ATLAS Electroweak physics
Alignment and timing calibration for SCT

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Z. Liang*

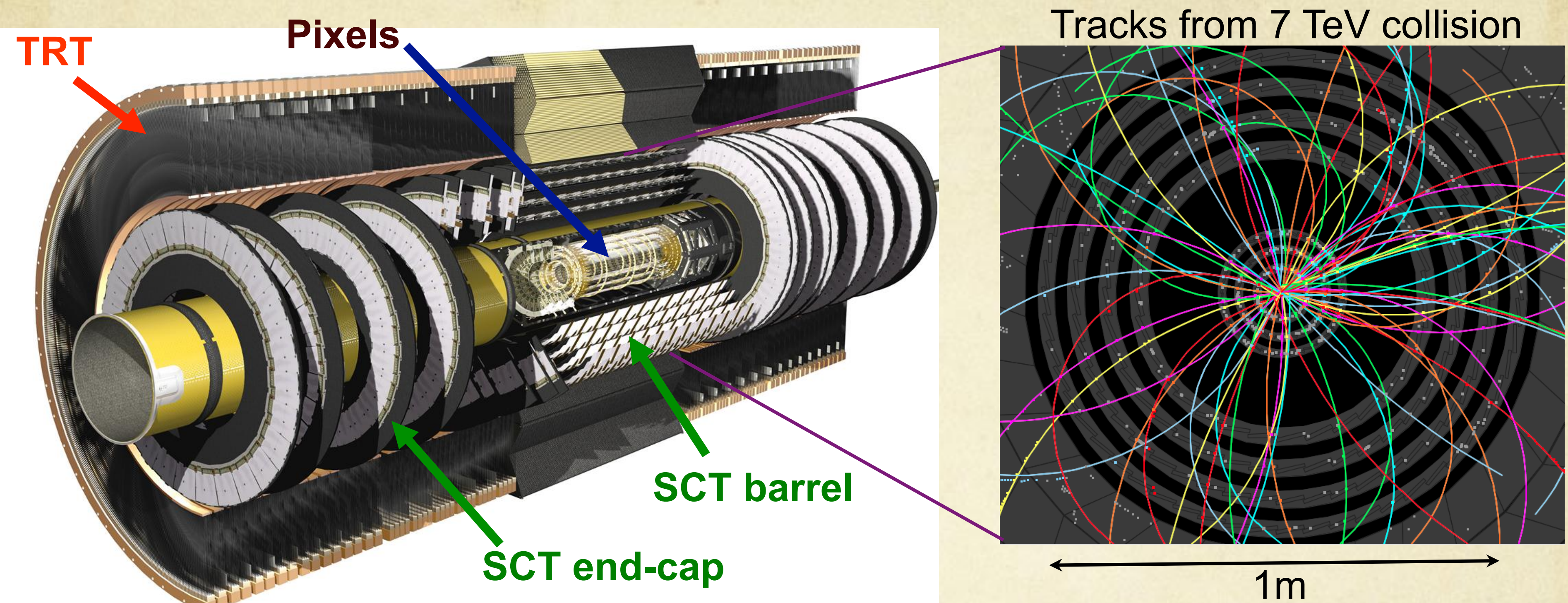
Particle Physics, University of Oxford, UK.

Outline

- Detector related topics
  - Laser alignment for ATLAS silicon strip detector (SCT)
  - SCT modules readout timing calibration

- ATLAS electroweak physics
  - Short overview on the latest topics
  - Detailed review on $W\gamma/Z\gamma$ analysis

Motivation for laser alignment



SCT = SemiConductor Tracker; intermediate particle tracker with 6M silicon strips.

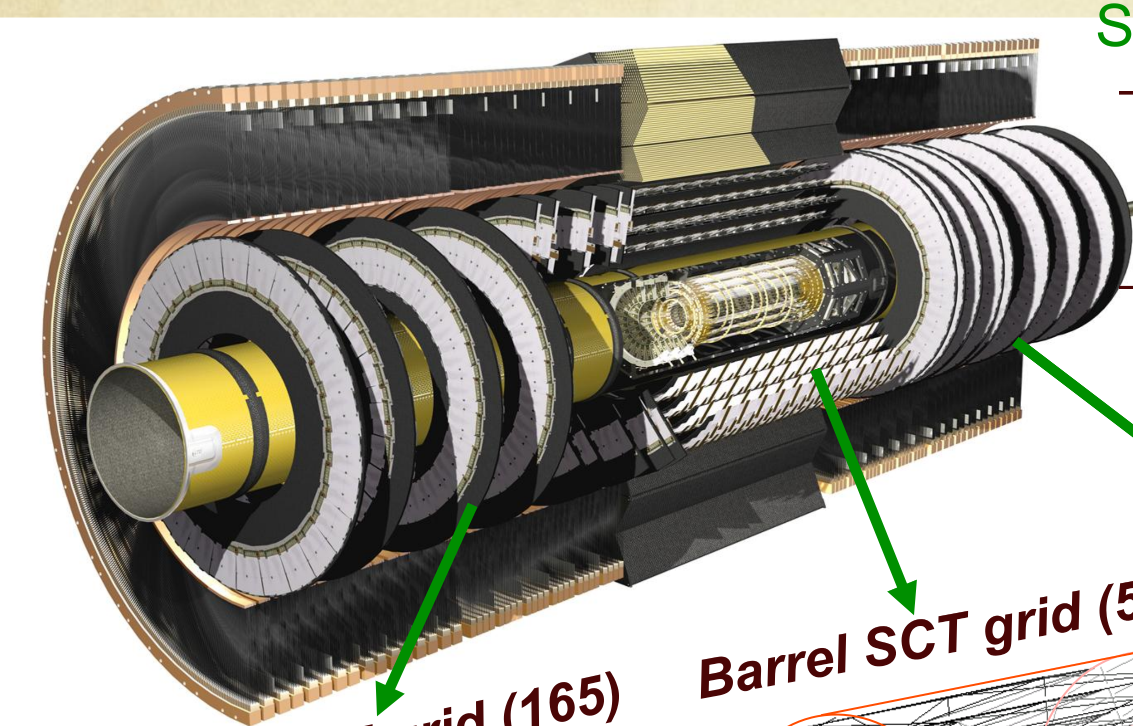
The alignment challenge:

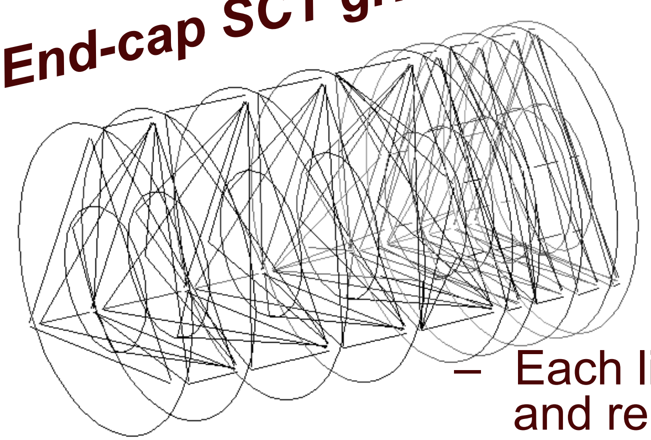
- The silicon strip detector (SCT) is large (6.2m long, 1m diameter)
  - may move slightly, e.g. due to heat dissipated in the front end electronics.
- We need to monitor the SCT stability to better than 10 μm

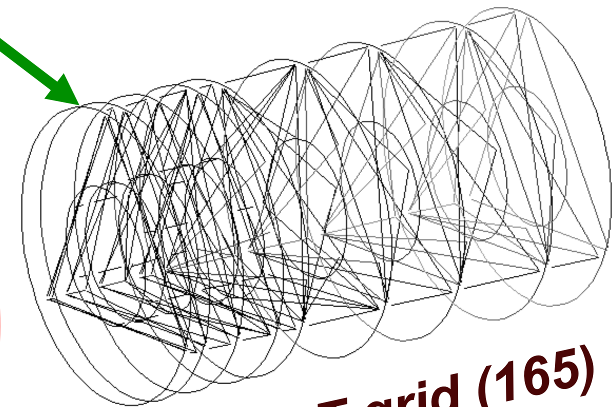
SemiConductor Tracker alignment monitor

Solution: *Interferometry !*

– A geodetic grid of length measurements between nodes attached to the SCT support structures.
– All 842 grid lengths are measured simultaneously using Frequency Scanning Interferometry (FSI) to a precision of < 1μm.



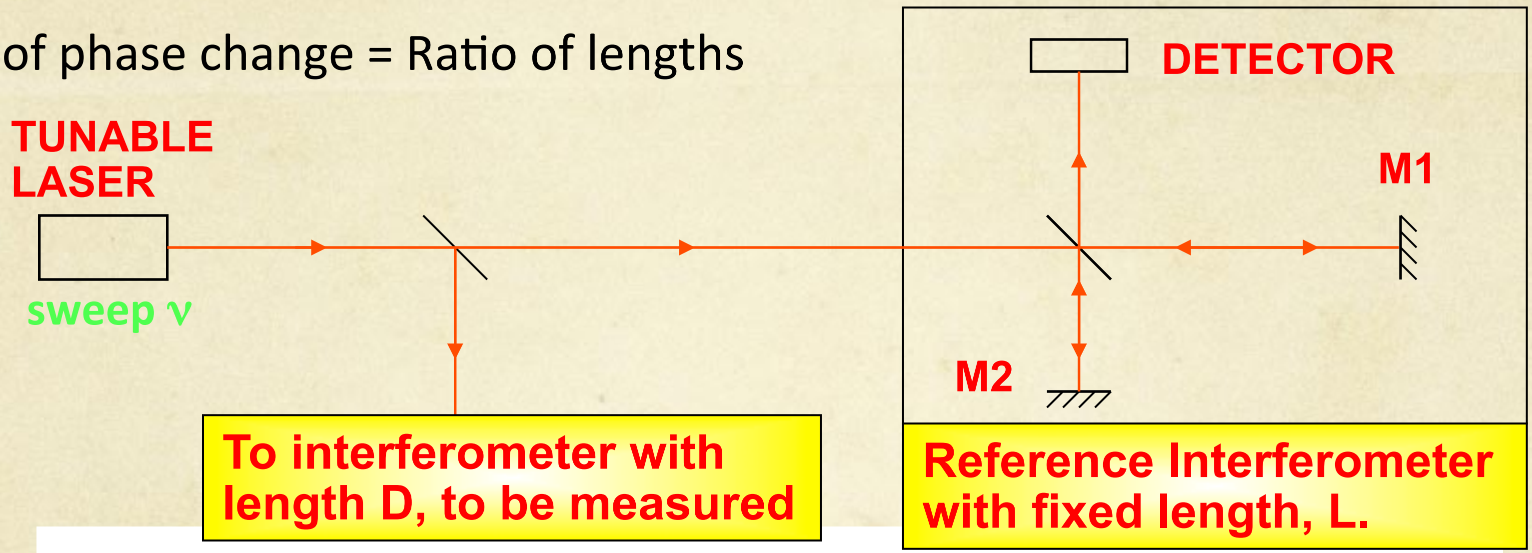


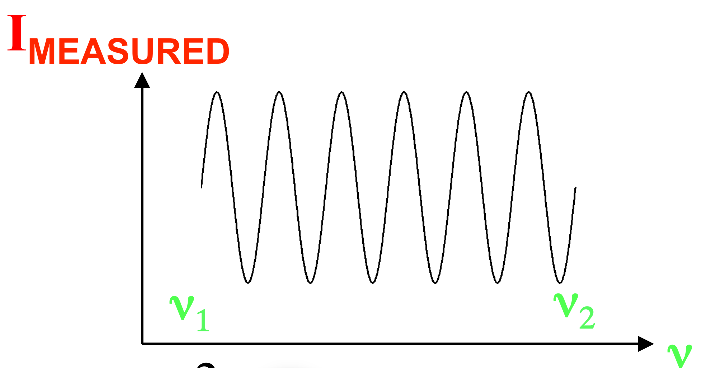


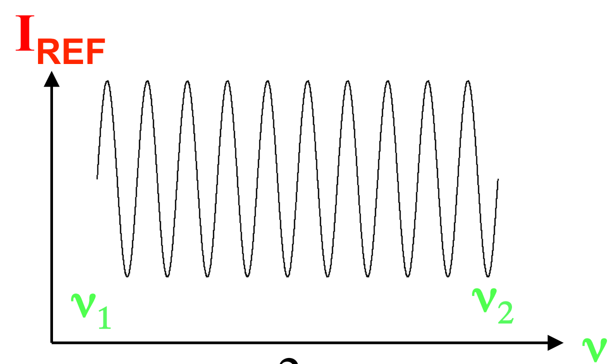
– Each line shown is a length measurement. FSI monitors shape and relative positions of SCT barrels and end-cap wheels.

Basic principle of Frequency Scanning Interferometry(FSI)

Ratio of phase change = Ratio of lengths







$$\Delta\theta_{GLI} = \frac{2\pi}{c}(D\Delta\nu + \nu\Delta D)$$

$$\Delta\phi_{REF} \approx \frac{2\pi}{c} L\Delta\nu$$

D is unknown length of grid line to be measured

$$\frac{\Delta\theta_{GLI}}{\Delta\phi_{REF}} \approx \frac{D}{L} \quad if \;\; \Delta D = 0$$

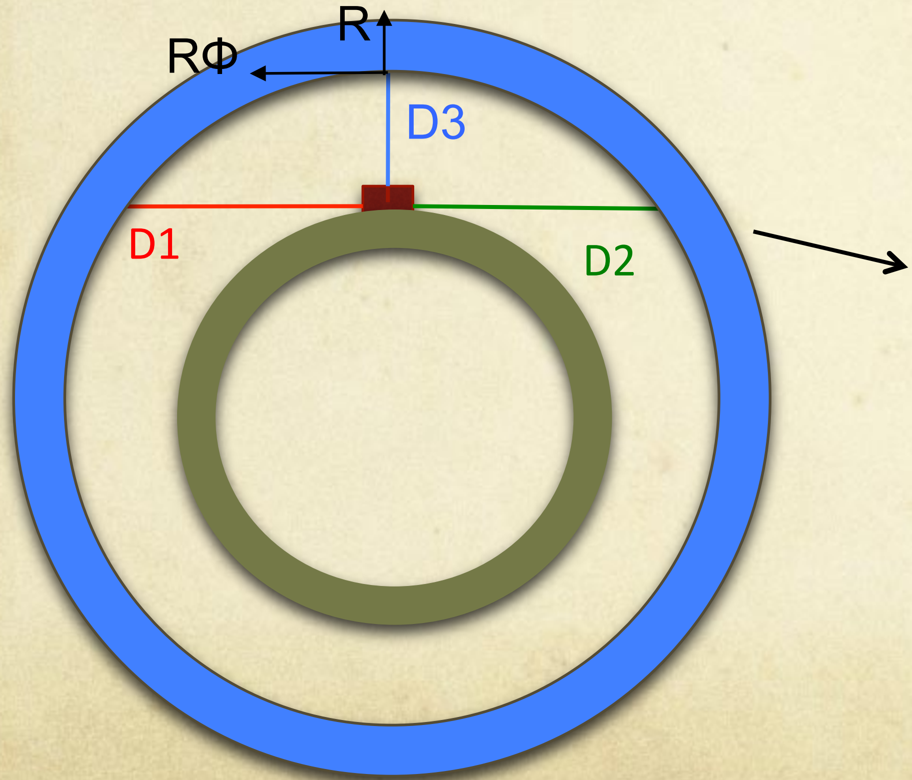
Example of grid line measurements

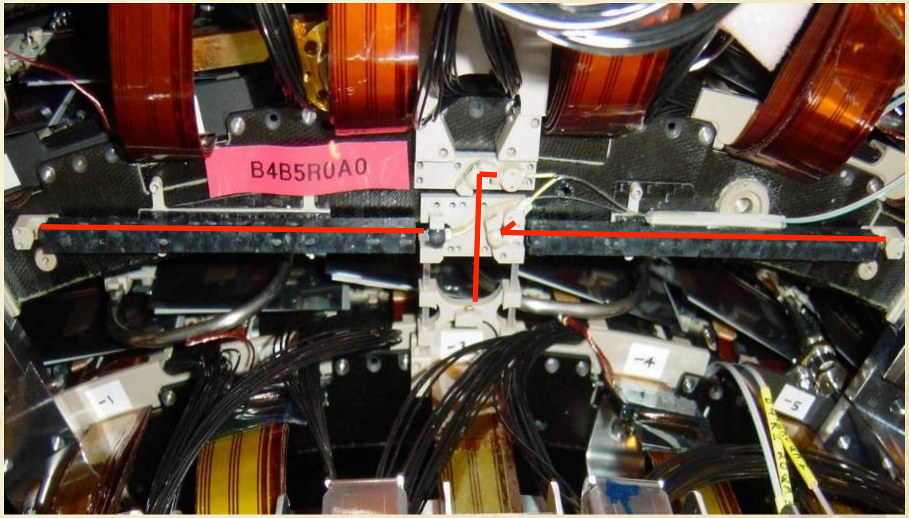
FSI monitors the relative movement between any two barrels of the SCT, using many assemblies of the type shown below. If there is a relative shift between barrels, we expect to see anti-correlations in the lengths of grid line D1 and grid line D2.

Grid line D1 monitors the positive RΦ direction

Grid line D2 monitors the negative RΦ direction

Grid line D3 monitors the positive R direction





An FSI assembly with three grid lines, between adjacent barrels.

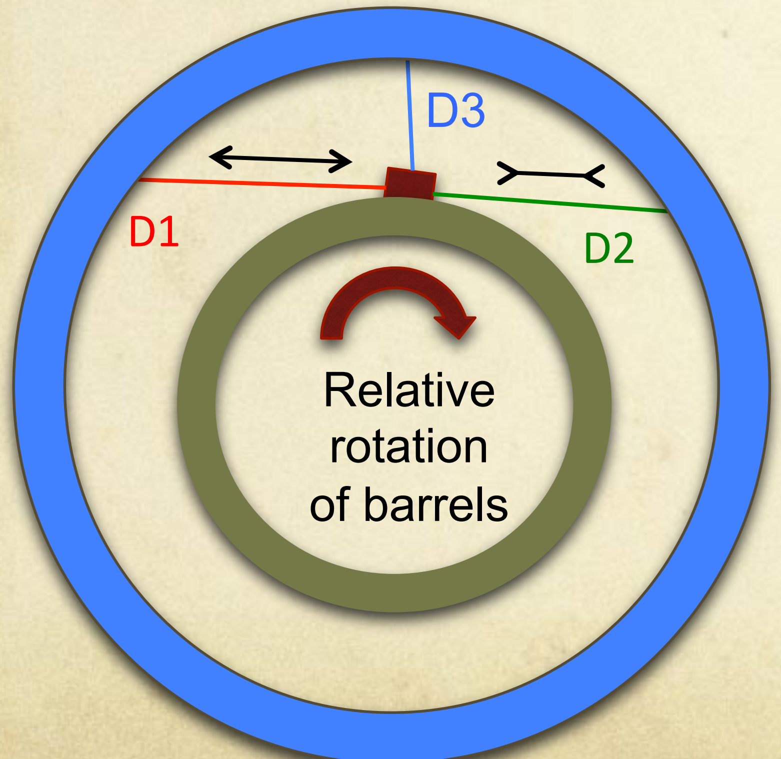
Vibrato mode analysis

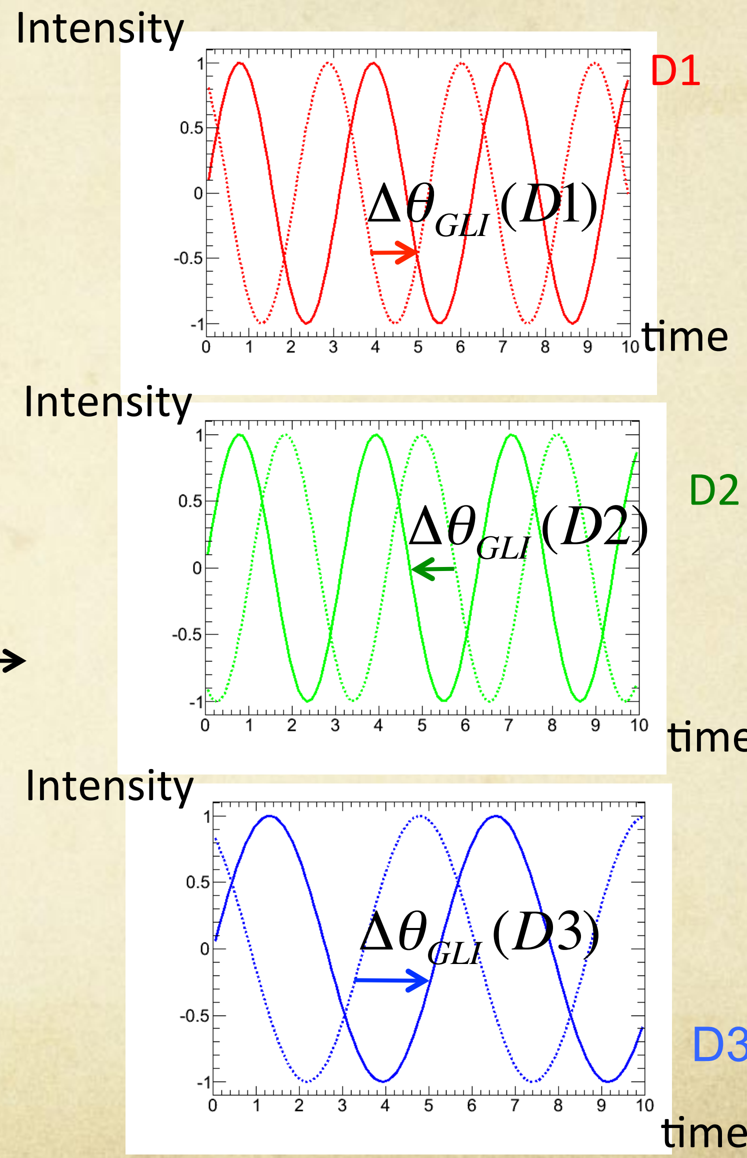
$$\Delta D = \frac{c}{2\pi} \cdot \frac{\Delta\theta_{GLI}}{\nu} + D\frac{\Delta\nu}{\nu}$$

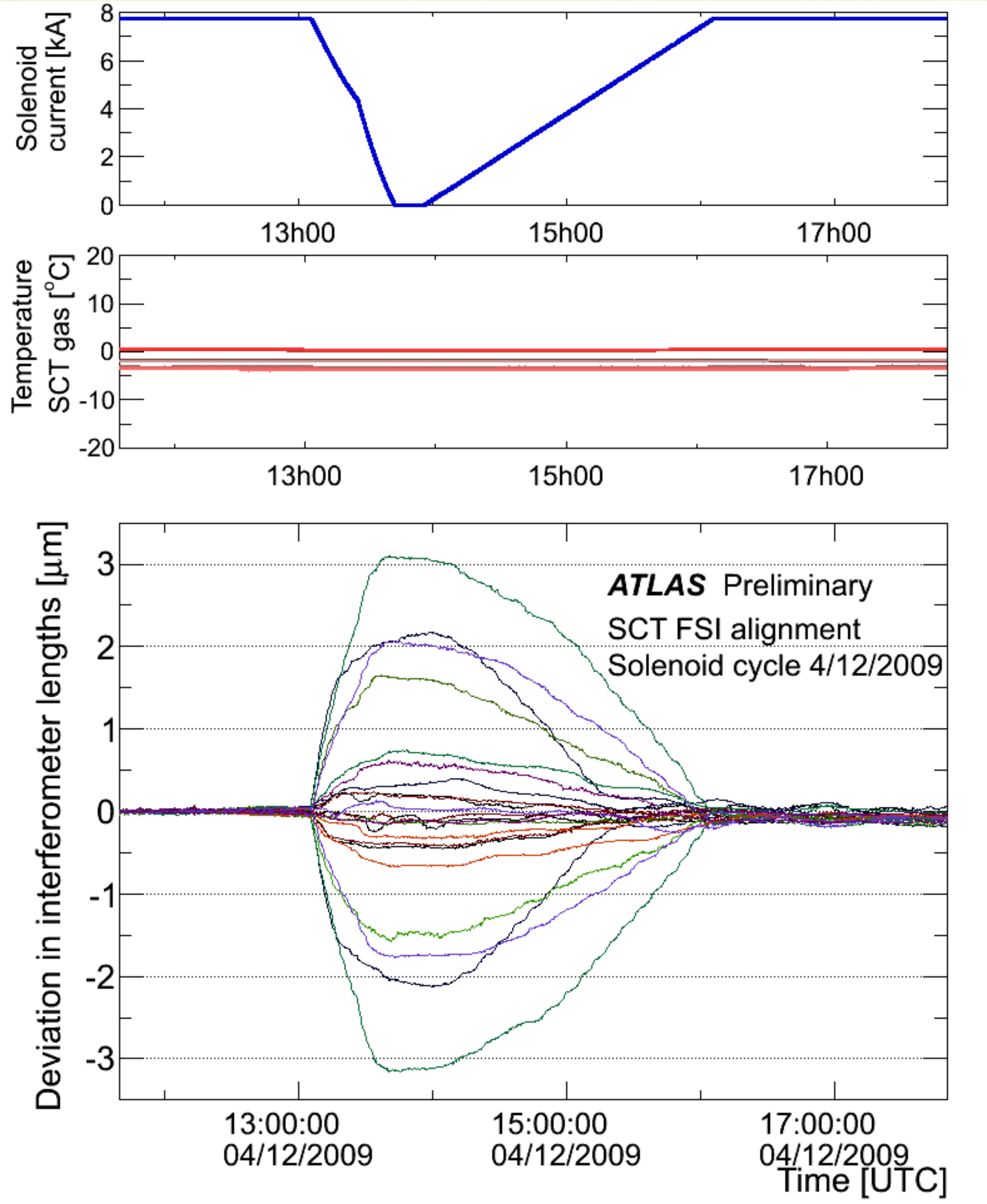
D1 length expands, positive phase shift

D2 length contracts, negative phase shift

D3 length expands, positive phase shift







Example: Solenoid cycle

Event: solenoid magnet ramped down and then back up.

