Recent Highlights of SM Z/γ^* production with the ATLAS Experiment

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on behalf of the ATLAS Collaboration

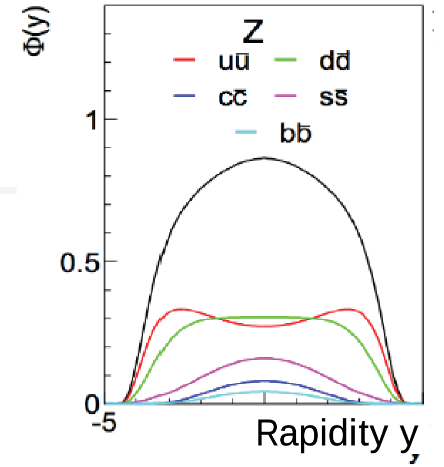
Z/γ^* production in ATLAS at $\sqrt{s}$=8, 13 TeV

- Z 3D differential cross sections
- New: $\sin^2\theta^{\ell}_{\mathrm{eff}}$ from angular coefficient A_4
- τ polarisation in $Z/\gamma^* \rightarrow \tau\tau$ decays
- New: $Z\gamma \rightarrow \nu\nu\gamma$ cross section at 13 TeV

ICHEP, July 2018

Drell–Yan triple-differential cross section at √s=8TeV - I

JHEP 12 (2017) 059



- At LO electroweak and perturbative QCD theory 3D Z cross section:

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q \boxed{P_q}\left[\boxed{f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2)} + (q \leftrightarrow \bar{q})\right]$$

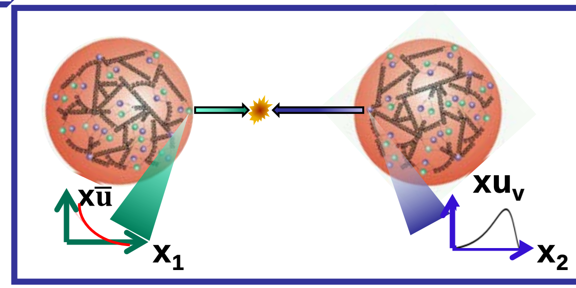
$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$$

(θ^*: decay angle in CS frame)

V-A lepton&quark couplings, $\sin^2\theta_W$

$$\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$

PDF

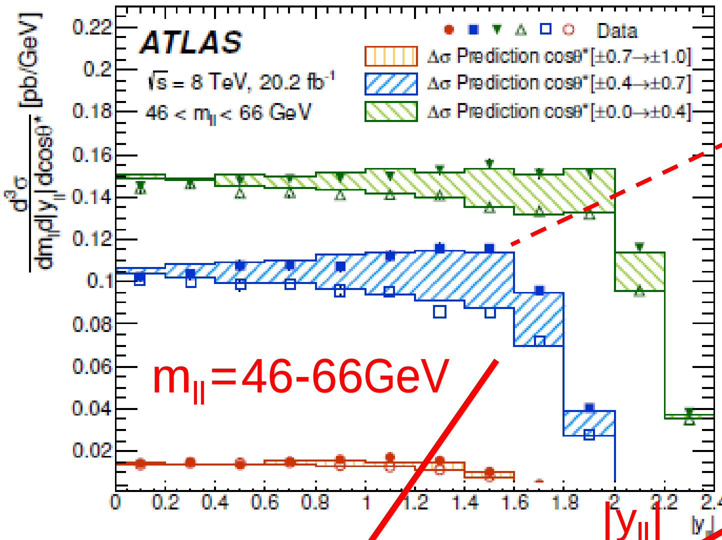


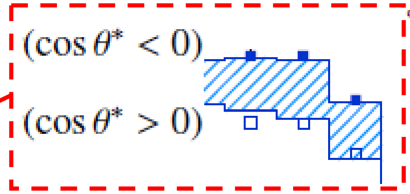
- Sensitivity of cross section to PDFs mainly from $y_{\ell\ell}$ dependence: important to know PDFs!
- Terms linear in cos θ induce forward-backward asym A_{FB} (parity violation): access to $\sin^2\theta_W$
- Differential cross section in 654 bins of $m_{\ell\ell}$ (46 to 200GeV) x $|y_{\ell\ell}|$ (0 to 3.6) x $\cos\theta^*$ (-1 to +1)
- Unfolded with Bayesian method corrected to born level
- Systematic uncertainties classified as correlated or uncorrelated between bins and propagated

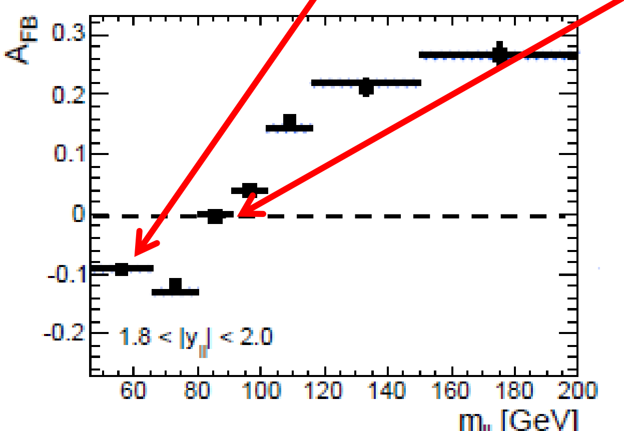
Drell–Yan triple-differential cross section at $\sqrt{s}$=8TeV - II

20.2 fb^{-1}

Triple-diff σ in ($m_{\ell\ell}$ bins)







$$A_{\rm FB} = \frac{\mathrm{d}^3\sigma(\cos\theta^* > 0) - \mathrm{d}^3\sigma(\cos\theta^* < 0)}{\mathrm{d}^3\sigma(\cos\theta^* > 0) + \mathrm{d}^3\sigma(\cos\theta^* < 0)}$$

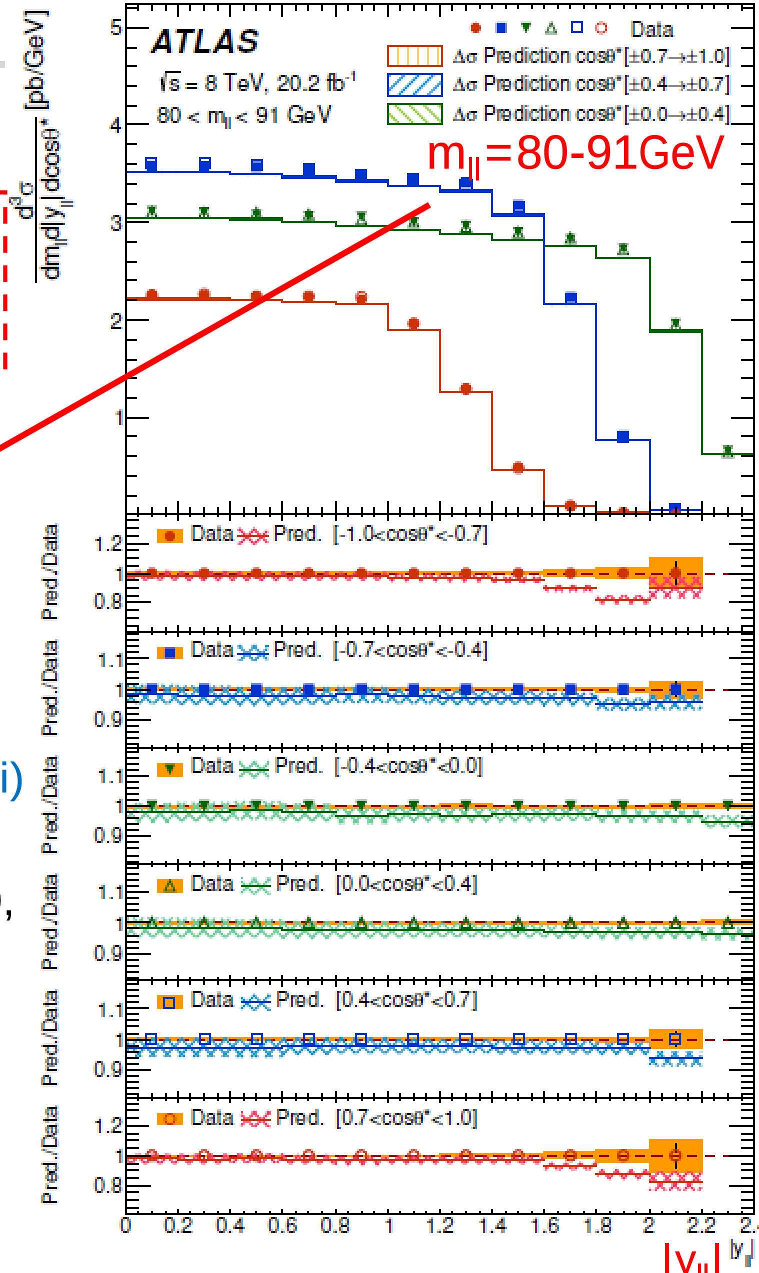
Cross section very precise near pole: <1% (without lumi)

