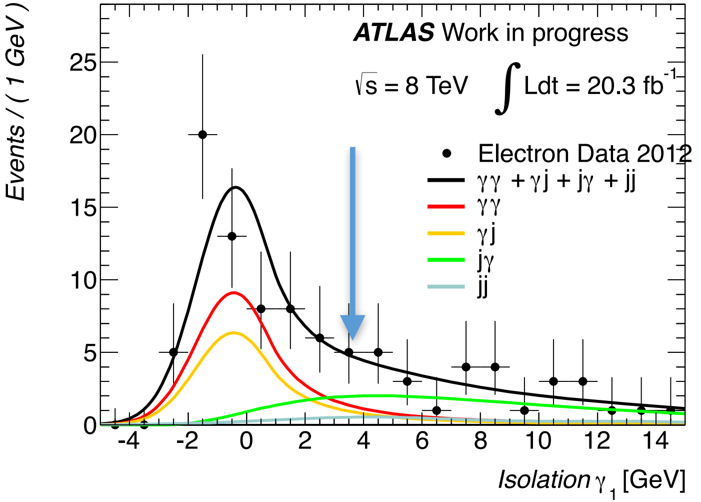
02

Projection of the fitted 2D function onto the isolation of the leading pt photon.

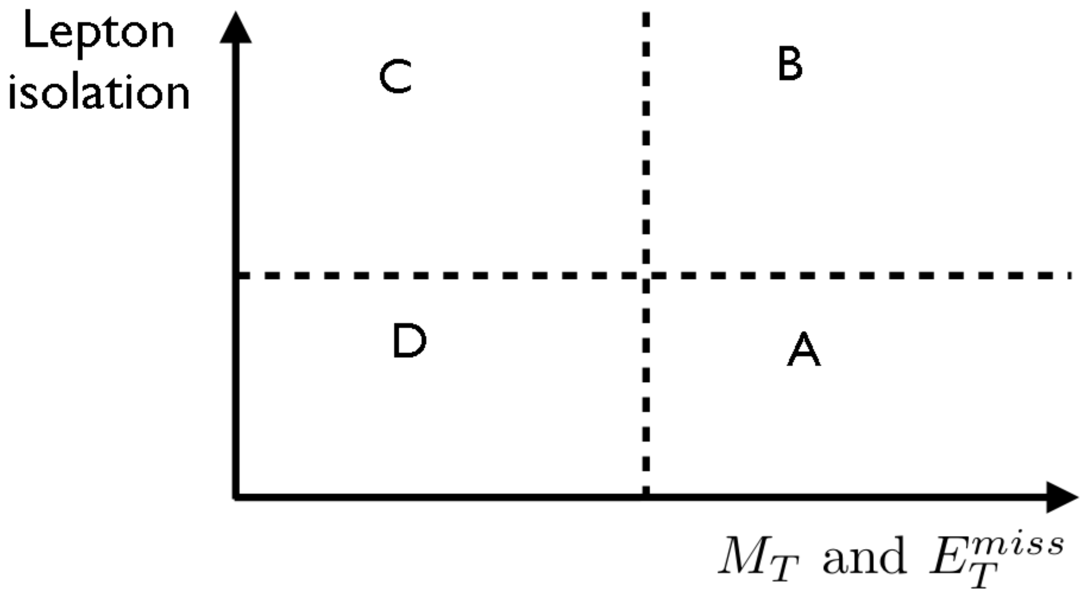








ABCD method for jet->lepton



ABCD method

✓Assumption:no correlation between variables on two axes.

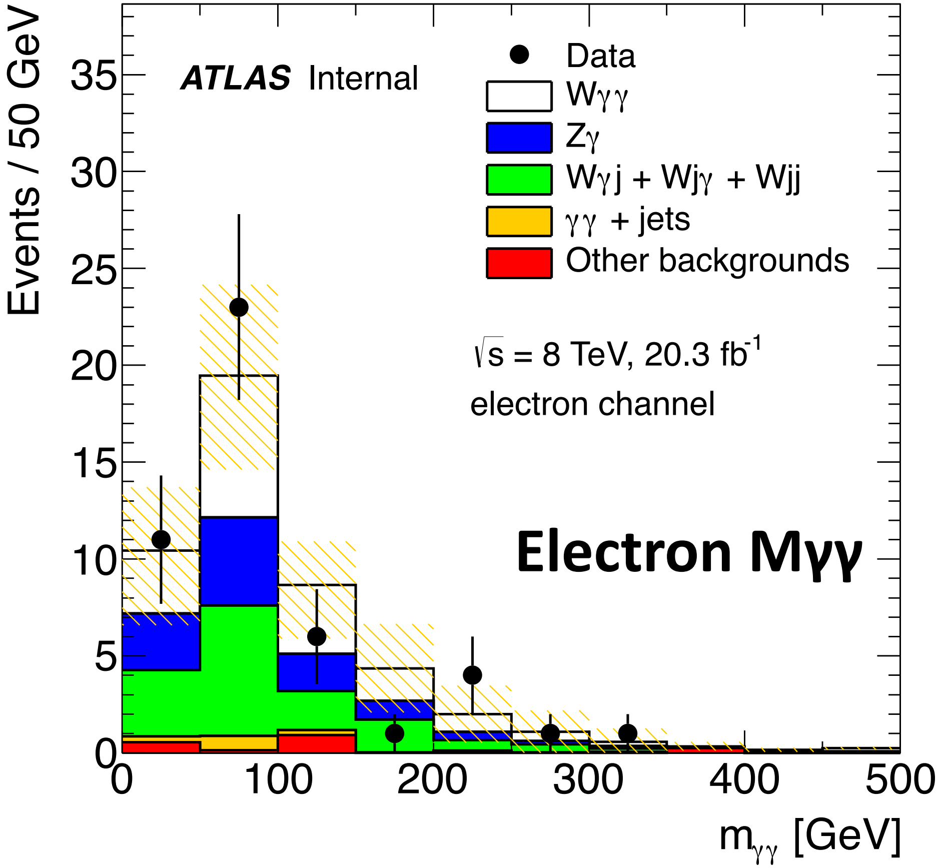
✓Define control regions B,C,D by reversing cuts.

