ATLAS
EXPERIMENT

Electroweak Precision Measurements with ATLAS

Maarten Boonekamp (CEA, IRFU),
on behalf of the ATLAS Collaboration

Outline

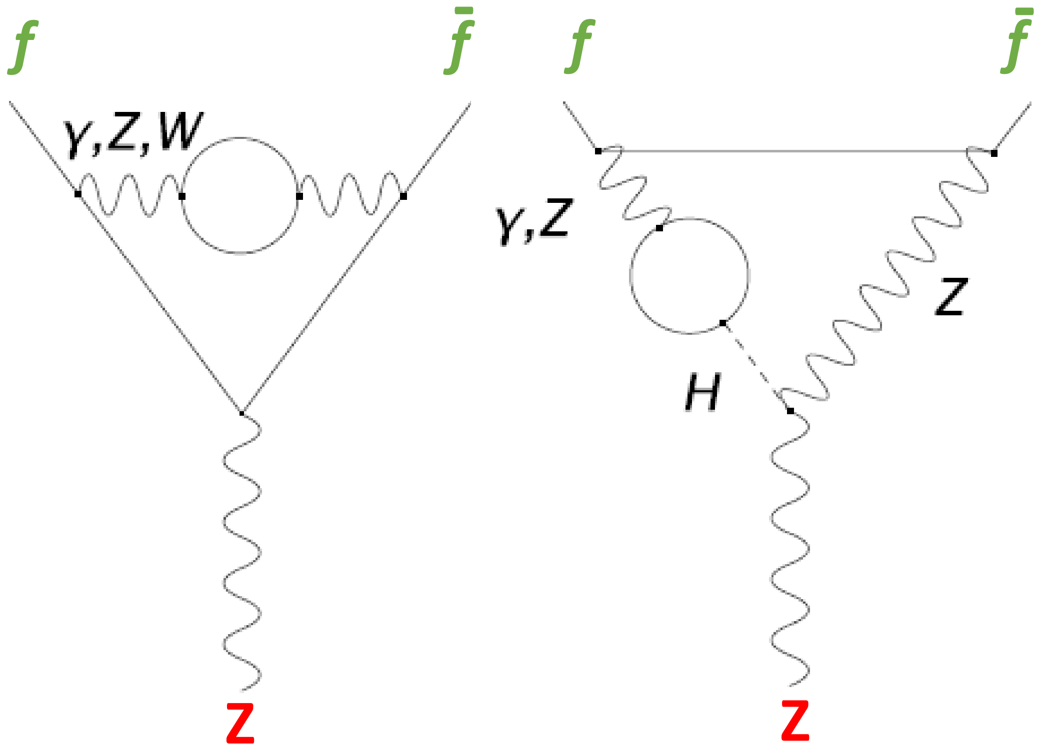
- Motivation : a window into the Higgs sector

- The weak mixing angle and associated measurements
- The W boson mass
- Vector boson scattering at high energy

- Current status and prospects

A window into the Higgs sector

Loop effects on gauge boson properties



L.O.

$$g_V^{tree} \equiv (T_3^f - 2Q_f \sin^2\theta_W^{tree})$$
$$g_A^{tree} \equiv T_3^f \,.$$

H.O.

$$g_{Vf} \equiv \sqrt{\rho_f}\,(T_3^f - 2Q_f \sin^2\theta_{eff}^f)$$
$$g_{Af} \equiv \sqrt{\rho_f}\,T_3^f \,,$$

$$\sin^2\theta_{eff}^f \equiv \kappa_f \sin^2\theta_W = \kappa_f\,(1 - m_W^2/m_Z^2)$$

$$\rho_f = 1 + \Delta\rho_{se} + \cdots$$
$$\kappa_f = 1 + \Delta\kappa_{se} + \cdots$$

Z boson couplings to fermions. Partial widths, asymmetries and the weak mixing angle

A window into the Higgs sector

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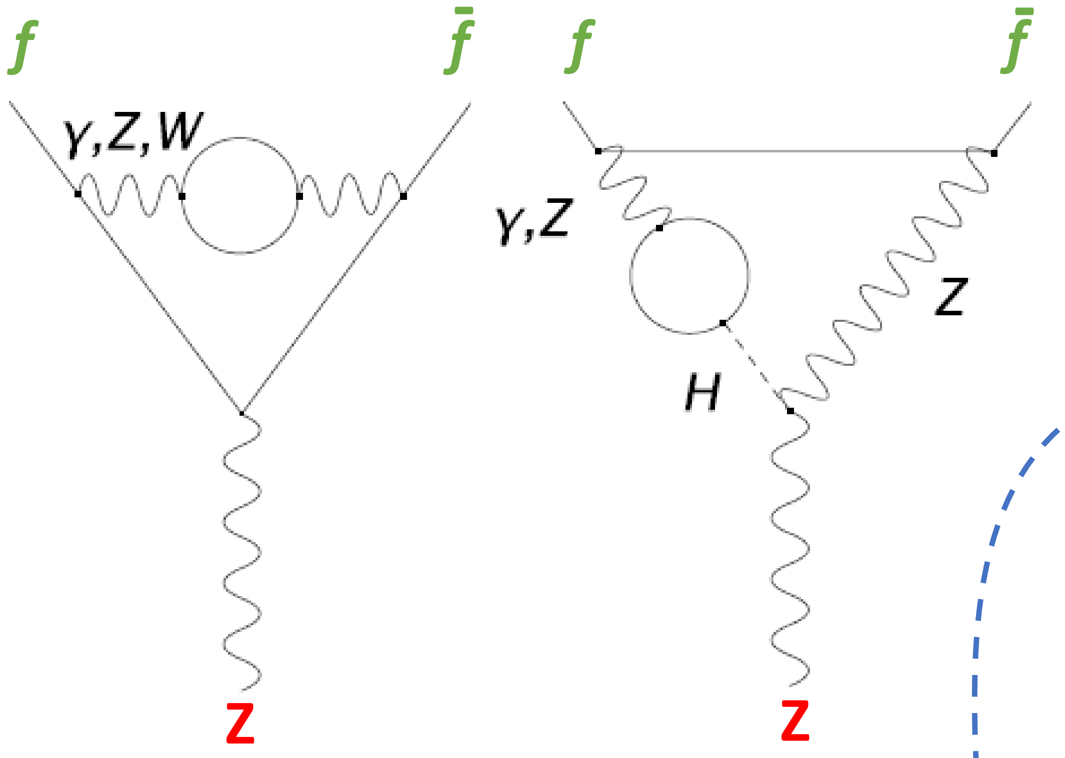

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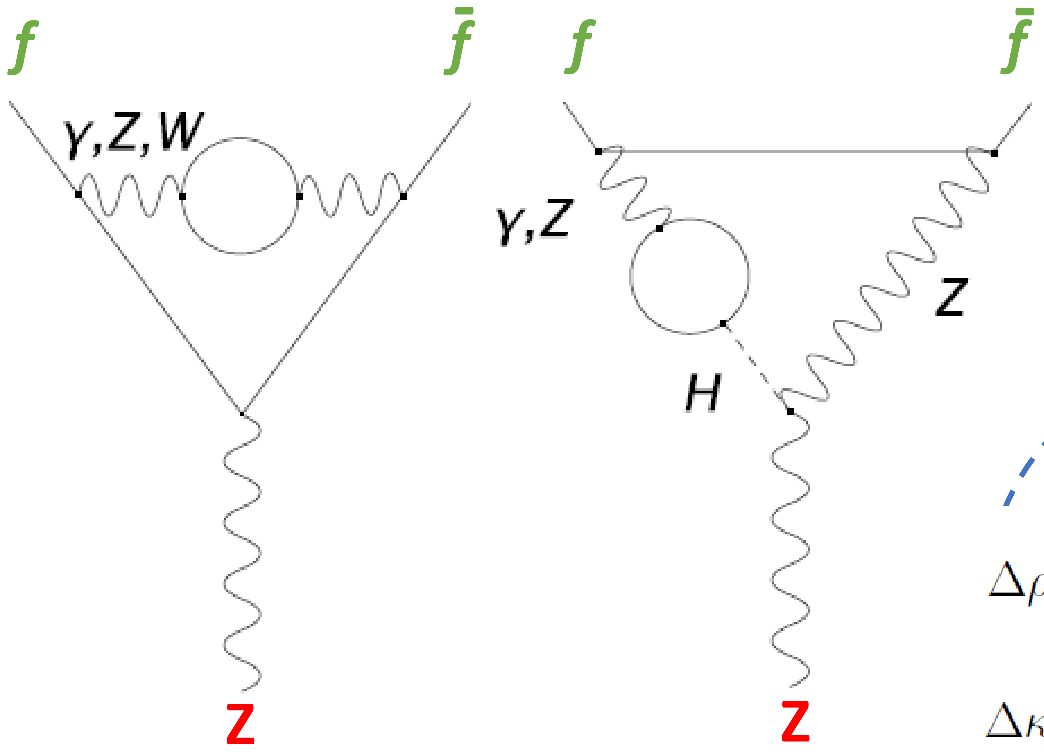

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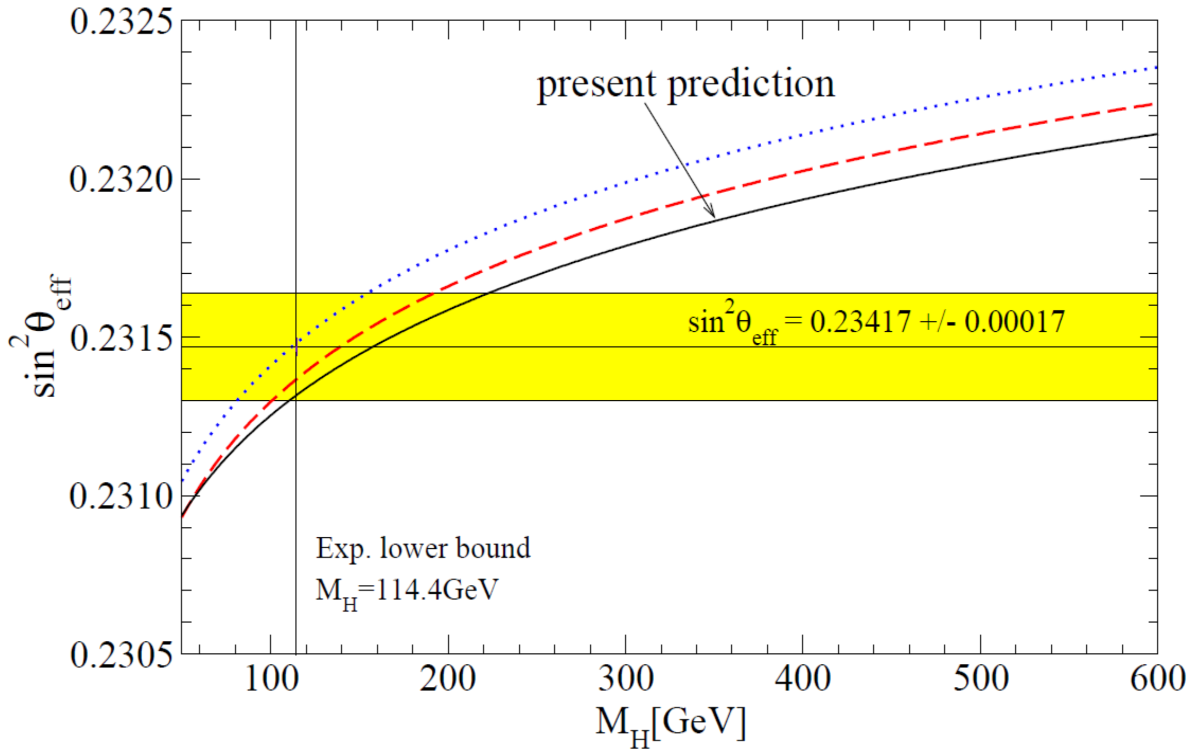
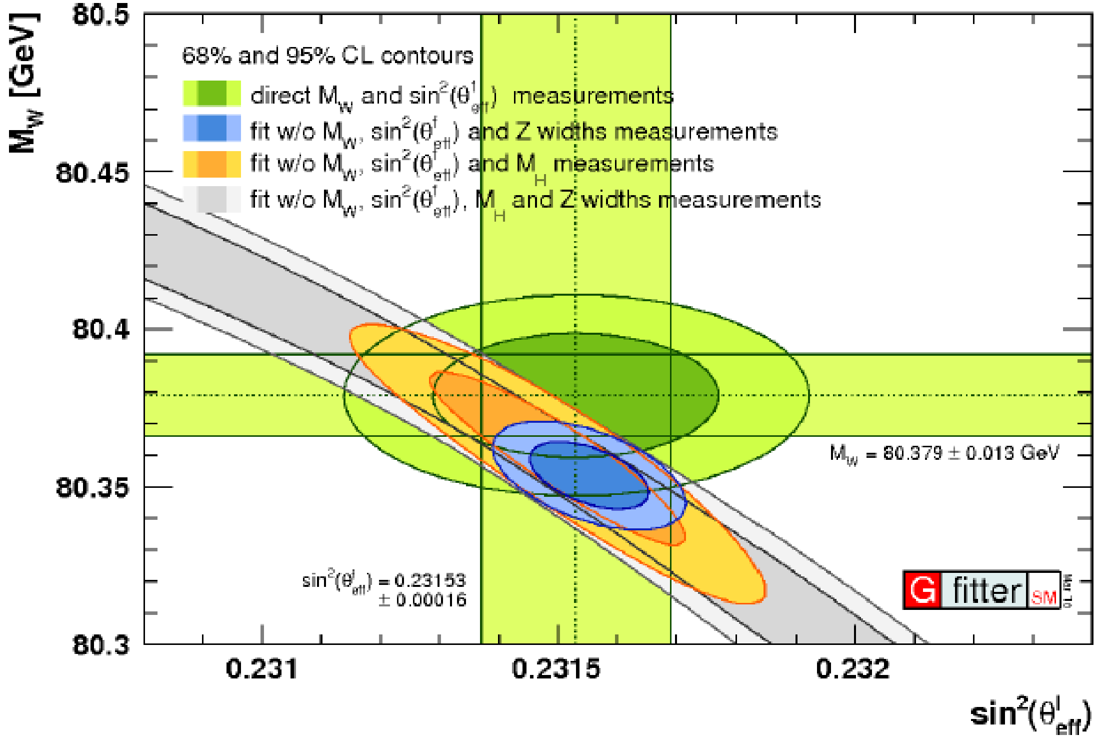
$$\Delta\rho_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \cdots\right]$$
$$\Delta\kappa_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2}\frac{\cos^2\theta_W}{\sin^2\theta_W} - \frac{10}{9}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \cdots\right]$$

Z boson couplings to fermions. Partial widths, asymmetries and the weak mixing angle

A window into the Higgs sector

Loop effects on gauge boson properties





Z boson couplings to fermions. Partial widths, asymmetries and the weak mixing angle

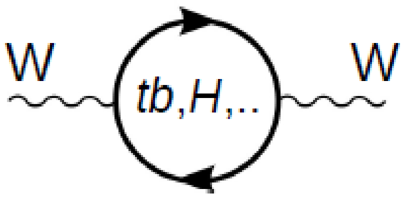
A window into the Higgs sector

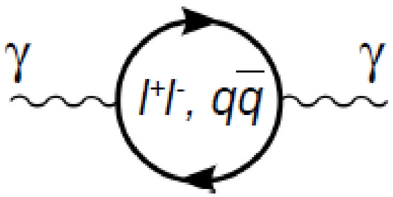
Loop effects on gauge boson properties : the W boson mass

At leading order, m_W is expressed as

$$m_W^2 \sin^2\theta_W = \frac{\pi \alpha}{\sqrt{2} G_\mu}, \quad \sin^2\theta_W = 1 - m_W^2 / m_Z^2$$