Low and high $m_{\ell\ell}$:

- Large cosθ*>0, cosθ*<0 asym
  - **A_{FB}**

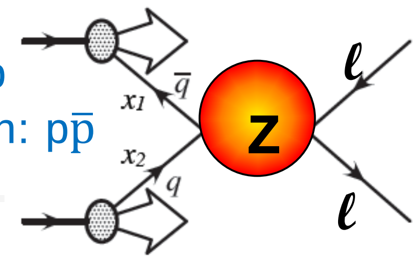
Next steps:

- PDFs
- Extract $\sin^2\theta_W$



Z production / decay angular Coefficients: pp $\rightarrow Z(/\gamma^*) \rightarrow \ell\ell$, 8TeV

LHC: pp
Tevatron: $p\bar{p}$



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- Initial-state parton, final-state lepton spin correlations carry info about Z polarisation
- 5D differential cross section can be decomposed as 1+8 harmonic polynomials $P_i(\cos\theta, \varphi)$, dependent on lepton polar θ, azimuthal φ multiplied by dimensionless angular coefficients $A_i(p_T^Z, y^Z, m^Z)$ that depend on Z kinematics p_T^Z, y^Z , m^Z

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \left\{(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T^Z, y^Z, m^Z) \cdot P_i(\cos\theta, \varphi)\right\}.$$

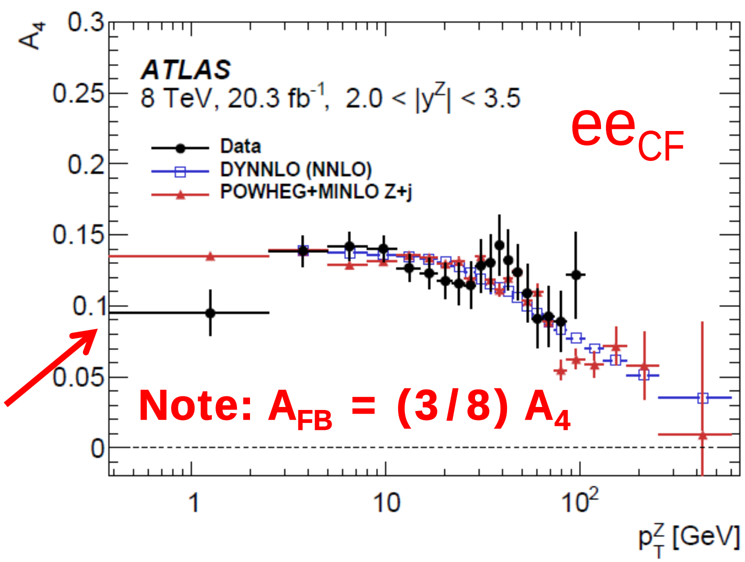
A_i	Couplings	Non-zero
A_3	$(v_l\ a_l) \cdot (v_q\ a_q)$ ~ $\sin^2\theta_W$	$\mathcal{O}(\alpha_S^1)$
A_4		$\mathcal{O}(\alpha_S^0)$

- Z production dynamics factorised from Z decay kinematics
- A_4 (and A_3) sensitive to $\sin^2\theta_W$ but strongly reduced

at LHC due to lack of knowledge of parent quark direction

- Sensitivity reduction strongest at low values of $|y^Z|$
  - enhanced importance for production at high $|y^Z|$

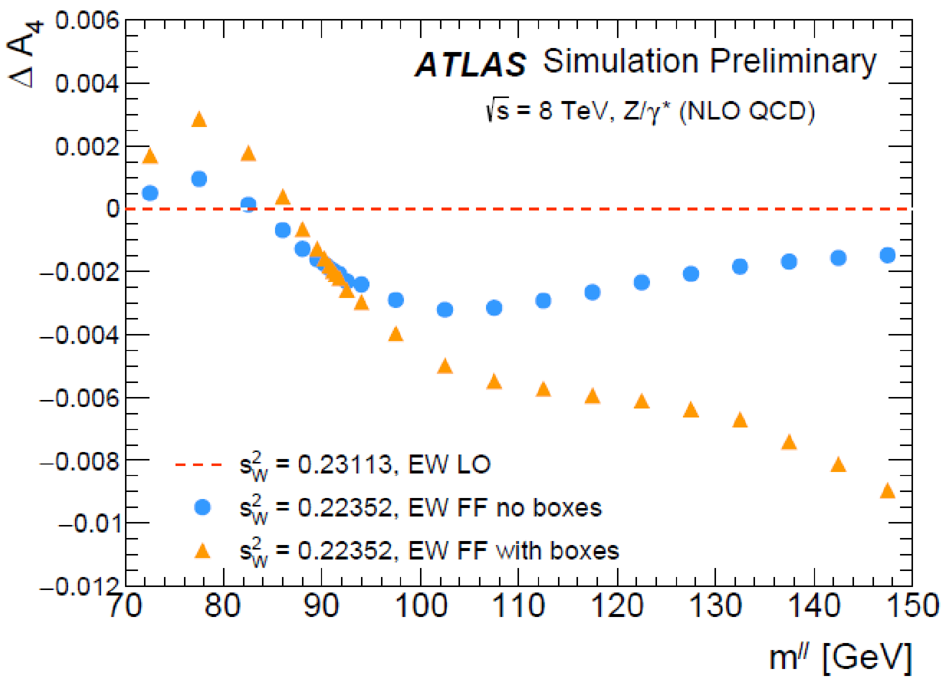
- Follow up: A_i ATLAS publication at $\sqrt{s}$=8TeV, 20.2fb^{-1}
- ee, μμ final states in 8x8 bins of $(\cos\theta, \varphi)$
  - CC: two leptons p_T^l >25GeV in Central $|\eta_\ell|$<2.4
  - CF: Central e + Forward e (p_T^l>20GeV, $|\eta_\ell|$>2.5)
    - ➢ Unique reach adds sensitivity to $\sin^2\theta_W$!



Measurement of $\sin^2\theta^{\ell}_{\rm eff}$ at $\sqrt{s}$=8TeV: EW corrections

ATLAS-CONF-2018-037

- Hadron colliders tools for $\sin^2\theta^{\ell}_{\rm eff}$: simulate in a LO EW scheme in effective Born approx. for given $\sin^2\theta^{\ell}_{\rm eff}$ different from on-mass-shell ($\sin^2\theta_W = 1 - m^2_W / m^2_Z$), to account for EW corrs.
- Here: use EW form factors to assess impact of weak corrs to Born-like σ for $\ell\ell$ production
  - Improved Born Approximation (similar methodology as at LEP)
    - per-event weight using TauSpinner framework and form factors from Dizet library
  - EW corrections: in terms of five complex (flavour dependent) form factors
    - At Z pole ($\rightarrow \ell\ell$) form factors K^{ℓ}_{Z}. Ratio effective vector to axial-vector couplings:



$$\frac{v_l}{a_l} = 1 - 4 \cdot |q_f| \cdot \underbrace{K^l_Z \cdot \underbrace{\sin^2\theta_W}_{\text{on-mass shell}}}_{\sin^2\theta^{\ell}_{\rm eff}}$$

- ΔA_4: including EW corrections (without and with boxes which break factorisation assumption) to POWHEG-BOX generator input: 0.23113
- Shift of A_4=0.001 $\rightarrow$ shift of $\sin^2\theta^{\ell}_{\rm eff}$ =20x10^{-5}
  - EW corrections are important!

$\sin^2\theta^{\ell}_{\rm eff}$ at √s=8TeV: predictions and mapping A_4 as $\sin^2\theta^{\ell}_{\rm eff}$