✓no correlation: NB*ND/(NA*NC) = 1 for background events

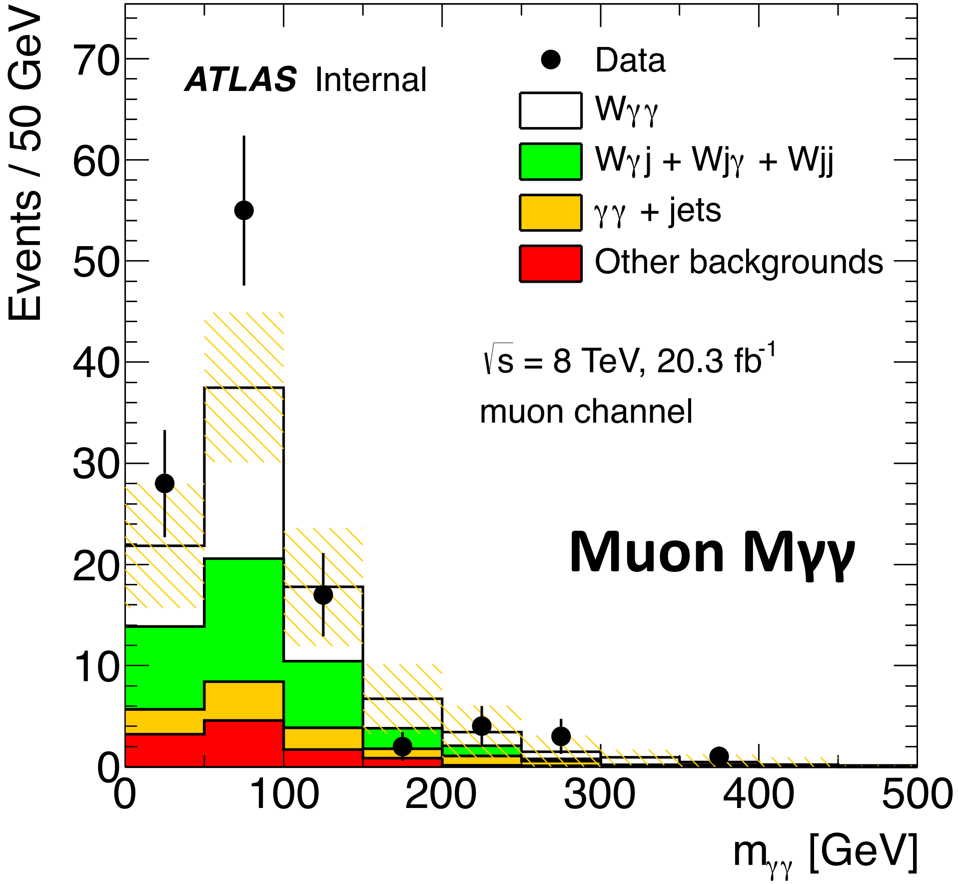
✓Count number of events in region B,C,D in data, extrapolate to region A.

$W\gamma\gamma$ signal yield

	Inclusive		Exclusive	
	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{jets} \geq 0$		$N_{jets} = 0$	
Data (N_{data})	47	110	15	53
$N_{sig} = N_{data} - N_{bkg}$	$17.1 \pm 8.6(stat.) \pm 5.1(syst.)$	$58 \pm 14(stat.) \pm 8(syst.)$	$6.1 \pm 4.4(stat.) \pm 2.0(syst.)$	$29 \pm 9(stat.) \pm 6(syst.)$



Electron Mγγ



Muon Mγγ

Data consistent with signal +background prediction.

Fiducial cross section measurement

$$\sigma^{ext\,fid}_{W\gamma\gamma} = \frac{N^{obs}_{l\nu\gamma\gamma} - N^{bkg}_{l\nu\gamma\gamma}\ *}{\int \mathcal{L}dt \times \epsilon_{W\gamma\gamma\rightarrow l\nu\gamma\gamma}}$$

Signal yield

XSec in :

$$\epsilon = A \times C = \frac{N_{fid,\ truth}}{N_{true,\ ext\ fid}} \times \frac{N_{reco}}{N_{fid,\ truth}}$$

*** Maximum-log likelihood approach**

Cuts	Extended Fiducial Region $pp \rightarrow \ell\nu\gamma\gamma$
Lepton	$p_T^\ell > 20$ GeV
	$p_T^\nu > 25$ GeV
	$\lvert\eta^\ell\rvert < 2.5$
W-Boson	$m_T > 40$ GeV
Photon	$E_T^\gamma > 20$ GeV
	$\lvert\eta^\gamma\rvert < 2.37$
	$\Delta R(\ell,\gamma) > 0.7$
	$\Delta R(\gamma,\gamma) > 0.4$
	iso. fraction $\epsilon_h^p < 0.5$
Jets	$p_T^{\mathrm{jet}} > 30$ GeV
	$\lvert\eta^{\mathrm{jet}}\rvert < 4.4$
	$\Delta R(\ell, \mathrm{jet}) > 0.3$
	$\Delta R(\gamma, \mathrm{jet}) > 0.3$
	Exclusive selection: $N_{\mathrm{jet}} = 0$