Higher-order corrections, dominantly W and γ self-energies,





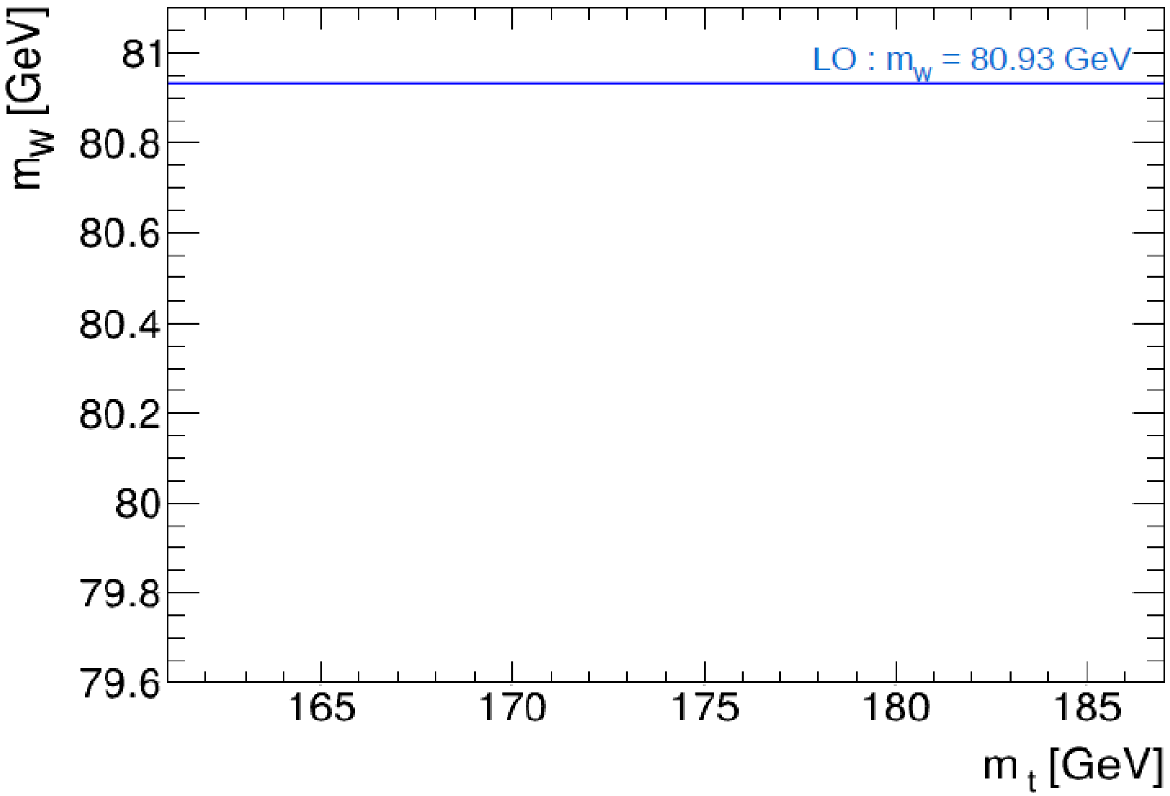
...

modify this relation to $m_W^2 \sin^2\theta_W = \frac{\pi \alpha}{\sqrt{2} G_\mu} \frac{1}{1 - \Delta r}$

A window into the Higgs sector

Loop effects on gauge boson properties : the W boson mass

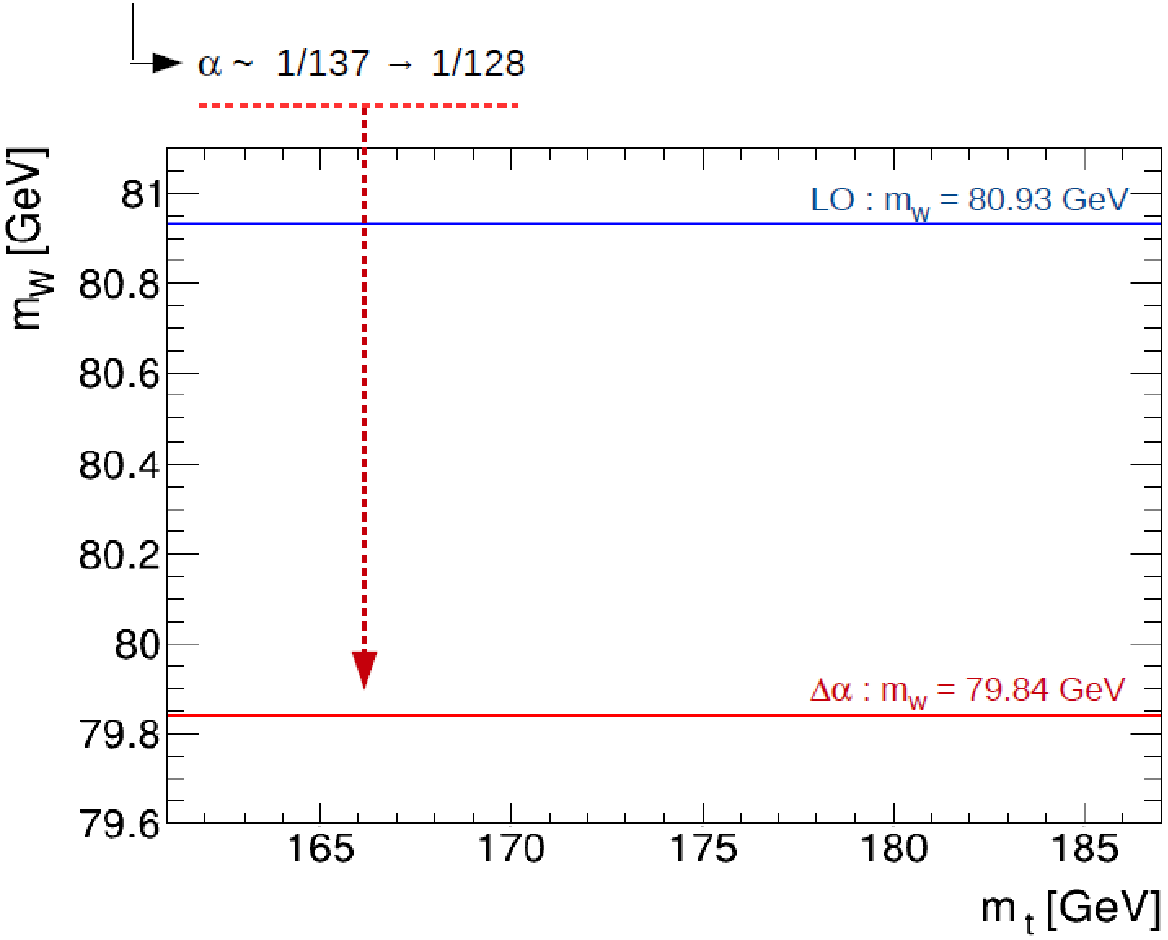
$\Delta r \; = \; 0$ (leading order)



A window into the Higgs sector

Loop effects on gauge boson properties : the W boson mass

$$\Delta r = \Delta\alpha$$

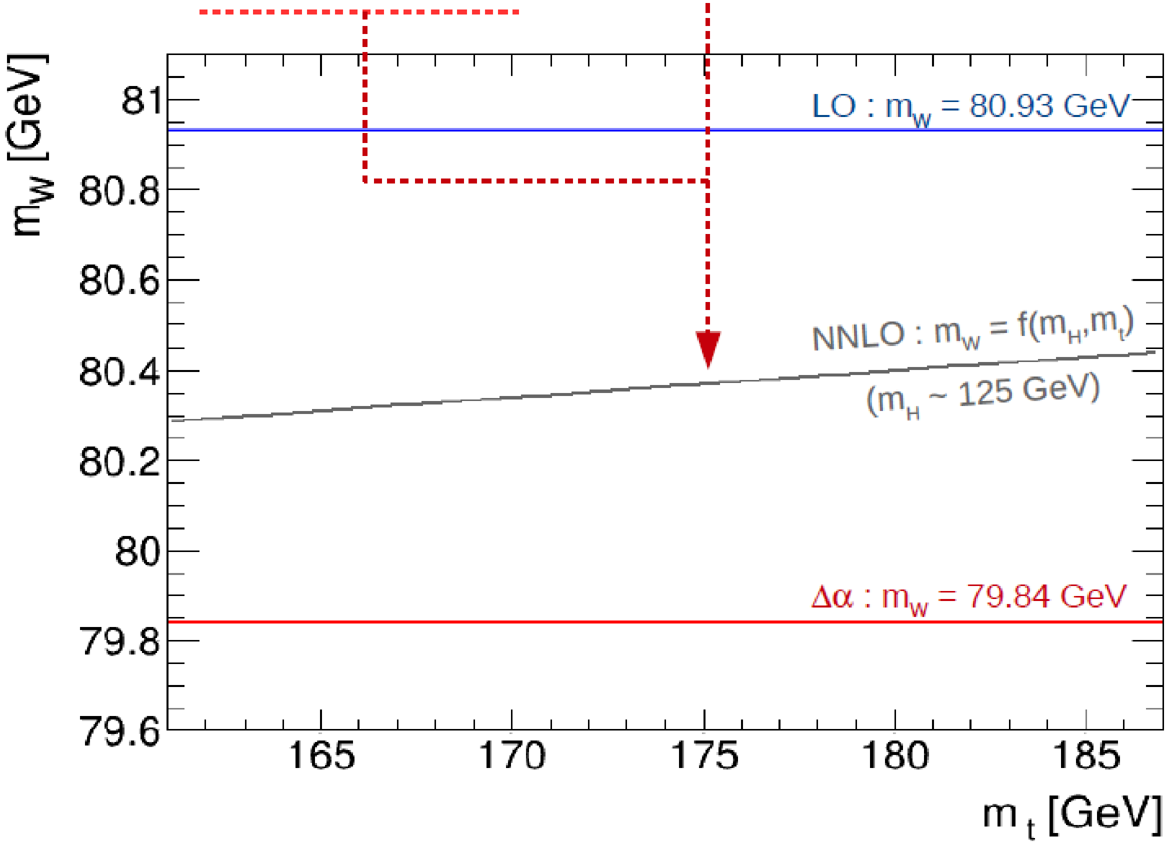


A window into the Higgs sector

Loop effects on gauge boson properties : the W boson mass

$$\Delta r = \Delta\alpha - \tan\theta_W \Delta\rho(m_{top}) + \Delta r^{SM}_{rem}(m_{top}, m_H) + \ldots$$

$\alpha \sim 1/137 \rightarrow 1/128$



A window into the Higgs sector

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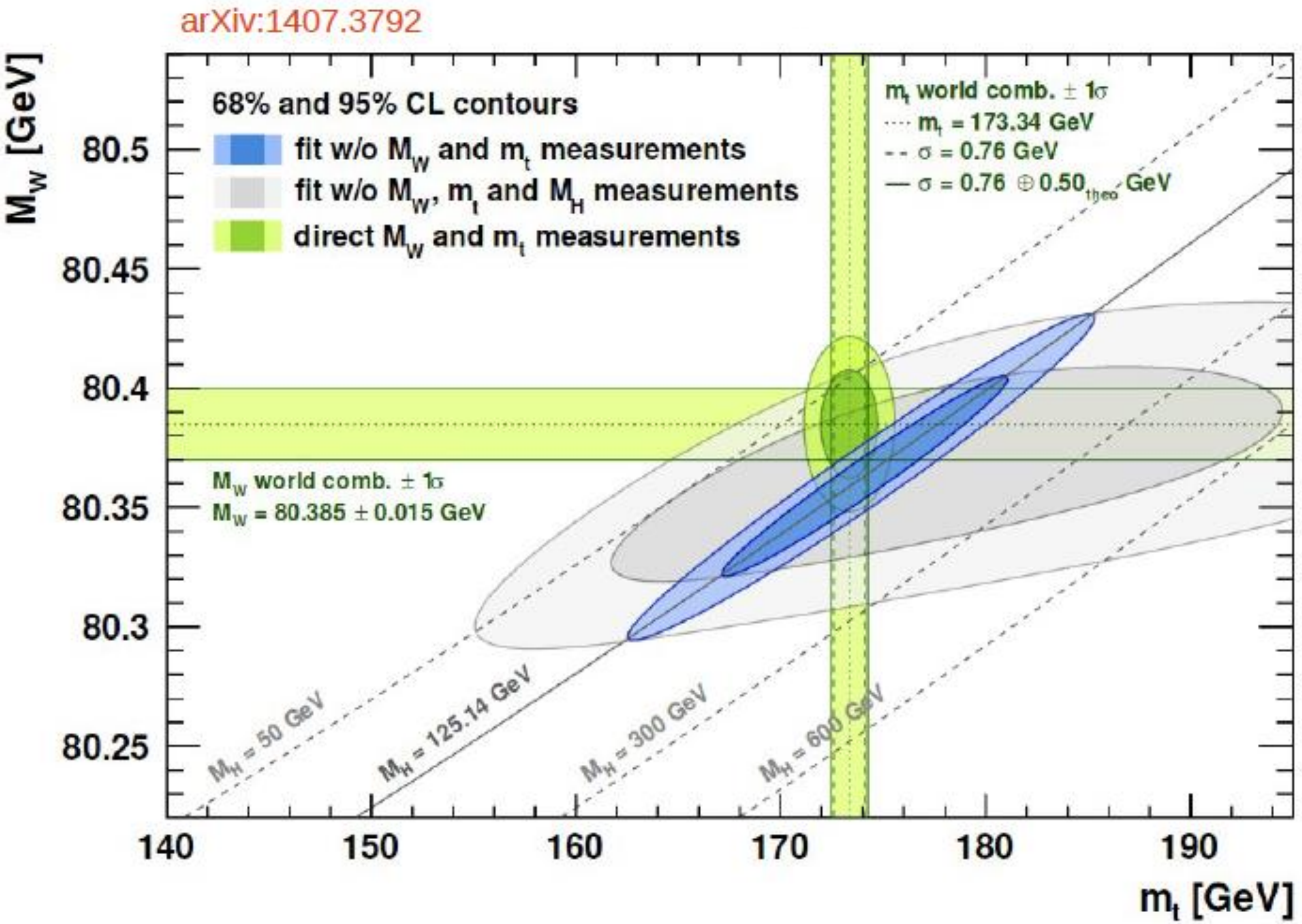
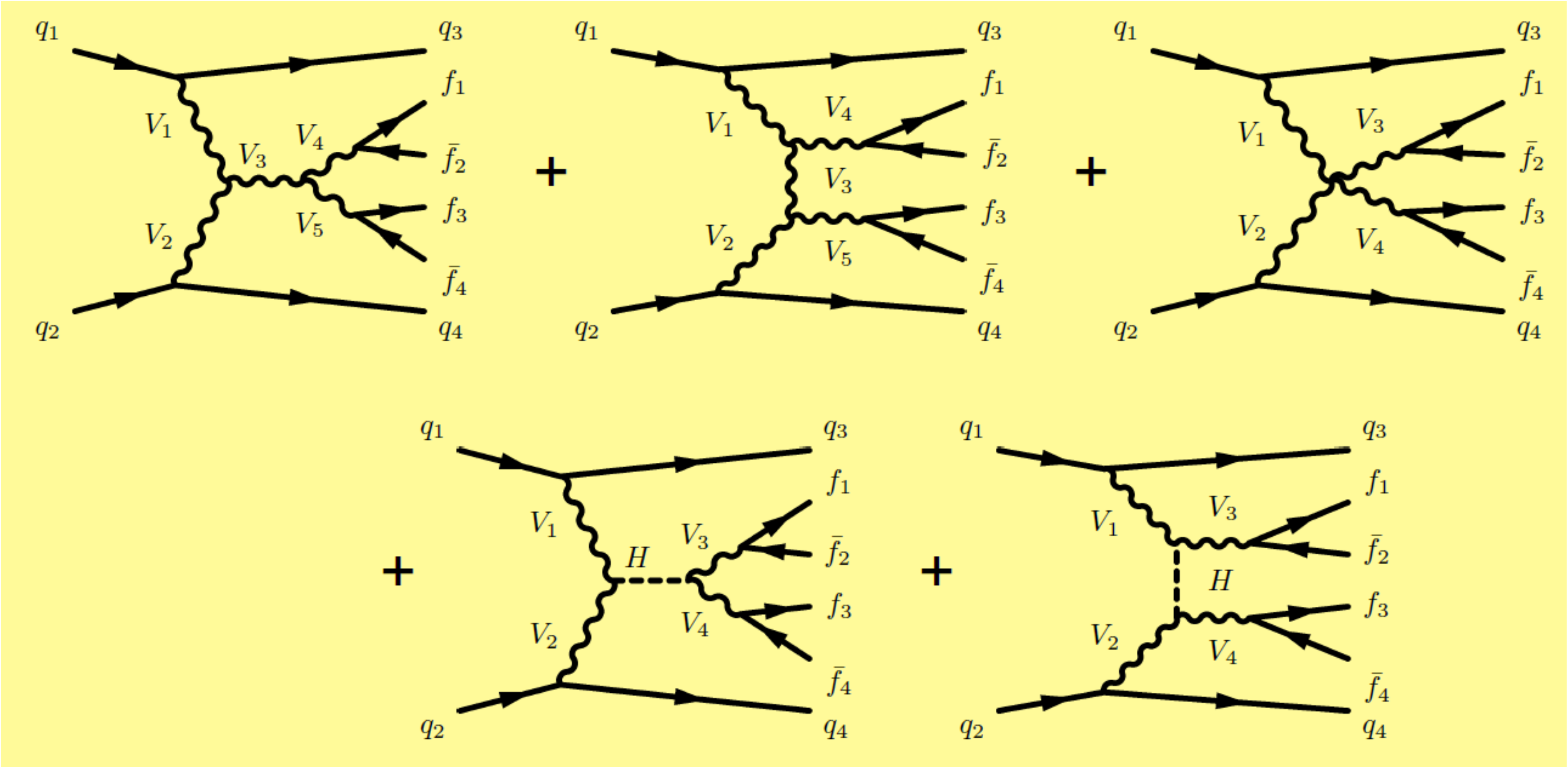