ATLAS-CONF-2018-037

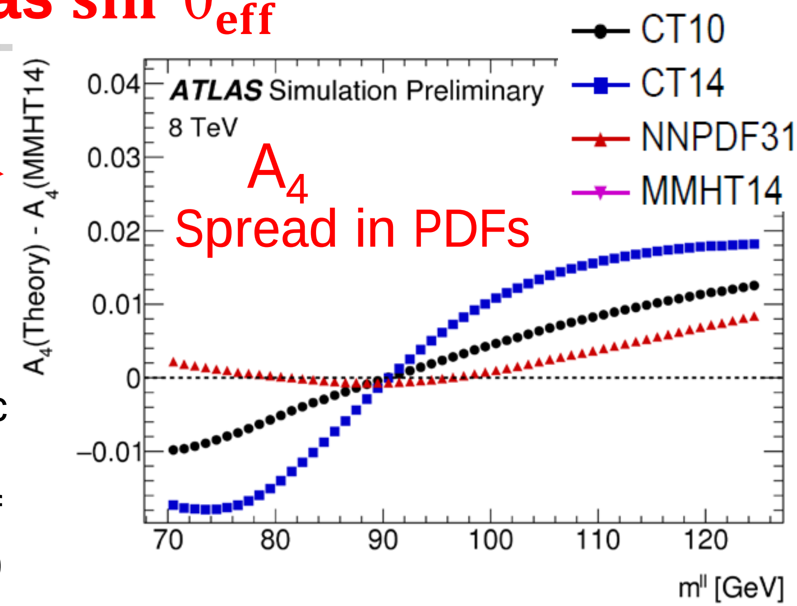
e.g. vs m^Z

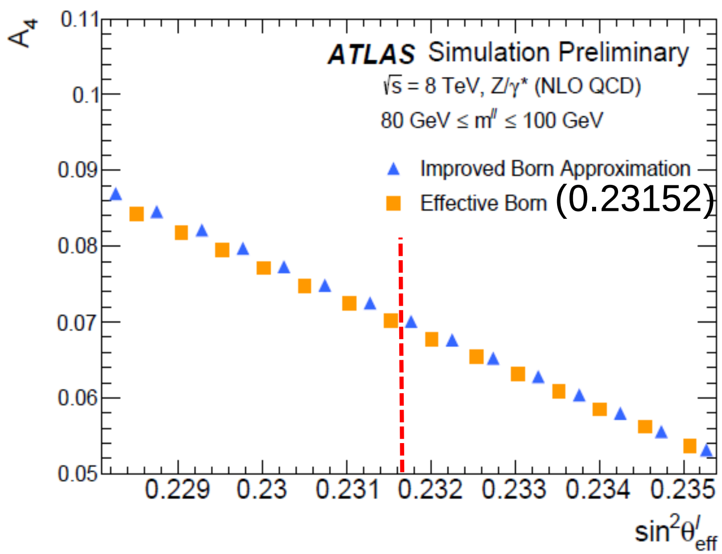
- PDF uncertainties dominate predictions of A_4
- $A_4 \rightarrow \sin^2\theta^{\ell}_{\rm eff}$: linear parm, varied ±100x10^{-5} around 0.23152 (PDG value)

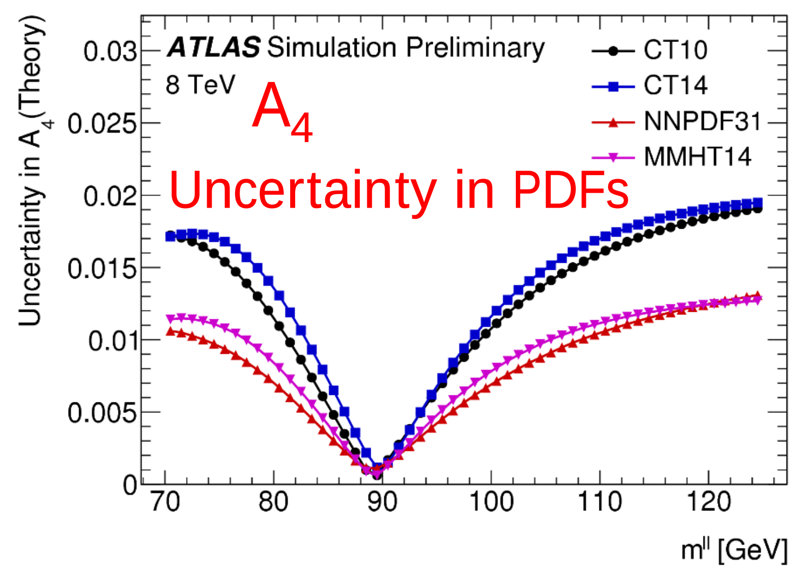
Analysis bin j

$$A_{4,j}(\sin^2\theta^{\ell}_{\rm eff},\ \theta) = a_j(\theta)\times\sin^2\theta^{\ell}_{\rm eff} + b_j(\theta)$$

- Predicted A_4 vs. $\sin^2\theta^{\ell}_{\rm eff}$ from DYTurbo (fast analytic integration NLO QCD+LO EW) corrected with tabulated EW corrs derived with per-event weight of TauSpinner and EW LO + QCD NLO (POWHEG-BOX)







- θ: systematic variations about nominal
    - Dominant uncertainty: PDF

Measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ at $\sqrt{s}$=8TeV: measurement - I

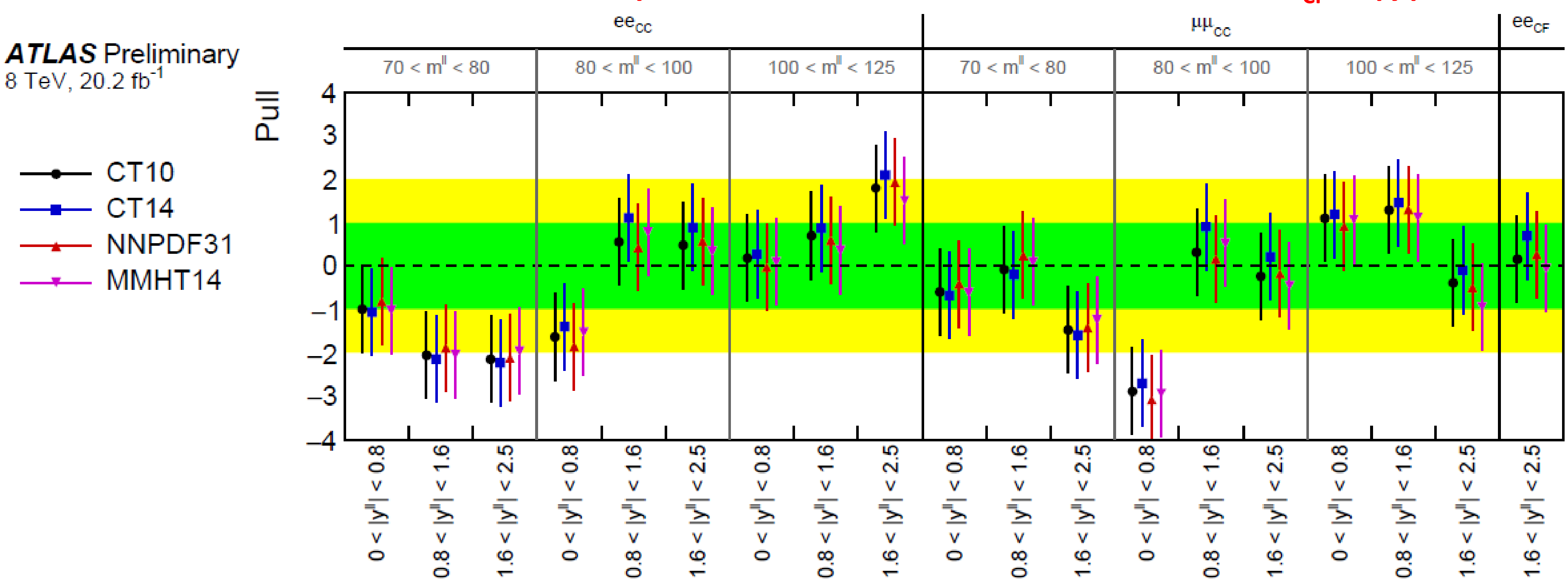
ATLAS-CONF-2018-037

ee_{CC} and $\mu\mu_{CC}$	
m^Z	[70, 80, 100, 125] GeV
$\lvert y^Z \rvert$	[0, 0.8, 1.6, 2.5]
ee_{CF}	
m^Z	[80,100] GeV
$\lvert y^Z \rvert$	[1.6, 2.5, 3.6]

RESULTS:

- Main uncertainties: on A_4 → data statistics, on interpretation of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ → also PDFs
- Compatibility of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ in 20 measurements channels (9 ee_{CC} +9 $\mu\mu_{CC}$ + 2ee_{CF})

Pulls of each measurement with respect to the most sensitive measurement: ee_{CF} in |y|=2.5-3.6