Comparison to theoretical predictions

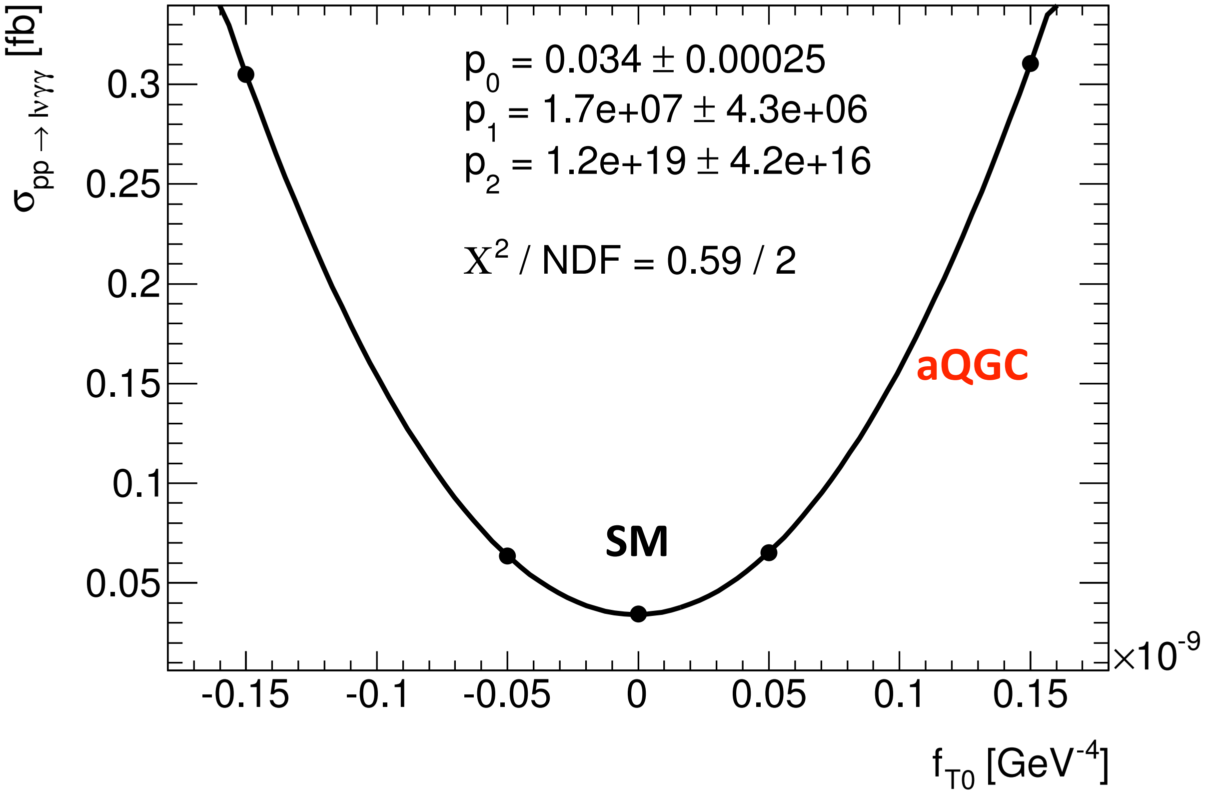
σ~3.7

σ~2.2

	σ^{fid} [fb]	σ^{MCFM} [fb]
inclusive ($\mathrm{N_{jet}} \geq 0$)		
$pp \to \mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) $^{+1.6}_{-1.5}$ (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$pp \to e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+2.0}_{-1.8}$ (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$pp \to \ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) $^{+1.3}_{-1.2}$ (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
exclusive ($\mathrm{N_{jet}} = 0$)		
$pp \to \mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.2}_{-1.1}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$pp \to e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) ± 1.2 (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$pp \to \ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20

- ✓VBFNLO (NLO) : 2.88 fb (inclusive)
- ✓K factor: σNLO/σLO ~3.
- ✓Exclusive measurement agrees with the SM NLO predictions within the uncertainties.

aQGC analysis



Procedure

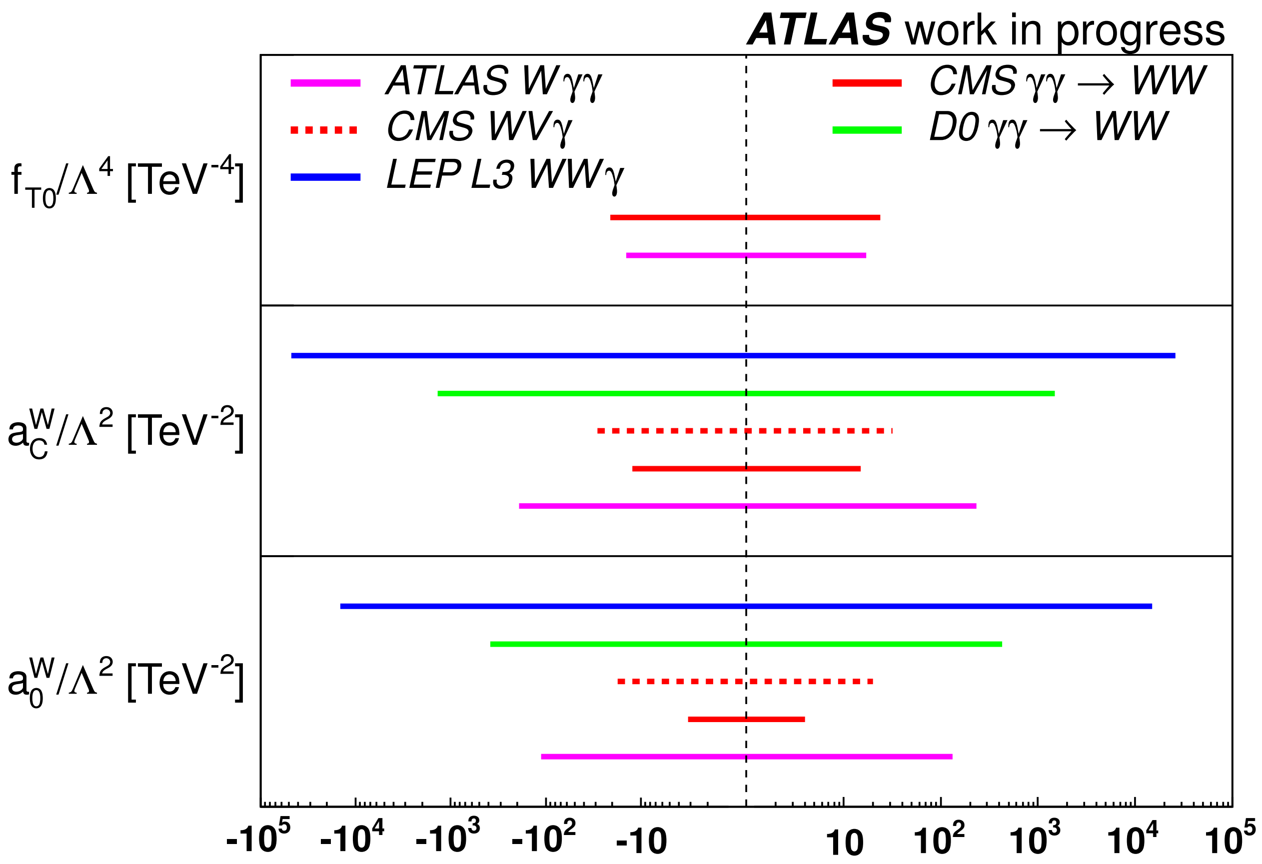
✓ **Cross sections fitted to a parabolic function.**

$$N(f) = A \times C \times \int \mathcal{L}dt \times (p_2 f^2 + p_1 f + p_0)$$

✓ **Profile likelihood fit to derive the 95% CL limits.**

aQGC analysis

Limits



- √ ATLAS Wγγ limit on FT0 improved compared to CMS γγ->WW.
- √ Exclusive candidates with Mγγ > 300 GeV used.
- √ Form factor approach is used for unitarity concern.

$$\left(1 + \frac{s}{\Lambda_{\mathrm{FF}}^2}\right)^{-n}$$

Summary of 8 TeV Wγγ analysis

First observation of tri-boson production in the Wγγ final state

with a significance of ~3.7 (2.2) σ for the Inclusive (exclusive) case.

aQGC limits provided

for selected dim-8 operators.