A window into the Higgs sector

Real contributions to weak boson interactions



Vector boson scattering at high energy

A window into the Higgs sector

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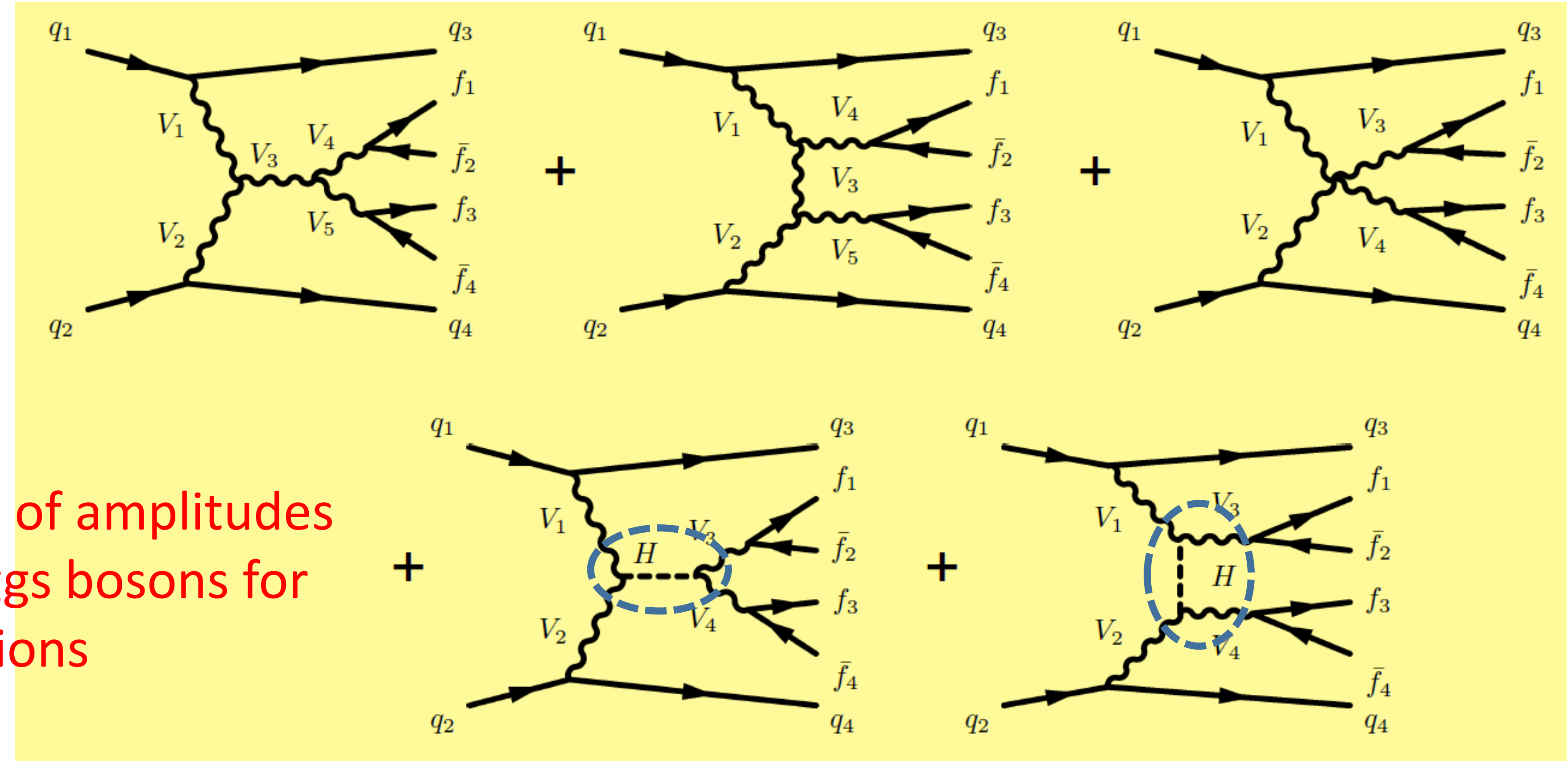

Contribution of amplitudes involving Higgs bosons for $V_L V_L$ interactions

Vector boson scattering at high energy

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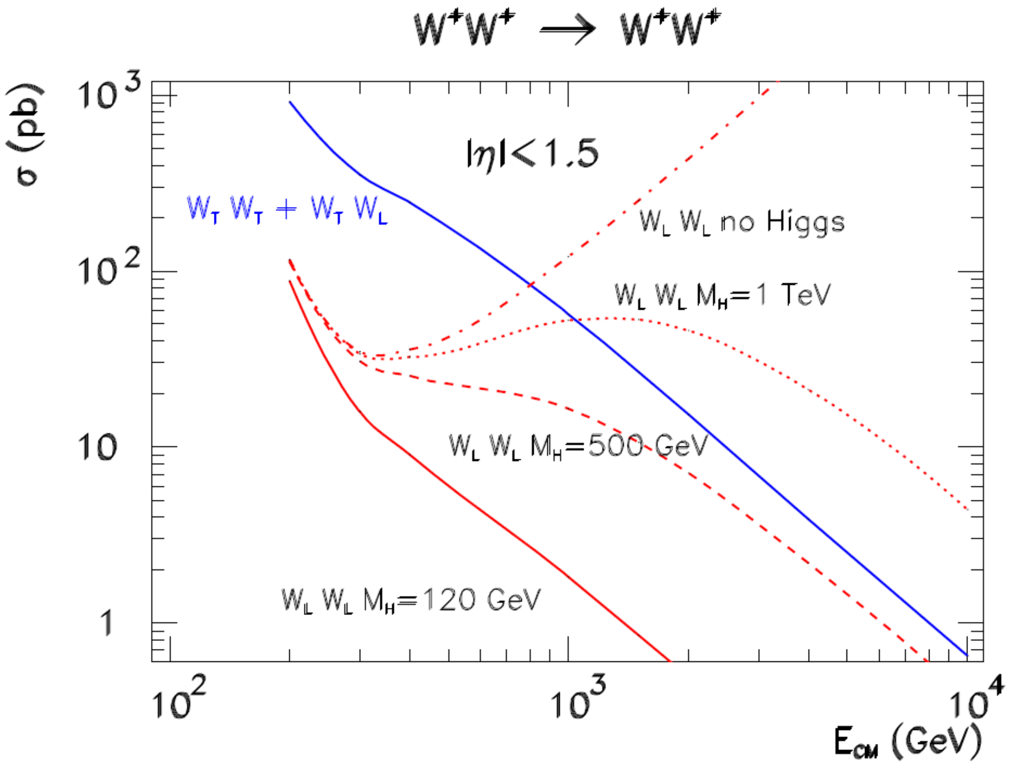
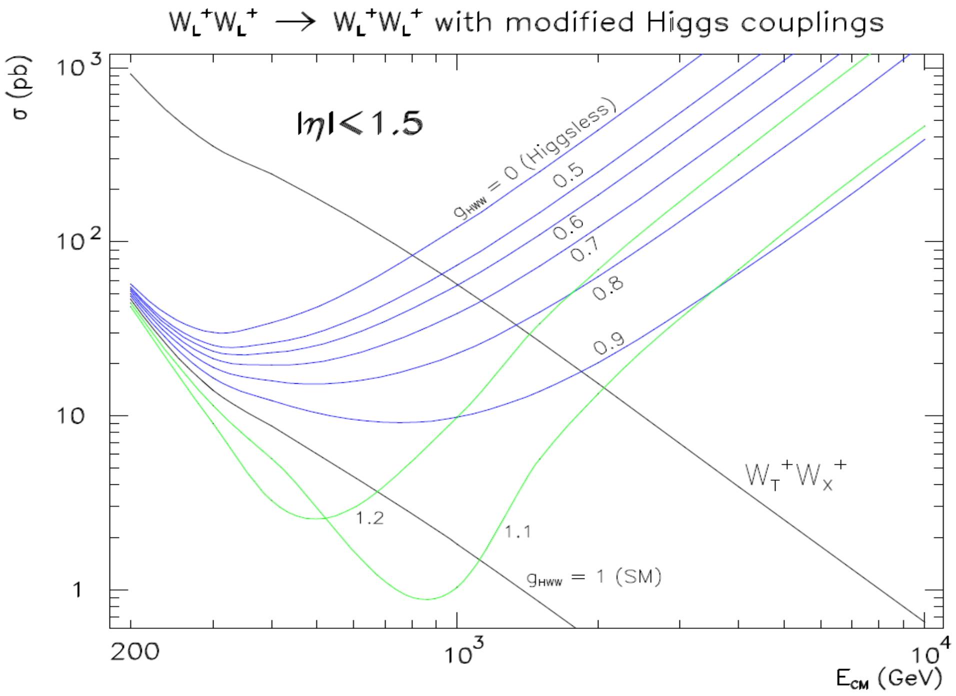
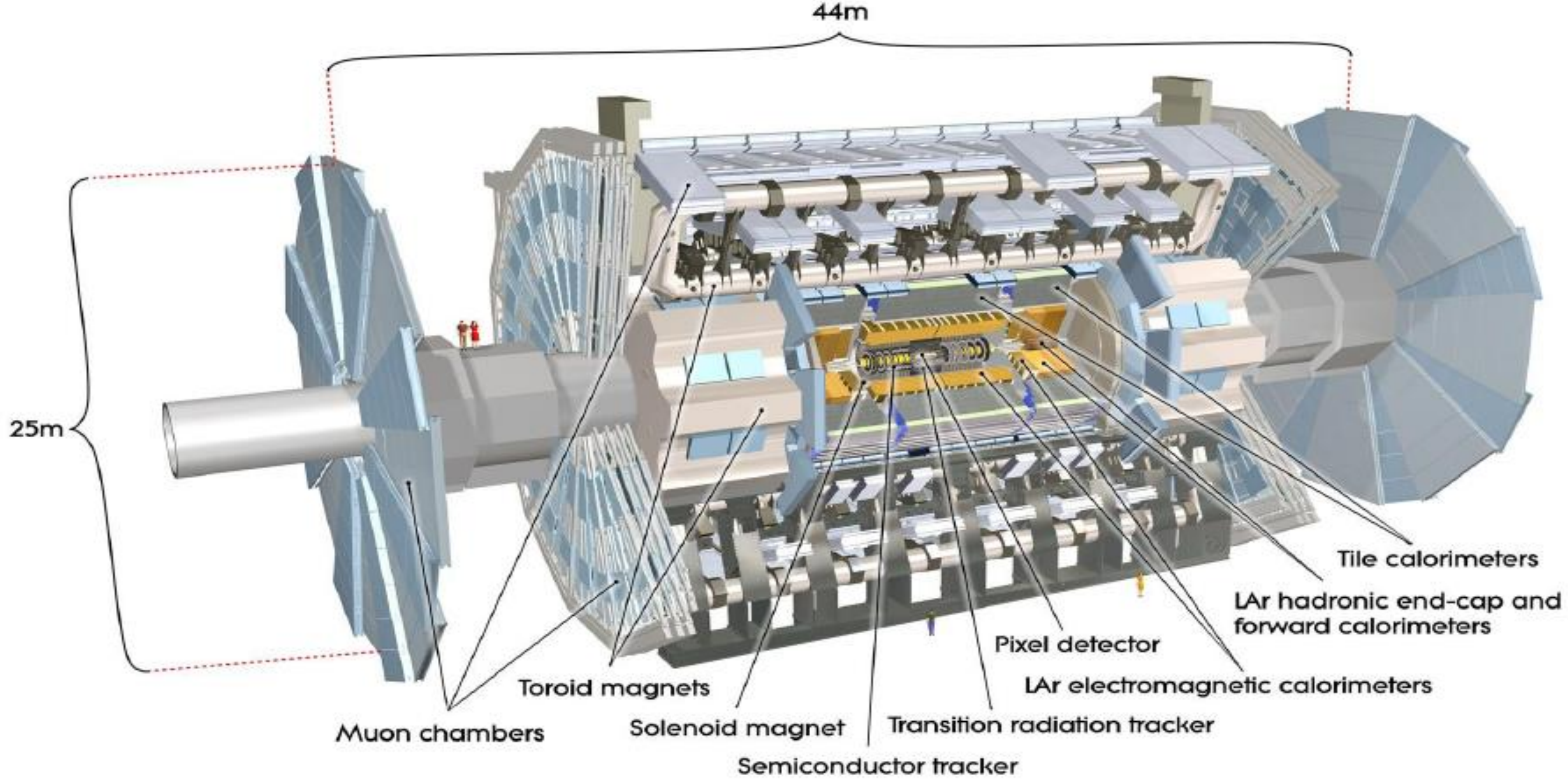




Vector boson scattering at high energy

The ATLAS detector



Of particular importance to the measurements discussed here :

Muons (Inner Detector, Muon Spectrometer)