$\sin^2\theta^{\ell}_{\rm eff}$ measurement - II

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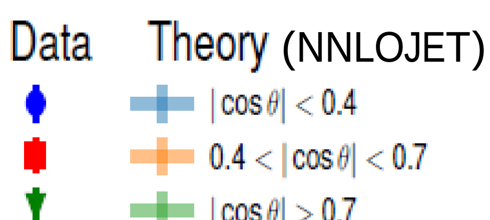
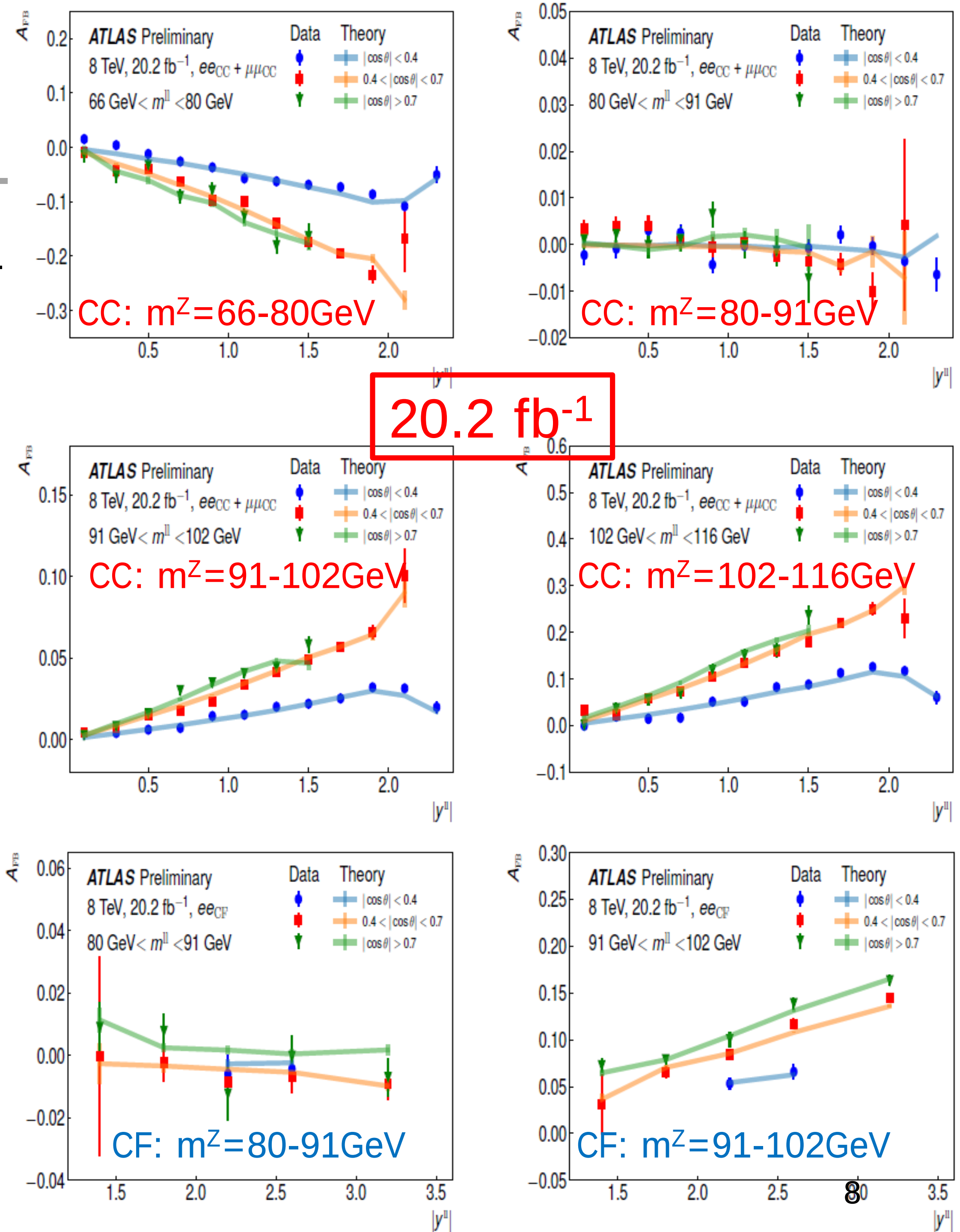
- Result cross-checked using forward-backward asymmetry **A_{FB} vs. $|y^Z|$** (from 3D Z cross section) blinded results for $\sin^2\theta^{\ell}_{\rm eff}$

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*}$$

- Check compatibility between the three analysis channels, expected and observed variations as a function of PDF set, and impact of the EW form factor corrections
  - All consistent!

A_{FB} vs. $|y^Z|$





Measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ at $\sqrt{s}$=8TeV: measurement - III

20.2 fb^{-1}

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- Contributions of the different channels to the measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
			Uncertainties		
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
			Uncertainties in measurements		
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
			Uncertainties in predictions		
(MMHT) PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

x 10^{-5}

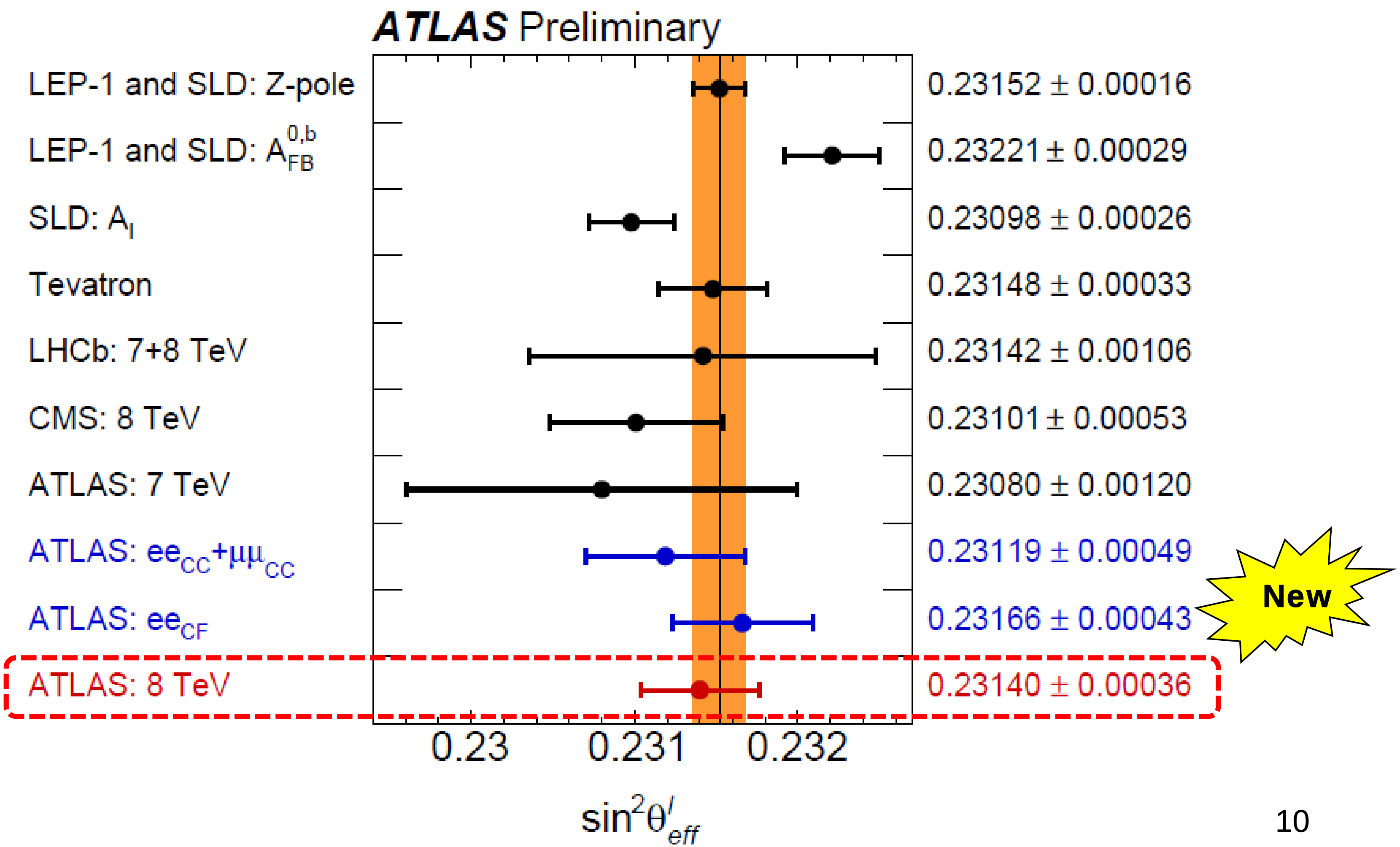
- ee_{CF} is most precise though it has only 1.5M events (compared to 13.5M ee_{CC} + $\mu\mu_{CC}$)
- Measurement uncertainty 36 x 10^{-5}
  - data stat and PDF uncertainty roughly equal. MC stats next largest uncertainty.

Measurement of $\sin^2\theta^{\ell}_{eff}$ at √s=8TeV: measurement - IV

ATLAS-CONF-2018-037

$\sin^2\theta^{\ell}_{eff}$ = 0.23140 ± 0.00021(stat.) ± 0.00024(PDF) ± 0.00016(syst.) (0.00036 tot)

- Competitive measurement from a hadron collider that adds consistency to the landscape!