To be submitted to PRL shortly

Summary and prospects

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01 **Gauge boson coupling**
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at the LHC

03 **ATLAS detector**

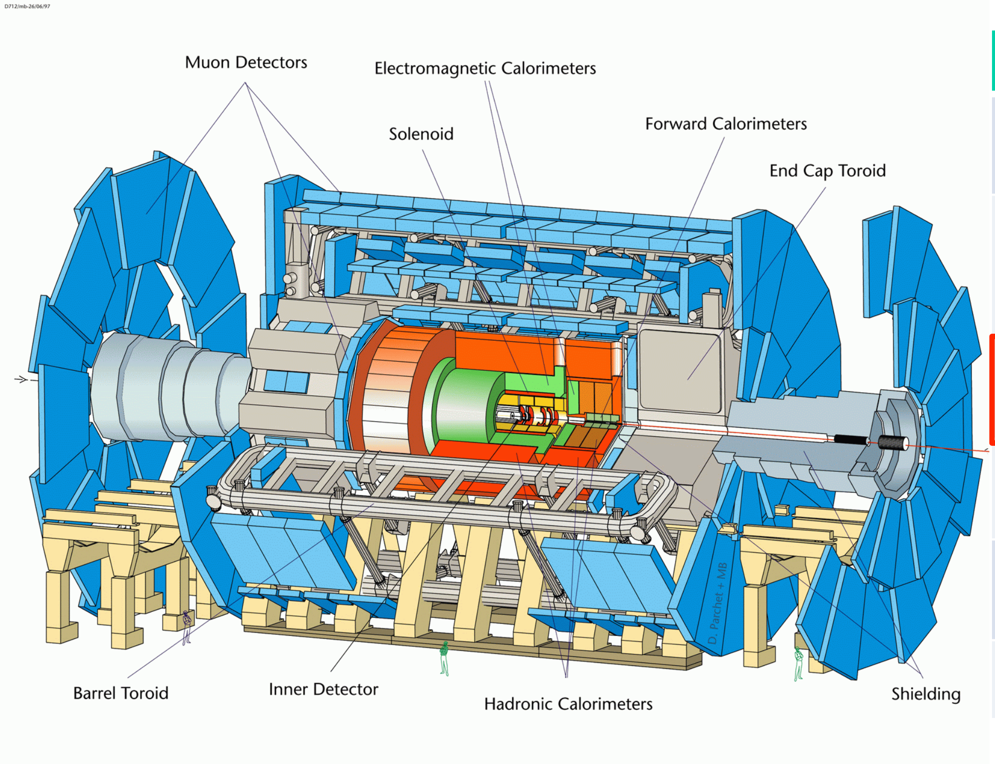
04 **pp->Wγγ+X**
Triboson production from QGC

Run 2 prospects

- ✓ LHC is scheduled to deliver pp collisions in Spring, 2015.
- ✓ Exciting opportunities of studying QGCs with Run 2 data.

The ATLAS detector

ATLAS and CMS are both general-purpose detectors located at the LHC



	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4}\, p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4}\, p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)

Wγγ Analysis strategy and Event selection

Analysis strategy: Inclusive and Exclusive Measurements + aQGC limits.

Signature : 1 lepton+ MET + 2 isolated photons.

- Standard Event level selection.(NPV cut, GRL)
- Triggers: EF_3g15vh_loose (el), EF_mu18_2g10_medium (muon).
- Required objects:
  - At least one tight++ electron or tight muon with Pt $>$ 20 GeV.
  - Second lepton veto with Pt $>$ 10 GeV.
  - MET $>$ 25 GeV.
  - At least two isolated tight photons with Pt $>$ 20 GeV.
  - Overlap removal: $dR(l;\gamma) > 0.7$ and $dR(\gamma;\gamma) > 0.4$.
- Transverse mass of the W boson $>$ 40GeV.
- $M_{l\gamma}$, $M_{l\gamma\gamma}$ away from Z mass peak, $Pt(l\gamma\gamma) > 30$ GeV for electron channel to suppress Zγ background.

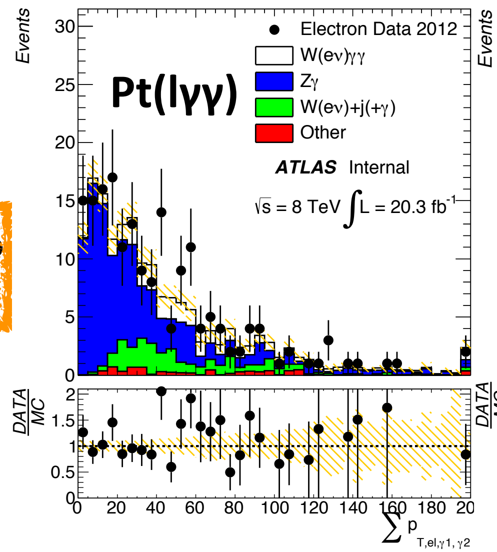
✓ Combined EF triggers extend lepton Pt range, improved the significance.

✓ Zγ background suppression in the electron channel. (electron faking a photon)

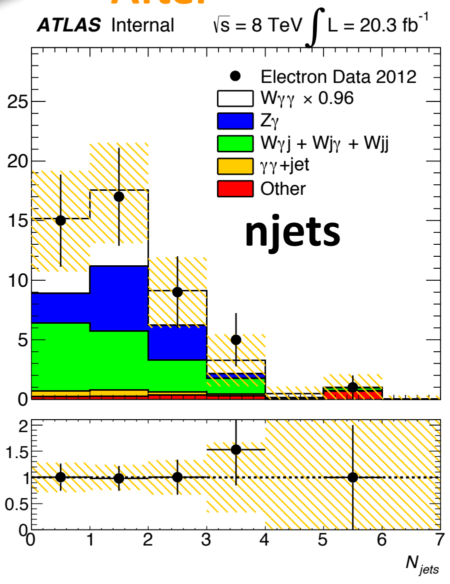
Jet cuts used to categorize inclusive and exclusive (njet=0) measurements.

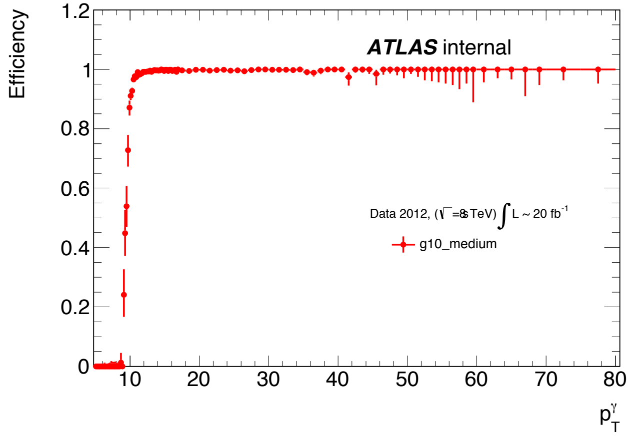
- Pt $>$ 30 GeV, $|\eta| < 4.4$, JVF.