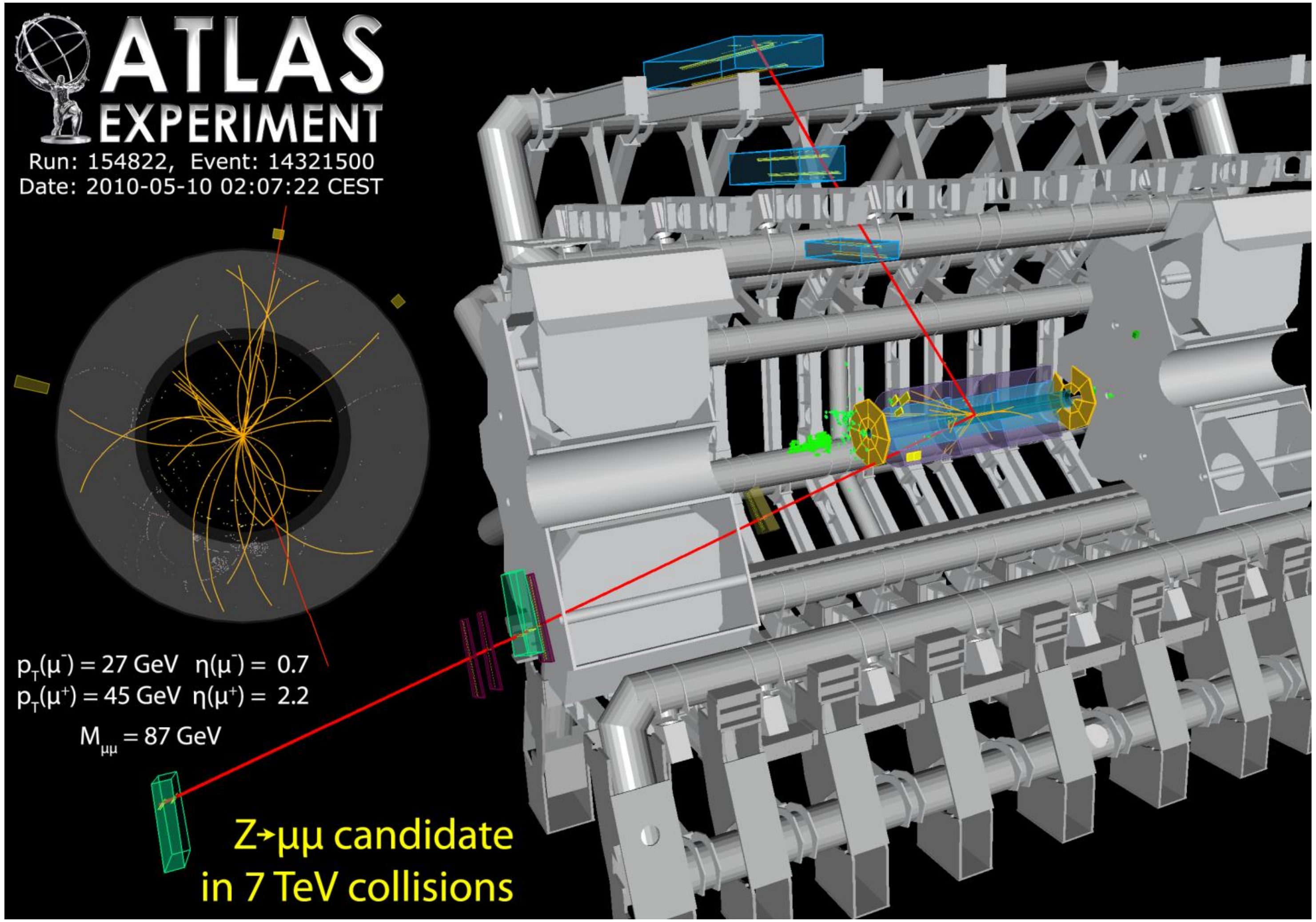
Electrons (Inner Detector, EM calorimeter & forward calrimeters)

Missing transverse energy (full calorimeter system)

The effective weak mixing angle

$pp \rightarrow \ell^+ \ell^- + X$

A Z candidate



Effective mixing angle from the lepton angular distributions

Factorized expression for Z boson production and decay at hadron colliders:

$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi}$$

Production ↑

$$= \frac{3}{16\pi} \frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

Decay ↓

$$\{(1+\cos^2\theta) + 1/2\, A_0(1-3\cos^2\theta) + A_1\, \sin 2\theta\, \cos\phi$$
$$+1/2\, A_2\, \sin^2\theta\, \cos 2\phi + A_3\, \sin\theta\, \cos\phi + A_4\, \cos\theta$$
$$+A_5\, \sin^2\theta\, \sin 2\phi + A_6\, \sin 2\theta\, \sin\phi + A_7\, \sin\theta\, \sin\phi\}.$$

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Unpolarized cross section

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Production

Decay

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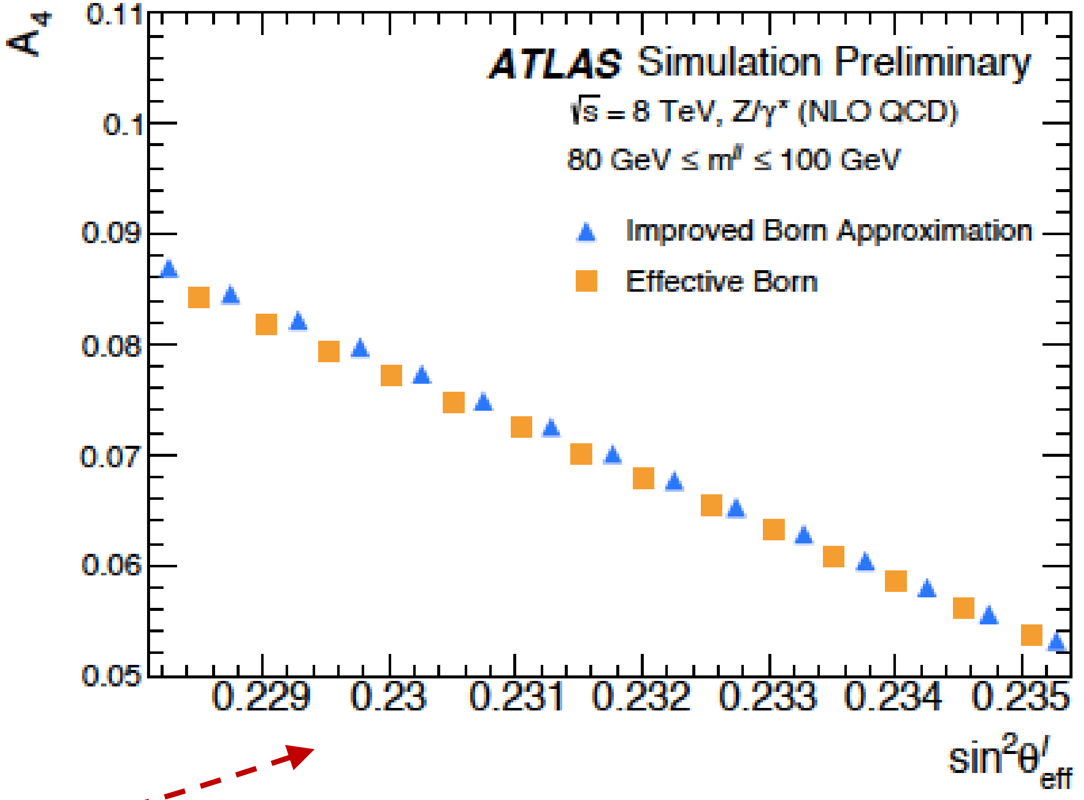


Unpolarized cross section

F/B asymmetry :

$A_4 = 8/3\, A_{FB} \sim a + b\, \sin^2\theta^l_{eff}$

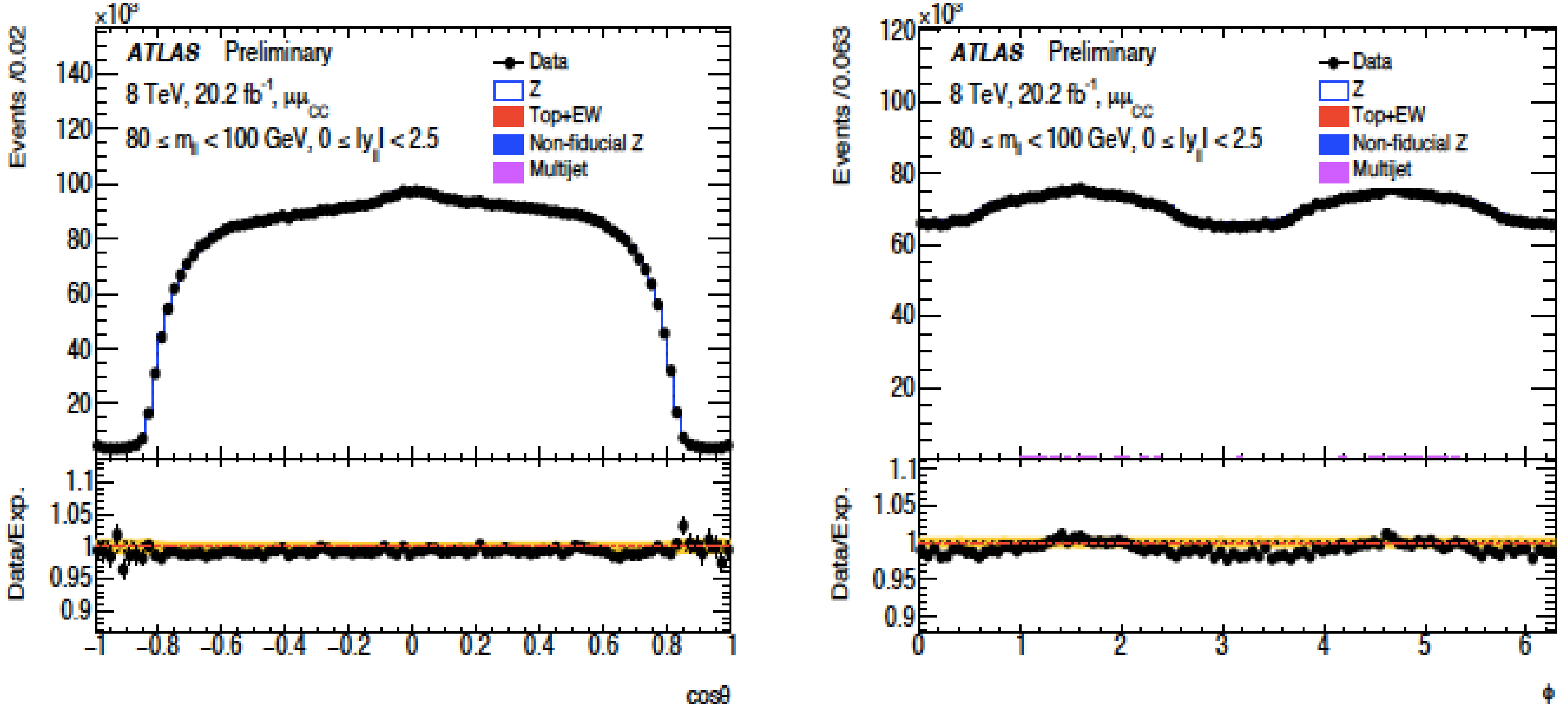
Measurement of the Ai coefficients (20 fb^{-1}, 8 TeV)

The observed angular distributions reflect the angular decomposition discussed above:

Event selection :

- Two muons of opposite charge
- p_T > 20 GeV
- $|\eta|$< 2.5

8M candidates in the muon channel. Similar selections in the electron channel.

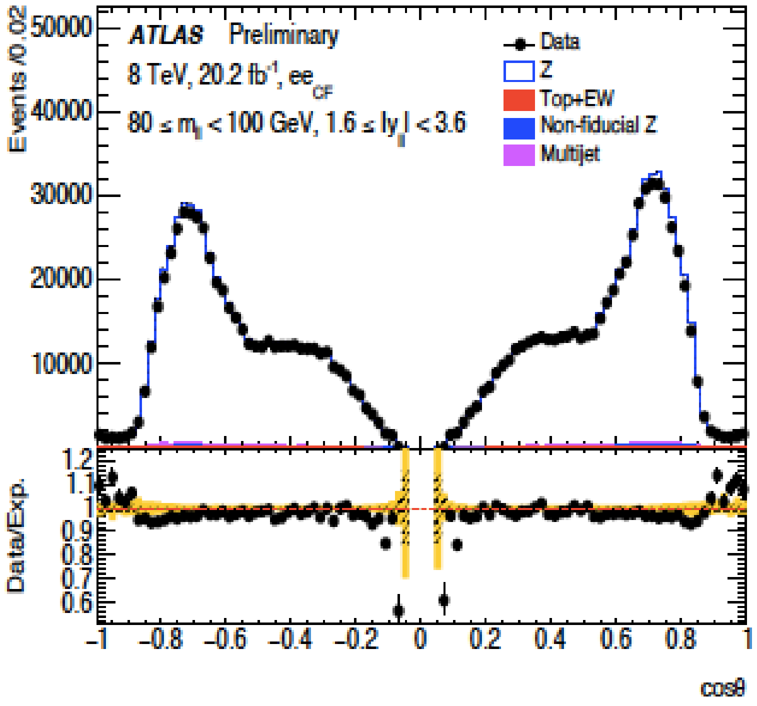


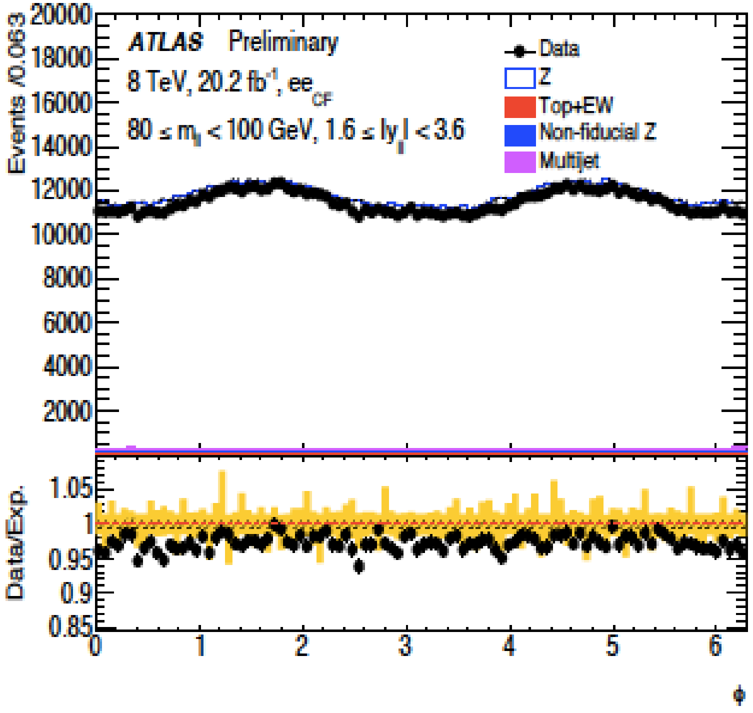
Measurement of the Ai coefficients

The observed angular distributions reflect the angular decomposition discussed above:

Event selection :
- Two reconstucted electrons
- p_T > 20 GeV
- $|\eta_1|$< 2.5, 2.5 <$|\eta_2|$< 4.9

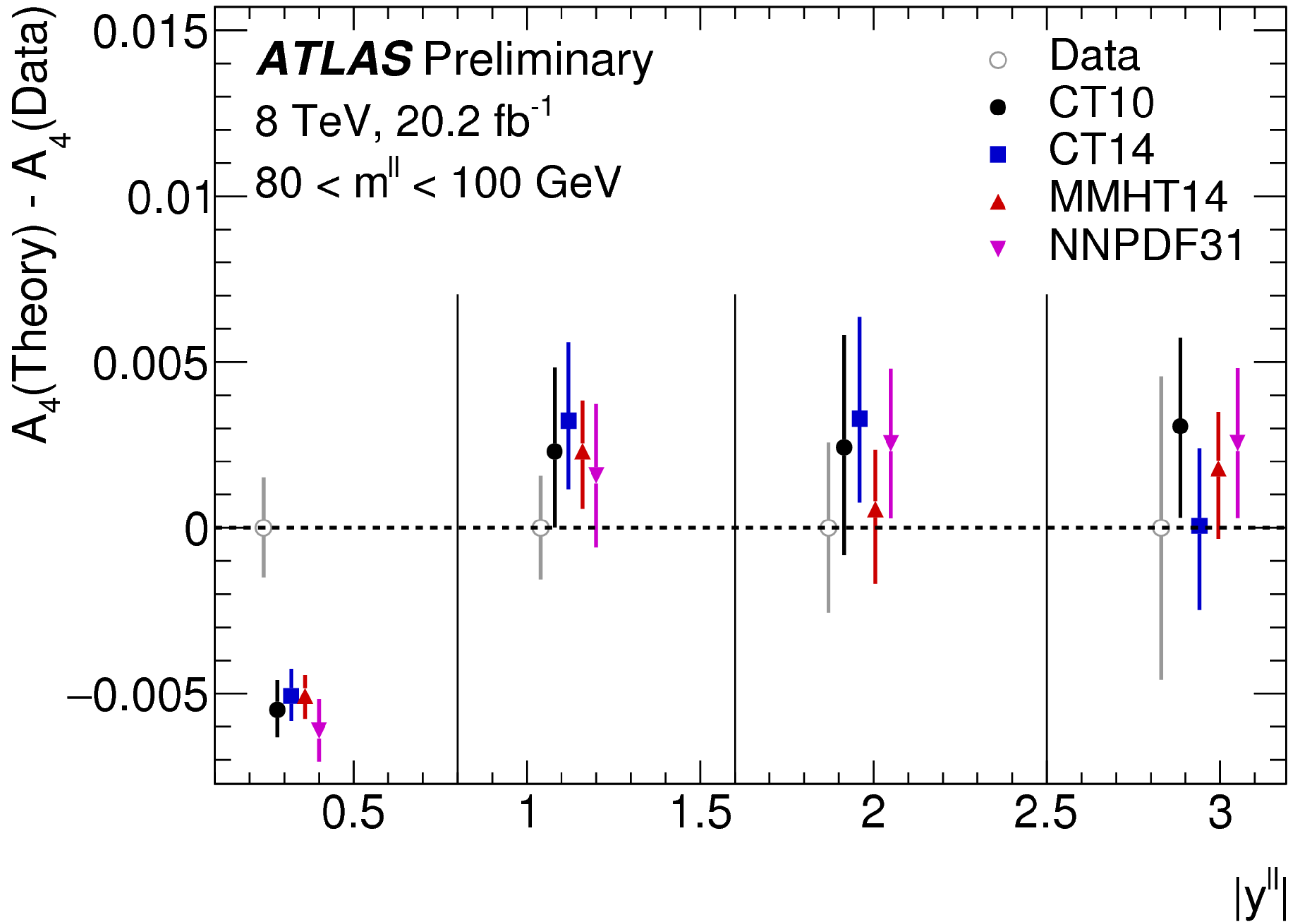
1.1M candidates from 20 fb^{-1} at 8 TeV