τ polarisation in Z→ττ decays at √s=8TeV

$$P_\tau = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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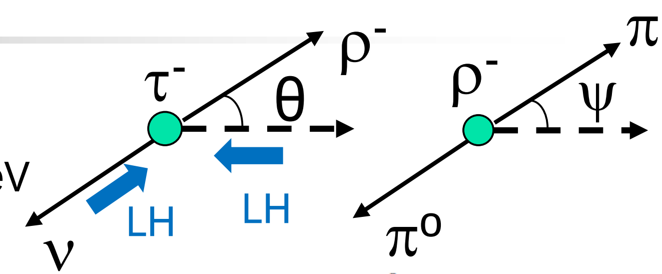
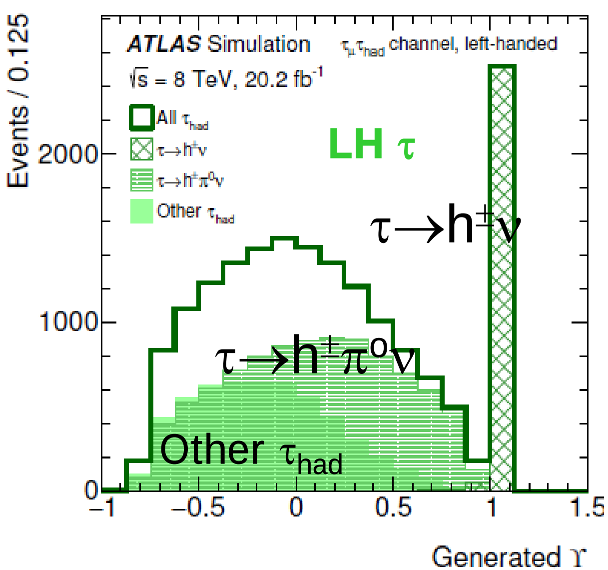
τ polarisation in Z/γ* decays a measure of parity violation

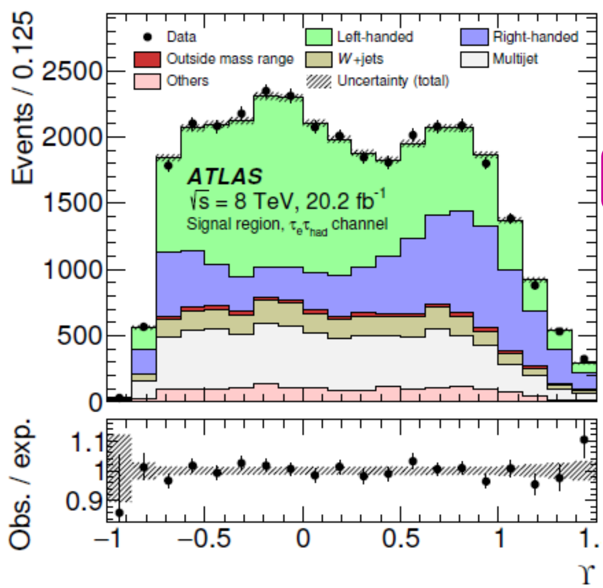


- $Z/\gamma^* \to \tau\tau$: $\tau_{lep} \to e/\mu\nu\nu$ + $\tau_{had} \to$ hadrons ν, m_{Z/γ^*}=66-116GeV
- P_τ: asymmetry for positive (σ_+) or negative (σ_-) helicity
- $\tau \to \rho\nu$, $\rho \to \pi^\pm\pi^o$ has sensitivity. Also $\tau \to h^\pm N\pi^o\nu$.
- ψ carries info on τ helicity $\propto$ energy sharing between $\pi^\pm$ & π^o

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{h^0}}{E_T^{\tau\text{had-vis}}} = 2\frac{p_T^{\text{track}}}{E_T^{\tau\text{had-vis}}} - 1$$

- Reconstructed spectra affected by acceptance, object reconstruction, event selection etc…
- Dominant bkgs: W+jets and multijet production (from same-sign (SS) control region)
- Fit model: extended binned max likelihood fit to Υ simultaneously in signal and SS regions
  - Uncertainties dominated by signal modeling and τ_{had} identification





Channel	P_τ in mass-selected region
$\tau_e - \tau_{had}$	-0.20 ± 0.02 (stat) ± 0.05 (syst)
$\tau_\mu - \tau_{had}$	-0.13 ± 0.02 (stat) ± 0.05 (syst)
Combination	-0.14 ± 0.02 (stat) ± 0.04 (syst)

- Alpgen+Pythia6 with Tauola:

$$P_\tau = -0.1517 \pm 0.0014\ (\text{stat}) \pm 0.0013\ (\text{syst}).$$

- Use Υ as discriminant for ττ final states from different helicity states

Zγ production cross section: Zγ →ννγ at 13TeV

New

ATLAS-CONF-2018-035

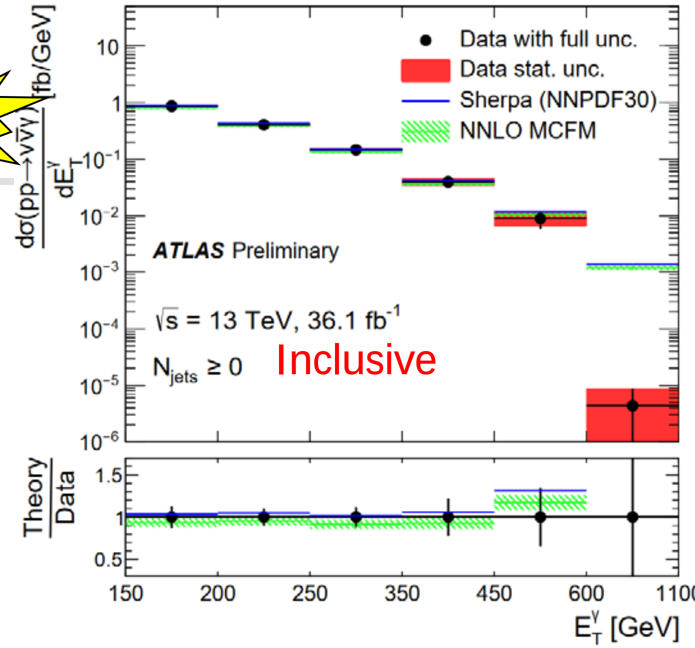
See talk of Rustem Ospanov Thurs at 17:30 for aTGCs!

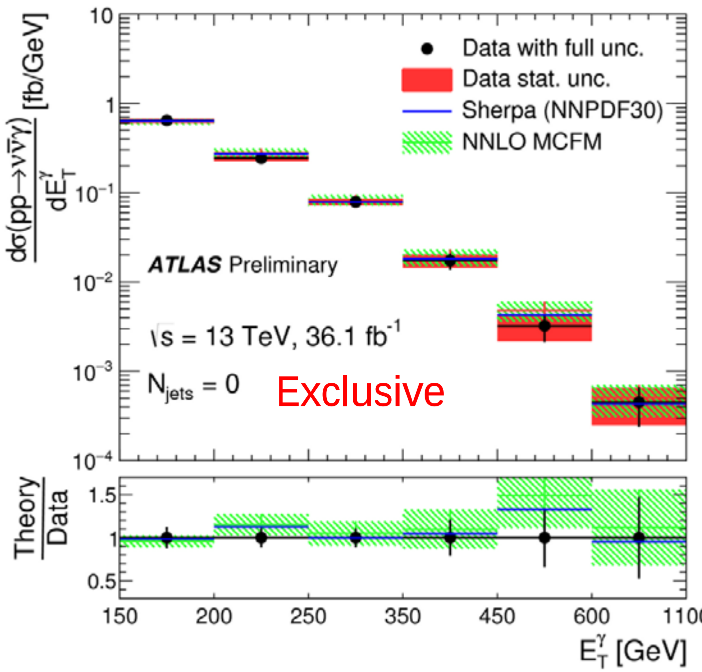
Analysis of Z(→νν)γ

- 2015-2016@13TeV : 36.1fb-1
- Fiducial differential cross section vs. E_T^{γ} (and E_T^{miss})

Signal and background:

- one isolated and well identified γ E_T>150GeV
- Large E_T^{miss} >150 GeV (and E_T^{miss} significance) for νν
- Inclusive: Njets≥0, exclusive: Njets=0 with anti-k_t R=0.4
- Other requirements/vetos to reduce bkg
- Dominant bkg like W(ℓν)γ where ℓ goes undetected
  - data-driven control regions where lepton veto or E_T^{miss} significance inverted
  - S/B~3/2
- Dominant uncertainties come from γ energy scale (and jet energy scale for the exclusive measurement)
- Comparisons to NNLO MCFM and Sherpa (NNPDF30)
  - Good agreement with SM expectations





Summary

Overview of SM Z/γ^* production with ATLAS Experiment

- Drell–Yan triple-differential Z cross section and A_4 coefficient at $\sqrt{s}$=8TeV
  - Precision provides unique insight into PDFs and sensitivity to $\sin^2\theta_W$!
  - A_4 coefficient used to extract $\mathbf{\sin^2\theta^{\ell}_{eff}}$ with competitive precision
- τ polarisation in $Z/\gamma^* \rightarrow \tau\tau$ decays
  - Υ variable: discrimination of final states with produced from different helicities
- $Z(\rightarrow\nu\nu)\gamma$ fiducial differential cross section
  - Measurements in corners of phase space interesting to probe aTGCs