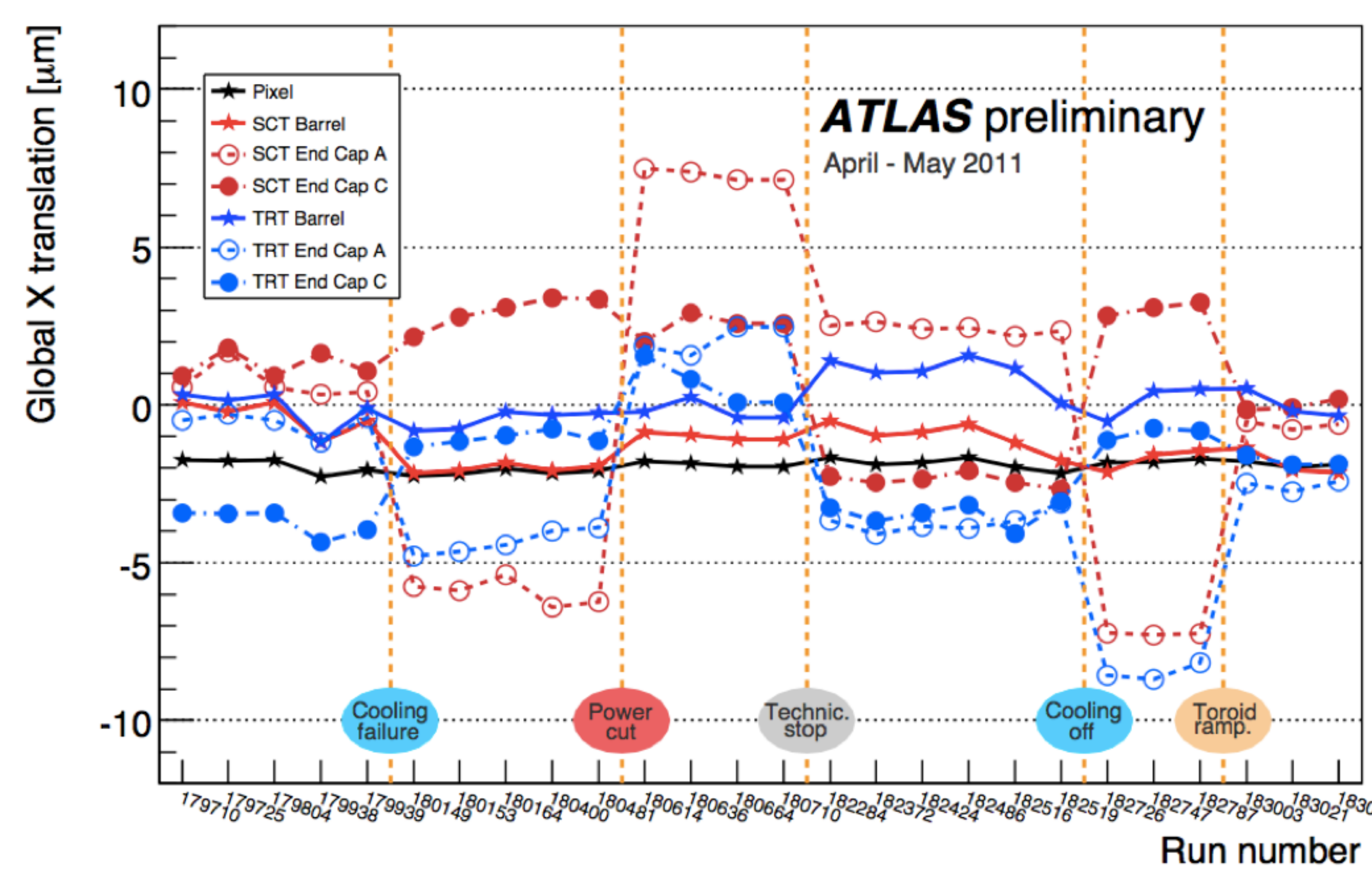
The interferometer lengths were found to be very stable: **stdev σ ~11 nanometres** in the hour before the ramp.

Correlated movements of up to **+/- 3μm** are seen when the solenoid field changes between on/off.

After the solenoid cycle the interferometers show very small hysteresis and return to the start values to within **stdev σ ~ 49nm**.

Interaction with track based alignment

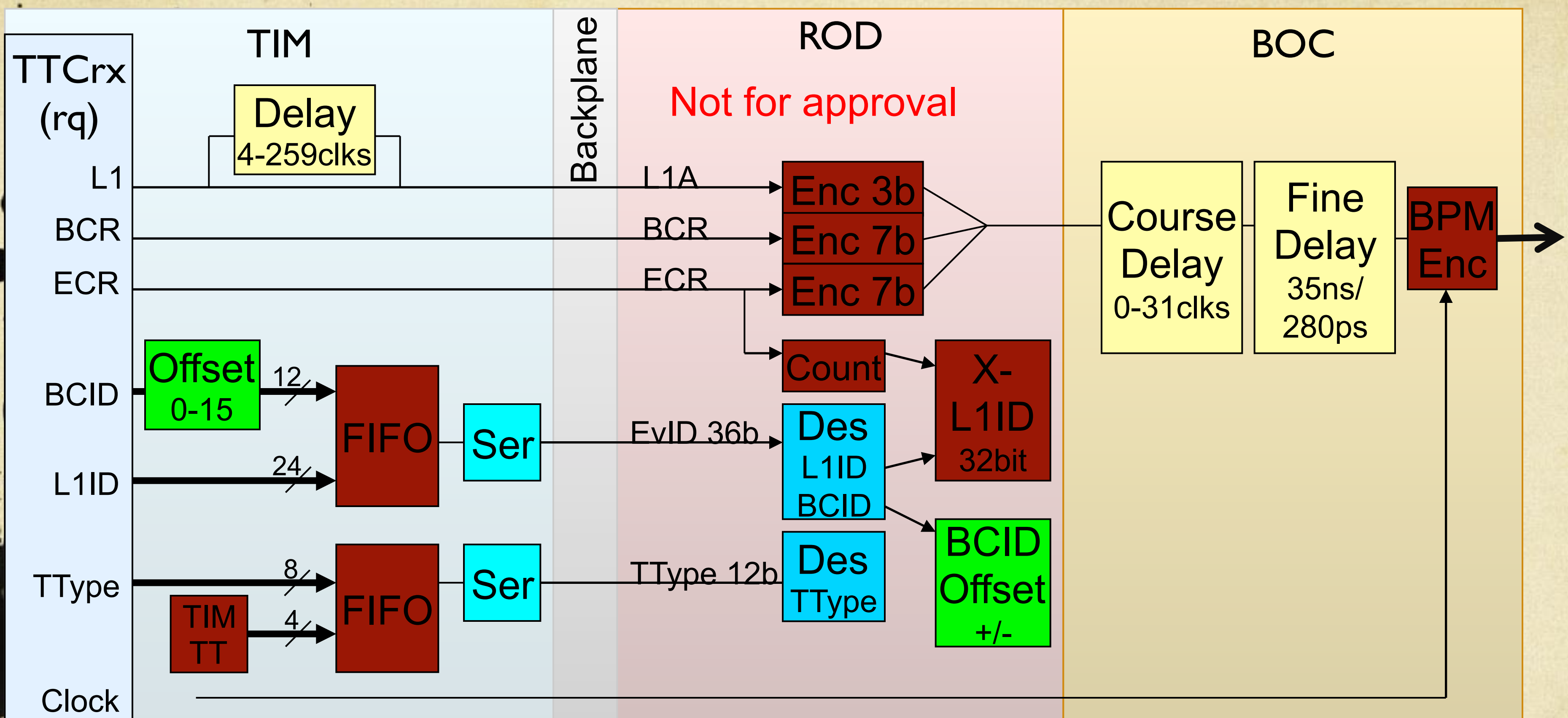
- Laser alignment provides cross check to track based alignment
  - Provide fast feedback to any detector movement
- Confirm the large detector movement during technical stop



Motivation of readout timing calibration

- SCT reads out three bunch-crossings around LVL1 accept signal.
- Timing issue in SCT readout
  - Time of flight
  - Charge collections time
  - signal transition time in optical communication system.
- Difficult to take everything into account correctly
- In case the readout timing is not synchronized
  - Hit efficiency decreases.
  - Hits from one track will be reconstructed in two events (ghost hits)
- Need to do in-situ timing calibration during collisions data taking

TTC Signal Flow - SCT Timing Delay Options



TIM TTCrx
0-25ns in
104ps steps

TIM
4-259 clocks

BOC
0-31 clocks

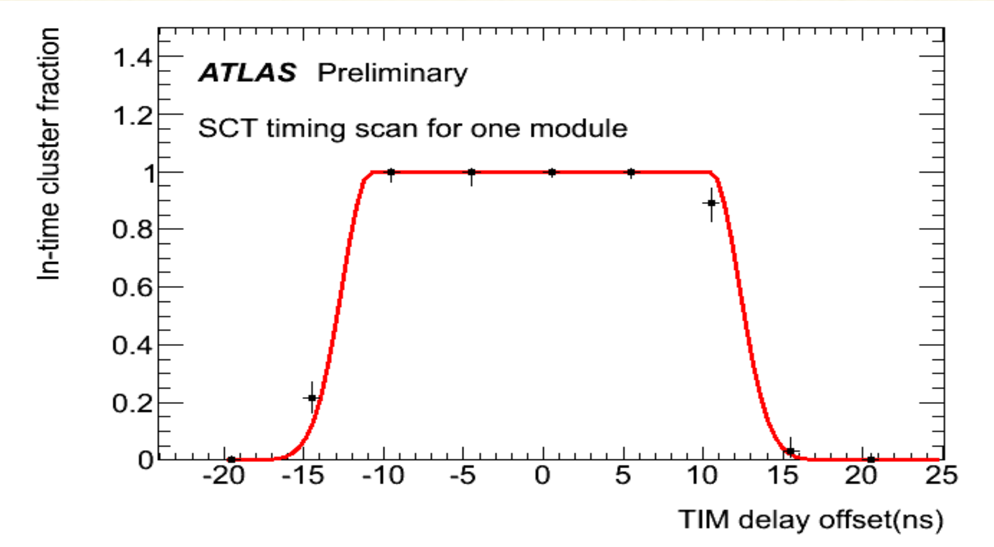
BOC
0-35ns in
280ps steps

TIM delay is common to all modules serviced by the crate

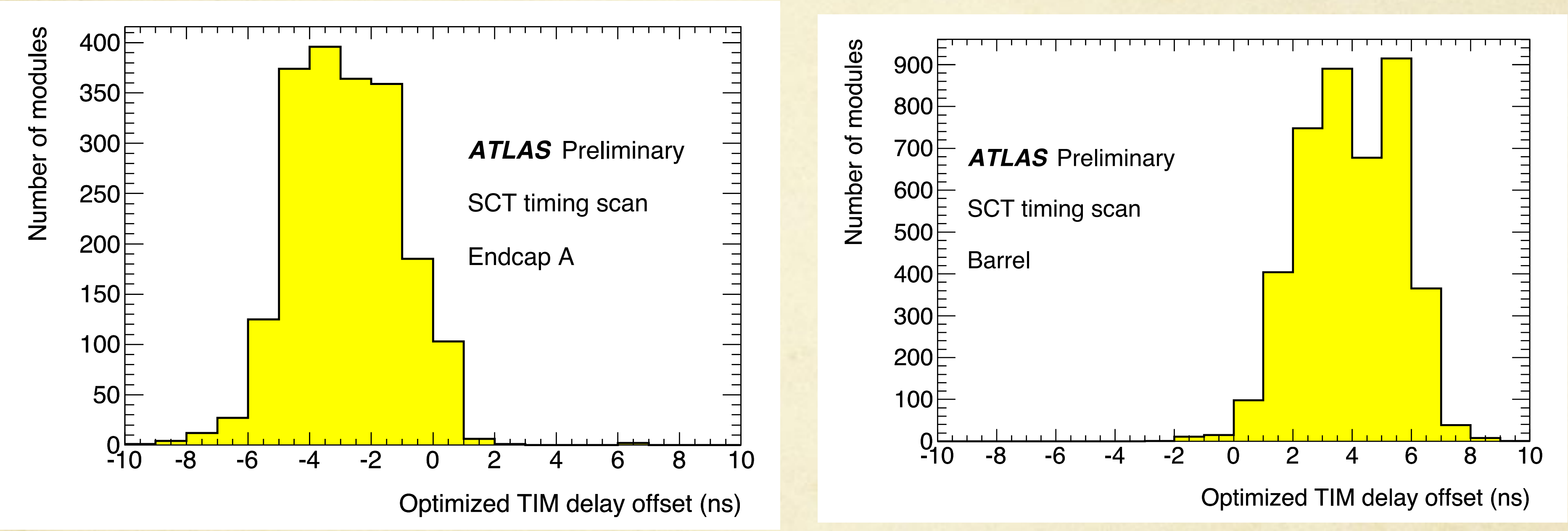
BOC delay is per module

Procedure of SCT timing scan

- Adjust global SCT timing(TIM delay time offset)
  - from -20ns to 20ns in the steps of 5ns during collision data taking。
- Study the how the fraction of in-time hits on tracks fraction changes with different TIM delay settings for each module.
  - Find the optimized TIM delay for each module, apply this delay as an offset in the BOC.
- Redo SCT optical calibration.
- Repeat above procedure for second, fine delay scan if needed, and fine delay scan has not been done yet.



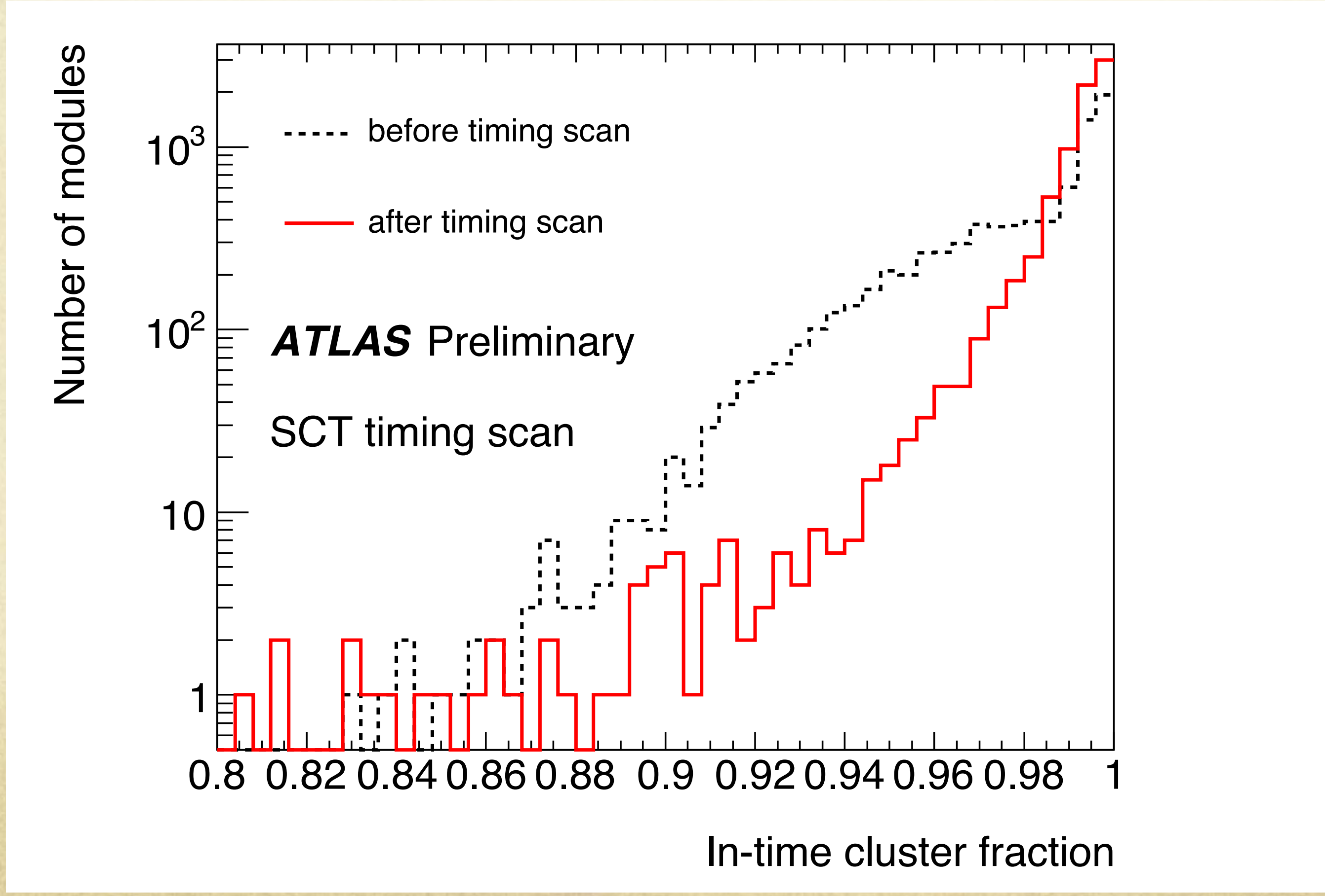
Plot3: Optimized TIM delay offset for Endcap A modules (For approval)



- Barrel and Endcap readout timing are different by ~10ns before timing scan
- synchronized to ~1ns precision after timing scan

In-Time hit efficiency before and after timing scan

- Higher In-time cluster faction on a track is recorded after timing scan.
- These calibration will be more important for future 25ns bunch crossing collision.



Introduction to AT LAS Electroweak group activity

- Electroweak group activity
  - Z backback forward asymmetry :
    - measurement of weak mixing angle.
  - W mass measurement :
    - precision measurement of m_W
  - Diboson (triboson) production
    - sensitive to triple (Quartic) Gauge Boson Couplings
    - WW, WZ, ZZ, Wγ, Zγ

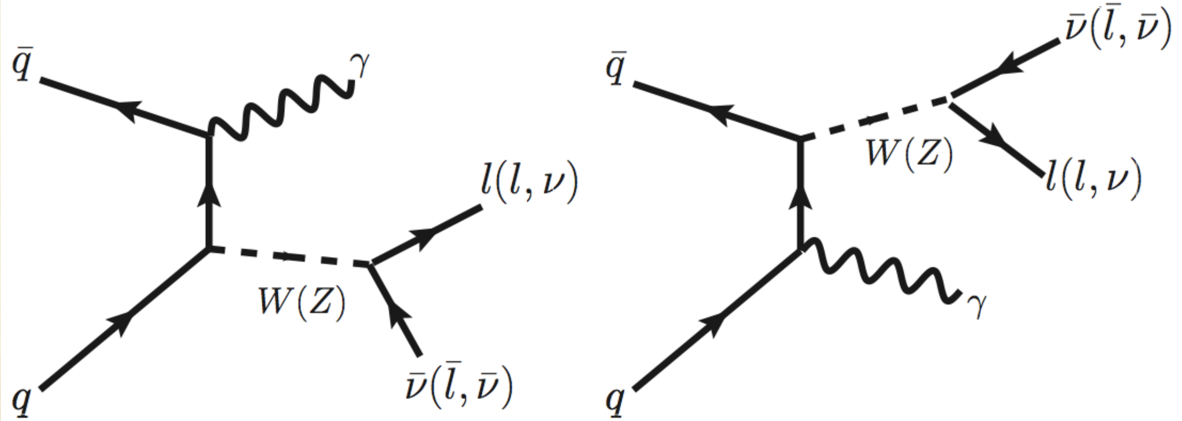
- New frontiers in electroweak physics at the LHC
  - VBF/VBS signatures
  - Triboson : Wγγ, Zγγ, WWW
  - Sensitive to Quartic Gauge boson Couplings

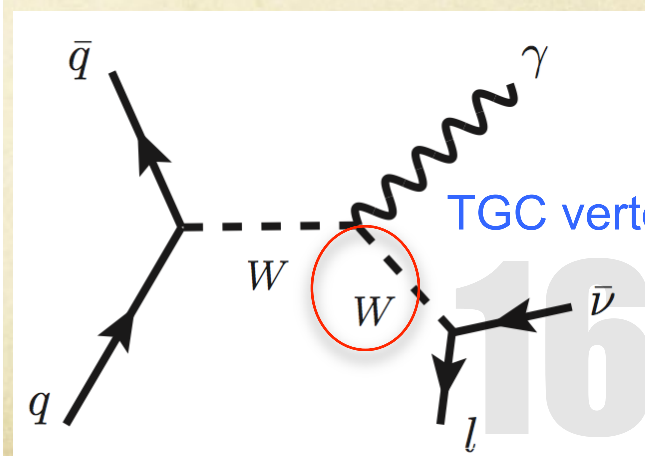
- My responsibility during the past year
  - Co-Convener of ATLAS Electroweak group

Motivation of diboson physics

- Diboson production cross-section measurements
  - Test of SM electroweak theory and perturbative QCD at TeV scale
  - Sensitivity to new particles decaying to dibosons (Technicolor, Little Higgs, SUSY, etc...)