Measurement of the Ai coefficients

Results:

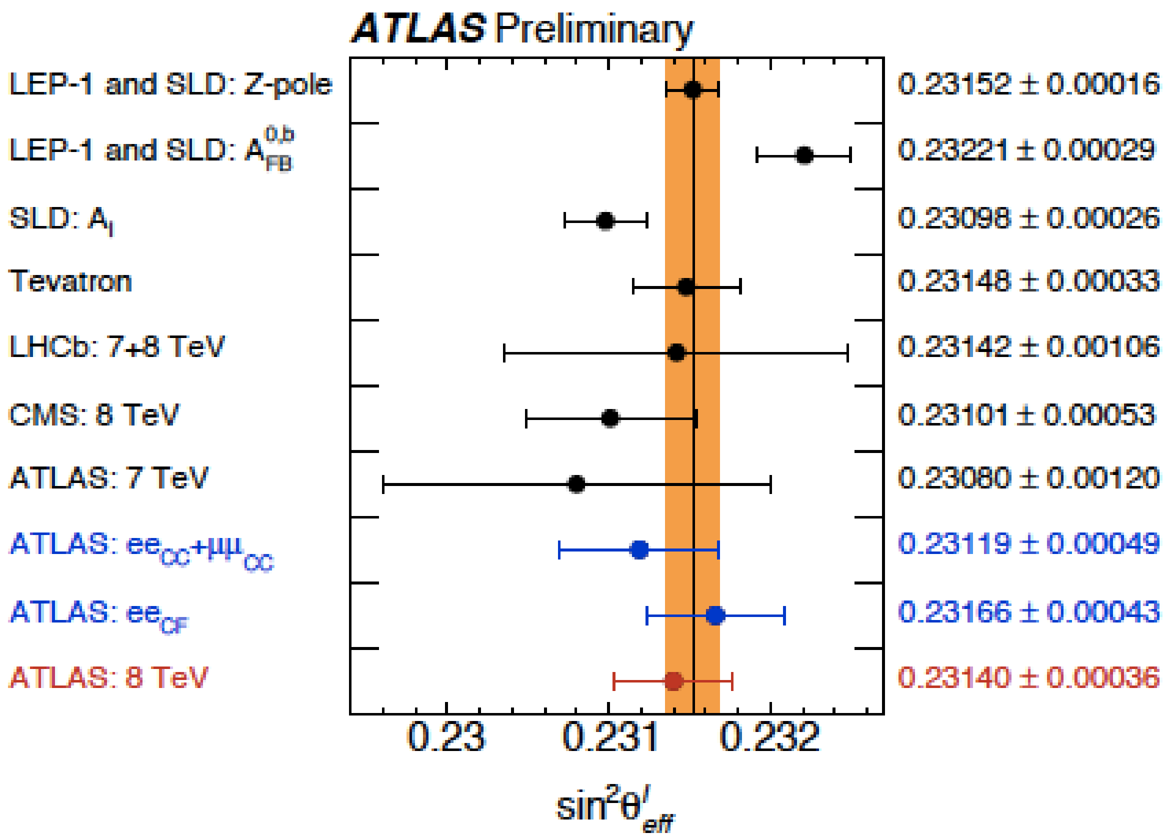


Predictions include PDF uncertainties for the four different PDF sets,
And assume $\sin^2\theta_W = 0.23152$.

Electrons and muons contribute for |y|<2.5,
Only electrons contrbute for |y|>2.5.

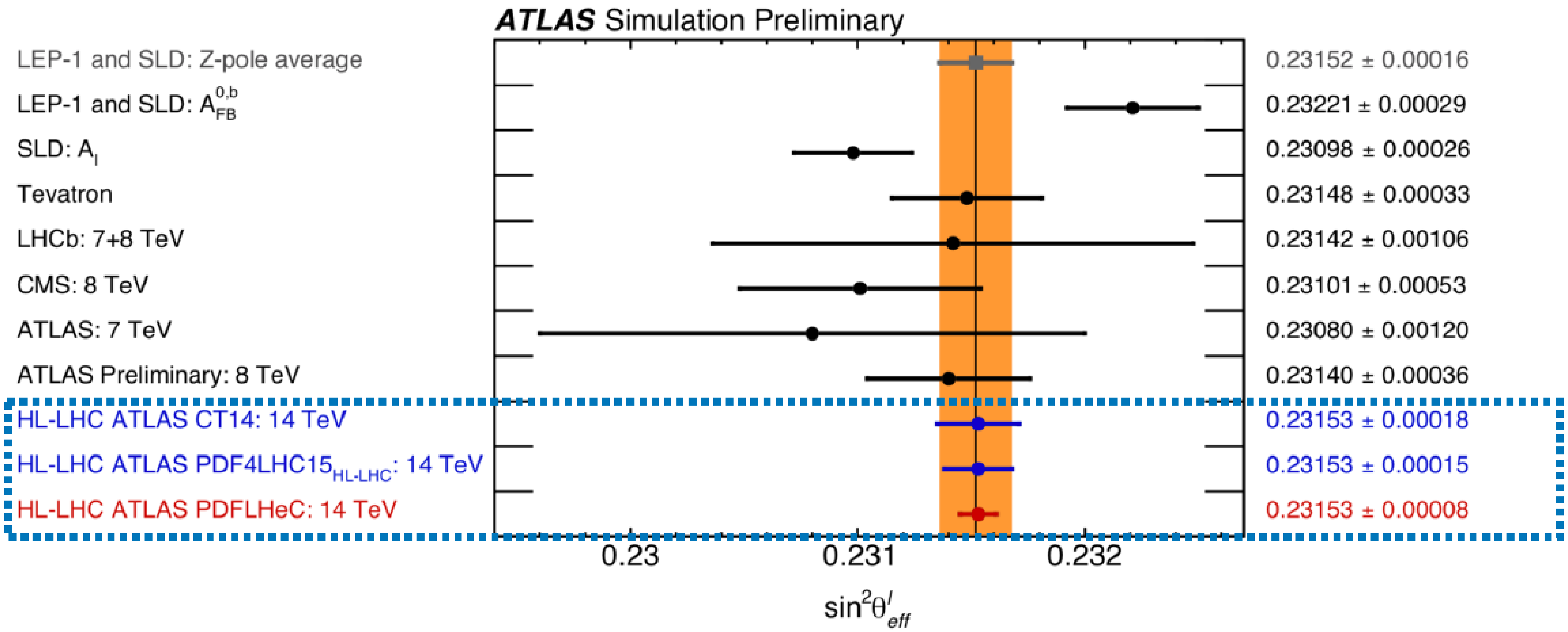
Results for the effective weak mixing angle

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



Competitive in precision with the previous best individual measurements (world average still a factor two better).

Prospects at the HL-LHC



Prospects @HL-LHC:

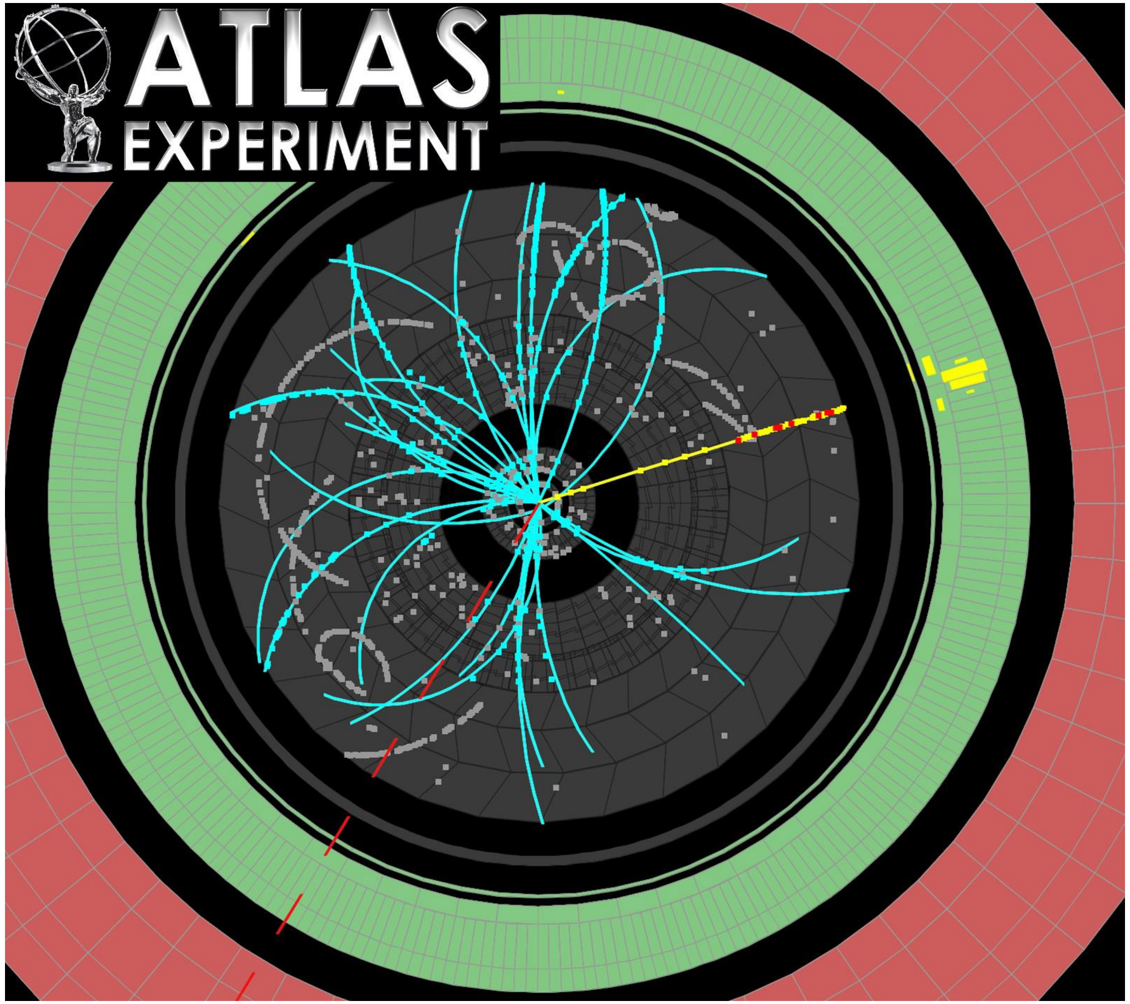
- reduction of statistical uncertainty (3000 fb^{-1})
- Extended pseudo-rapidity coverage ($|\eta|<4$)
- Expected reduction of PDF uncertainties

Including LHeC data: reduction of PDF (total) uncertainties by a factor of ~5 (2) wrt to HL-LHC PDFs.

The W boson mass

pp → $\ell^{\pm}$ ν + X

Event representation



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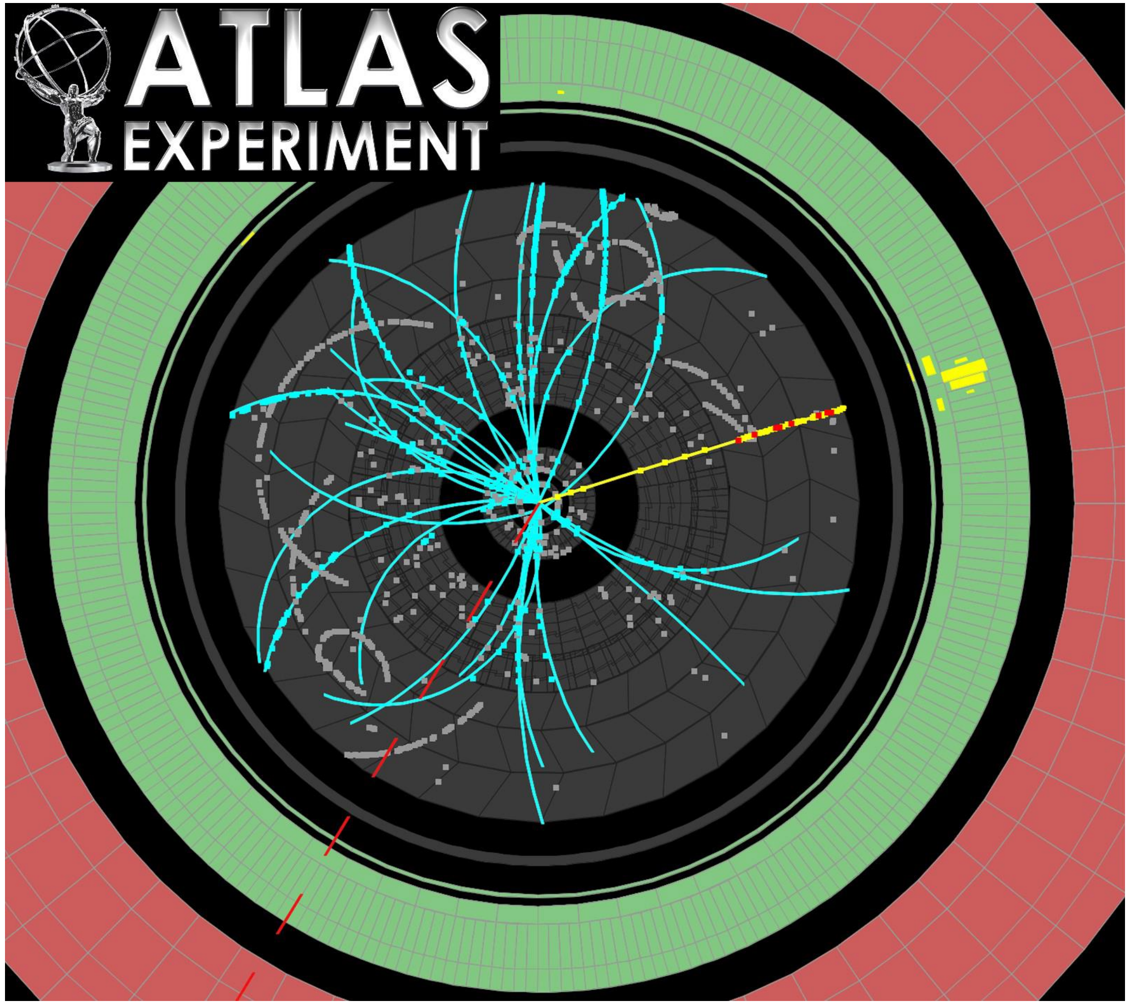