Thanks

Citations

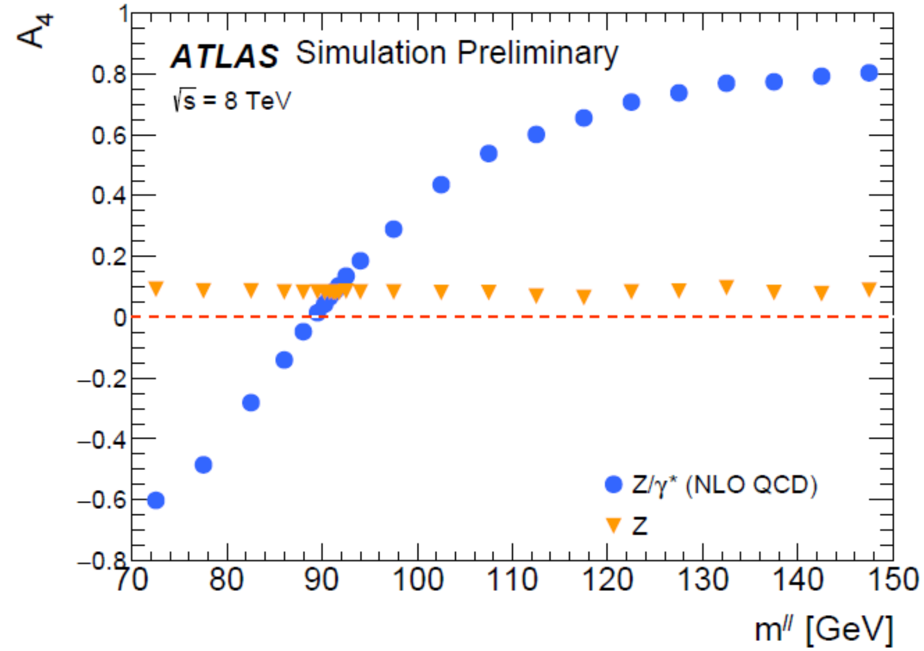
Z3D cross section	*JHEP 12 (2017) 059*
Z angular coefficients	*JHEP 08 (2016) 159*
$\sin^2\theta^{\ell}_{eff}$ from A_4	*ATLAS-CONF-2018-037*
Tau polarisation	*EPJC 78 (2018) 163*
$Z(\nu\nu)\gamma$ cross section	*ATLAS-CONF-2018-035*

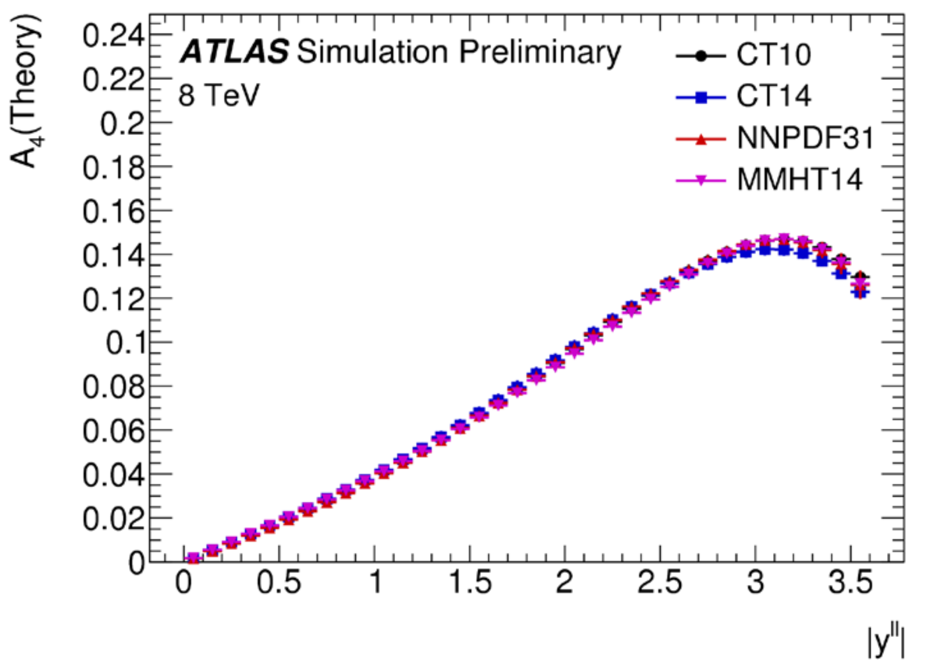
Back up...

$\sin^2\theta^{\ell}_{eff}$: some physics

ATLAS-CONF-2018-037

- $A_4 \cos\theta$ is parity violating. Large variation of as a function of m_{ll} is mostly due to interference between the γ vector amplitude and Z axial-vector amplitude
- asymmetry due to the weak mixing angle from self-interference of the Z vector and axial vector amplitudes
  - small and ~ m_{ll} independent
- Dependence versus rapidity reflects the level of dilution of asymmetry due to ambiguity in the knowledge of incoming valence quark direction which is derived from the direction of Z longitudinal boost