Before

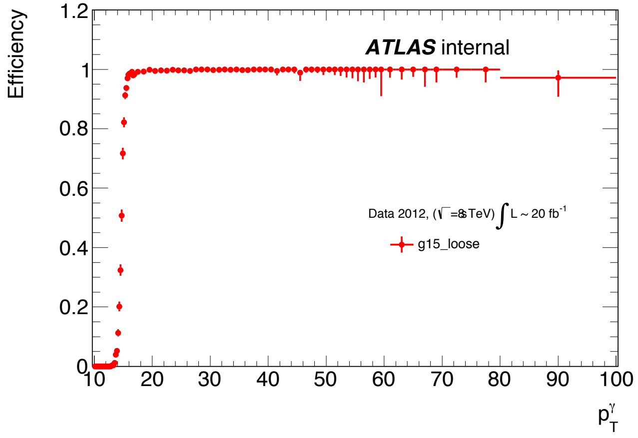


After

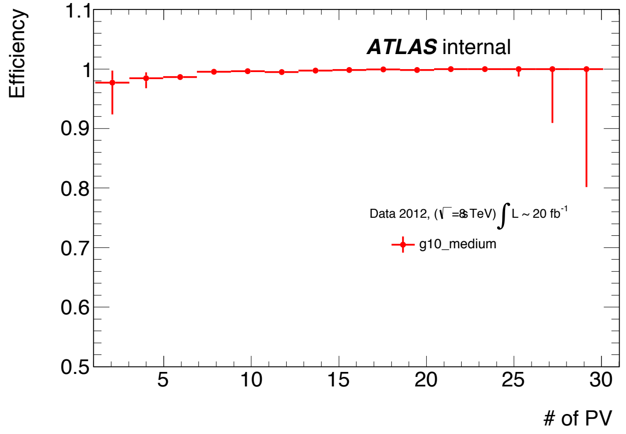




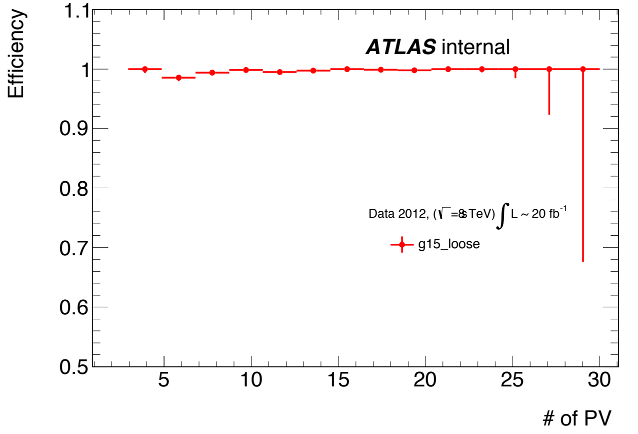
(a)



(b)



(c)



(d)

- Link to supporting note.
- Electron channel background studies:

https://indico.cern.ch/event/219384/contribution/5/material/slides/0.pdf

- Pt acceptance

studies:

to summarize, reduced the jet—>photon background by 50%, smaller systematic uncertainties.

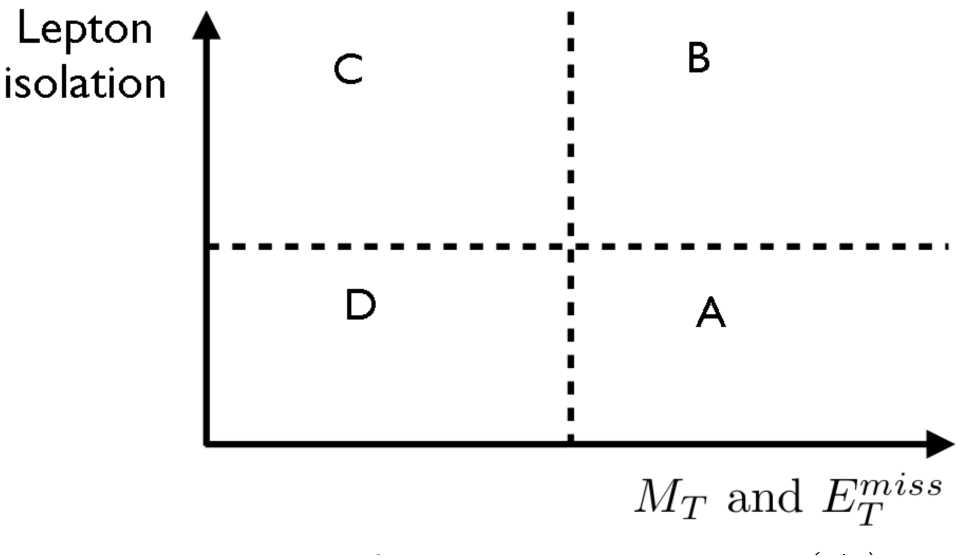
https://indico.cern.ch/event/231136/contribution/3/material/slides/0.pdf

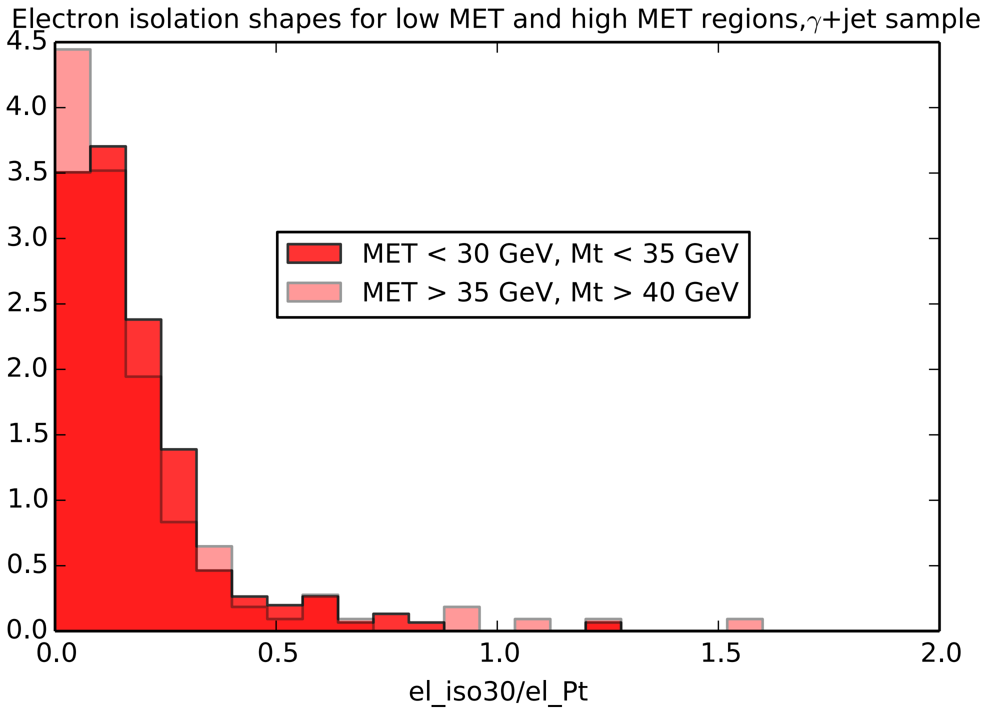
Category	Description	Name	Loose	Tight
Acceptance	$\lvert\eta\rvert < 2.37$, $1.37 < \lvert\eta\rvert < 1.52$ excluded	–	✓	✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the range $\lvert\eta\rvert < 0.8$ and $\lvert\eta\rvert > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \lvert\eta\rvert < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio in η of cell energies in 3×7 versus 7×7 cells	R_η	✓	✓
	Lateral width of the shower	w_{η_2}	✓	✓
	Ratio in ϕ of cell energies in 3×3 and 3×7 cells	R_ϕ		✓
EM Strip layer	Shower width for three strips around strip with maximum energy deposit	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\mathrm{tot}}$		✓
	Energy outside core of three central strips but within seven strips divided by energy within the three central strips	F_{side}		✓
	Difference between the energy associated with the second maximum in the strip layer, and the energy reconstructed in the strip with the minimal value found between the first and second maxima	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Table 1: Variables used for loose and tight photon identification cuts.