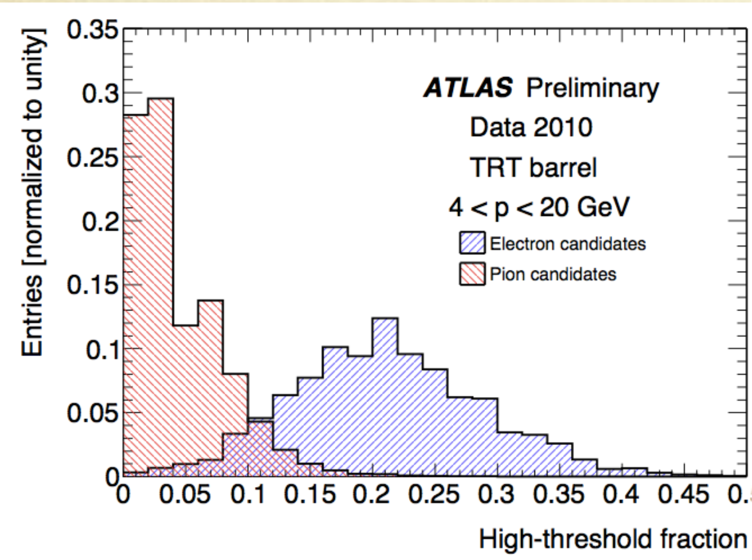
- Anomalous Triple Gauge Couplings (aTGC)
  - **The Higgs mechanism ≠ a Higgs boson !**
  - Vector boson self-couplings fundamental prediction of the Electroweak Sector of SM
  - Its study is important to understanding electroweak symmetry mechanism

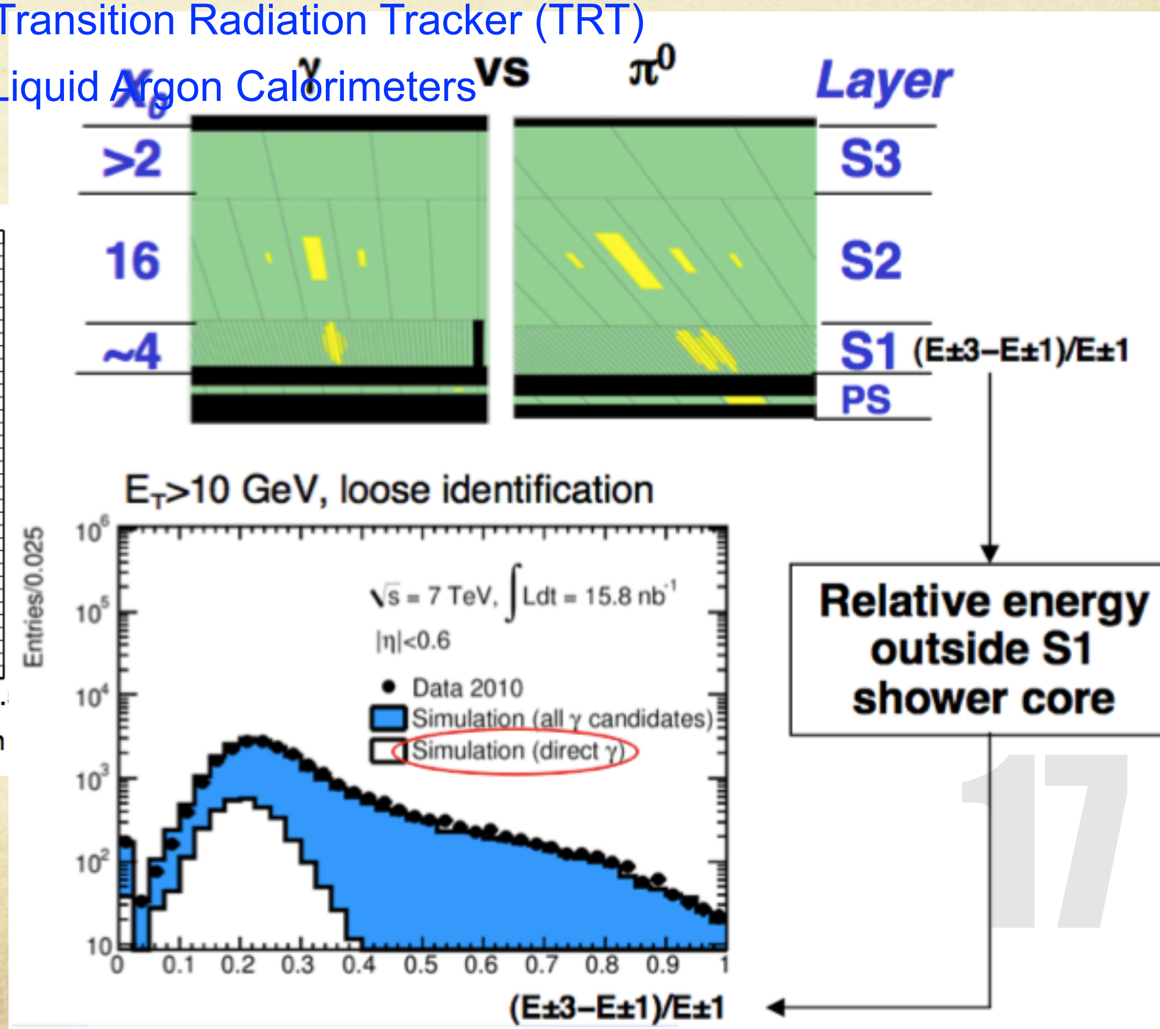




ATLAS electron and photon identification

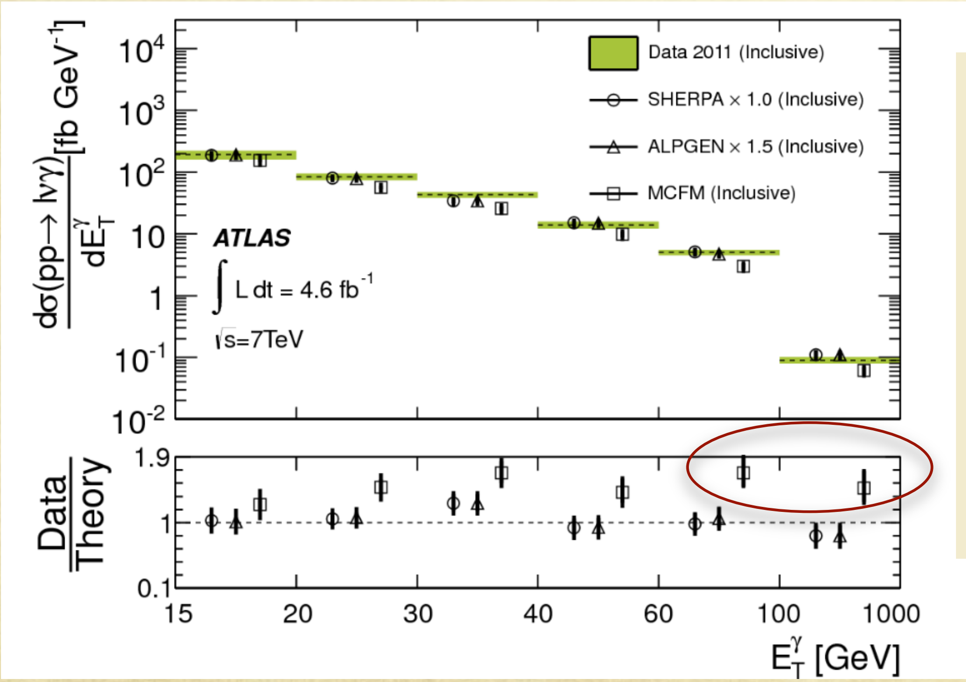
- Photon identification
  - Use EM shower shape in Liquid Argon Calorimeters
- Electron identification
  - Use high threshold hits in Transition Radiation Tracker (TRT)
  - Use EM shower shape in Liquid Argon Calorimeters





W γ (lν γ): photon E_T spectrum

- Unfolded Photon E_T spectrum compared to MCFM NLO predictions
  - Discrepancy in high E_T for inclusive measurement (without jet veto)
- Data compared to Sherpa/Alpgen predictions
  - Very good agreement in event kinematics
  - Scale up the Alpgen predictions by a factor of 1.5 to match data.

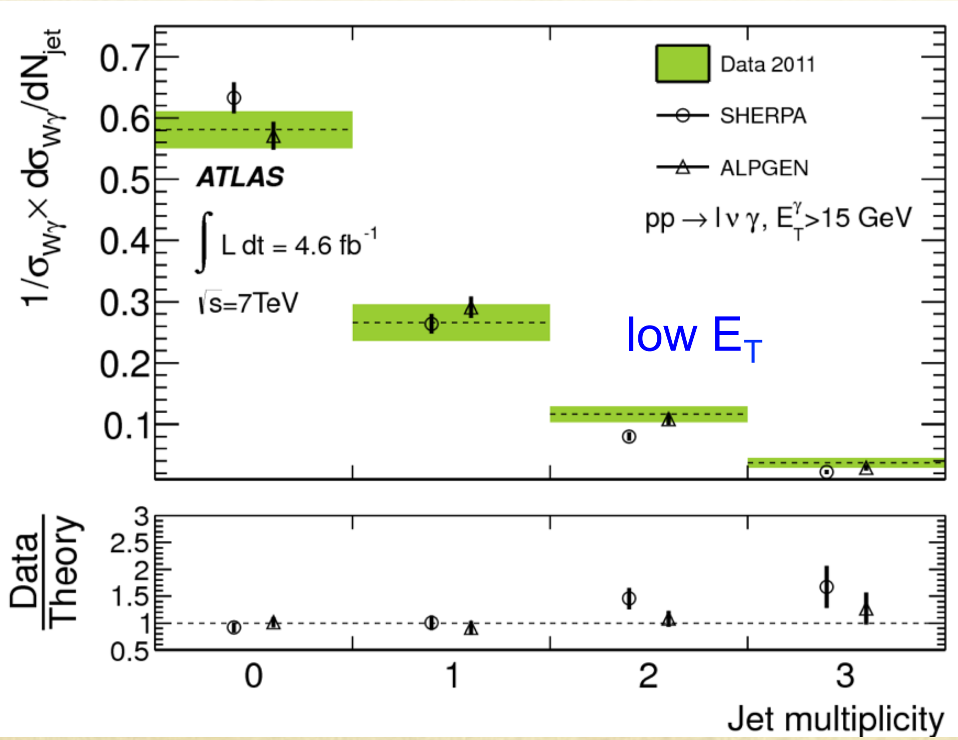


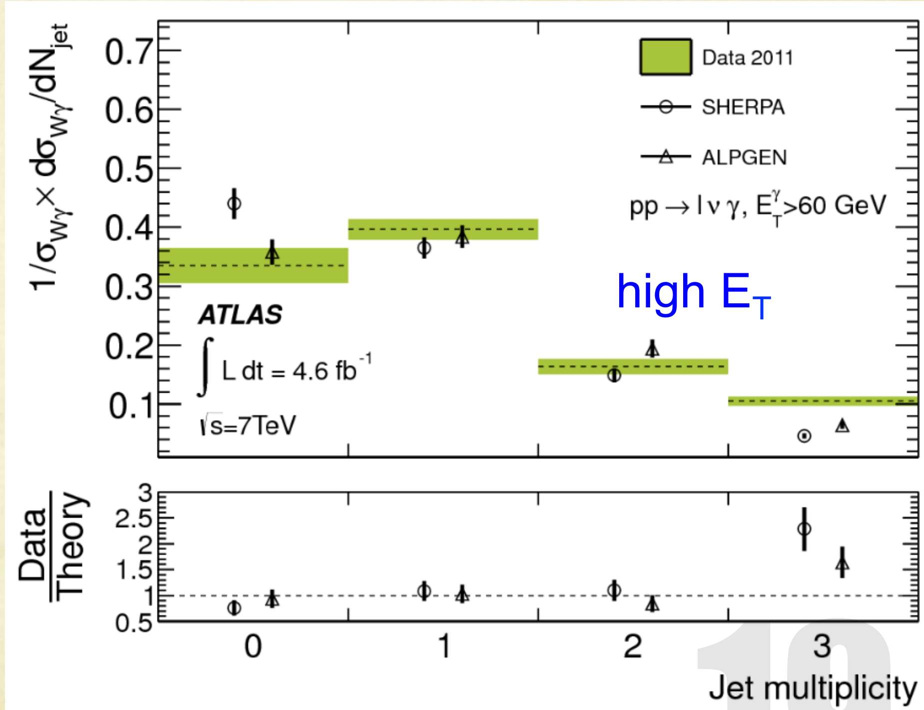
- Wγ (lνγ) Selection highlight
- One high pT lepton with pT>25GeV
- E_T^{miss}>35 GeV
- One isolated photon with pT>15GeV

Sherpa :Matrix element calculation for Wγ+0/1/2/3 partons
Alpgen: Matrix element calculation for Wγ+0/1/2/3/4/5 partons

W γ (lv γ): Jet multiplicity

- Jet multiplicity depends strongly on photon E_T threshold.
  - Dominant contribution from 0jet bin in low E_T region
  - Dominant contribution from 1jet bin in high E_T region
  - Contributions from 2jet or 3jet bins are not negligible

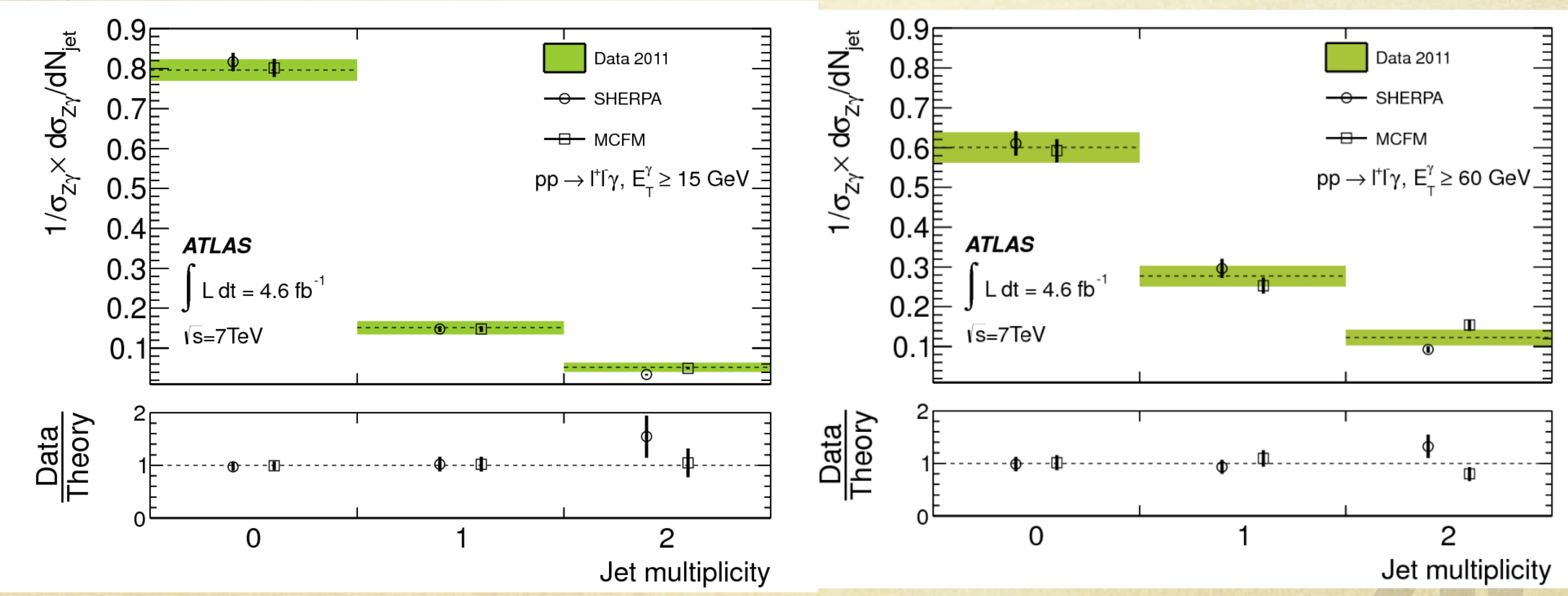




Sherpa :Matrix element calculation for Wγ+0/1/2/3 partons
Alpgen: Matrix element calculation for Wγ+0/1/2/3/4/5 partons

$Z\gamma$ ($l^+l^-\gamma$): jet multiplicity

- Jet multiplicity depends strongly on photon pT threshold.
- Very different from jet multiplicity in Wγ.

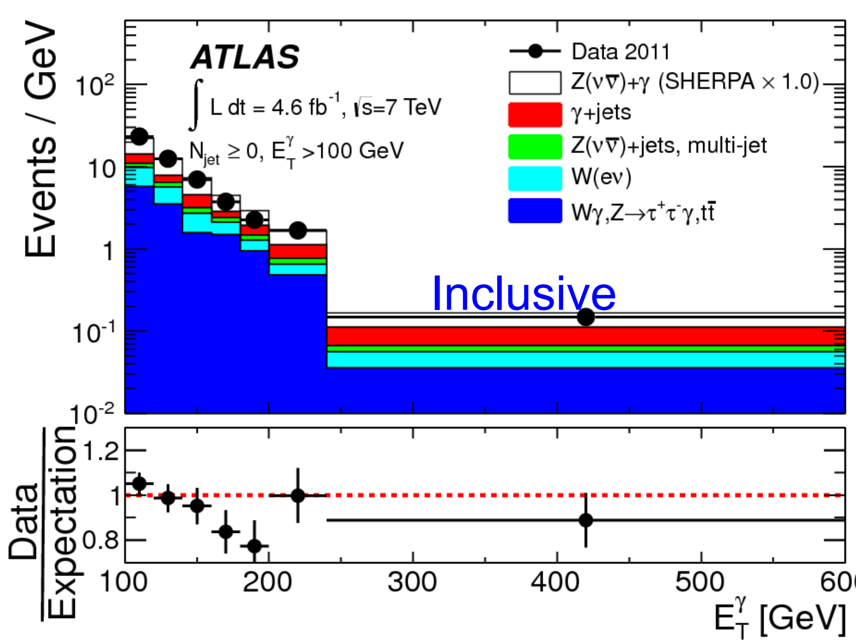


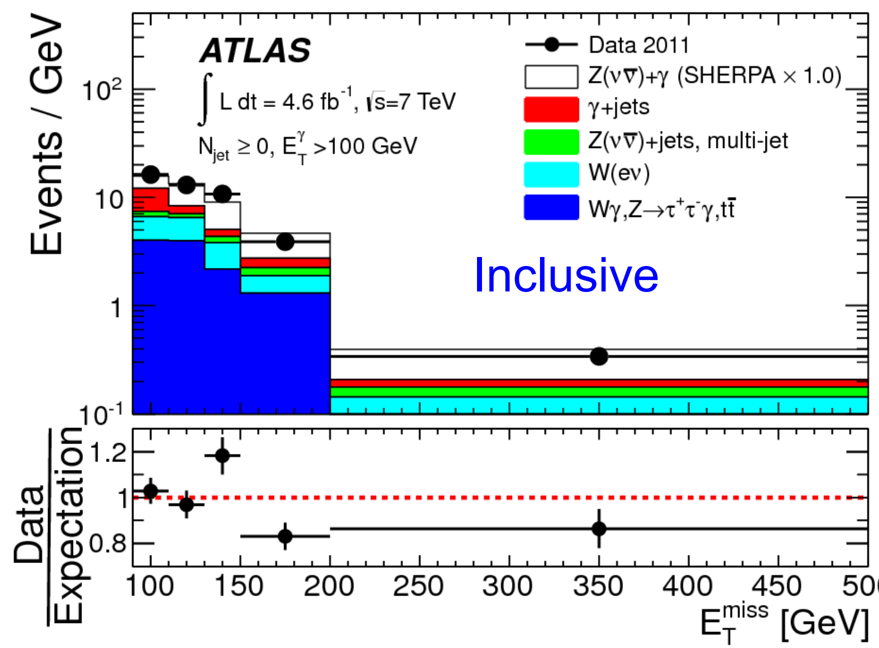
$Z\gamma\ (\nu\ \nu\ \gamma)$

- First measurement with neutrino decay channel (ννγ)
  - Very sensitive to Z-Z-γ and Z-γ-γ aTGC.