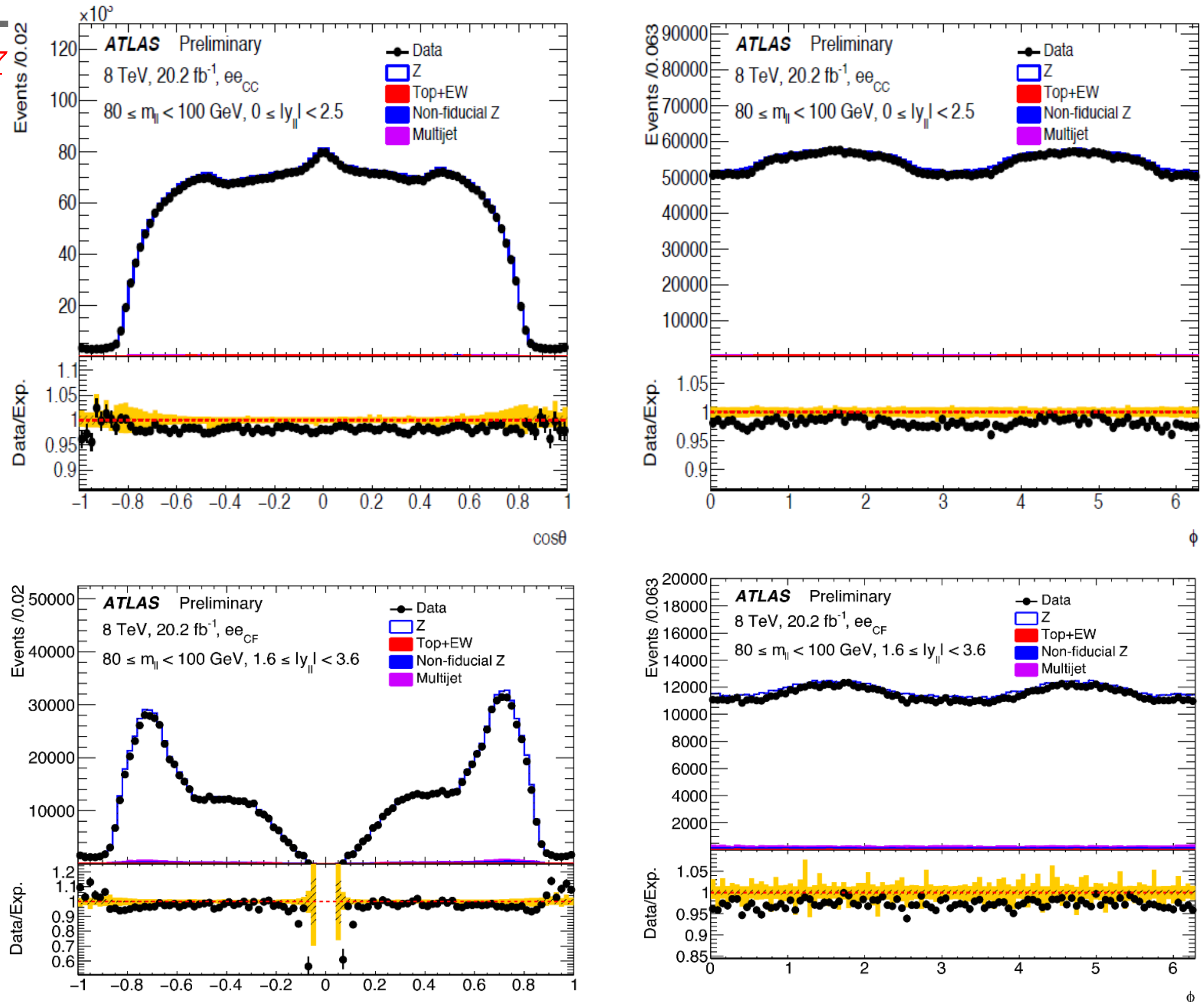


$\sin^2\theta^{\ell}_{\mathrm{eff}}$ at $\sqrt{s}$=8TeV: reco cos θ, φ at Z pole

ATLAS-CONF-2018-037

ee_{CC}

ee_{CF}



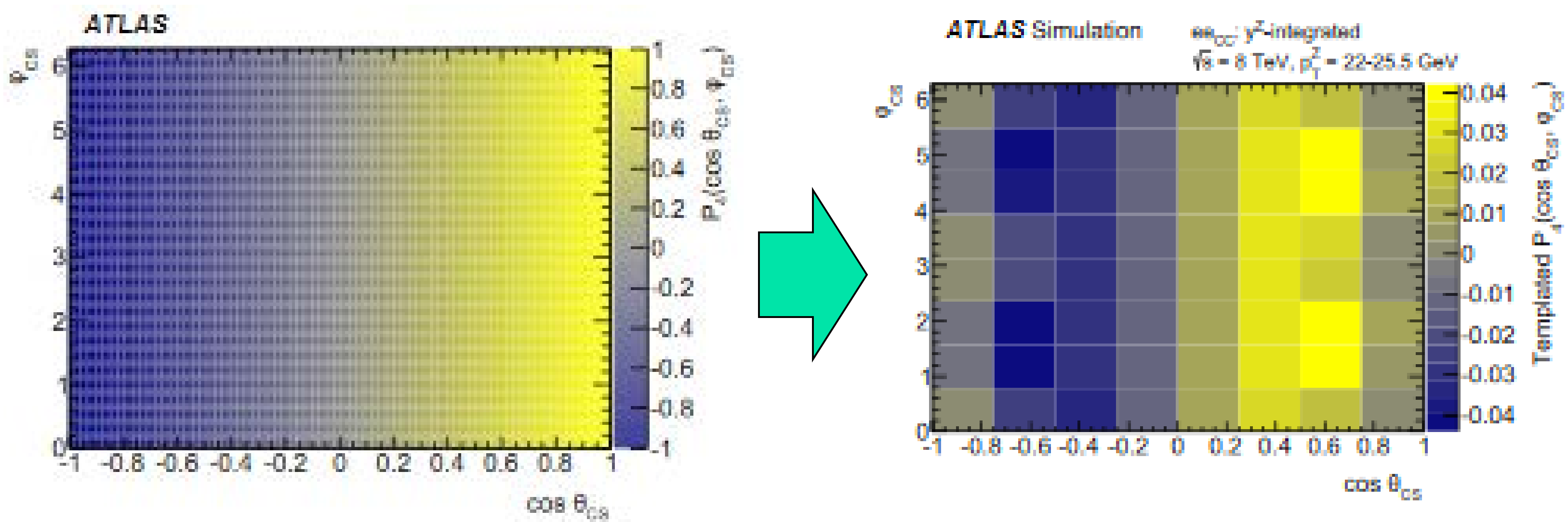
Measurement of $\sin^2\theta^{\ell}_{eff}$ at $\sqrt{s}$=8TeV: "Folding" Methodology

JHEP 08 (2016) 159   *ATLAS-CONF-2018-037*

Lepton selection requirements break the angular decomposition

- Extract reference coefficients A_i and unpolarised cross section σ from signal MC (POWHEG+PYTHIA8) in full lepton phase space in each measurement bin
- Using reference values, reweigh MC to isotropic (flat) to remove all Z polarisation info
- Apply selection requirements, corrections etc…
- Get nine separate polynomial templates for each measurement bin by weighting by P_i terms
  - 4D templates ($\cos\theta$, φ, $m_{\ell\ell}$, $y_{\ell\ell}$) that encompass all lepton selection efficiencies/migrations

P_4



- Number of expected events: LH based on signal & bkg templates with A_i, σ as normalisations
  - varied templates reflecting systematic uncertainties (nuisance parameters NP: θ)
- Compare data and expectations: LH built as product of Poisson N_{exp} and N_{data}

$\sin^2\theta^{\ell}_{\mathrm{eff}}$ at $\sqrt{s}$=8TeV: measurements

ATLAS-CONF-2018-037

Measured A_4

$m^{\ell\ell}$ (GeV)	70 – 80			80 – 100				100 – 125		
$\lvert y^{\ell\ell}\rvert$	0 – 0.8	0.8 – 1.6	1.6 – 2.5	0 – 0.8	0.8 – 1.6	1.6 – 2.5	2.5 – 3.6	0 – 0.8	0.8 – 1.6	1.6 – 2.5
Central value	−0.0681	−0.2684	−0.5087	0.0195	0.0448	0.0923	0.1445	0.0975	0.3311	0.6722
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0199	0.0391	0.0015	0.0016	0.0026	0.0046	0.0086	0.0099	0.0234
Stat.	0.0149	0.0160	0.0324	0.0013	0.0013	0.0021	0.0037	0.0073	0.0079	0.0188
Syst.	0.0093	0.0119	0.0220	0.0008	0.0008	0.0014	0.0027	0.0045	0.0062	0.0139
PDF (meas.)	0.0004	0.0044	0.0046	0.0001	0.0002	0.0004	0.0008	0.0009	0.0015	0.0050
p_{T}^{Z} modelling	0.0028	0.0031	0.0058	0.0003	0.0003	0.0004	0.0007	0.0014	0.0015	0.0033
Leptons	0.0044	0.0063	0.0095	0.0004	0.0003	0.0005	0.0010	0.0019	0.0040	0.0071
Background	<0.0001	0.0008	0.0040	<0.0001	0.0001	<0.0001	0.0001	0.0006	0.0015	0.0023
MC stat.	0.0083	0.0089	0.0180	0.0007	0.0007	0.0012	0.0023	0.0038	0.0042	0.0102

Measured $\sin^2\theta^{\ell}_{\mathrm{eff}}$ for different PDFs

PDF set	CT10	CT14	MMHT14	NNPDF31
Central value	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	40	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

x 10^{-5}

$\sin^2\theta^{\ell}_{\text{eff}}$ at $\sqrt{s}$=8TeV: A_4 predictions

ATLAS-CONF-2018-037

Predicted A_4

$m^{\ell\ell}$ (GeV)	70 – 80			80 – 100				100 – 125		
$\lvert y^{\ell\ell}\rvert$	0 – 0.8	0.8 – 1.6	1.6 – 2.5	0 – 0.8	0.8 – 1.6	1.6 – 2.5	2.5 – 3.6	0 – 0.8	0.8 – 1.6	1.6 – 2.5
Central value (NNLO QCD)	−0.0870	−0.2907	−0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
ΔA_4 (NNLO - NLO QCD)	0.0003	0.0010	0.0021	−0.0001	−0.0005	−0.0009	−0.0015	−0.0007	−0.0022	−0.0041
ΔA_4 (EW)	0.0008	0.0028	0.0056	0.0002	0.0007	0.0015	0.0026	−0.0008	−0.0026	−0.0048
$\Delta \sin^2\theta^{\ell}_{\text{eff}}$ (EW)	0.00129	0.00130	0.00133	0.00024	0.00024	0.00025	0.00026	−0.00120	−0.00123	−0.00119
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0035	0.0094	0.0137	0.0007	0.0017	0.0021	0.0021	0.0040	0.0102	0.0140
PDF	0.0034	0.0092	0.0127	0.0007	0.0016	0.0020	0.0019	0.0039	0.0100	0.0131
QCD scales	0.0006	0.0019	0.0052	0.0003	0.0003	0.0004	0.0008	0.0005	0.0022	0.0049