source	$N_{\gamma\gamma}$	$N_{\gamma j}$	$N_{j\gamma}$	N_{jj}
Control Region Statistics	±5.1 (±6.7%)	±4.5 (±28%)	±3.1 (±35%)	±0.7 (±13%)
Background Model G+N	±0.1 (±0.1%)	±0.1 (±0.6%)	±1.0 (±11%)	±0.5 (±9%)
Background Model CB	±0.2 (±0.3%)	±1.1 (±7%)	±0.6 (±7%)	±0.09 (±1.7%)
Antitight Definition $L'5$	±0.6 (±0.7%)	±1.6 (±10%)	±0.8 (±9%)	±0.1 (±2%)
Antitight Definition $L'3$	±1.2 (±1.6%)	±1.5 (±9.4%)	±1.5 (±17%)	±0.2 (±3.5%)
MC Generator	±0.8 (±1%)	±1.6 (±10%)	±1.3 (±14%)	±0.1 (±2%)
Signal Leakage Inputs	±0.07 (±0.1%)	±0.05 (±0.3%)	±0.8 (±9.4%)	±0.04 (±0.8%)
total	±5.3 (±7%)	±5.4 (±33%)	±4.0 (±45%)	±0.85 (±16%)

ABCD method for jet->lepton





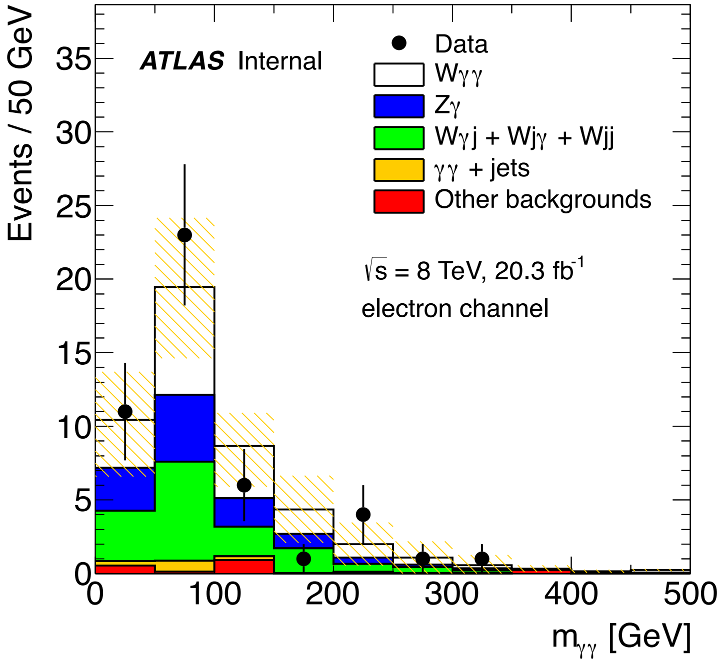
ABCD method

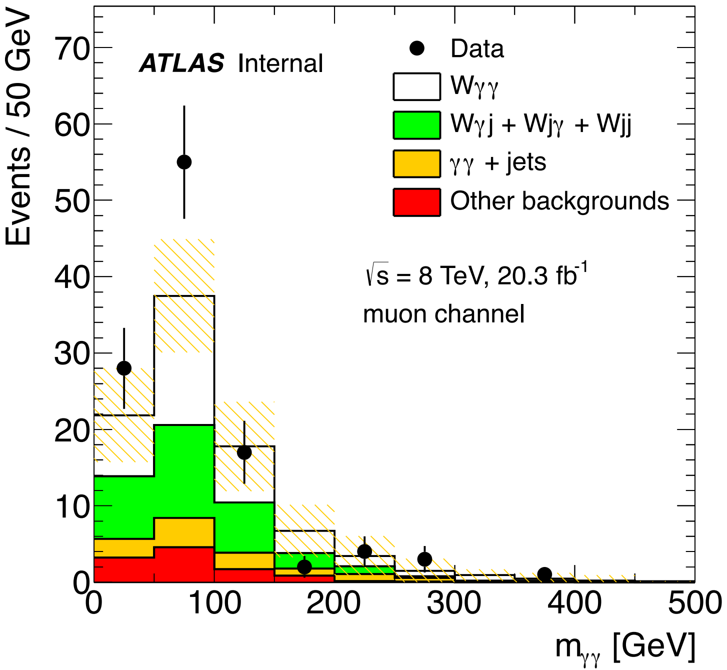
- ✓Assumption:no correlation between variables on two axes.
- ✓Define control regions B,C,D by reversing cuts.

- ✓no correlation: NB*ND/(NA*NC) = 1 for background events
- ✓Count number of events in region B,C,D in data, extrapolate to region A.