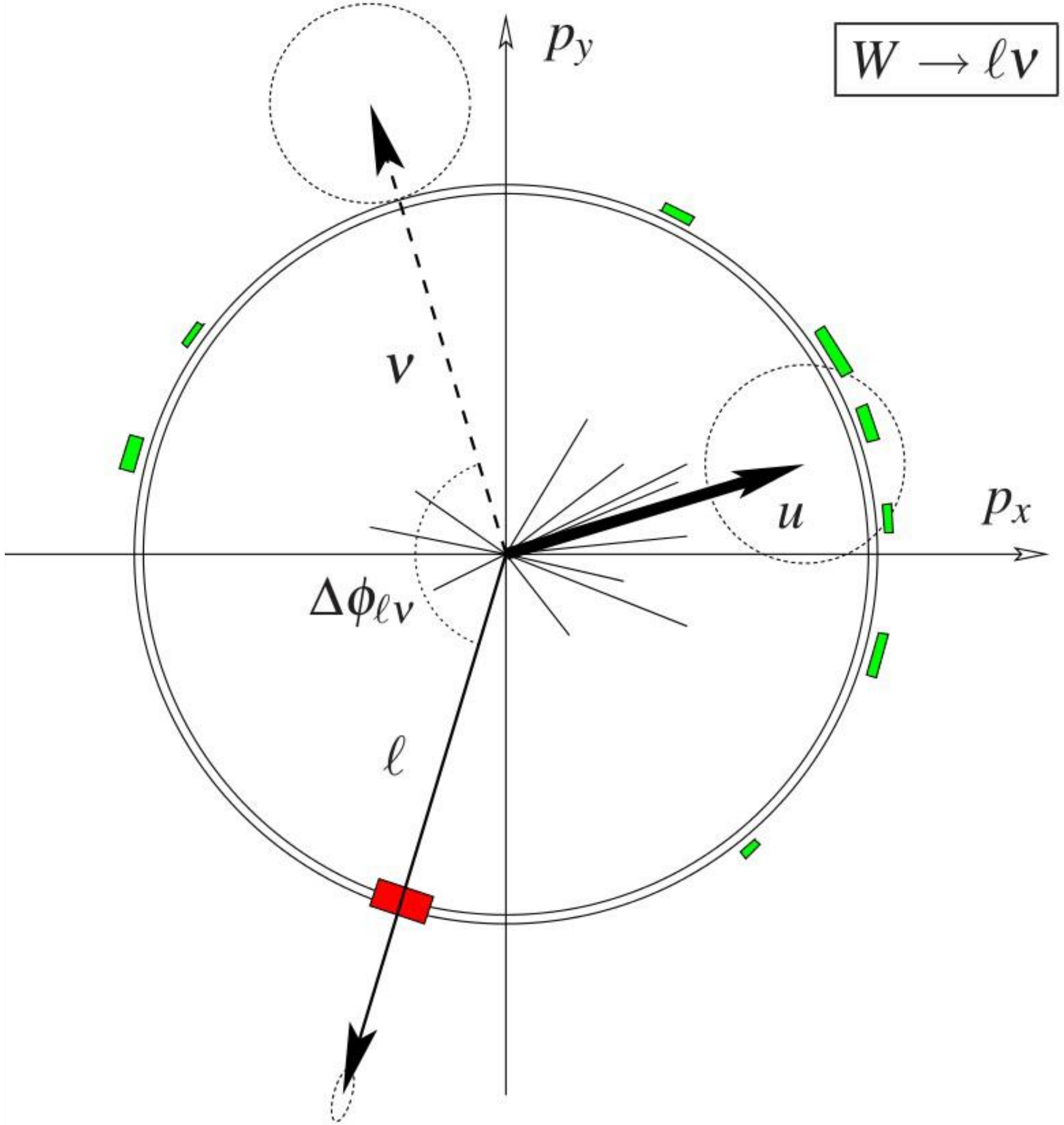

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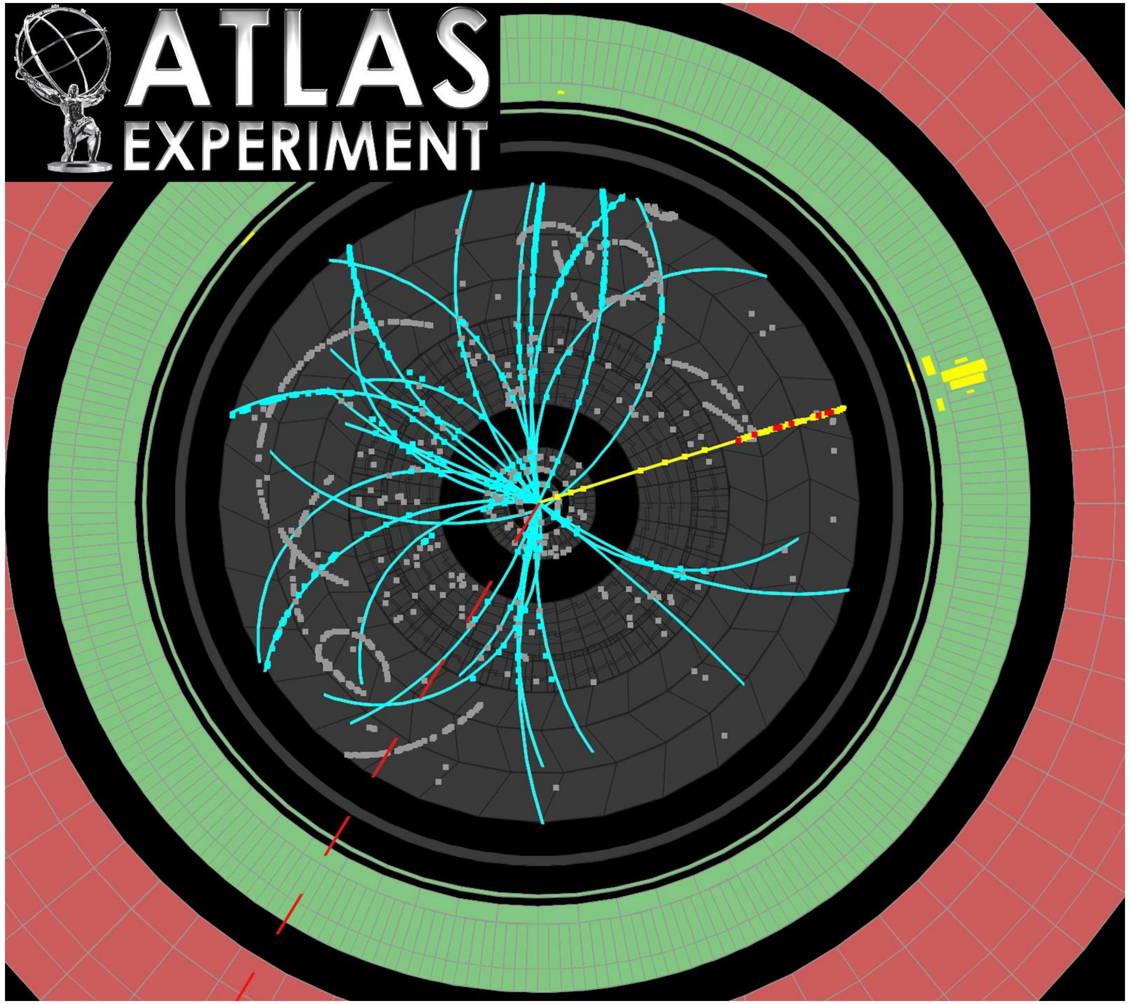
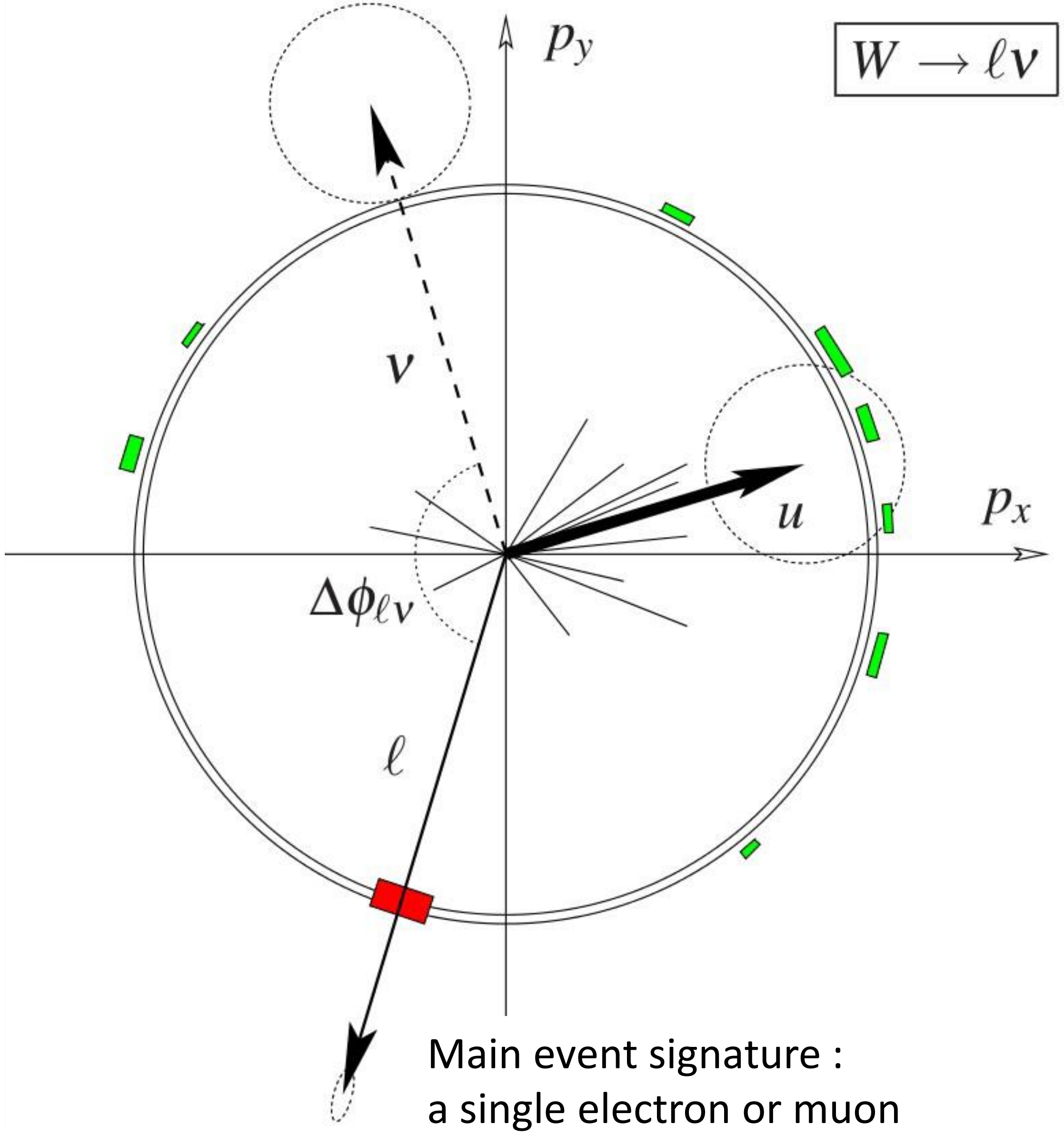
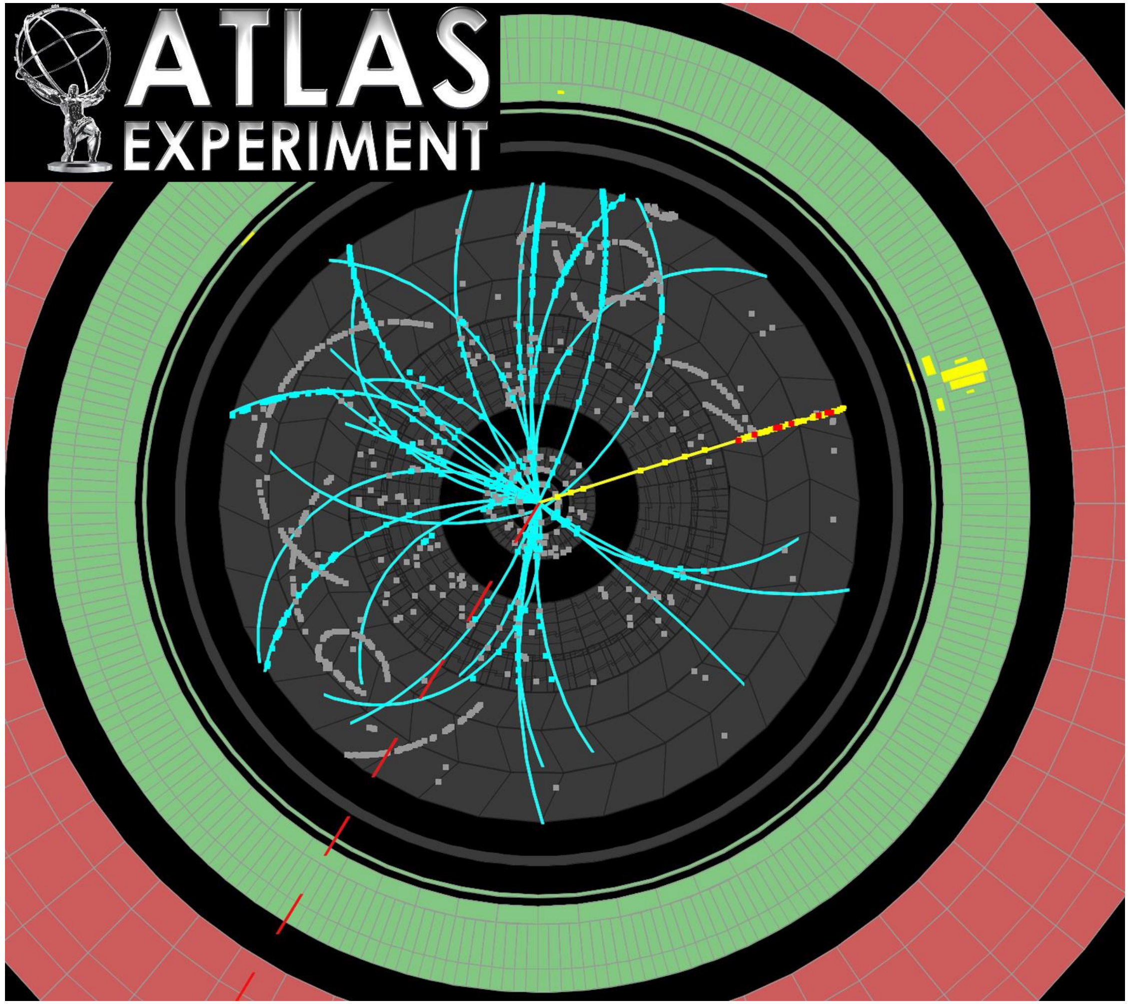
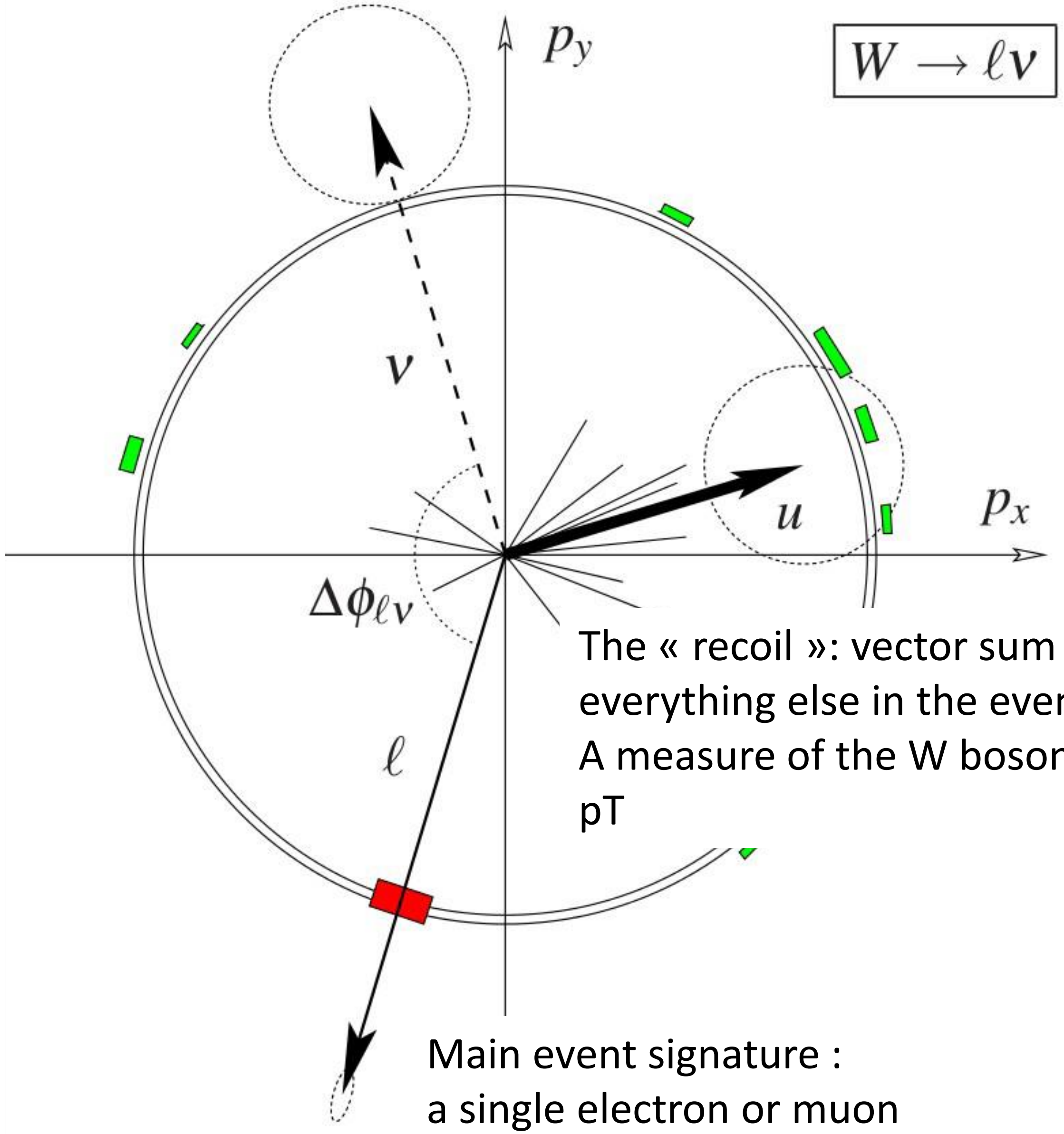