	$\nu\bar{\nu}\gamma$ $N_{\mathrm{jet}} \geq 0$
$N^{\mathrm{obs}}_{Z\gamma}$	1094
$W(e\nu)$	$171 \pm 2 \pm 17$
$Z(\nu\bar{\nu})$+jets, multi-jet	$70 \pm 13 \pm 14$
$W\gamma$	$238 \pm 12 \pm 37$
γ+jets	$168 \pm 20 \pm 42$
$Z(\tau^+\tau^-)\gamma$	$11.7 \pm 0.7 \pm 0.9$
$t\bar{t}$	$11 \pm 1.2 \pm 1.0$
$N^{\mathrm{sig}}_{Z\gamma}$	$420 \pm 42 \pm 60$

- Selection highlight
- ❑ E_T^{Miss}>90GeV
- ❑ One isolated photon with pT>100GeV
- ❑ Veto event with good lepton

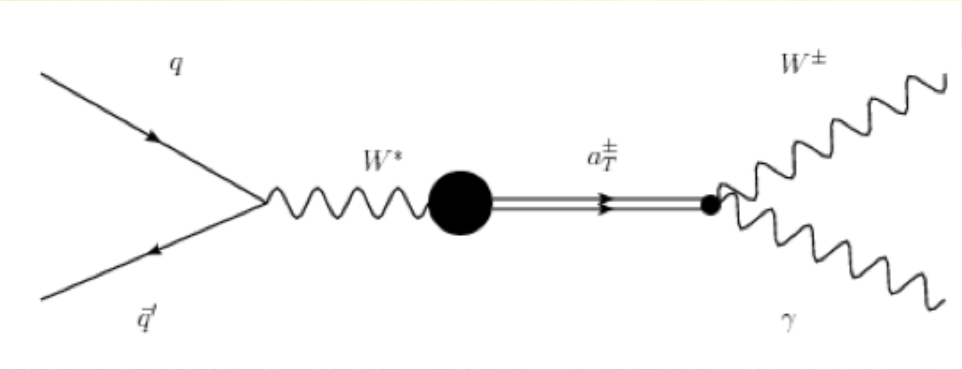


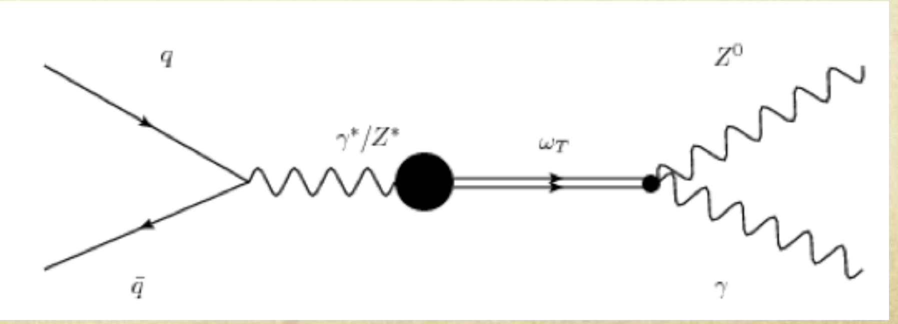


Wγ/Zγ : Narrow resonance search

- First narrow resonance search using Wγ final state in all HEP experiments
  - No experimental limits from CMS/CDF/D0 in this final state.
  - Do the search as model independent as possible
  - Choose Low Scale Technicolor as benchmark model

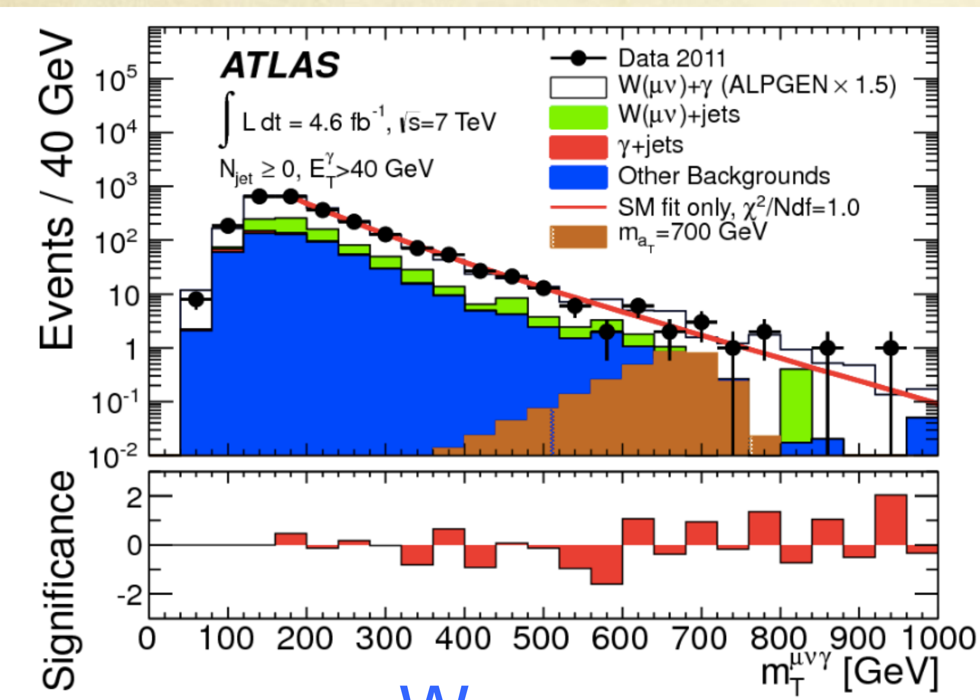
- Low Scale Technicolor predicts narrow resonance decays into Vγ
  - $\omega_T \rightarrow Z\gamma$
  - $a_T \rightarrow W\gamma$



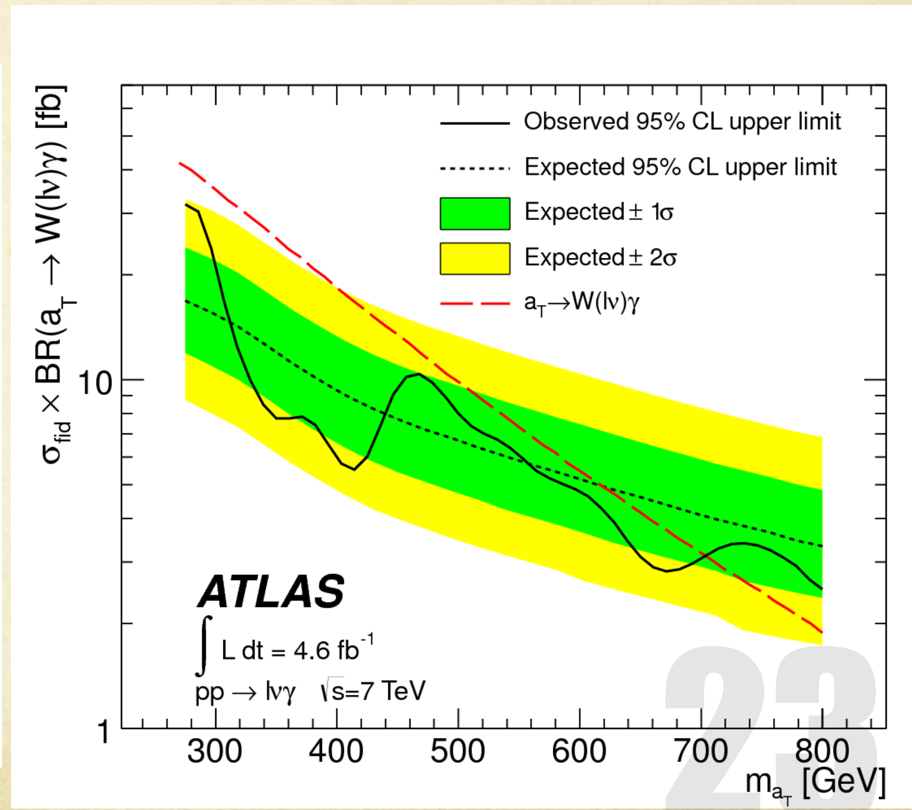


Wγ/Zγ : Narrow resonance search (2)

- First narrow resonance search using Wγ final state in all HEP experiments
- The most stringent limits in the Zγ final state.
  - Double-exponential function to model to the shape of Vγ mass
  - No deviation from SM predictions



Wγ



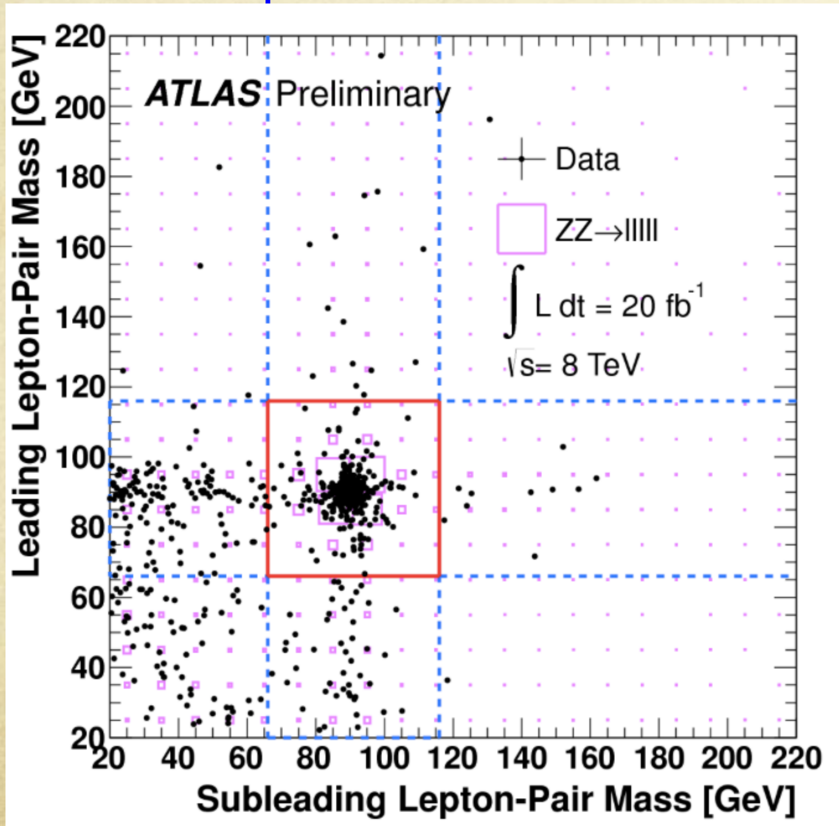
Wγ

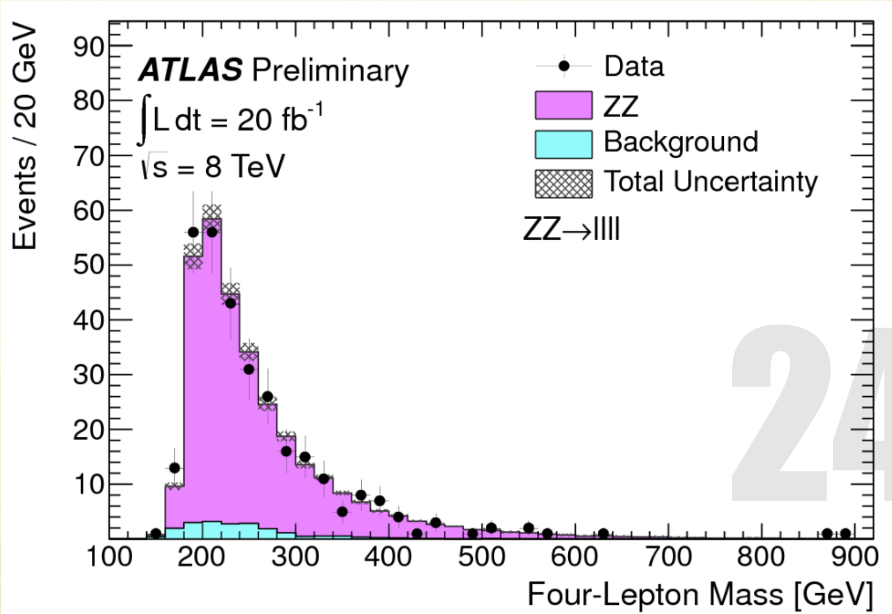
ZZ @ 8TeV

- Moriond CONF note with full 8TeV dataset
  - http://cds.cern.ch/record/1525555
  - Focus on total cross section measurements for on-shell production using ZZ-> 4l events.
    - Explore a larger phase space and differential distribution in 8TeV publication this summer.

- Selection highlight

❑ 4 isolated lepton with pT>7GeV
- Use forward muon
- Enhanced muon acceptance | η | < 2.7

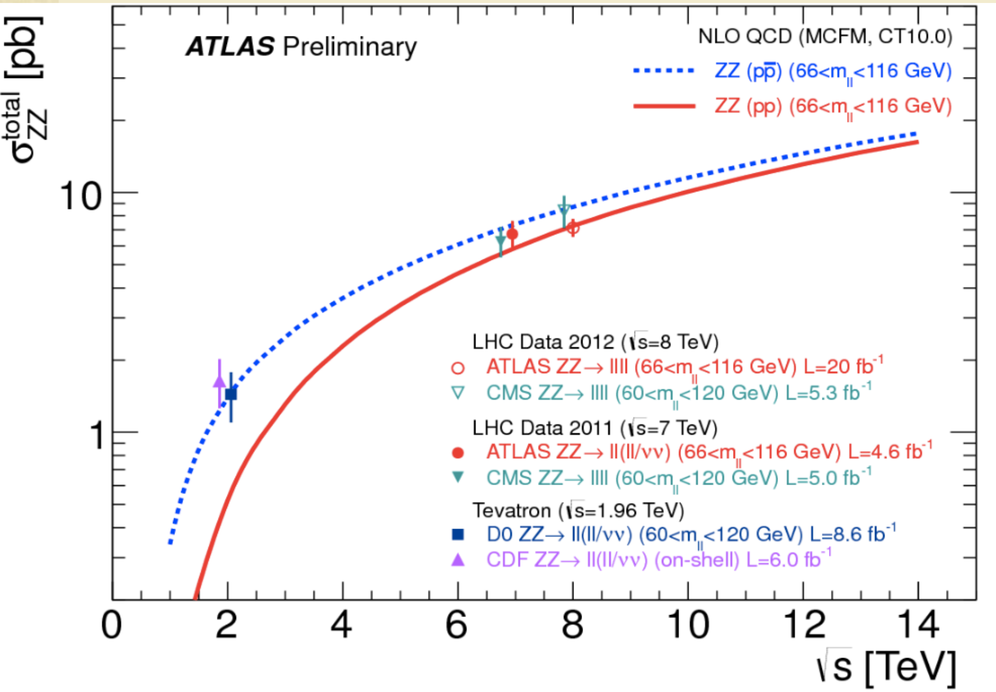




ZZ

- Latest 8TeV Moriond CONF note results and 7TeV results from ZZ paper

	dataset	Channel	Measured σ^{tot} [pb]	Theoretical σ^{tot} [pb]
7 TeV	4.6 fb^{-1}	$4l, 2l2\nu$	$6.7 \pm 0.7(\text{stat.})^{+0.4}_{-0.3}$ (syst.) ± 0.3(lumi.)	$5.89^{+0.22}_{-0.18}$
8 TeV	Moriond 2013 (20 fb^{-1})	$4l$	$7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3$ (syst.) ± 0.3(lumi.)	$7.2^{+0.3}_{-0.2}$



- Latest Moriond 8TeV CONF note results
  - Improved accuracy compared to 7TeV
  - Good agreement with SM expectation
  - Statistical uncertainty reduces compared to ICHEP 2012 results

Old result: 8TeV ICHEP 2012 CONF note results

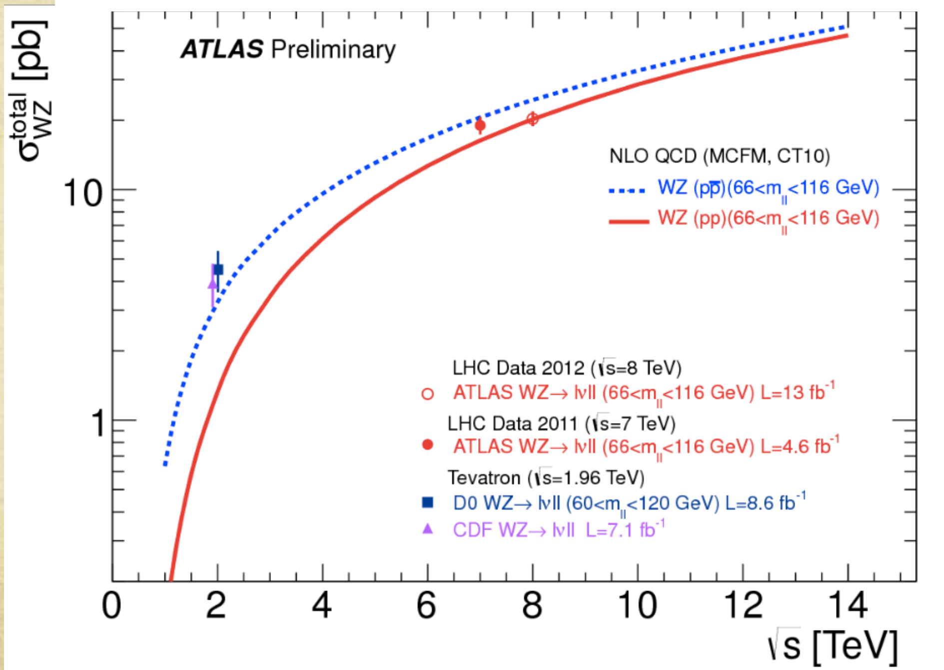
	dataset	Channel	Measured σ^{tot} [pb]	Theoretical σ^{tot} [pb]
8 TeV	ICHEP 2012 (5.8 fb^{-1})	$4l$	$9.3^{+1.1}_{-1.0}(\text{stat.})^{+0.4}_{-0.3}$ (syst.) ± 0.3(lumi.)	$7.2^{+0.3}_{-0.2}$

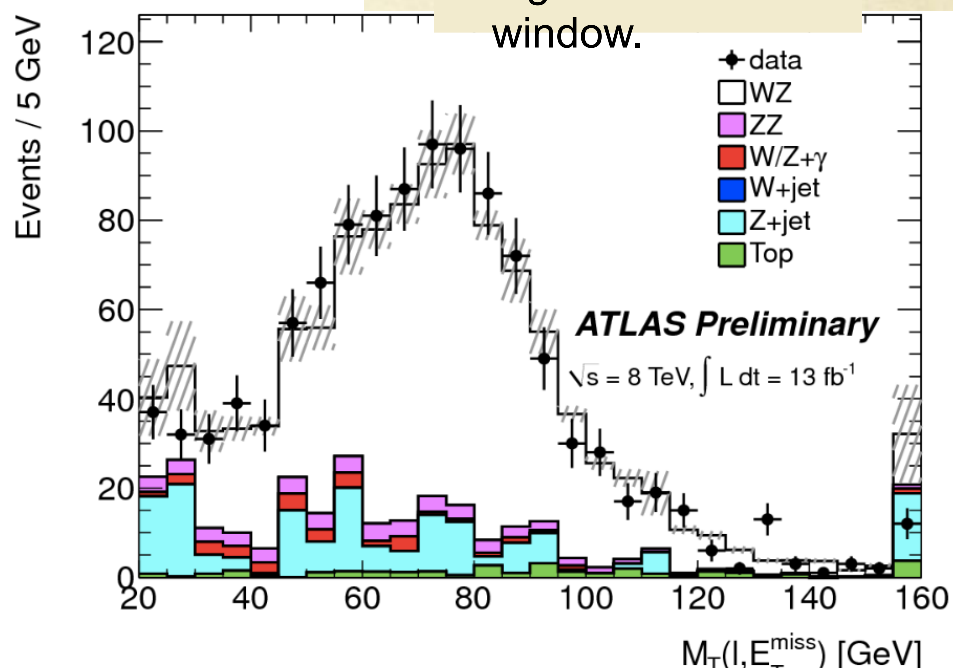
WZ @ 8TeV

- Moriond CONF note with HCP dataset ($13 fb^{-1}$).
  - https://cds.cern.ch/record/1525557
  - First 8TeV WZ measurement in LHC experiments
    - 8TeV measurement is in a excellent agreement with theory

	Measured σ^{tot} [pb]	Theoretical σ^{tot} [pb]
8 TeV	$20.3^{+0.8}_{-0.7}$(stat.)$^{+1.2}_{-1.1}$ (syst.) $^{+0.7}_{-0.6}$(lumi.)	20.3 ± 0.8
7 TeV	$19.0^{+1.4}_{-1.3}$(stat.)± 0.9 (syst.) ± 0.4(lumi.)	$17.6^{+1.1}_{-1.0}$

- Selection highlight
  - 3 high pT lepton
    - pT>15GeV
  - Large E_T^{Miss}
  - Tight Z mass window.





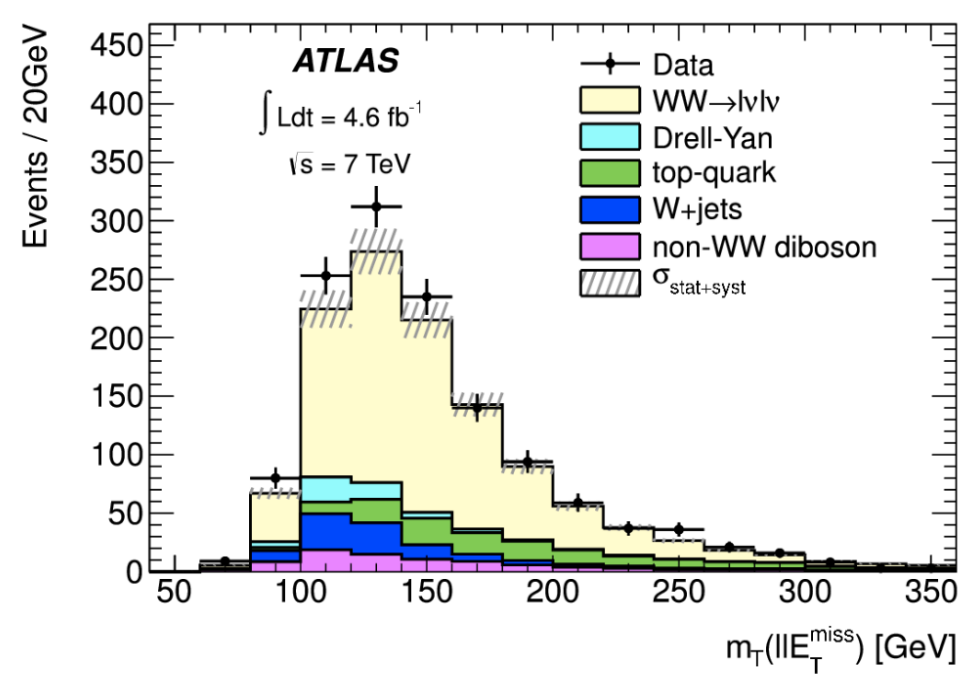
WW @ 7TeV

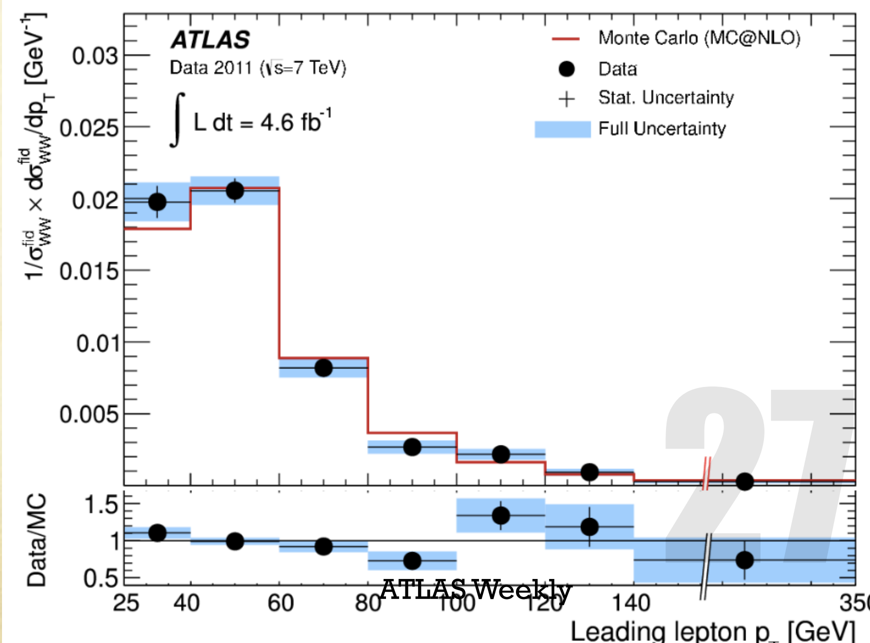
- 7TeV Paper submitted to PRD
  - http://arxiv.org/pdf/1210.2979.pdf

- Selection highlight
- Require exactly two isolated leptons
- Veto events with hard jet (reject top)
- large E_T^{Miss}

- First differential measurement of lepton p_T spectrum.