Wγγ signal yield

	Inclusive		Exclusive	
	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{jets} \geq 0$		$N_{jets} = 0$	
Data (N_{data})	47	110	15	53
Fake photon background	$15 \pm 5(\text{stat.}) \pm 5(\text{syst.})$	$30 \pm 8(\text{stat.}) \pm 7(\text{syst.})$	$6 \pm 2(\text{stat.}) \pm 2(\text{syst.})$	$14 \pm 5(\text{stat.}) \pm 5(\text{syst.})$
Fake lepton background	$1.5 \pm 0.6(\text{stat.}) \pm 1.0(\text{syst.})$	$11 \pm 4(\text{stat.}) \pm 5(\text{syst.})$	$0.2 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.})$	$6 \pm 3(\text{stat.}) \pm 3(\text{syst.})$
$Z\gamma(\gamma)$	$11.2 \pm 1.1(\text{stat.})$	$3.9 \pm 0.2(\text{stat.})$	$2.4 \pm 0.5(\text{stat.})$	$2.8 \pm 0.2(\text{stat.})$
Other backgrounds	$2.2 \pm 0.6(\text{stat.})$	$6.7 \pm 2.0(\text{stat.})$	$0.3 \pm 0.1(\text{stat.})$	$1.1 \pm 0.3(\text{stat.})$
Backgrounds (N_{bkg})	$29.9 \pm 5.2(\text{stat.}) \pm 5.1(\text{syst.})$	$51.6 \pm 9.2(\text{stat.}) \pm 8.6(\text{syst.})$	$8.9 \pm 2.1(\text{stat.}) \pm 2.0(\text{syst.})$	$23.9 \pm 5.8(\text{stat.}) \pm 5.8(\text{syst.})$
$N_{sig} = N_{data} - N_{bkg}$	$17.1 \pm 8.6(\text{stat.}) \pm 5.1(\text{syst.})$	$58.4 \pm 13.9(\text{stat.}) \pm 8.6(\text{syst.})$	$6.1 \pm 4.4(\text{stat.}) \pm 2.0(\text{syst.})$	$29.1 \pm 9.3(\text{stat.}) \pm 5.8(\text{syst.})$





Fiducial cross section measurement

Signal yield

$$\sigma^{ext\,fid}_{W\gamma\gamma} = \frac{N^{obs}_{l\nu\gamma\gamma} - N^{bkg}_{l\nu\gamma\gamma}}{\int \mathcal{L}dt \times \epsilon_{W\gamma\gamma\to l\nu\gamma\gamma}} \quad *$$

$$\epsilon = A \times C = \frac{N_{fid,\ truth}}{N_{true,\ ext\ fid}} \times \frac{N_{reco}}{N_{fid,\ truth}}$$

Measured from signal MC(electron channel).

	Inclusive Selection	Exclusive Selection
Correction Factor ϵ	$(19.6 \pm 0.5$ (stat.)) %	$(15.1 \pm 0.7$ (stat.)) %
Acceptance A	$(82.5 \pm 0.4$ (stat.)) %	$(82.5 \pm 0.6$ (stat.)) %
Efficiency C	$(23.7 \pm 0.6$ (stat.)) %	$(18.4 \pm 0.8$ (stat.)) %

Cuts	Extended Fiducial Region $pp \to \ell\nu\gamma\gamma$
Lepton	$p_T^\ell > 20$ GeV $p_T^\nu > 25$ GeV $\lvert\eta^\ell\rvert < 2.5$
W-Boson	$m_T > 40$ GeV
Photon	$E_T^\gamma > 20$ GeV $\lvert\eta^\gamma\rvert < 2.37$ $\Delta R(\ell,\gamma) > 0.7$ $\Delta R(\gamma,\gamma) > 0.4$ iso. fraction $\epsilon_h^p < 0.5$
Jets	$p_T^{\rm jet} > 30$ GeV $\lvert\eta^{\rm jet}\rvert < 4.4$ $\Delta R(\ell,{\rm jet}) > 0.3$ $\Delta R(\gamma,{\rm jet}) > 0.3$ Exclusive selection: $N_{\rm jet} = 0$

* Maximum-log likelihood approach used in the computation for individual channels and combination of the two

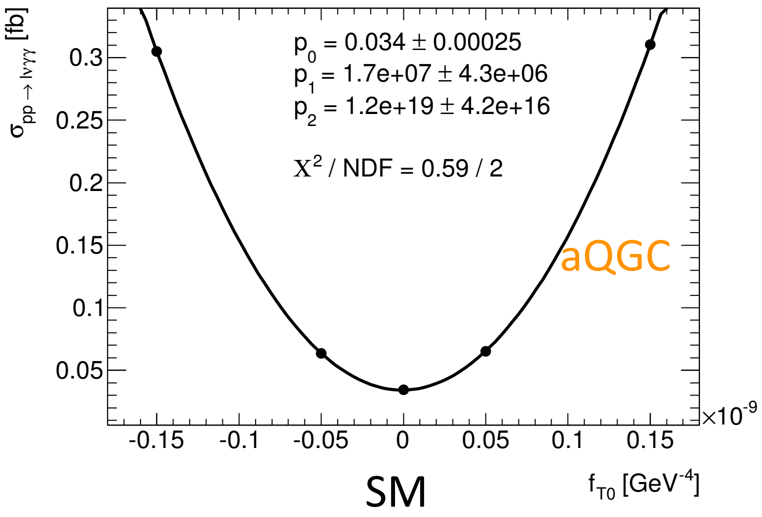
anomalous Quartic Gauge boson Coupling

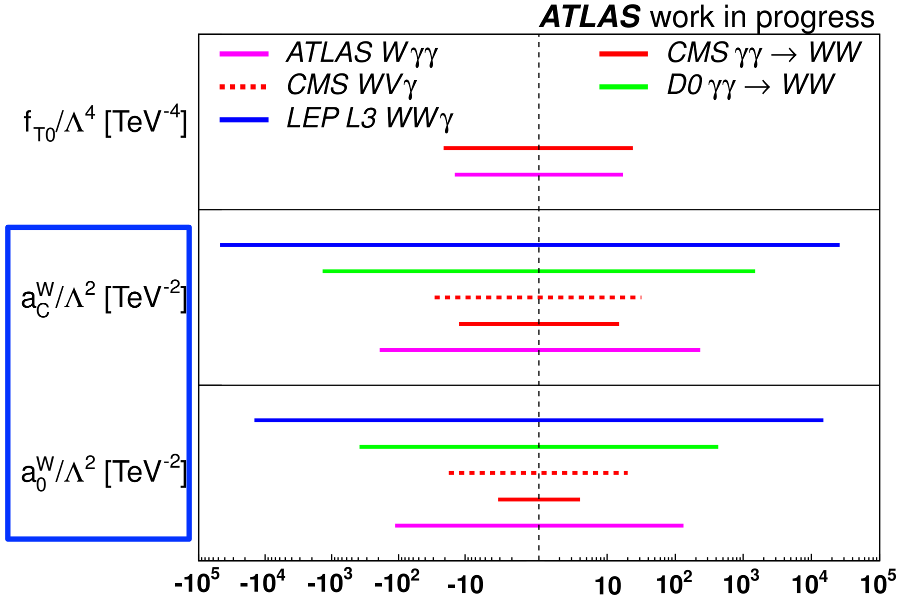
Procedure

- ✓Example: fT0
- ✓Cross sections are generated with non-zero aQGC terms (fT0 shown here as f), fitted to a parabolic function.

$$N(f) = A \times C \times \int \mathcal{L}dt \times (p_2 f^2 + p_1 f + p_0)$$

- ✓Profile likelihood fit is performed to derive the 95% CL limits.