τ polarisation in $Z\to\tau\tau$ decays

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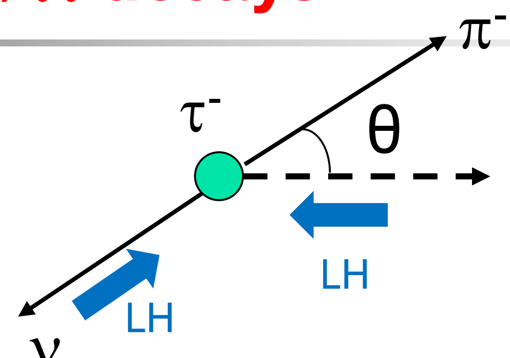
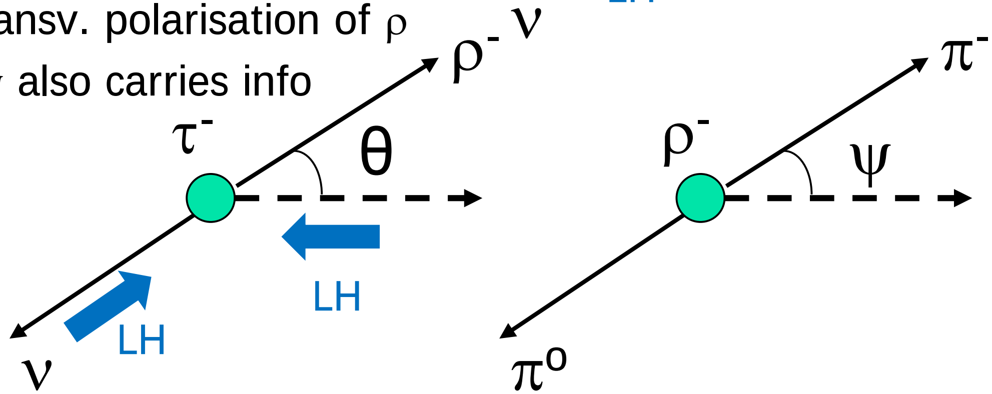
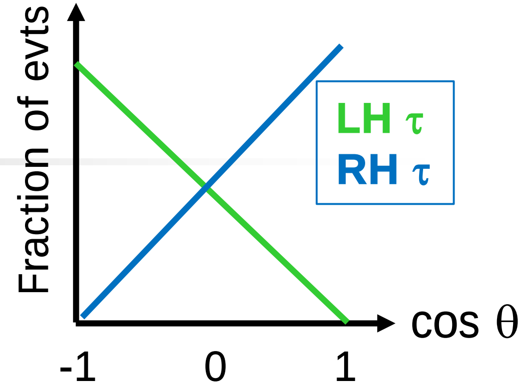
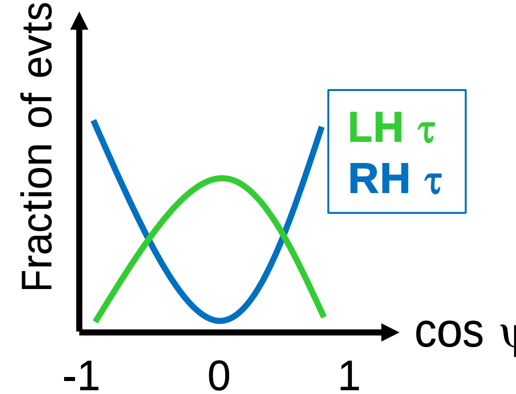
- $\tau\to\pi\nu$ has highest sensitivity
  - Angle θ
- $\tau\to\rho\nu$, $\rho\to\pi^{\pm}\pi^{o}$ has higher Br. Sensitivity diluted due to mixing of long. and transv. polarisation of ρ
  - Angle ψ also carries info





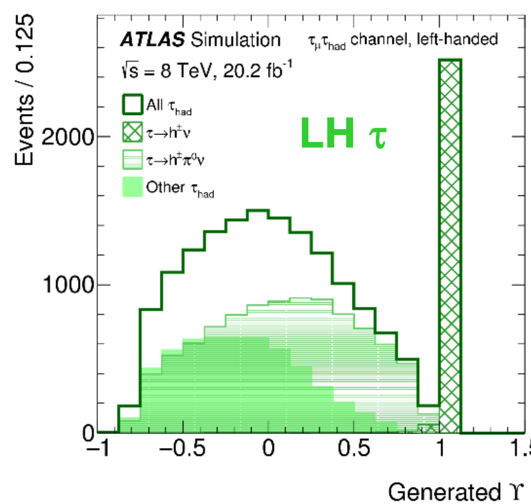


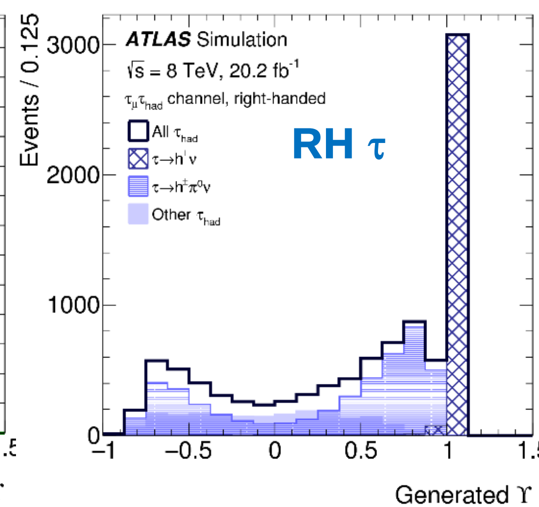


- θ cannot be measured at LHC
- Angle ψ related to the energy sharing between $\pi^{\pm}$ and π^{o} x

$$\Upsilon_{\text{theory}} = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}.$$

Proxy: $$\Upsilon = \frac{E_{\mathrm{T}}^{\pi^\pm} - E_{\mathrm{T}}^{h^0}}{E_{\mathrm{T}}^{\tau\text{had-vis}}} = 2\frac{p_{\mathrm{T}}^{\text{track}}}{E_{\mathrm{T}}^{\tau\text{had-vis}}} - 1,$$

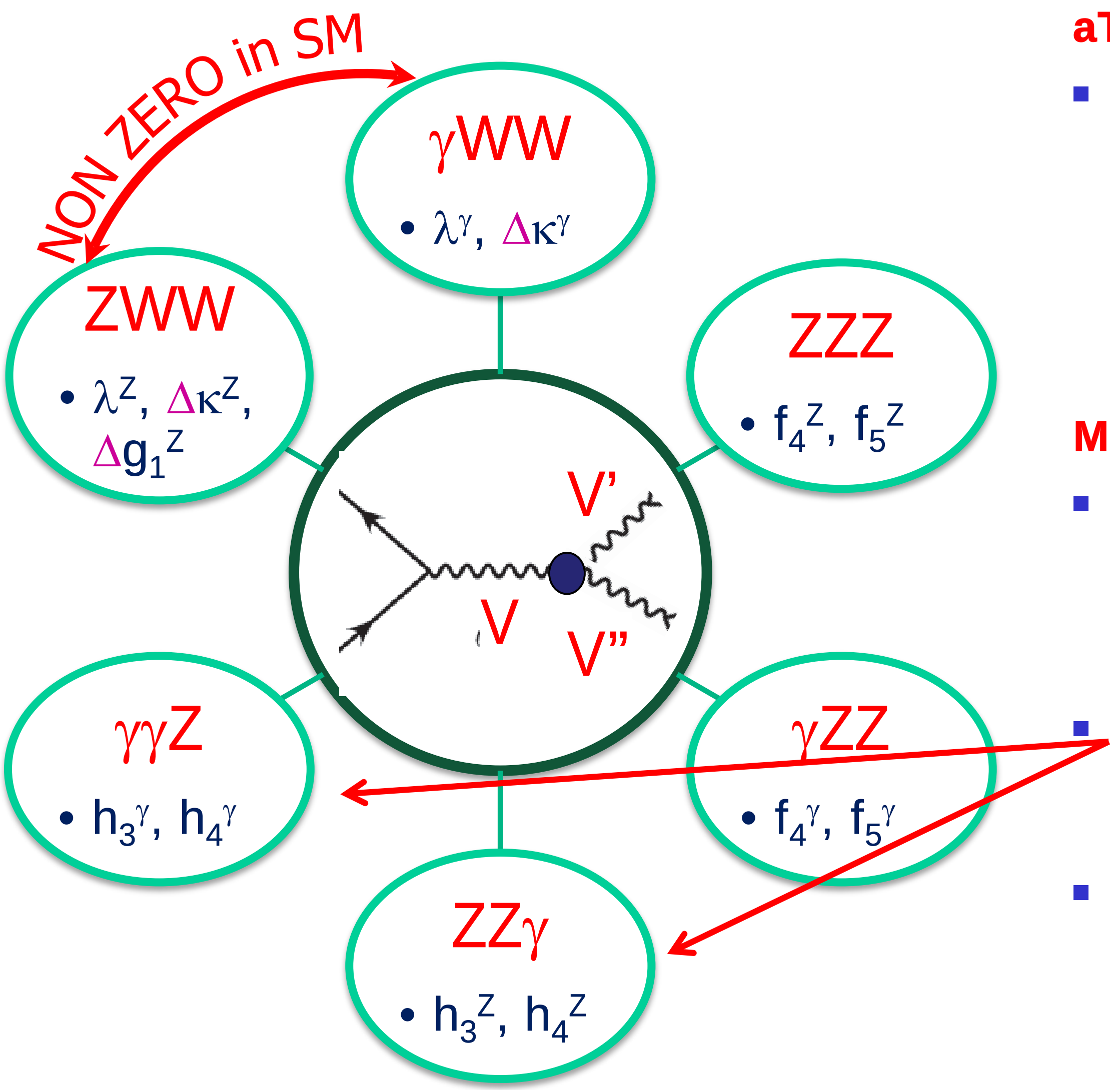




TGC

$Z\gamma \rightarrow \nu\nu\gamma$, production cross section 13TeV

- Test EW sector: gauge boson self-interactions VVV
  - anomalous Triple Gauge Couplings (aTGC)



aTGC methodology

- Measure diboson kinematic distributions or cross sections vs. variables sensitive to aTGCs
  - Presence of aTGC distorts shape

Measurement $Z\gamma \rightarrow \nu\nu\gamma$ in the SM

- in SM: either through γ emission by initial state quarks or through quark/gluon fragmentation into γ
  - TGC forbidden at tree level
- Yields of Z with high E_T from the exclusive (zero-jet) selection are used to set aTGC limits
- Present here: fiducial differential cross section vs. E_T