	Measured σ^{tot} [pb]	Theoretical σ^{tot} [pb]
7 TeV	51.9 ± 2.0(stat.)±3.9 (syst.) ±2.0(lumi.)	44.7 ± 2.8





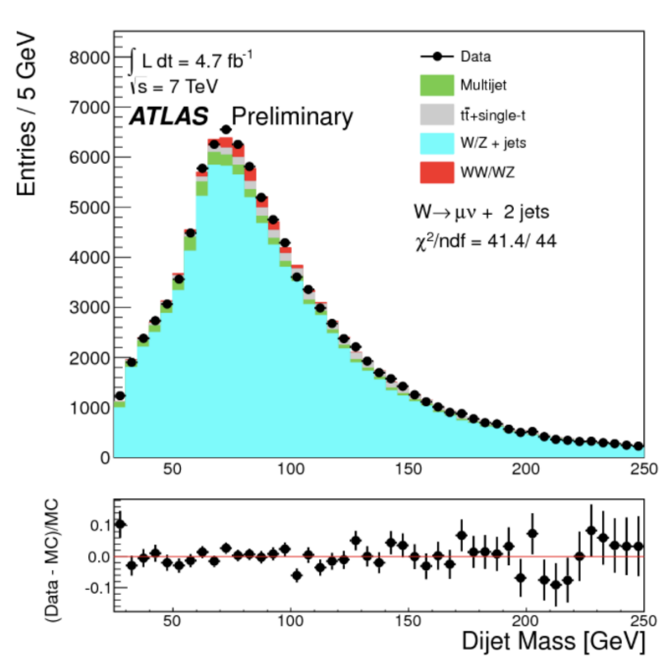
ATLAS Weekly

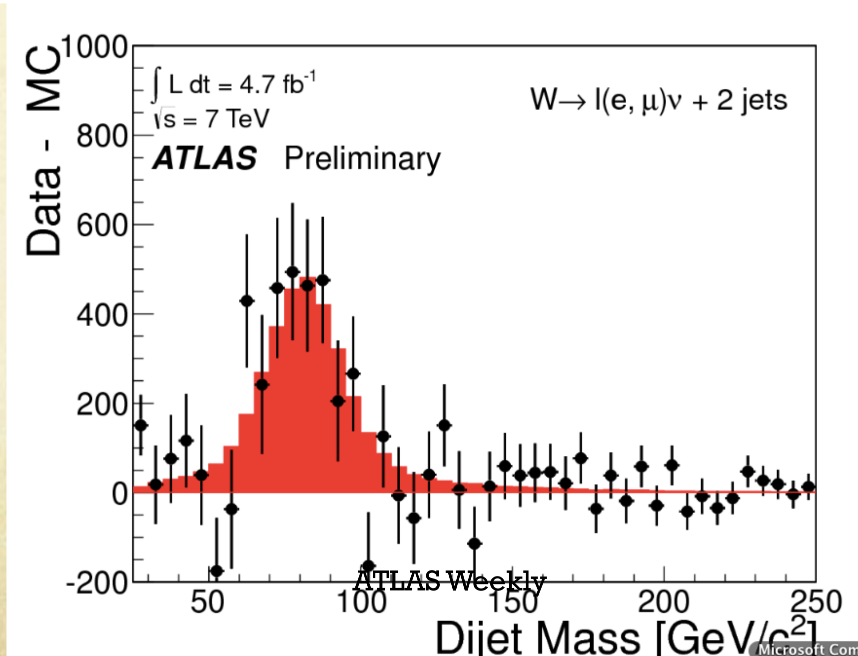
WW/WZ -> $l\nu$ ji @7TeV

- Main backgrounds
  - W/Z + jets and ttbar
- Main systematics
  - Jet energy scale and resolution uncertainty
  - W+jet and ttbar dijet mass shape

- Selection highlight
- One high pT lepton
- large E_T^{Miss}
- Exactly two jets

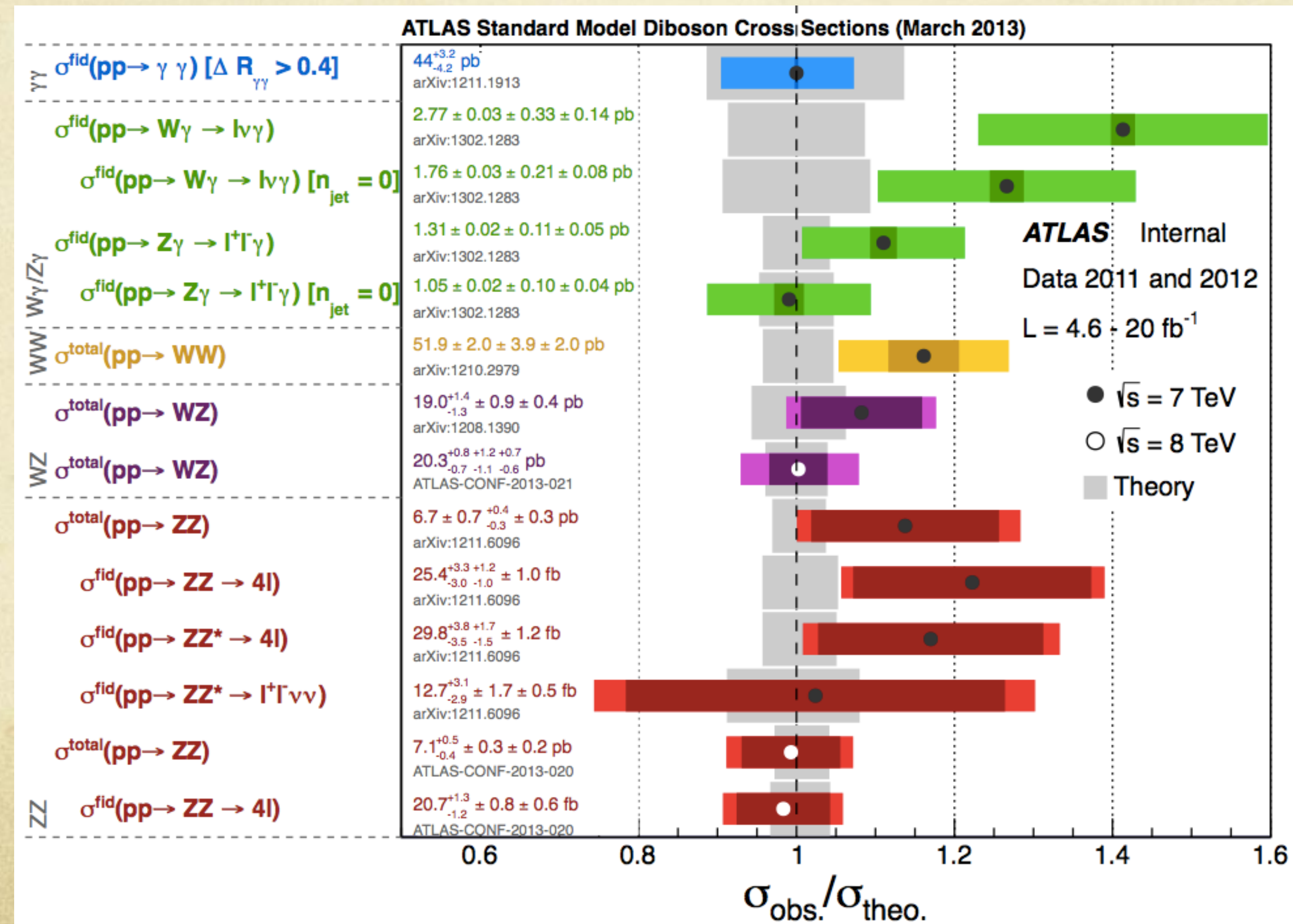
	dataset	Channel	Measured σ^{tot} [pb]	Theoretical σ^{tot} [pb]
7 TeV	4.6 fb^{-1}	$WW/WZ \rightarrow l\nu jj$	72 ± 9(stat.)±15 (syst.) ±13(MC stat.)	63.4 ± 2.6





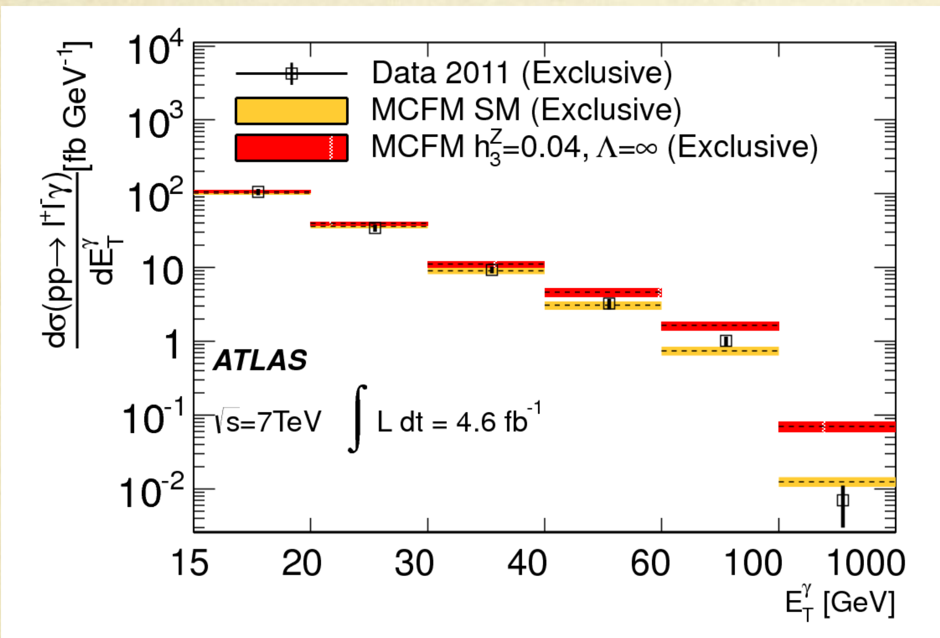
Diboson cross sections measurements overview

- Cross-section measurements
  - performed in WW,ZZ,WZ,Wγ and Zγ channels
  - Latest 8TeV results Improved accuracy compared to 7TeV



Triple Gauge Couplings

- The s-channel diagrams contain the triple gauge coupling vertex
  - New physics may modify these couplings.
- aTGCs modify the event kinematics
  - Effects of aTGCs increase with $\hat{s}$



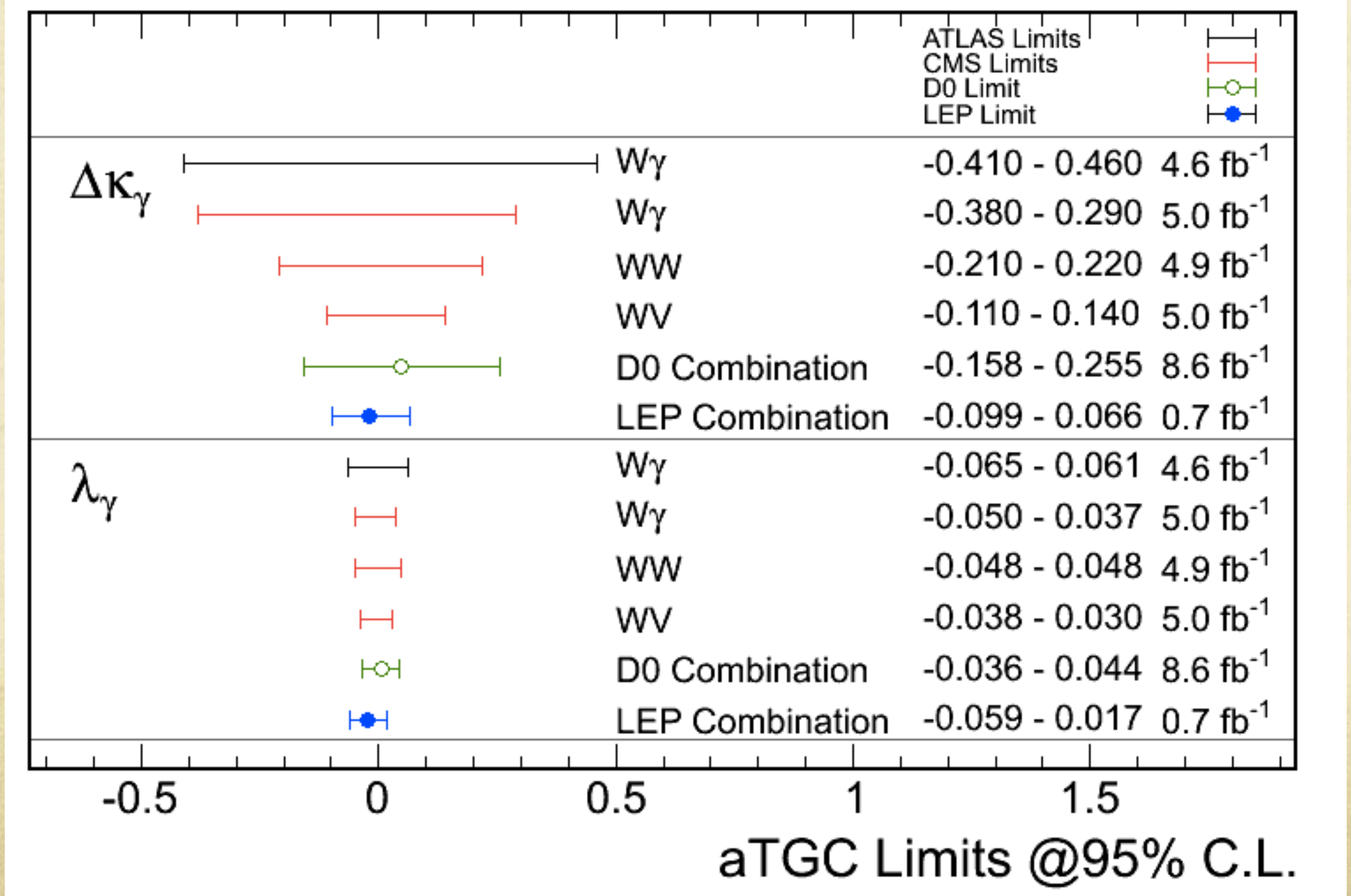
coupling	parameters	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	Zγ
$Z\gamma\gamma$	h_3^γ, h_4^γ	Zγ
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ

Zγ

aTGC limits is comparable or better than Tevatron results

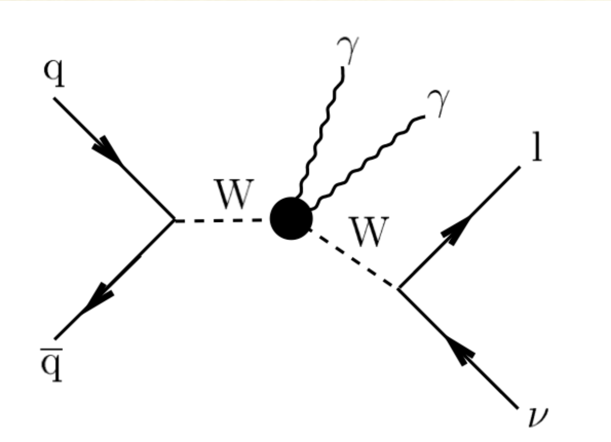
Charged aTGC results

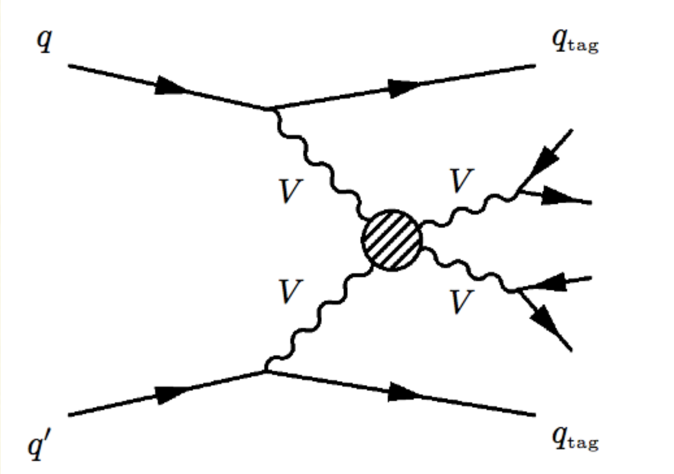
- aTGC results summary from Wγ,WZ,WW and WV
- aTGC measurements show no apparent deviation from SM



New frontiers in electroweak physics at the LHC

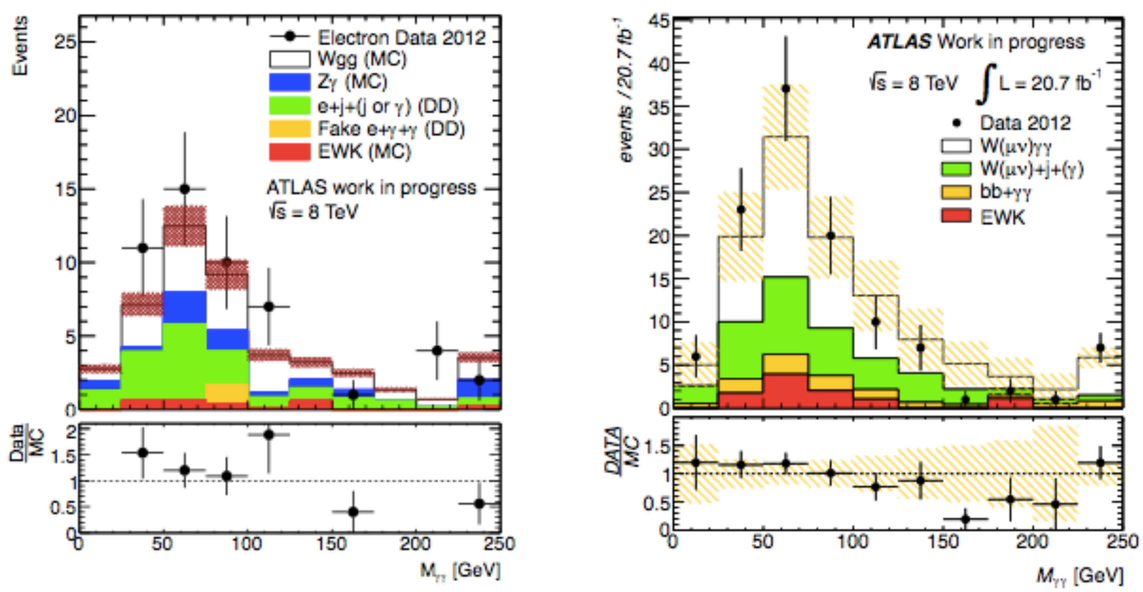
- **Quartic Gauge Boson Couplings (QGCs)**
  - SM model predicts gauge boson self coupling
    - Four gauge boson vertex:
      - WW$\gamma\gamma$, WWZγ, WWWW, WWZZ, ZZZZ …





- Triboson V$\gamma\gamma$
  - Mainly probing WW$\gamma\gamma$ vertex
- Vector boson scattering WW->WW, WZ->WZ, ZZ->ZZ
  - Sensitive to WWWW, WWZZ, ZZZZ vertex

W γ γ measurements



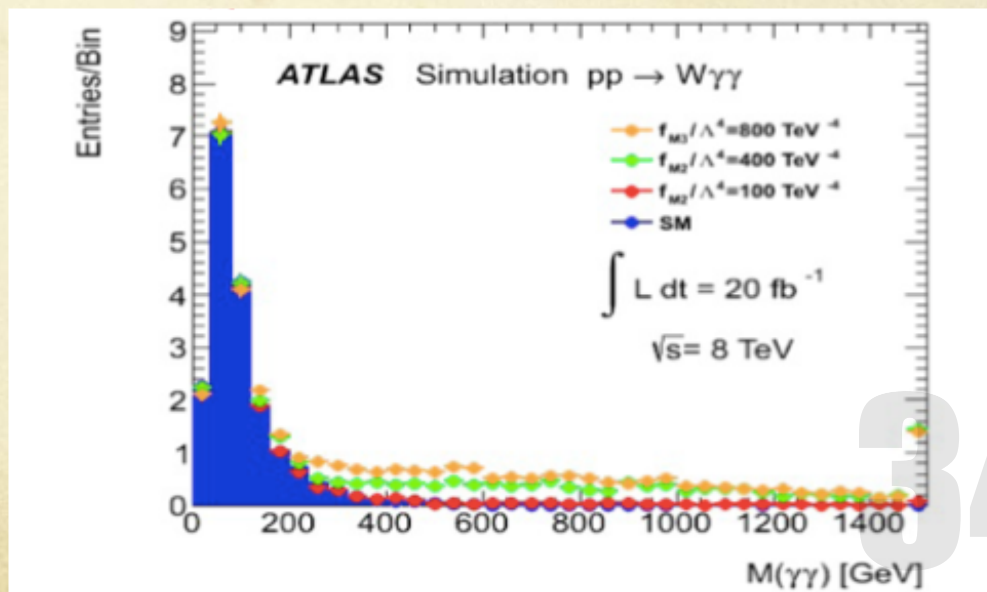
- ❑ Mu18_2g15 or 3g15 Trigger
- ❑ Two isolated photon with pT>20Ge
- ❑ One lepton with pT>25GeV
- ❑ MET>25GeV
- ❑ MT>40GeV

Cross section

	$\sigma^{ext\ fid}$ [pb]
$pp \rightarrow \mu\nu\gamma\gamma$	0.0067 + 0.0013 - 0.0012 (Stat.) ± 0.0014 (Syst.) ± 0.0002 (Lumi.)
$pp \rightarrow e\nu\gamma\gamma$	0.0052 + 0.0017 - 0.0016 (Stat.) + 0.0016 - 0.0017 (Syst.) ± 0.0002 (Lumi.)
$pp \rightarrow \ell\nu\gamma\gamma$	0.0061 ± 0.0010 (Stat.) ± 0.0013 (Syst.) ± 0.0002 (Lumi.)