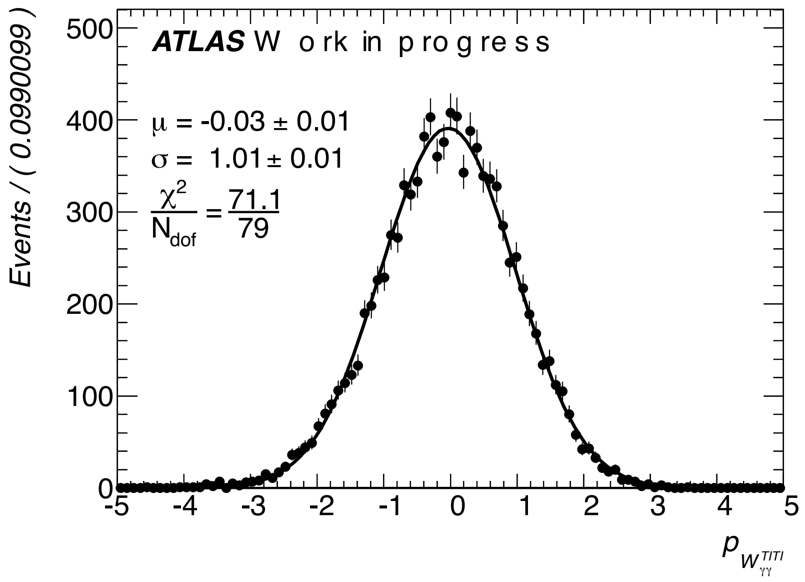


LEP parametrization

Results

- ✓VBFNLO used for generating cross sections for aQGC points.
- ✓**Exclusive candidates with Mγγ > 300 GeV used.**
- ✓Form factor approach is used for unitarity concern.

$$\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^{-n}$$



(a)

The signal ($W_{\gamma\gamma}$) and background ($W_{\gamma j}$, $W_{j\gamma}$, W_{jj}) yields can be obtained by fitting eq. 53 to data, i.e. by maximizing the extended likelihood function defined as:

$$\mathcal{L}(\vec{\theta}|\vec{x}_1, \vec{x}_2, \ldots) = P_{W_{tot}}(N) * \prod_{i=0}^{N} F_{tot}(\vec{x}_i|\vec{\theta}), \tag{54}$$

with respect to $\vec{\theta} = (W_{\gamma\gamma}, W_{\gamma j}, W_{j\gamma}, W_{jj})$ given the data $\vec{x}_i$. Here, $P_{W_{tot}}(N)$ is the poisson probability of observing N events when W_{tot} events were expected.

$$\psi^i(\boldsymbol{\mu},\boldsymbol{\theta}) = N^i_{\text{sig}}(\boldsymbol{\mu})\left\{1+\sum_k \sigma_{ik}\xi_k\right\} + N_{\text{bkg}}\left\{1+\sum_k \sigma_{(i+m)k}\xi_k\right\},$$

$$L(N^i_{\text{ps}},\boldsymbol{\theta}_0;\boldsymbol{\mu},\boldsymbol{\theta}) = \prod_{i=1}^{m} \text{Poisson}(N^i_{\text{ps}},\psi^i(\boldsymbol{\mu},\boldsymbol{\theta})) \times \frac{1}{(2\pi)^m} e^{-\frac{1}{2}\left((\boldsymbol{\theta}-\boldsymbol{\theta}_0)\cdot C^{-1}\cdot(\boldsymbol{\theta}-\boldsymbol{\theta}_0)\right)}, \tag{40}$$

The profile likelihood ratio is:

$$\lambda(N^i_{\text{ps}},\boldsymbol{\theta}_0;\boldsymbol{\mu}_{\text{test}}) = \frac{L(N_{\text{ps}},\boldsymbol{\theta}_0;\boldsymbol{\mu}_{\text{test}},\hat{\hat{\boldsymbol{\theta}}})}{L(N_{\text{ps}},\boldsymbol{\theta}_0;\hat{\boldsymbol{\mu}},\hat{\boldsymbol{\theta}})}. \tag{41}$$

Here, the values μ and θ which maximizes the likelihood are denoted by $\hat{\mu}$ and $\hat{\theta}$, respectively and $\hat{\hat{\theta}}$ denotes the value of θ that maximizes the likelihood for a fixed value of $\mu = \boldsymbol{\mu}_{\text{test}}$. The pseudo experiment is considered less likely than actual if its profile likelihood ratio is smaller than that of actual data:

$$\lambda(N^i_{\text{ps}},\boldsymbol{\theta}_0;\boldsymbol{\mu}_{\text{test}}) < \lambda(N^i_{\text{data}},\mathbf{0};\boldsymbol{\mu}_{\text{test}}) \tag{42}$$

The TGCLim package uses 10000 pseudo experiments, corresponding to a statistical uncertainty of ±0.2% on a p-value of 5%.

A negative log-likelihood function can then be defined as follows

$$-\ln L(\sigma, \{x_k\}) = \sum_{i=1}^{2} -\ln\left(\frac{e^{-(N_s^i(\sigma,\{x_k\})+N_b^i(\{x_k\}))} \times (N_s^i(\sigma, \{x_k\}) + N_b^i(\{x_k\}))^{N_{obs}^i}}{(N_{obs}^i)!}\right) + \sum_{k=1}^{n} \frac{x_k^2}{2}. \tag{22}$$

Here, the expression inside the natural logarithm is essentially the Poisson probability that the expected number of signal and background events $(N_s^i(\sigma, \{x_k\}) + N_b^i(\{x_k\}))$ will produce the number of events observed in data (N_{obs}^i) in the $i-th$ channel and after the full analysis selection has been applied. The last addend in Equation 22 is the term that takes care of the Gaussian constraints on the nuisance parameters x_k, previously defined in equations 20 and 21. Each systematic k is ascribed to an independent source (if two different systematic uncertainties considered here are correlated, their linear sum is used as the total systematic uncertainty). A single random variable x_k is used over all channels in signal and background as the effect of each systematic is 100% correlated across channels and between signal and background components. It should be noted that, since each parameter x_k is gaussianly constrained, the number of degrees of freedom of the fit is unchanged.

To find the most probable value of σ, the log-likelihood function is thus minimized by letting all the nuisance parameters x_k free in the fit. The fit thus provides a total uncertainty, that contains both the statistical and all the systematic components. In order to obtain the systematic uncertainty breakdown, the procedure described in 7.3 is used. By subtracting in quadrature the systematic component to the total uncertainty from the fit, one then obtains the purely statistical uncertainty on the cross-section measurement. The minimization and error calculation is performed by using the Minuit package [34]. To calculate the cross section (fiducial or total) in a single channel i, we take the Poisson probability only in channel i rather than the product over all channels.