Main event signature :
a single electron or muon

Event representation



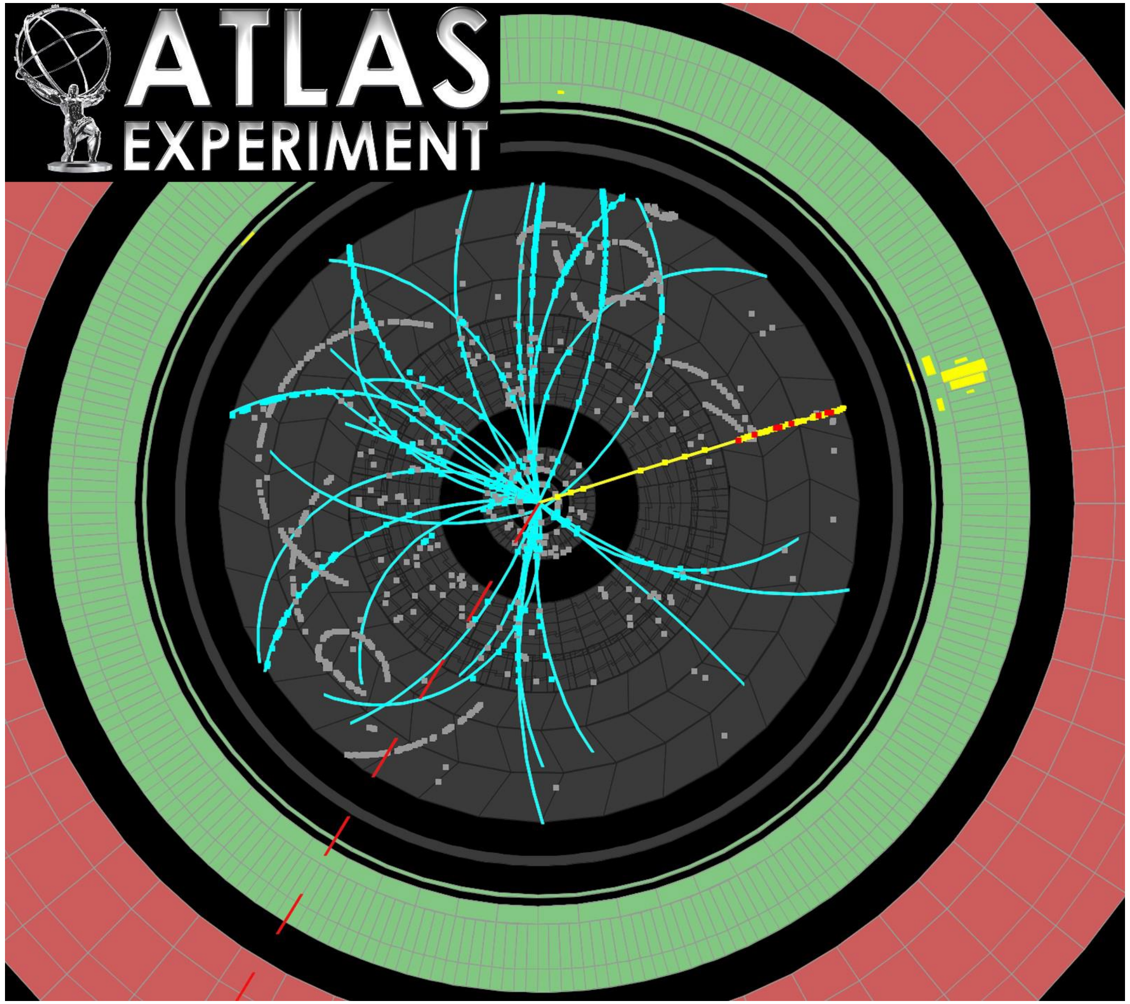


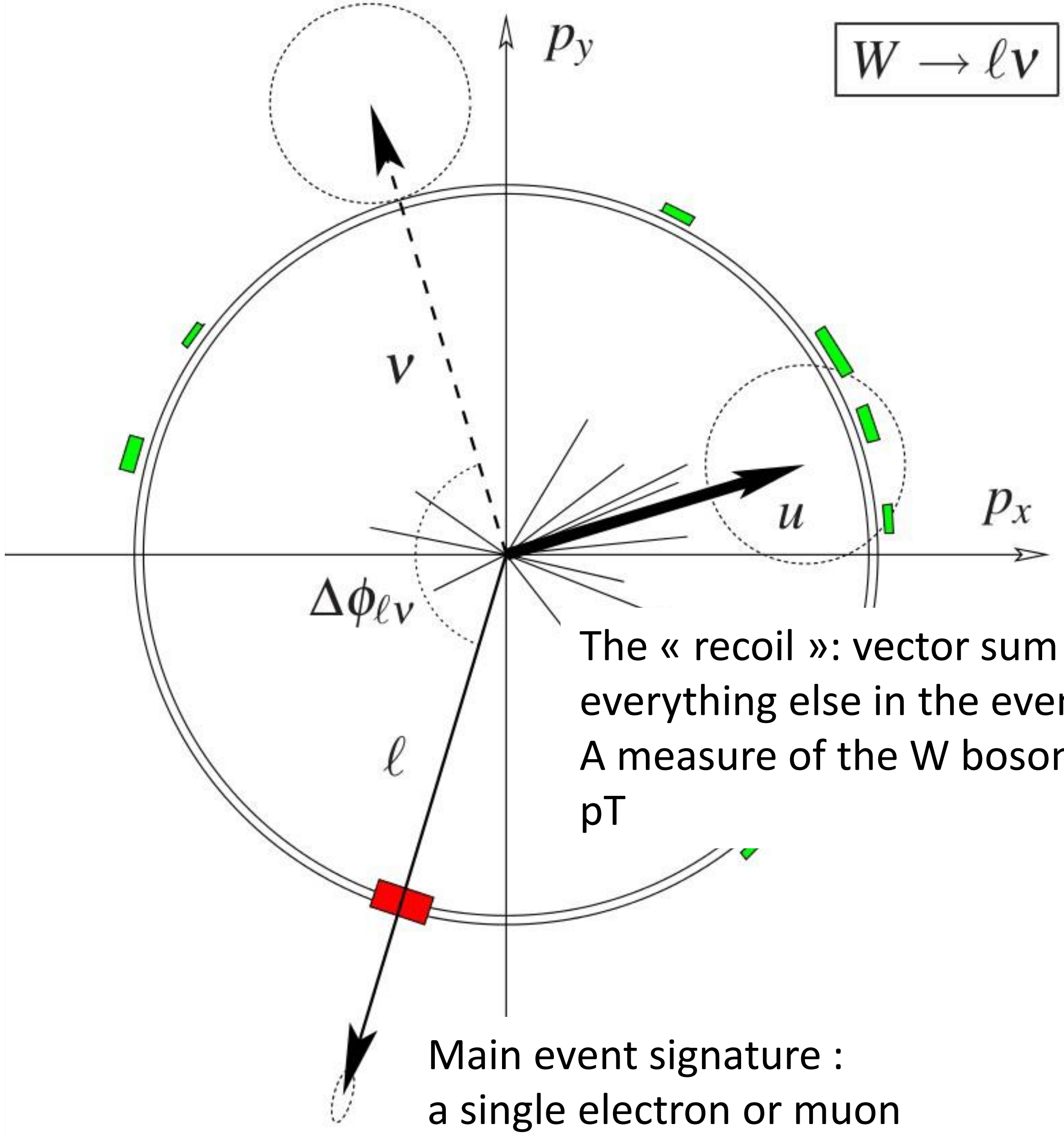
The « recoil »: vector sum of everything else in the event. A measure of the W boson pT

Main event signature :
a single electron or muon

Event representation

Derived quantities : missing transverse energy (measures the neutrino pT); transverse mass





The « recoil »: vector sum of everything else in the event. A measure of the W boson pT

Main event signature :
a single electron or muon

Measurement setup (5 fb^{-1}, 7 TeV)

Lepton selections

- Muons : $|\eta| < 2.4$; isolated (track-based)
- Electrons : $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated (track+calorimeter-based)

Kinematic requirements

- $p_T^l > 30$ GeV $p_T^{miss} > 30$ GeV
- $m_T > 60$ GeV $u_T < 30$ GeV

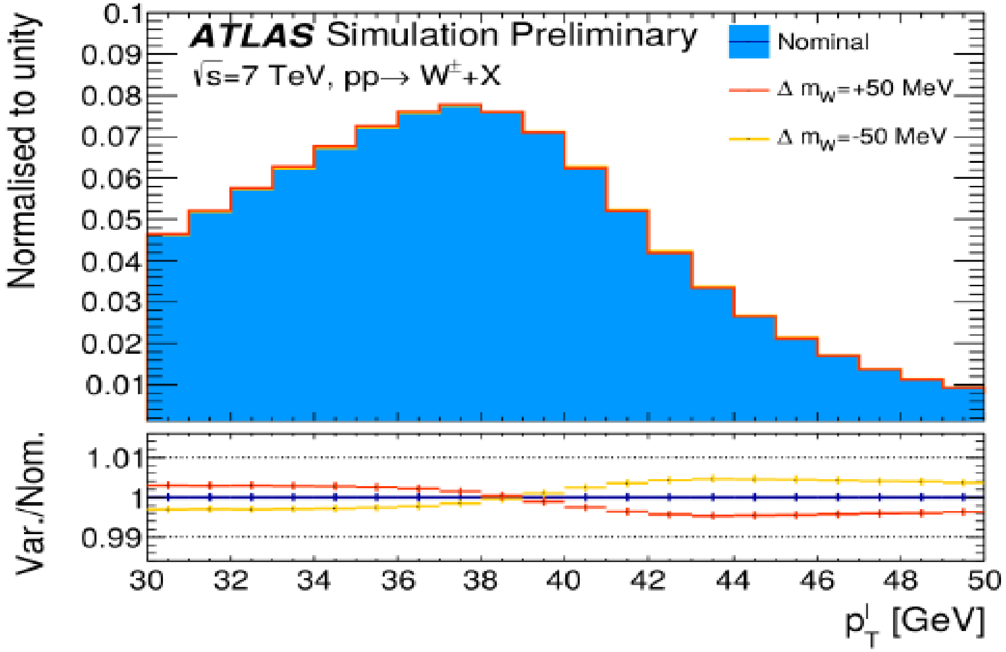
Measurement categories :

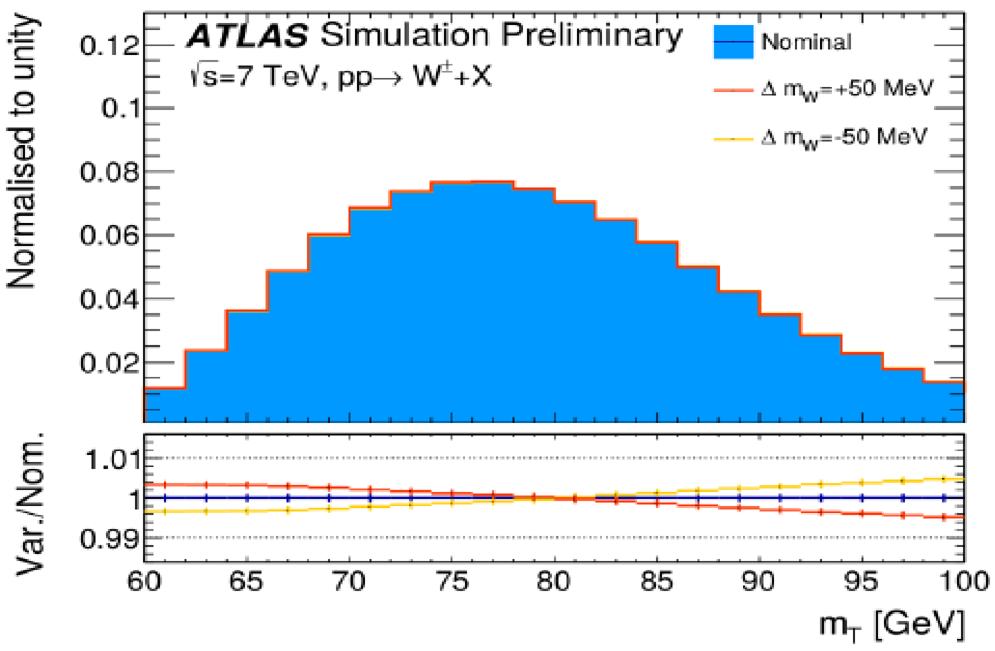
$\|\eta_\ell\|$ range	0 – 0.8	0.8 – 1.4	1.4 – 2.0	2.0 – 2.4	Inclusive	
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818	7.8 M events
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960	
$\|\eta_\ell\|$ range	0 – 0.6	0.6 – 1.2		1.8 – 2.4	Inclusive	
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716	5.9 M events
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525	

Measurement strategy

Mass fits

- Sensitive final state distributions : p_T^l , m_T , p_T^{miss}
- Signal distributions contructed from a single Monte Carlo sample, reweighting the boson invariant mass distribution, and compared to data. Mass determination by χ^2 minimization
- Resonance parametrisation : $\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$
- A blinding offset was applied throughout the measurement, and removed when consistent results were found (compatibility among decay channels, etc).