W$\gamma\gamma$:anomalous **Quartic Gauge Boson Couplings**

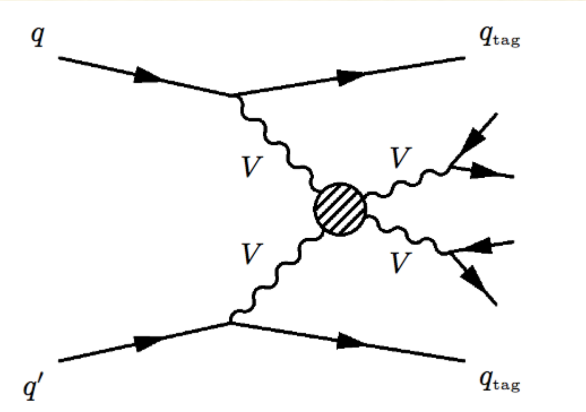
- anomalous **Quartic Gauge Boson Couplings in** V$\gamma\gamma$
  - Direct link to anomalous magnetic quadrupole moment
- Any deviation of aQGC enhance
  - photon pT spectrum and di-photon spectrum
- Expected limits on aQGC
  - 100 times better than LEP
  - Better than CMS limits



Quartic Gauge Boson Couplings and vector boson scattering(VBS)

- Wγ(Zγ)+2jet VBS process is sensitive to **Quartic Gauge Boson Couplings**
- Reminder of **Quartic Gauge Boson Couplings (QGCs)**
  - Important to electroweak symmetry breaking (EWSB)
  - SM model predicts gauge boson self coupling
    - Four gauge boson vertex:
      - WWγγ , WWZγ , WWWW, WWZZ, ZZZZ …
  - Vector boson scattering …
    - Wγ VBS: sensitive to WWγγ ,WWZγ vertex
    - Zγ VBS : sensitive to WWZγ vertex
  - VBS process has not been measured in previous experiment
    - Wγ/Zγ VBS is likely to be one of the first VBS measurements.
    - Advantage in Vγ VBS process:
      - relative large cross section

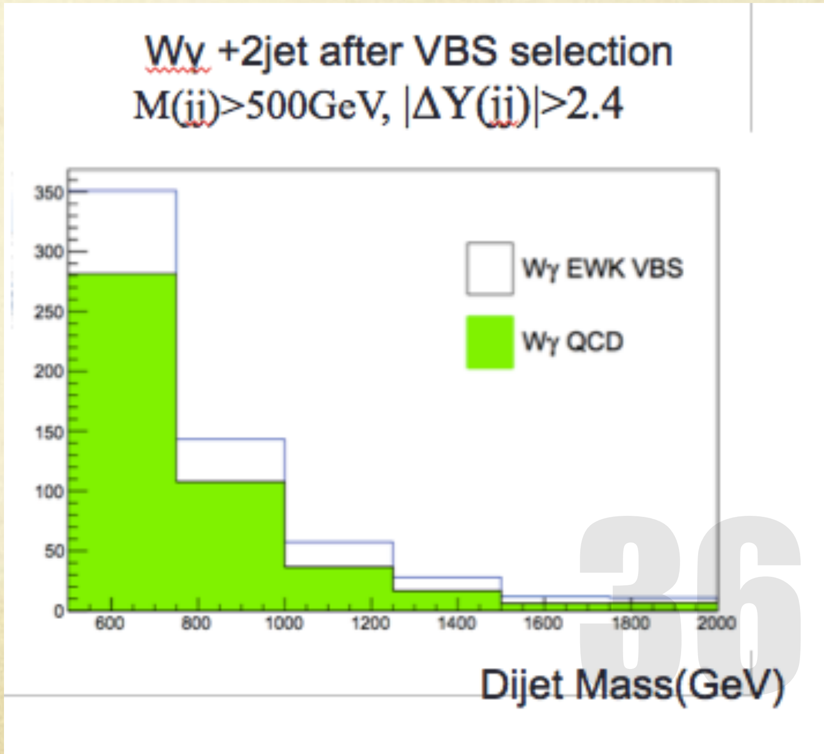
    10~100 times larger than WW and WZ VBS
      - Less background from QCD jets



Prospect of Wγjj VBS measurement @ 8TeV

Number of expected candidates @8TeV	Wγjj EWK signal	Wγjj QCD BG	S/sqrt(B)
After VBS selection	150	450	~7

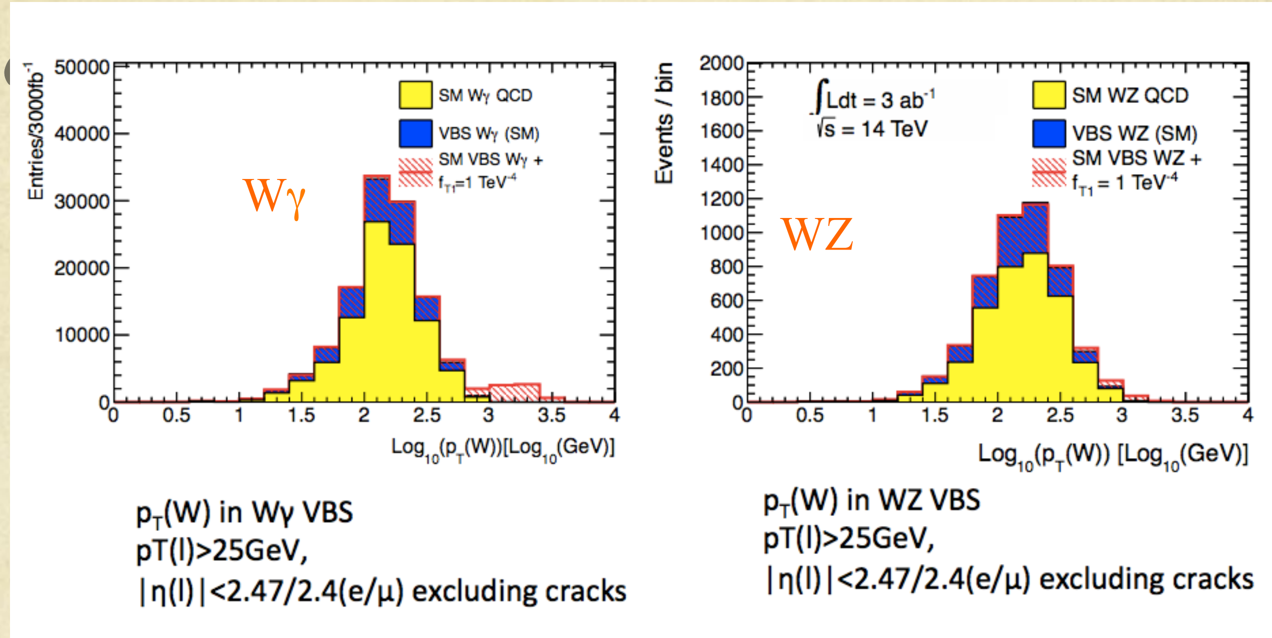
- Require Number of jet >=2
- VBS selection
  - ❑ M(jj)>500GeV
  - ❑ |ΔY(jj)|>2.4

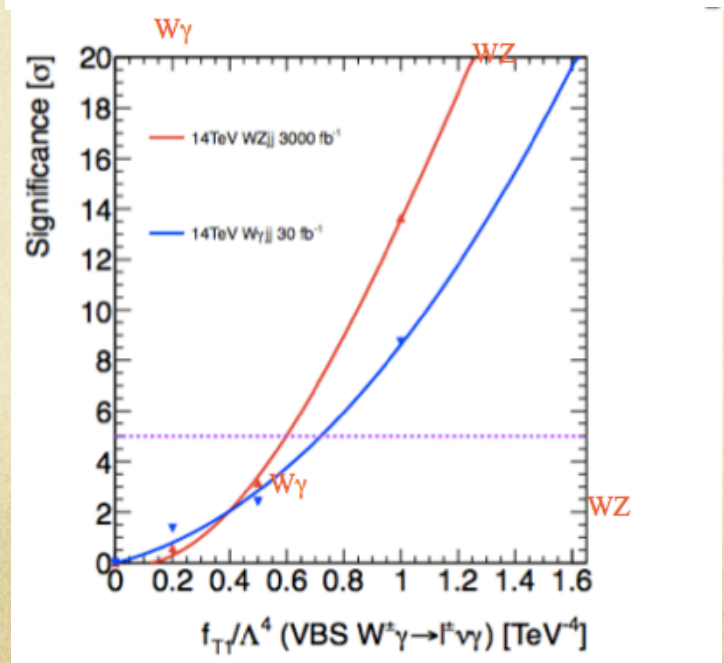


- ➢ On-going study
- ➢ Compared to other diboson VBS channels
  - ➢ 100 times more sensitive to aQGCs

Prospect of Wγjj aQGC sensitivity

Cs





Wγjj VBS process aQGCs sensitivity

- about 100 times more Sensitive than WZjj

Summary of ATLAS electroweak activity

- Precision electroweak measurements
  - First Weinberg angle measurement
  - The best result in hadron collider
- Diboson Cross-section measurements
  - performed in WW,ZZ,WZ,Wγ and Zγ channels
  - Latest 8TeV results Improved accuracy compared to 7TeV
- aTGC measurements show no apparent deviation from SM
- Lots of new measurements are on-going.
  - Diboson VBS process is sensitive to new physics in Higgs sector

backup

Precision electroweak physics
Weinberg angle measurement

- Reminder of Weinberg angle definition:

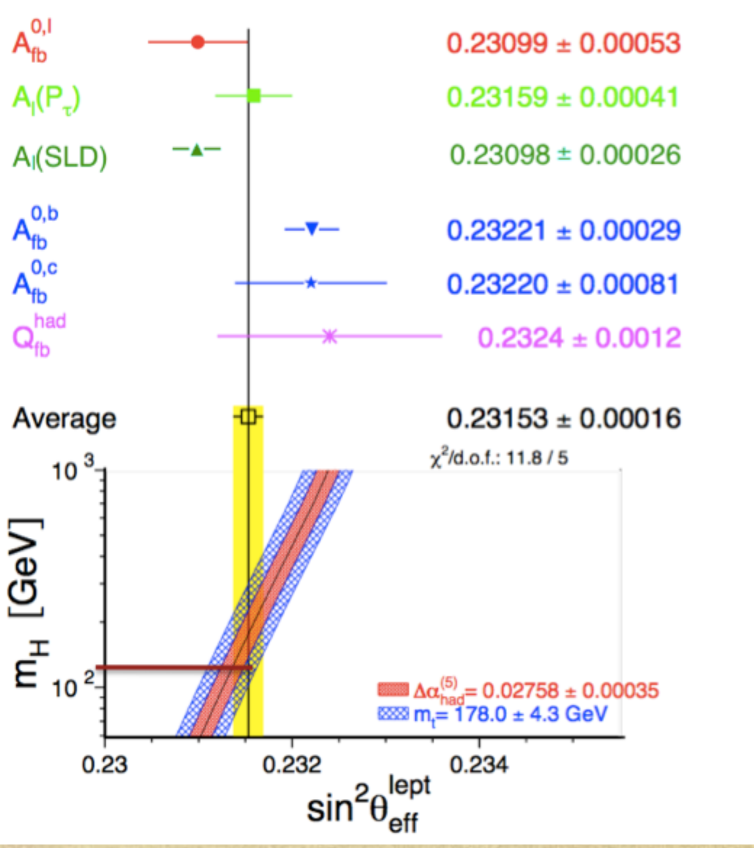
$$\sin^2(\theta_W) = 1 - \frac{m_W^2}{m_Z^2}$$

Experimental observable:

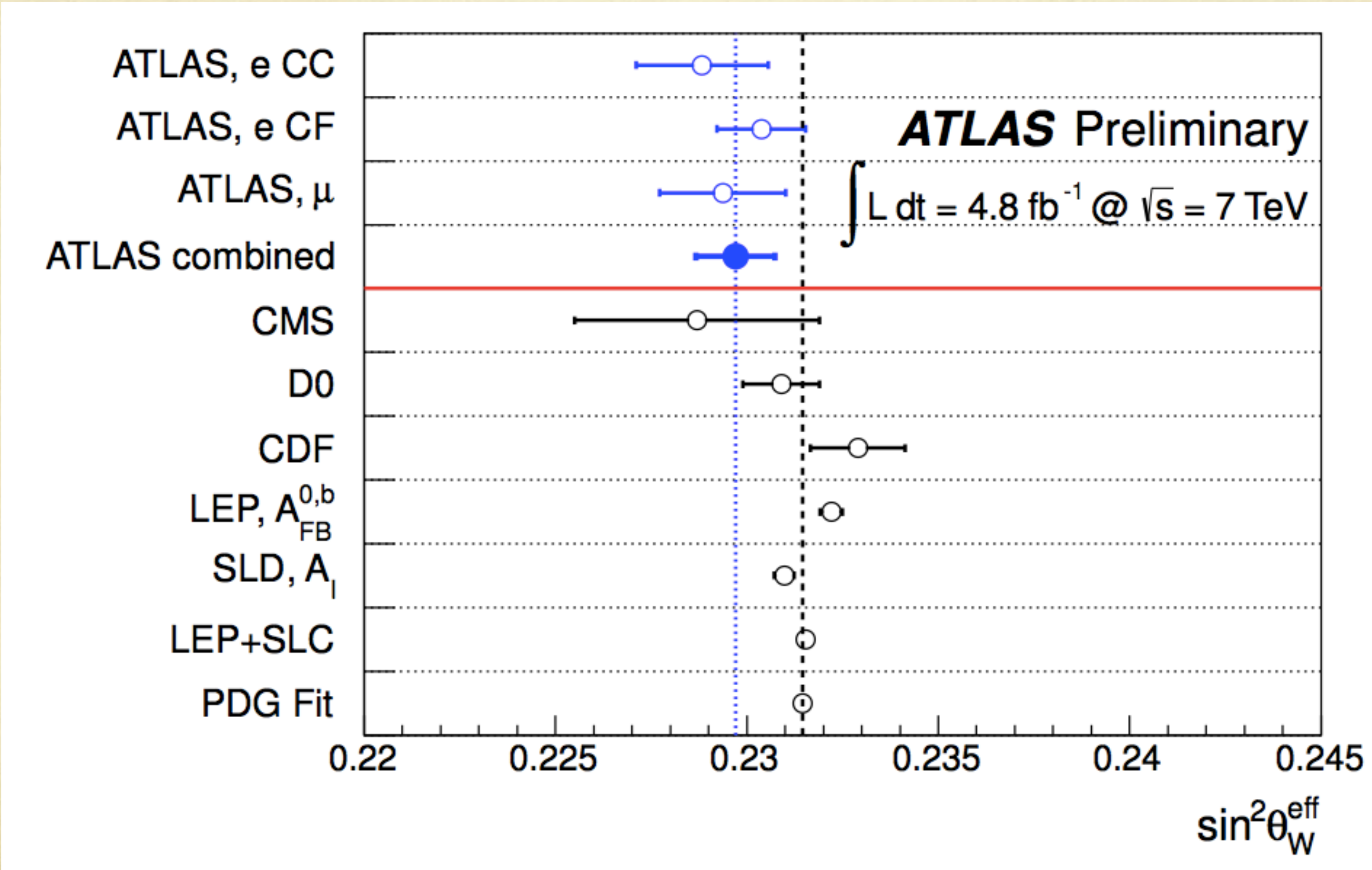
Backward –forward asymmetry in Z

- Precise Weinberg angle measurement constrains the mass of the Higgs boson.

- The largest deviation between the best EWK fit vs. data
  - Tension between LEP and SLD results: ~3σ



Weinberg angle measurement ATLAS Results and World Averages

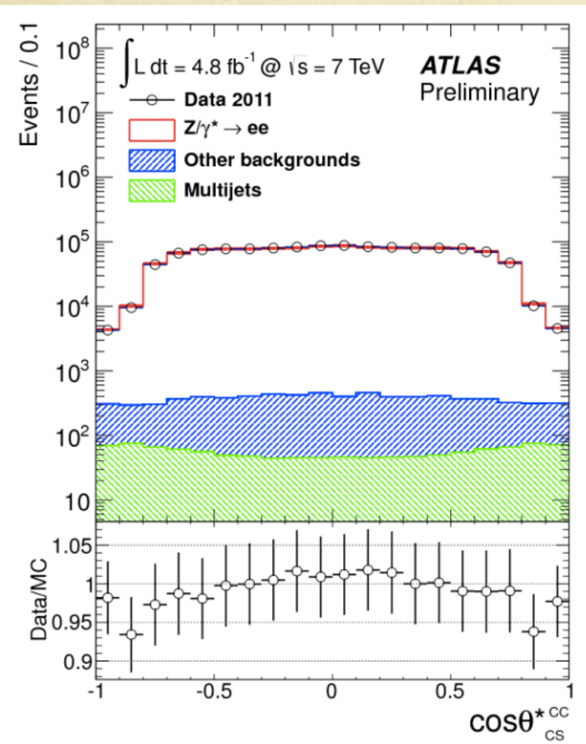


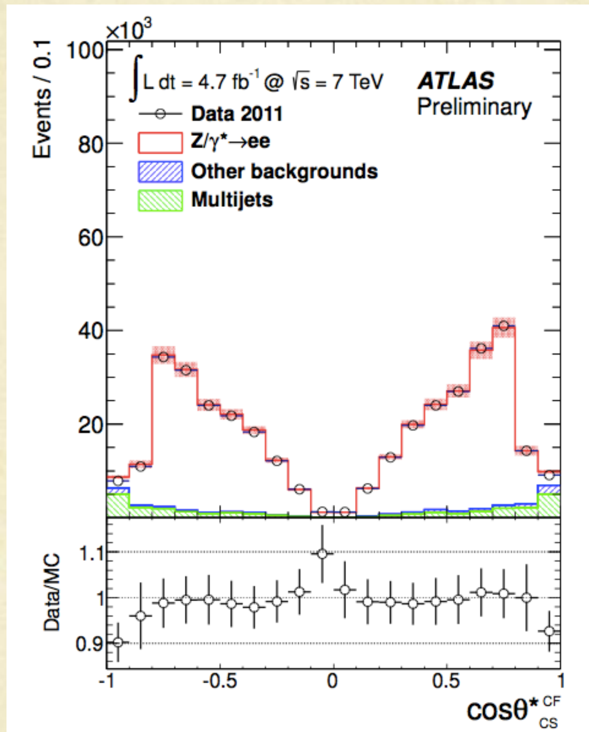
ATLAS-CONF-2013-043

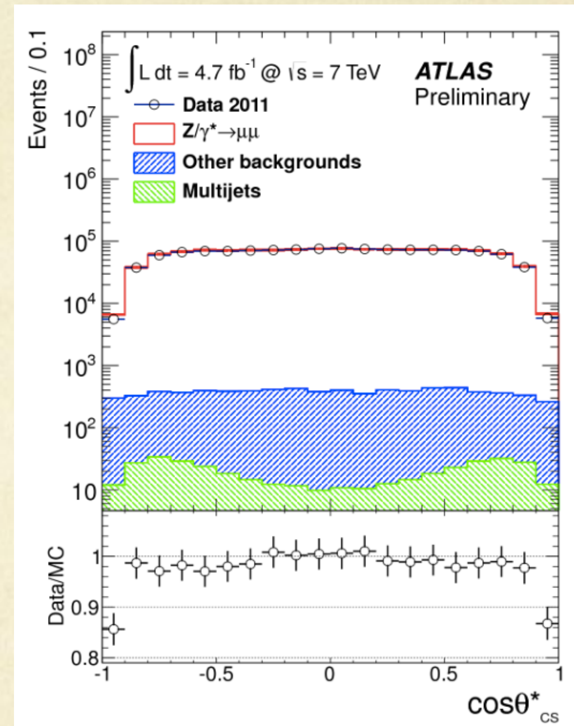
Backward-forward asymmetry in Z

ATLAS-CONF-2013-043

- Central-Central Electron channel
- Central-forward Electron channel
- Central-Central Muon channel







- Central lepton : |η|<2.5
- forward e: 2.5<|η|<4.9

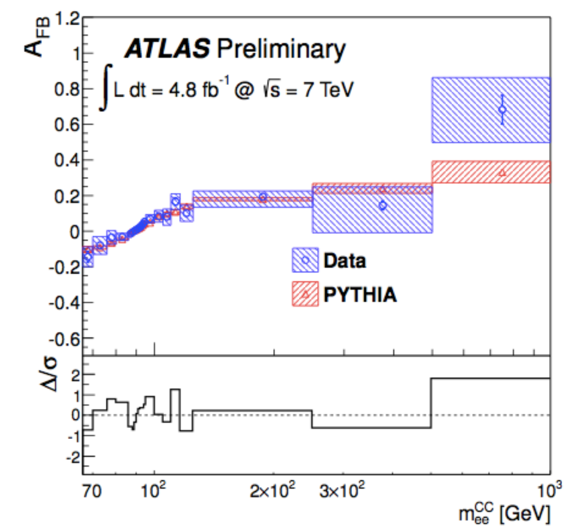
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

cos(θ)>0 → Forward (N_F)
cos(θ)<0 → Backward (N_B)

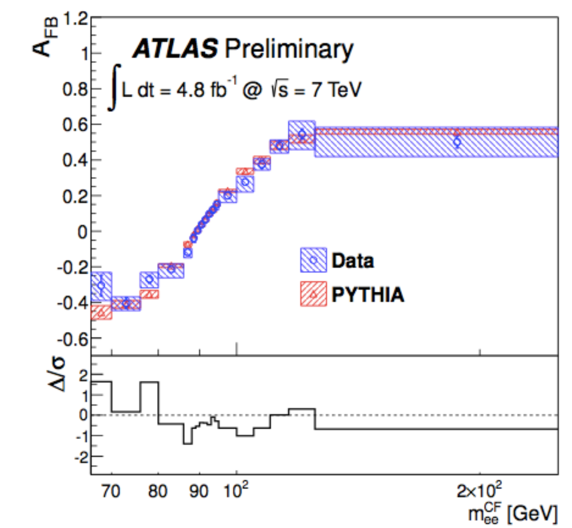
- Asymmetry is more visible in central-forward channel
- less dilution due to unknown incoming quark direction

Unfolded the AFB Spectra

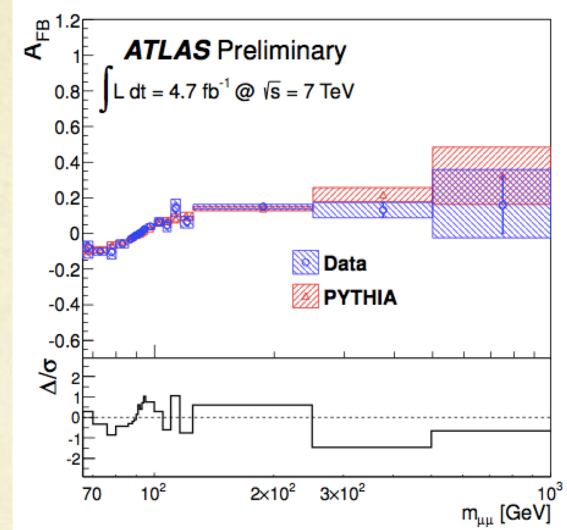
- Central-Central Electron channel



- Central-forward Electron channel



- Central-Central Muon channel



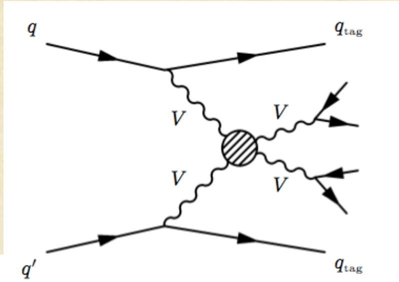
- Unfolded to born level.
  - Compared to LO Pythia prediction

ATLAS-CONF-2013-043

- Correcting for mass bin migration effect.
  - big impact from mass-bin- migration in low mass region

- Not included correction from dilution

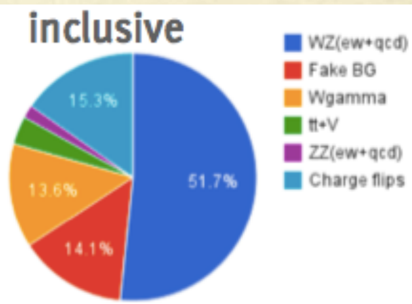
Same sign WW+ dijet VBS

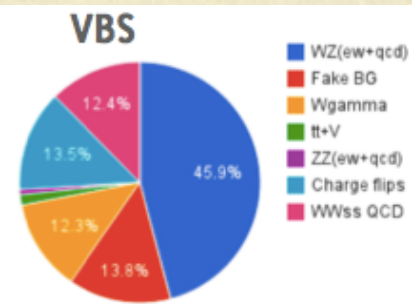


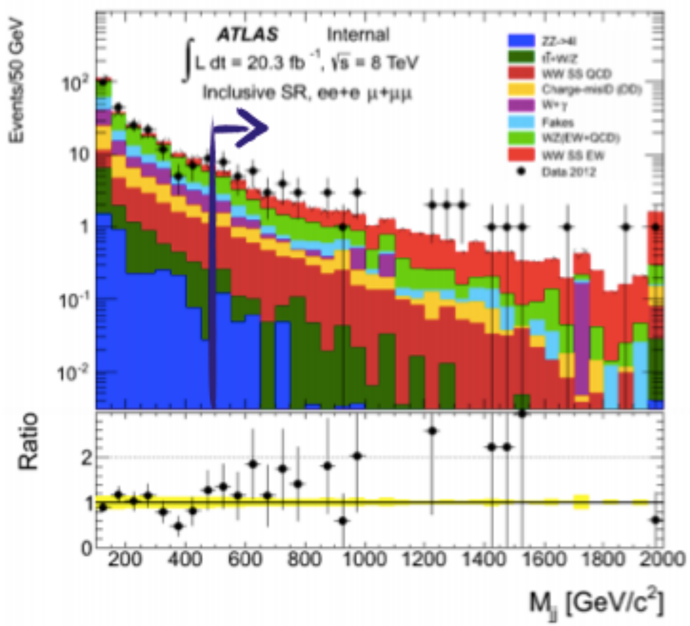
- Single lepton trigger
- Two same sign leptons with pT>25GeV
- MET>40GeV
- Two jets with pT>25GeV and m(jj)>150GeV

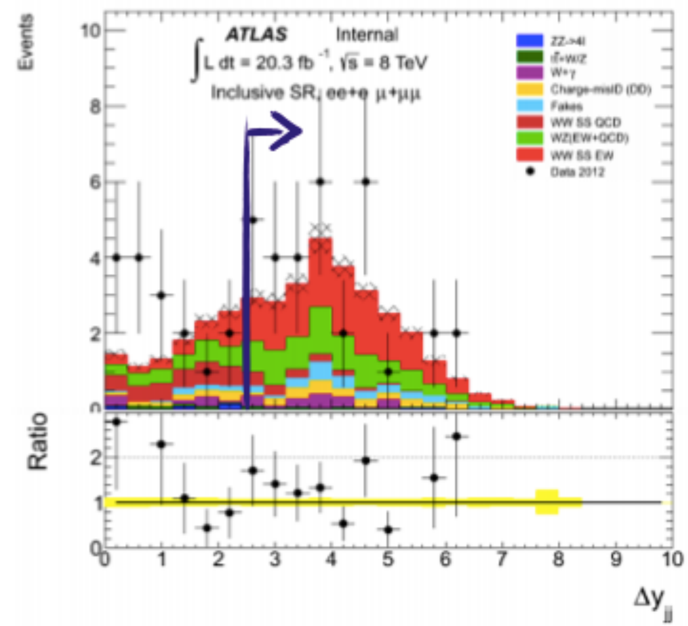
Events selected with

- $|M_{jj}|$ > 500 GeV → best sensitivity to inclusive WWjj ~48 signal events
- $|\Delta y_{jj}|$ > 2.4 → isolate EW component ~32 signal events



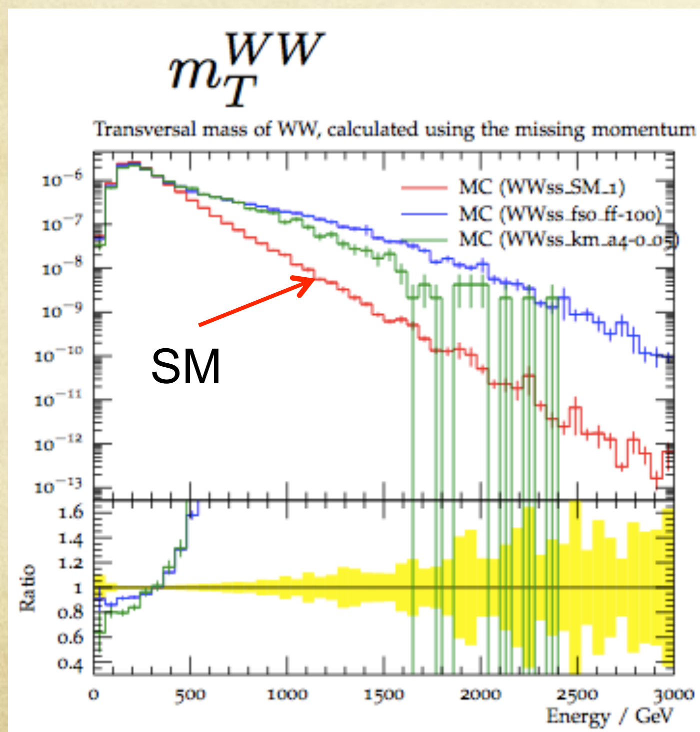


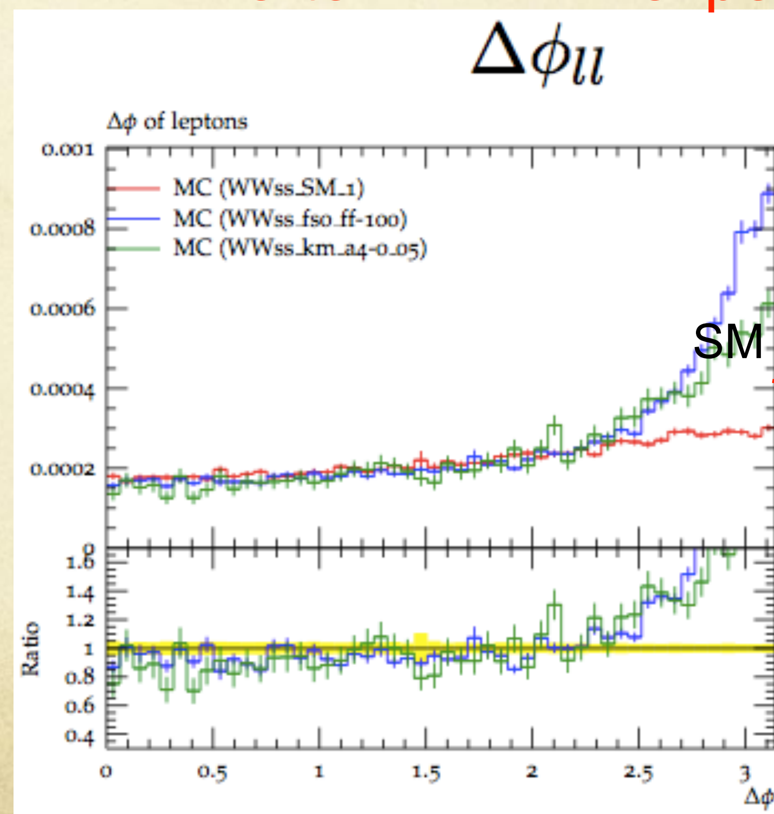




QGC in Same sign WW (W^+W^+jj or W^-W^-jj)

- Use W^+W^+/W^-W^- kinematics to study WWWW vertex
  - m_T^{WW} and $\Delta\Phi(l,l)$ are more sensitive
  - Dijet system kinematics (m(jj)) is less sensitive
- First aQGC limits on WWWW vertex in HEP experiment





Event selection

- Zγ ($l^+l^-\gamma$) Selection highlight
  - ❑ 2 high pT lepton with pT>25GeV
  - ❑ M(l^+,l^-)>40 GeV
  - ❑ One isolated photon with pT>15GeV
  - ❑ Major background
    - ❑ Z+jet : jet faking photon

- Wγ (lvγ) Selection highlight
  - ❑ One high pT lepton with pT>25GeV
  - ❑ E_T^{miss}>35 GeV
  - ❑ One isolated photon with pT>15GeV
  - ❑ Major background
    - ❑ W+jet : jet faking photon
    - ❑ γ+jet: jet faking lepton

Latest ATLAS Vγ publication:
4.6 fb^{-1}, 7 TeV
Phys. Rev. D 87, 112003 (2013)

- Zγ (vvγ) Selection highlight
  - ❑ E_T^{miss}>90GeV
  - ❑ One isolated photon with pT>100GeV
  - ❑ Veto event with good lepton
  - ❑ Major background
    - ❑ Z(vv)+jet : jet faking photon
    - ❑ W+jet : electron faking as photon
    - ❑ Wγ

Summary

- Wγ/Zγ Differential cross section measurements
  - The shapes agree better with Alpgen/Sherpa predictions
  - Observe discrepancy with MCFM in high ET region of inclusive Wγ events
- Wγ/Zγ Narrow resonance search
  - First narrow resonance search using Wγ final state in all HEP experiments
  - Most stringent narrow resonance search in Zγ
- Wγjj/Zγjj vector boson scattering study
  - Wγ/Zγ VBS is likely to be one of the first VBS measurements.
  - Important steps to understand the underlying mechanism in EWSB

Detector experience

- Detector experience:
  - SCT : Laser alignment , readout timing calibration
  - LAr : Electronic calibration
  - TileCal: 2004 combined test beam analysis

Fiducial phase space

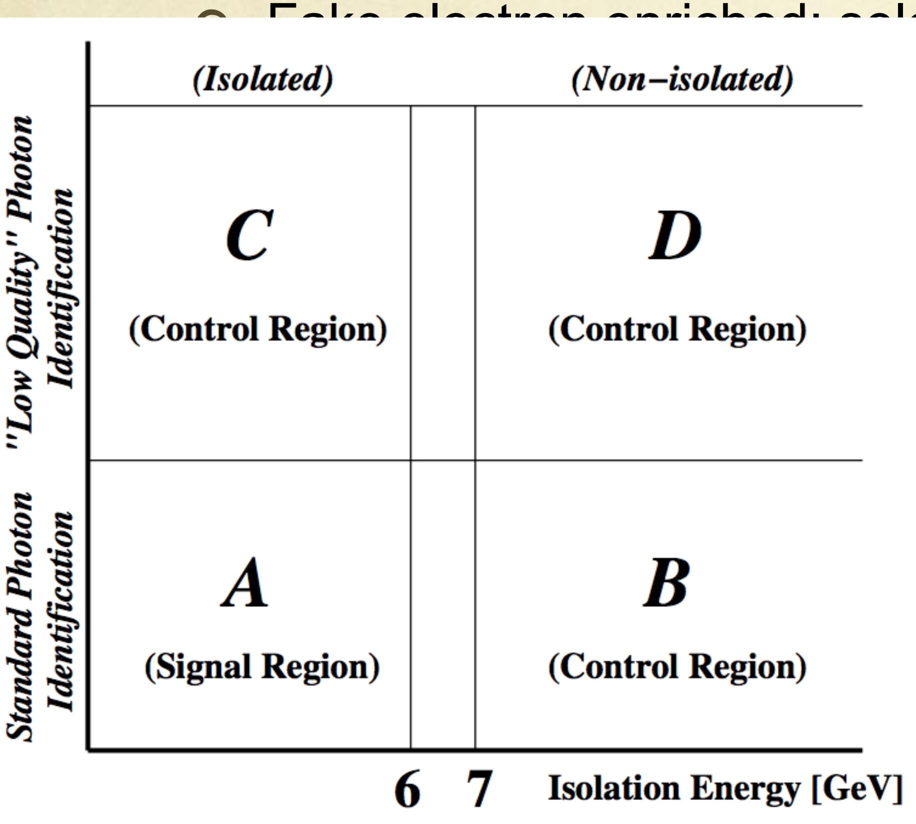
Cuts	$pp \to \ell\nu\gamma$	$pp \to \ell^+\ell^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Lepton	$p_{\mathrm{T}}^{\ell} > 25$ GeV	$p_{\mathrm{T}}^{\ell} > 25$ GeV	—
	$\lvert\eta_\ell\rvert < 2.47$	$\lvert\eta_\ell\rvert < 2.47$	—
	$N_\ell = 1$	$N_{\ell+} = 1, N_{\ell-} = 1$	$N_\ell = 0$
	$p_{\mathrm{T}}^{\nu} > 35$ GeV	—	—
Boson	—	$m_{\ell+\ell-} > 40$ GeV	$p_{\mathrm{T}}^{\nu\bar{\nu}} > 90$ GeV
Photon	$E_{\mathrm{T}}^{\gamma} > 15$ GeV	$E_{\mathrm{T}}^{\gamma} > 15$ GeV	$E_{\mathrm{T}}^{\gamma} > 100$ GeV
	$\lvert\eta^\gamma\rvert < 2.37$, $\Delta R(\ell,\gamma) > 0.7$		
	$\epsilon_h^p < 0.5$		
Jet	$E_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV, $\lvert\eta^{\mathrm{jet}}\rvert < 4.4$		
	$\Delta R(e/\mu/\gamma, \mathrm{jet}) > 0.3$		
	Inclusive : $N_{\mathrm{jet}} \geq 0$, Exclusive : $N_{\mathrm{jet}} = 0$		

Systematic Uncertainties

- Major experimental systematics
  - Photon Identification uncertainty : 5%
  - Photon isolation efficiency : 2~3%
  - EM scale and resolution: 2~3%
  - Jet energy scale (3% for exclusive measurement)

Background

- Fake photons (or fake lepton) background estimated from isolation shape of signal candidates.
  - Background shapes are taken from background enriched region (C,D)
    - Fake photon enriched: select shower shape similar to $\pi^0 \rightarrow 2\gamma$
    - Fake electron enriched: select candidates without TRT high
    - dates with large impact parameter

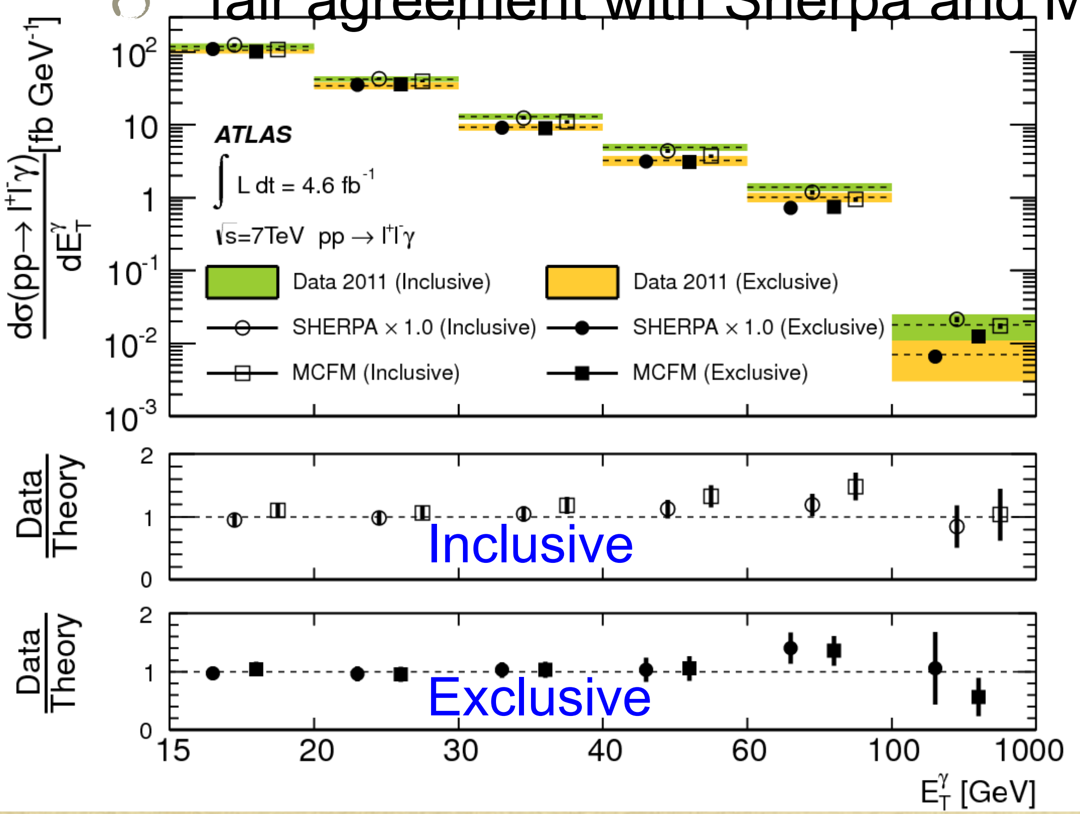


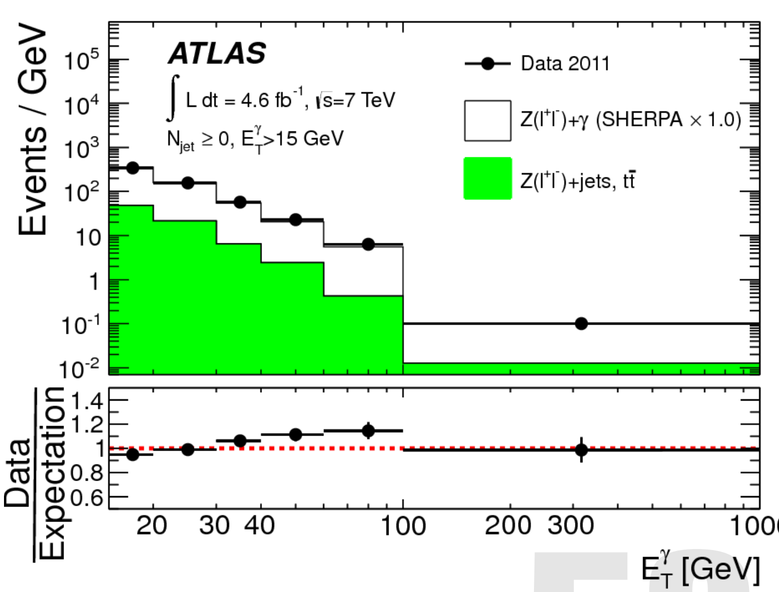
Wγ background

	$e\nu\gamma$	$\mu\nu\gamma$
	$N_{\rm jet} \geq 0$	
$N_{W\gamma}^{\rm obs}$	7399	10914
$W(\ell\nu)$+jets	$1240 \pm 160 \pm 210$	$2560 \pm 270 \pm 580$
$Z(\ell^+\ell^-) + X$	$678 \pm 18 \pm 86$	$779 \pm 19 \pm 93$
γ+jets	$625 \pm 80 \pm 86$	$184 \pm 9 \pm 15$
$t\bar{t}$	$320 \pm 8 \pm 28$	$653 \pm 11 \pm 57$
other background	$141 \pm 16 \pm 13$	$291 \pm 29 \pm 26$
$N_{W\gamma}^{\rm sig}$	$4390 \pm 200 \pm 250$	$6440 \pm 300 \pm 590$

$Z\gamma$ ($l^+l^-\gamma$): photon E_T spectrum

- First Zγ differential measurement:
  - Photon E_T , jet multiplicity and Zγ mass spectrum
- Photon E_T measurements
  - fair agreement with Sherpa and MCFM NLO predictions.





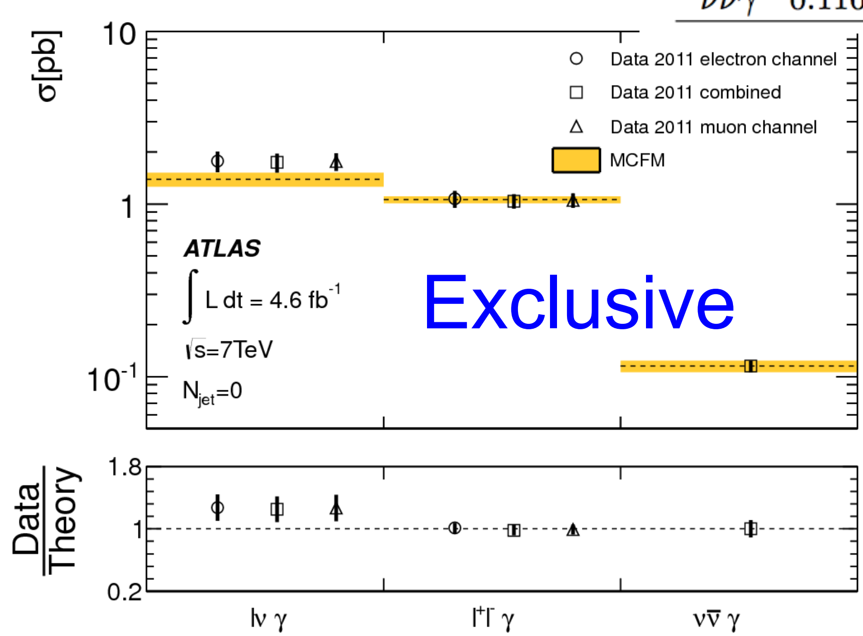
Inclusive

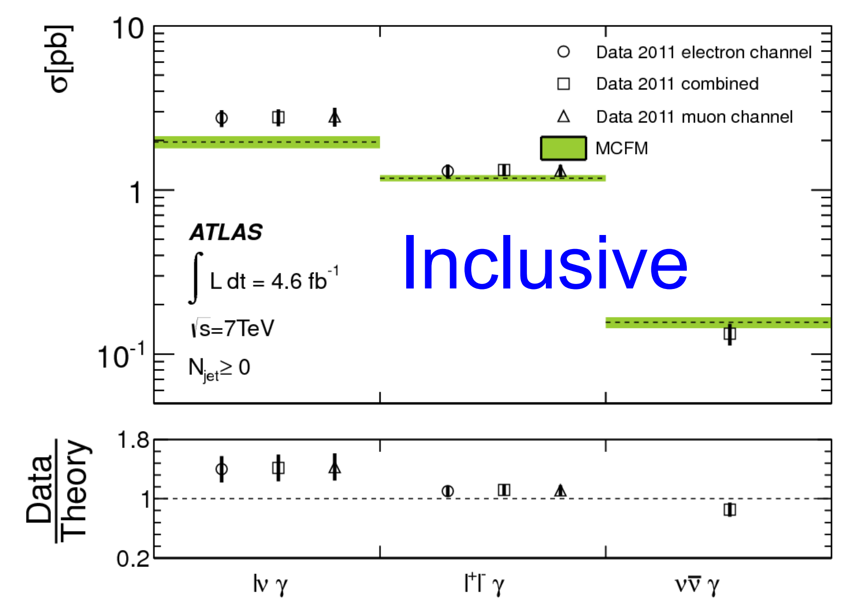
Integrated cross section measurement

- Measurement vs MCFM NLO predictions :
  - Inclusive Wγ measurement is about two sigma above predictions
  - Agreement is improved for exclusive Wγ measurement (with jet veto)

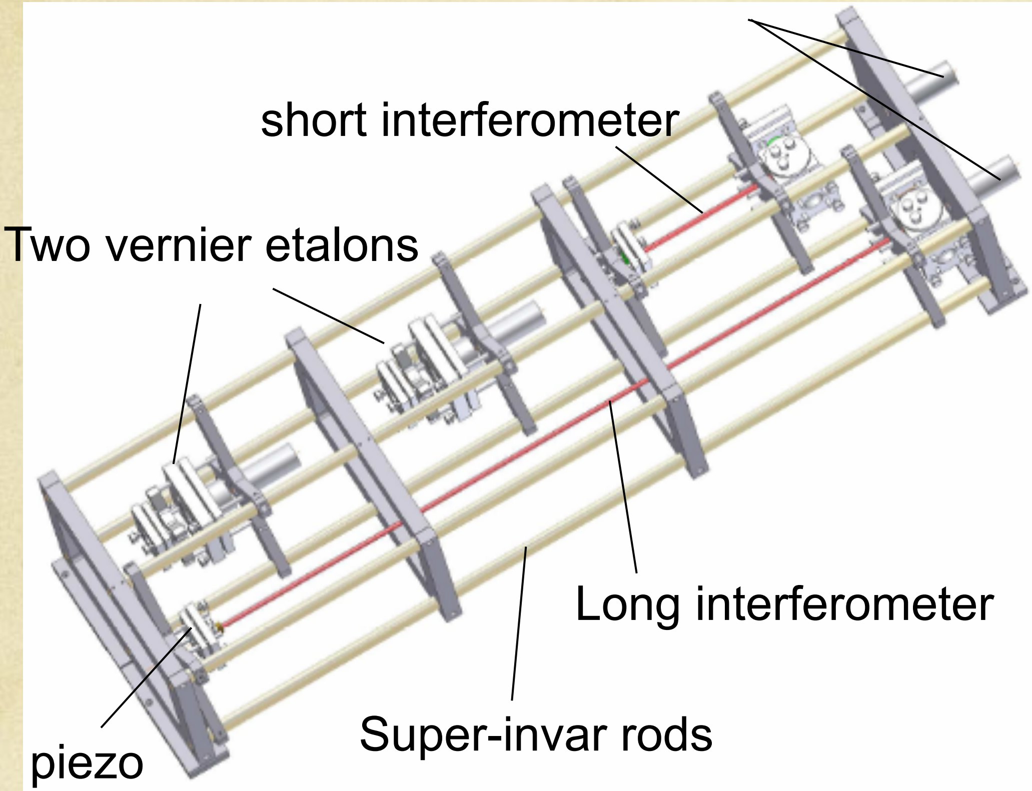
Fiducial cross section:

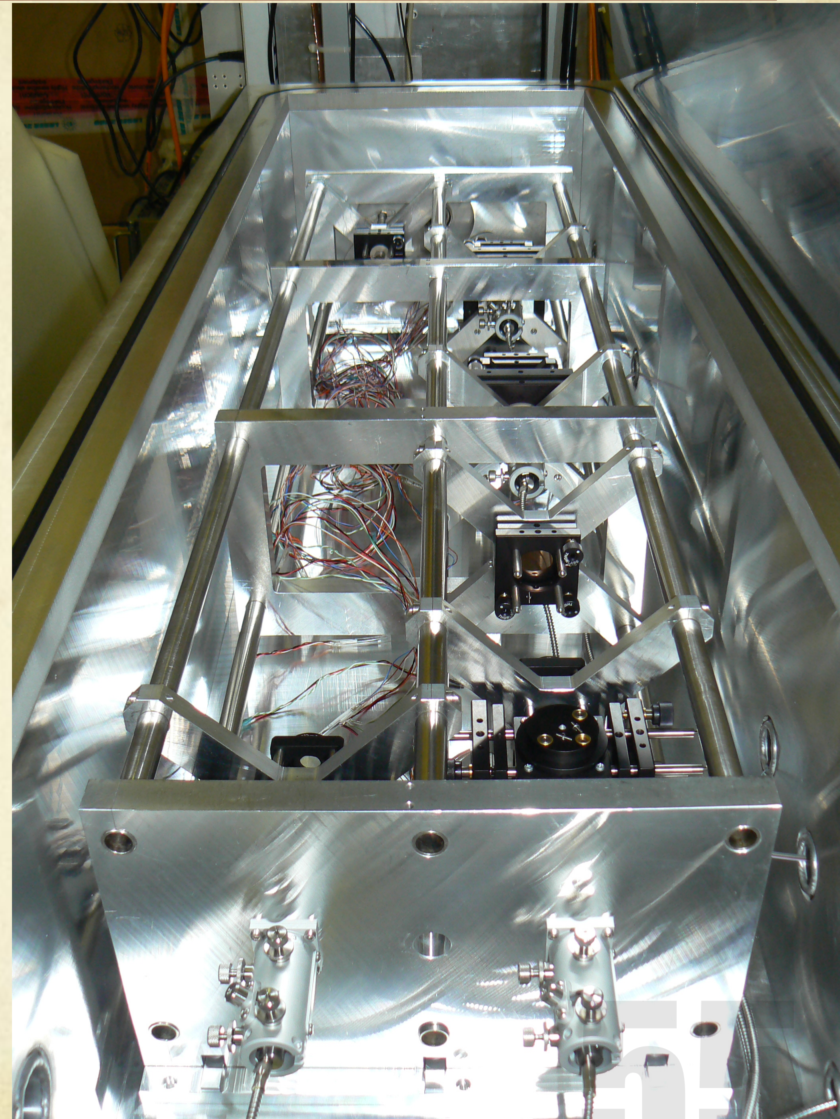
	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{\text{jet}} = 0$	
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009





Reference Interferometry System

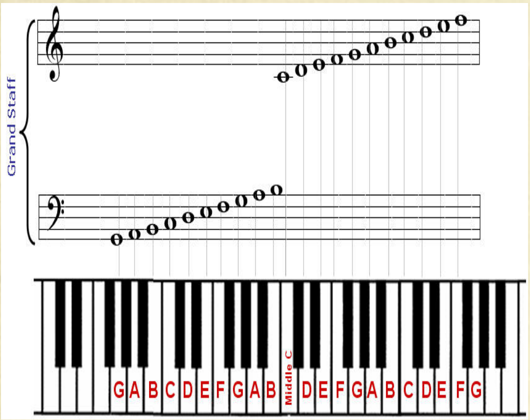




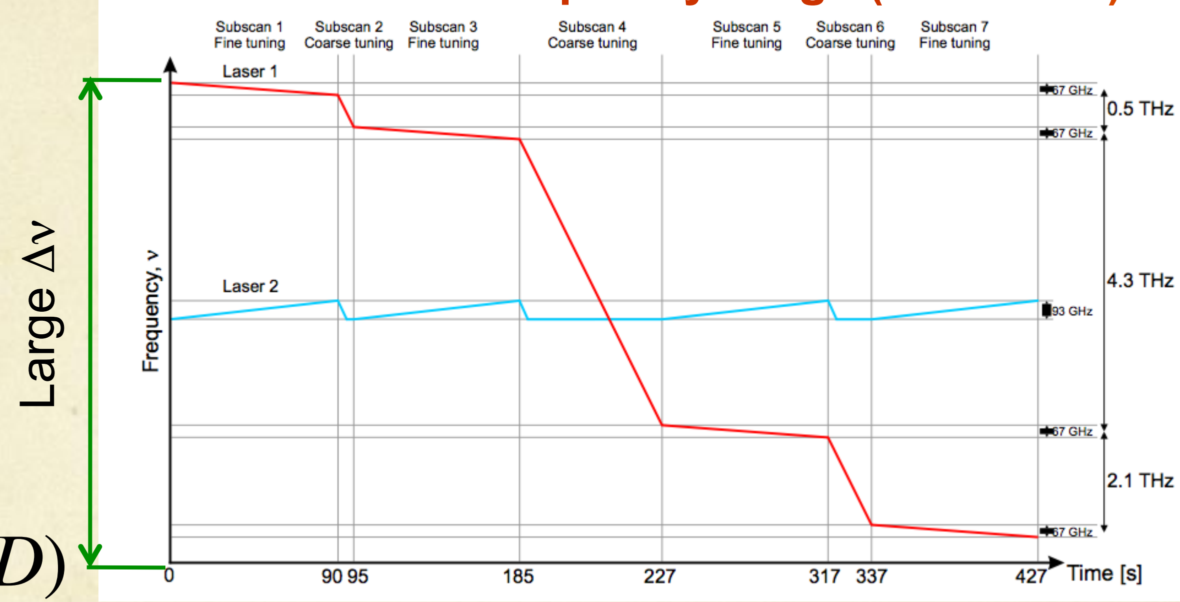
- Fibre collimators provides low M^2 beam.
- Super-invar / steel thermally compensating design to balance CTEs. $\Delta T(C_1L_1 - C_2L_2) = 0$.
- Both interferometers have four-fibre read-out for instantaneous phase measurement.
- Long reference has piezo for phase stepping.

Conventional FSI for absolute distance measurement

Like a long musical scale



Scan a LARGE frequency range (Δν~10THz):



$$\Delta\theta_{GLI} = \frac{2\pi}{c}(D\Delta\nu + \nu\Delta D)$$

- Measure absolute length D every 8 minutes. (wrt reference)
- νΔD term is cancelled using two lasers and a wavemeter.

Pros:

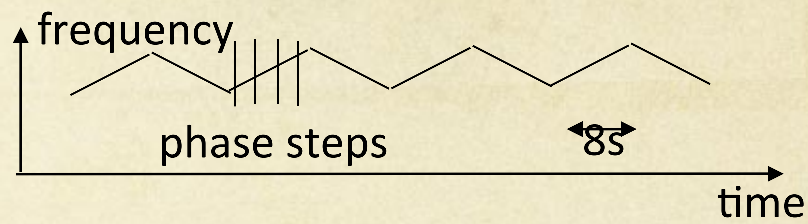
- Precise absolute measurement, D.
- Can power cycle laser without loss of precision.
- Excellent for long term monitoring.

Cons:

- Need large Δν & two lasers to reduce systematic errors arising from ΔD.
- Slow, about 8 minutes per measurement.
- Remaining errors are largest when the components are moving: limits resolution during interesting rapid events.

Laser alignment principle

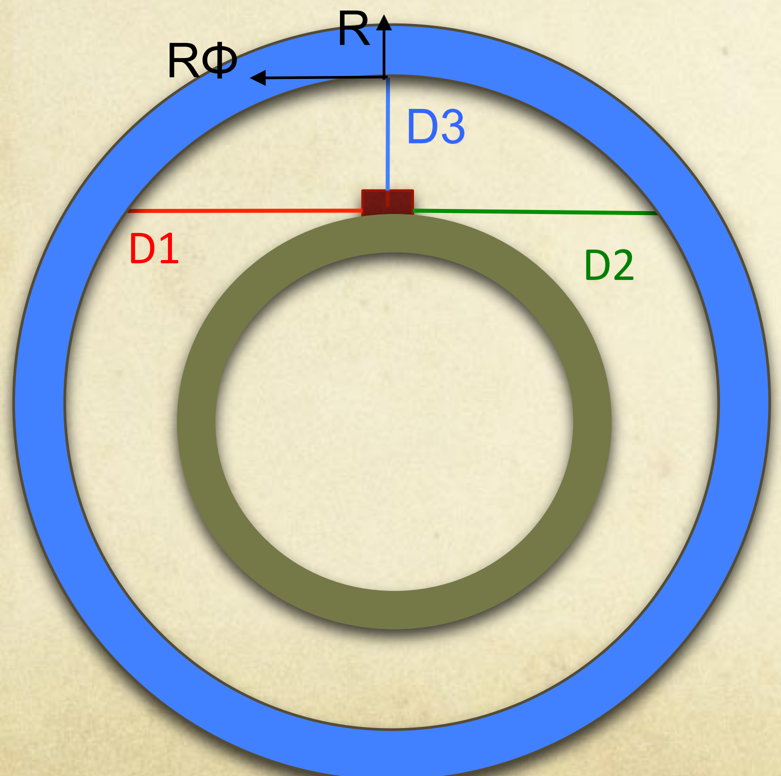
One 8s ramp of the laser frequency generates fringes in all grid line interferometers.
The instantaneous phase is measured.

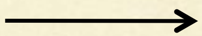


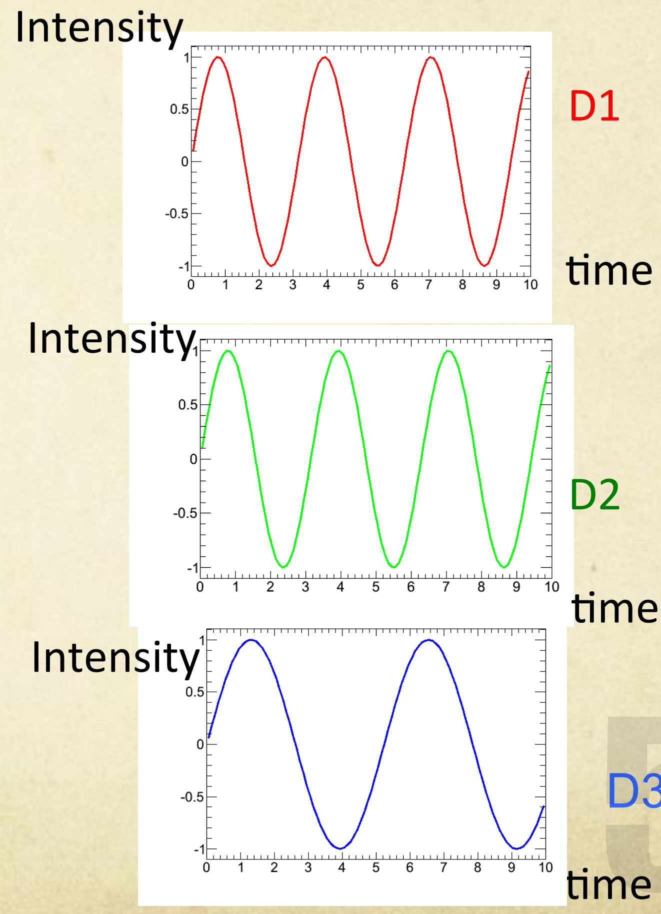
Grid line D1 monitors the positive RΦ direction

Grid line D2 monitors the negative RΦ direction

Grid line D3 monitors the positive R direction

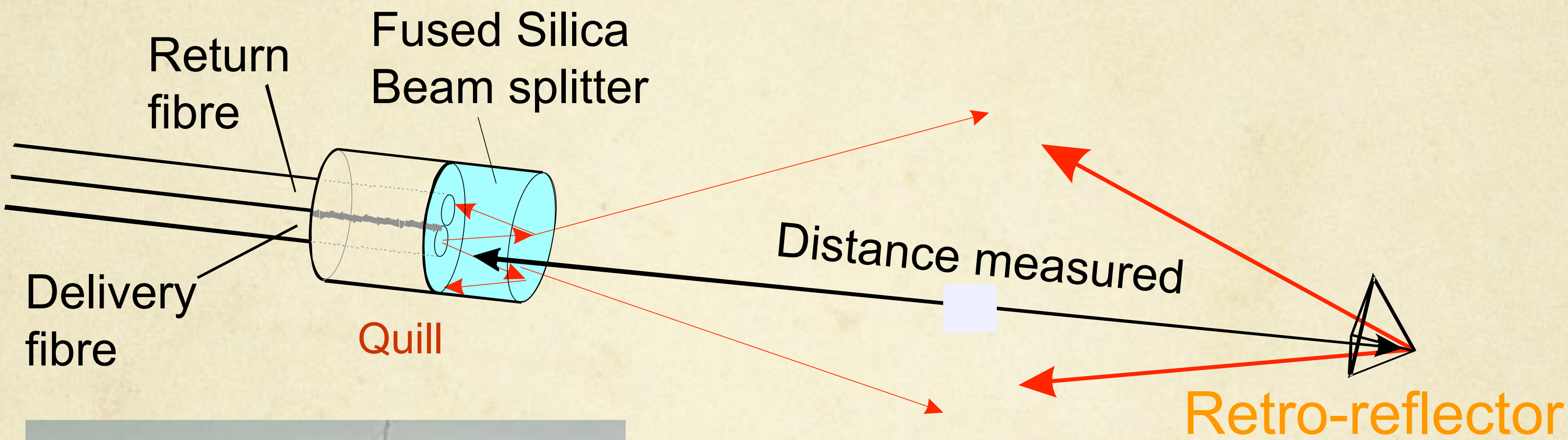






Grid Line Interferometer (GLI)

- Each length measurement line of the alignment grid inside the SCT consists of a quill (two parallel fibres and a beam splitter) and a retro-reflector.
- The optical path difference is measured. GLI lengths range from 40mm to 1500mm.

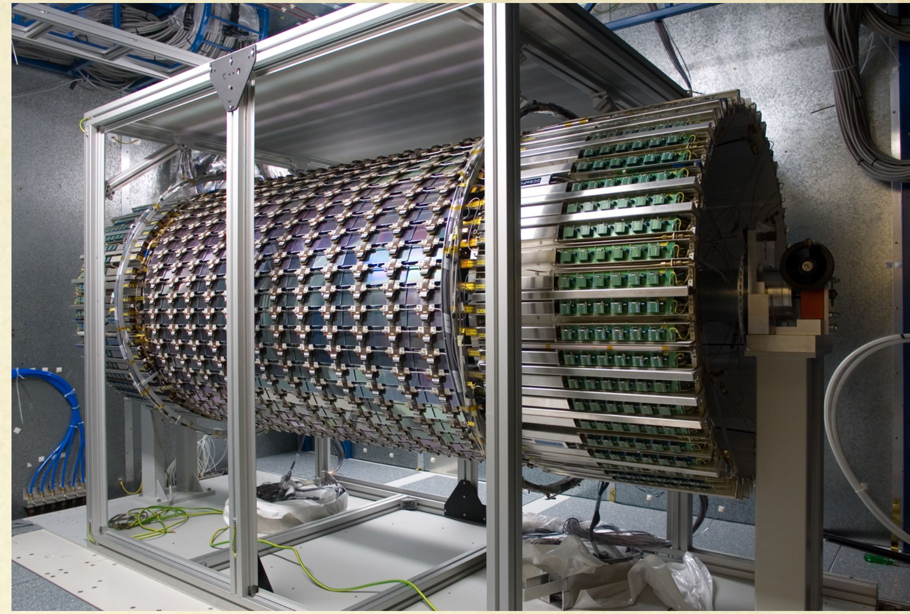


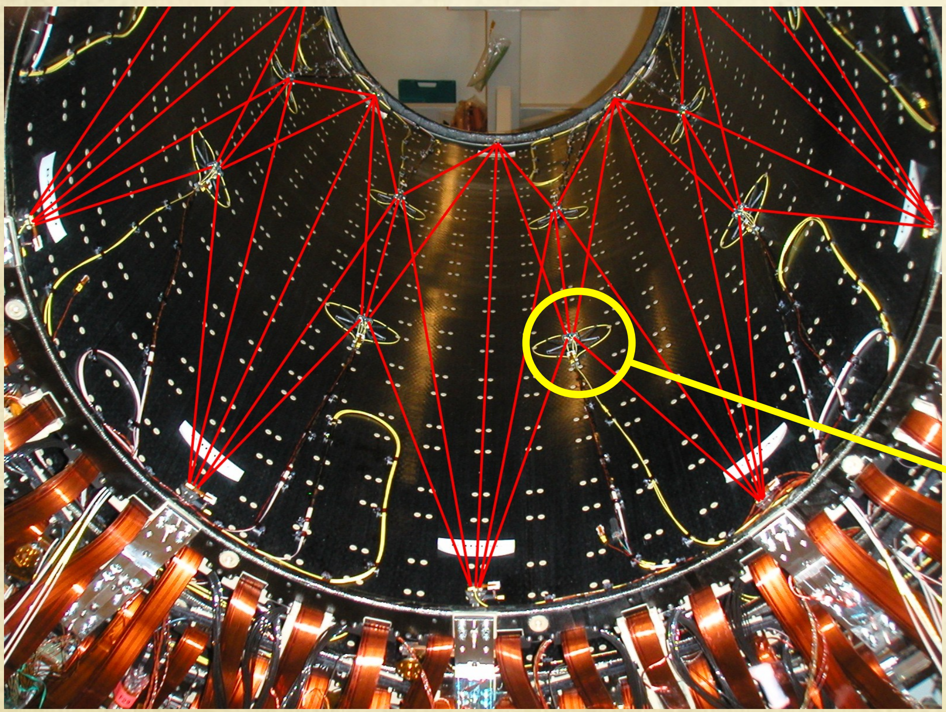
2.3 mm diameter

Frequency Scanning Interferometry

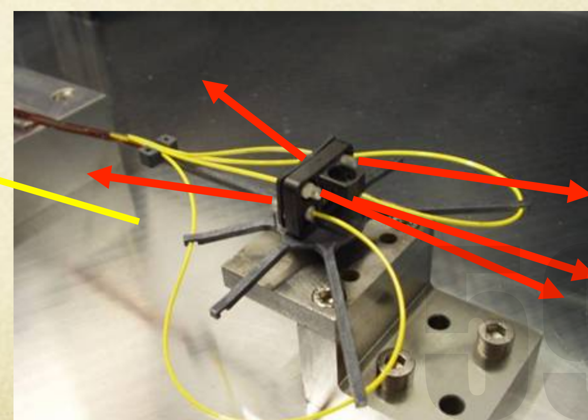
FSI alignment system: 842 simultaneous micron precise distance measurements between grid nodes attached to SCT.

Repeated grid measurements monitor shape *changes* of the SCT.





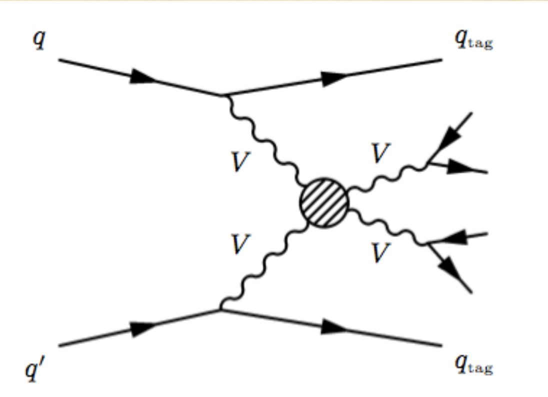
Barrel FSI grid node



Vector boson scattering (VBS)

- the scattering of longitudinally polarized vector bosons
  - violates unitarity at ~1TeV without higgs
- Important to check
  - whether Higgs boson unitarizes it fully or only partially

$O(\alpha^6_{EW})$



- The first VBS analysis :Same sign WW
  - Sensitive to WWWW vertex
  - Final state: W^+W^+jj or W^-W^-jj
  - Two type of diagram
    - $O(\alpha^6_{EW})$: including VBS, name it VVjj-EW
    - $O(\alpha^4_{EW}\alpha^s_s)$: $O(\alpha_s) = 2 \otimes O(\alpha_{EW}) = 4$, name it VVjj-QCD

$O(\alpha^4_{EW}\alpha^s_s)$