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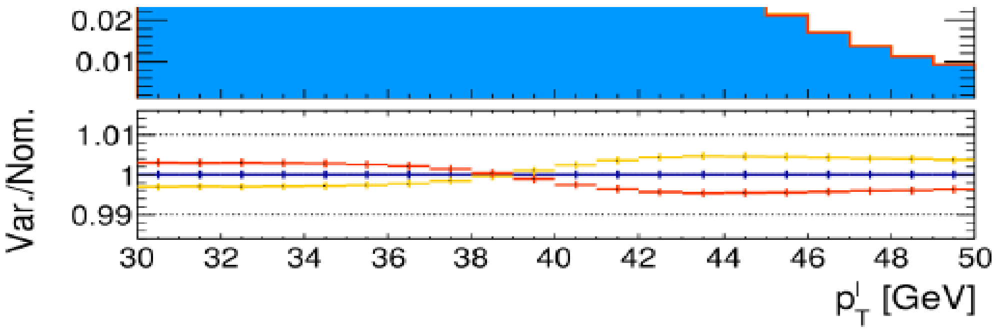
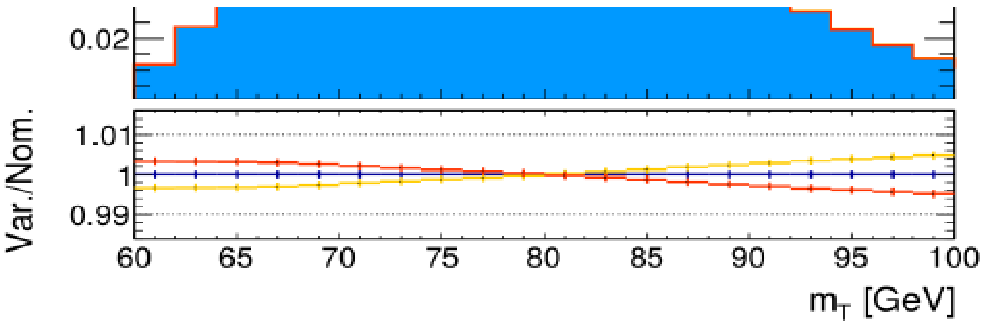
Extremely simple in principle, but all effects entering the observed distributions:

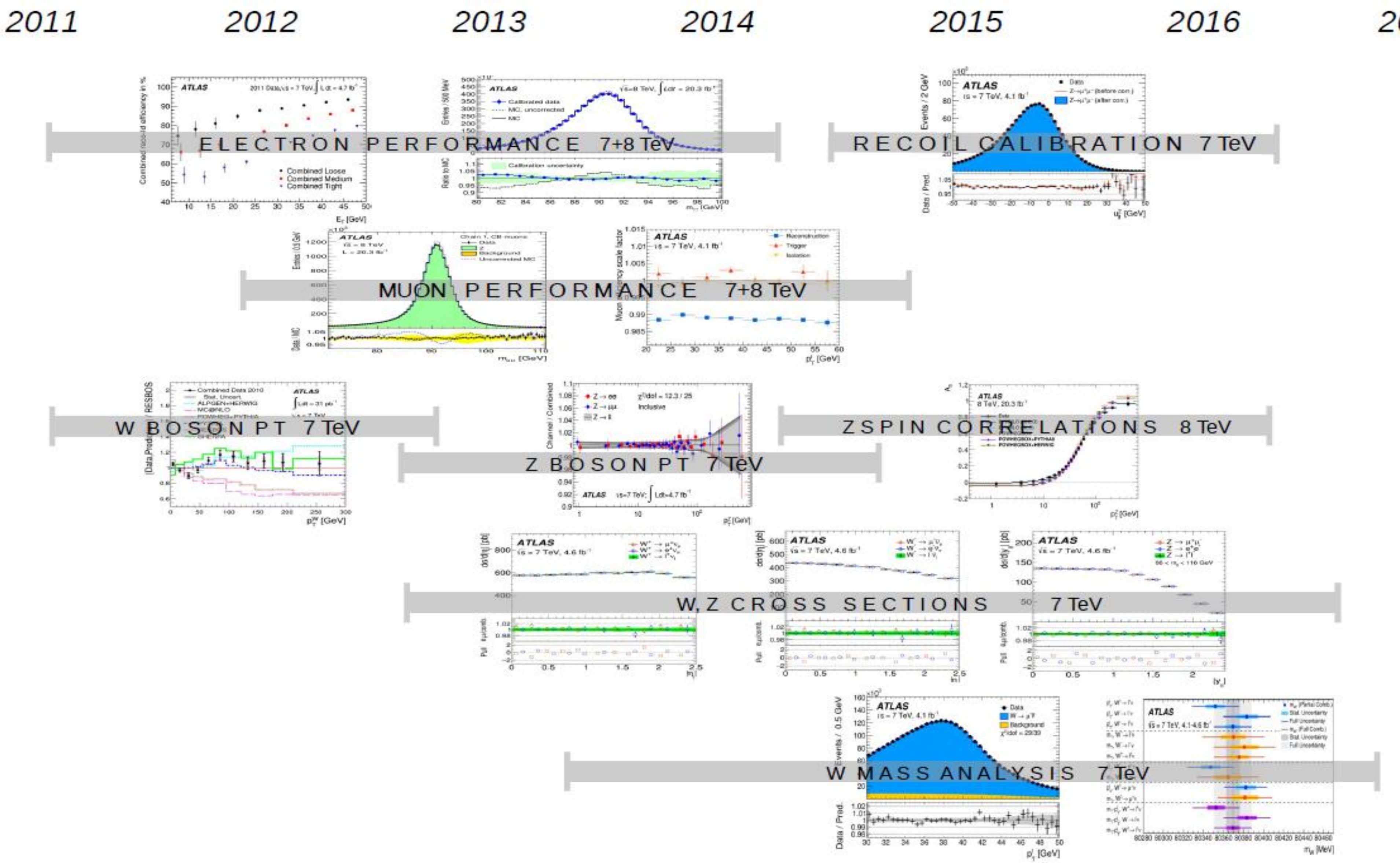
- Detector calibration
- Physics modelling of W production and decay

need to be controlled to 0.01 – 0.1%





Timeline (main project and ancillary measurements)

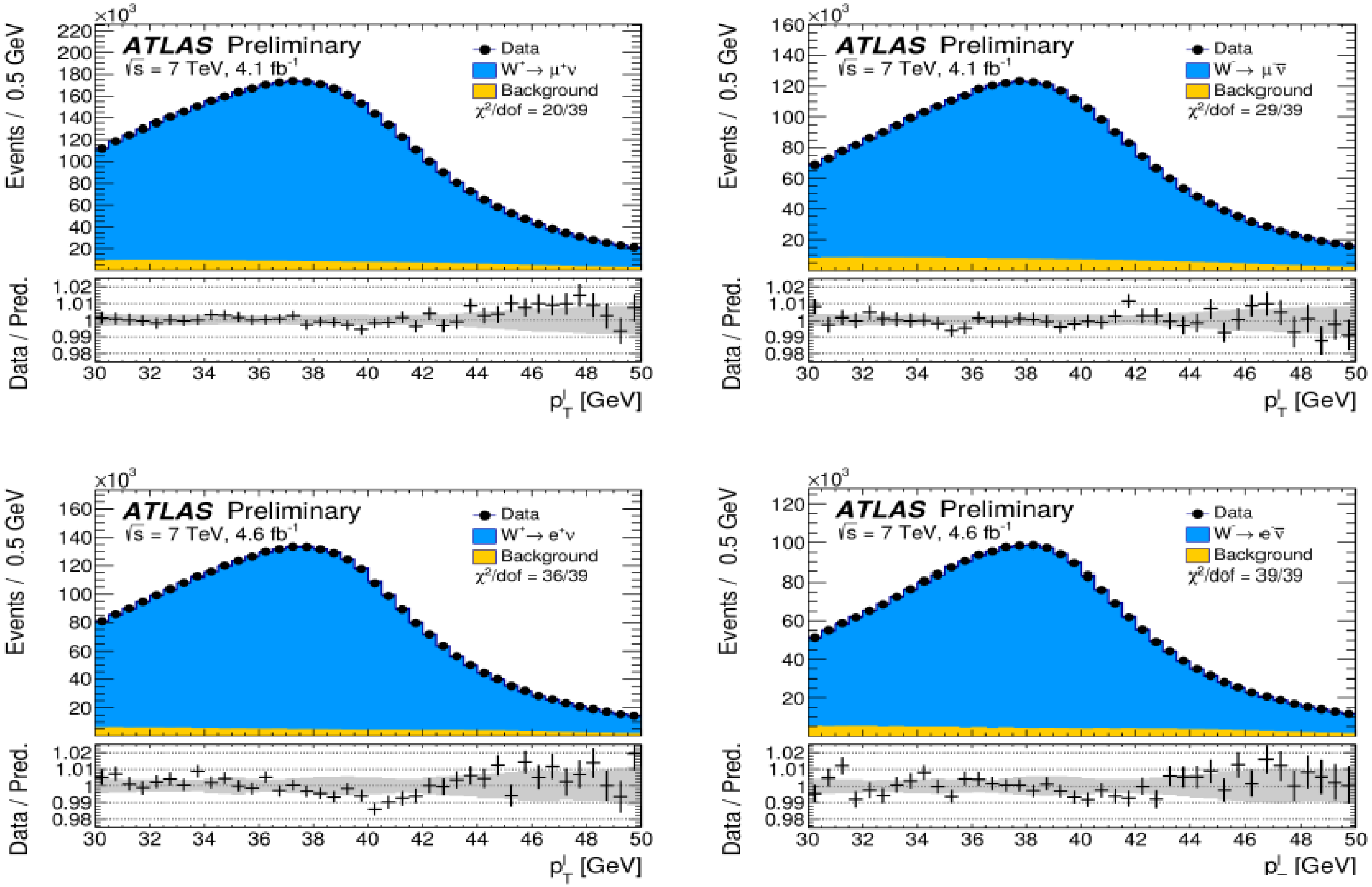


Results

W+ W-

Muons

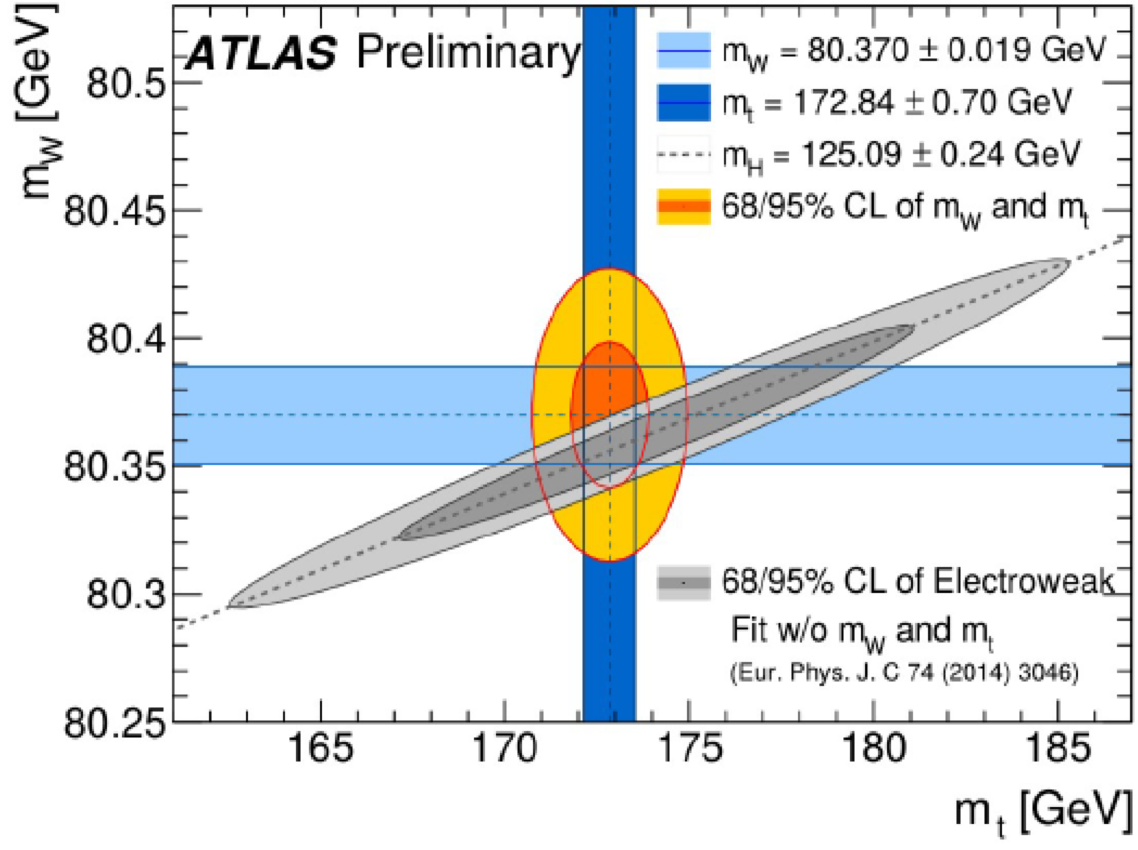
Electrons

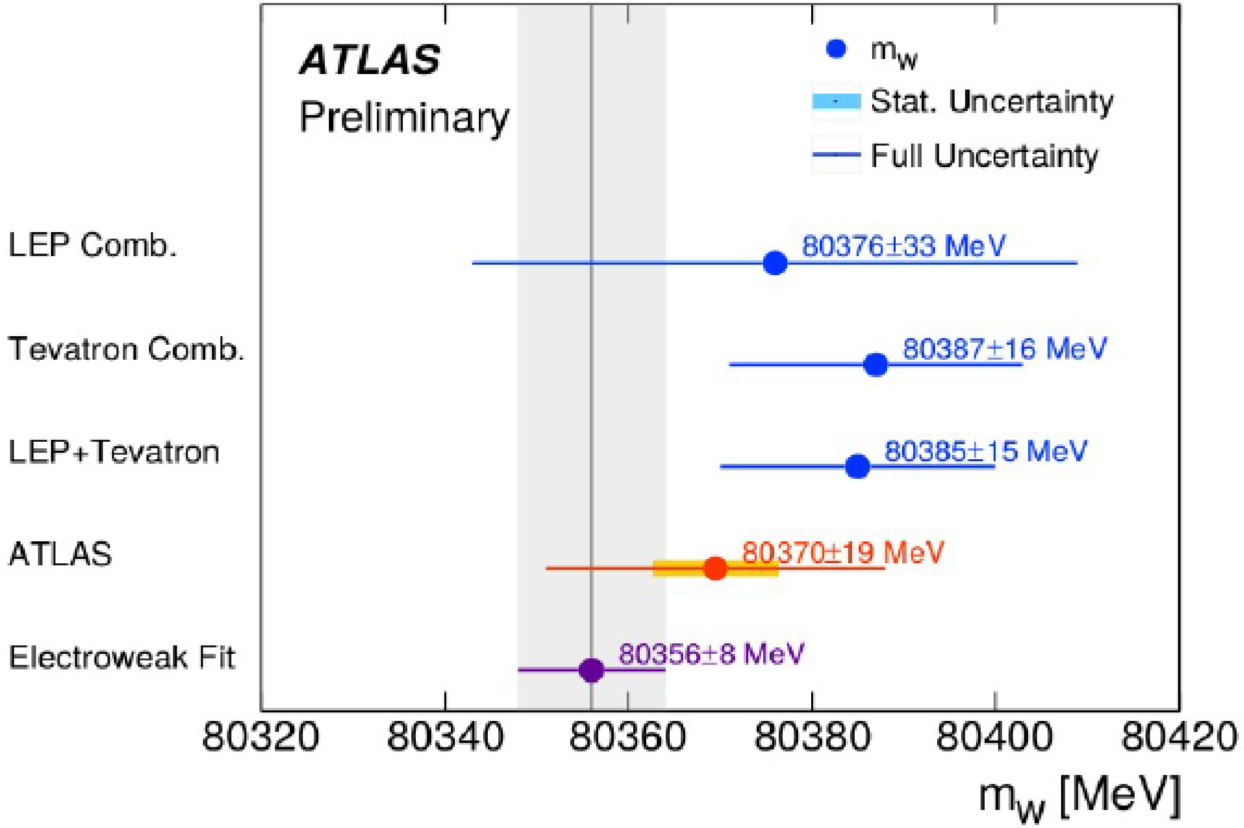


(predictions set to the result of the combined m_W fit to all distributions)

Results

m_W = 80.370 ± 0.007 (stat.) ± 0.011 (exp.syst.) ± 0.014 (mod.syst.) GeV
= <u>80.370 ± 0.019 GeV</u>



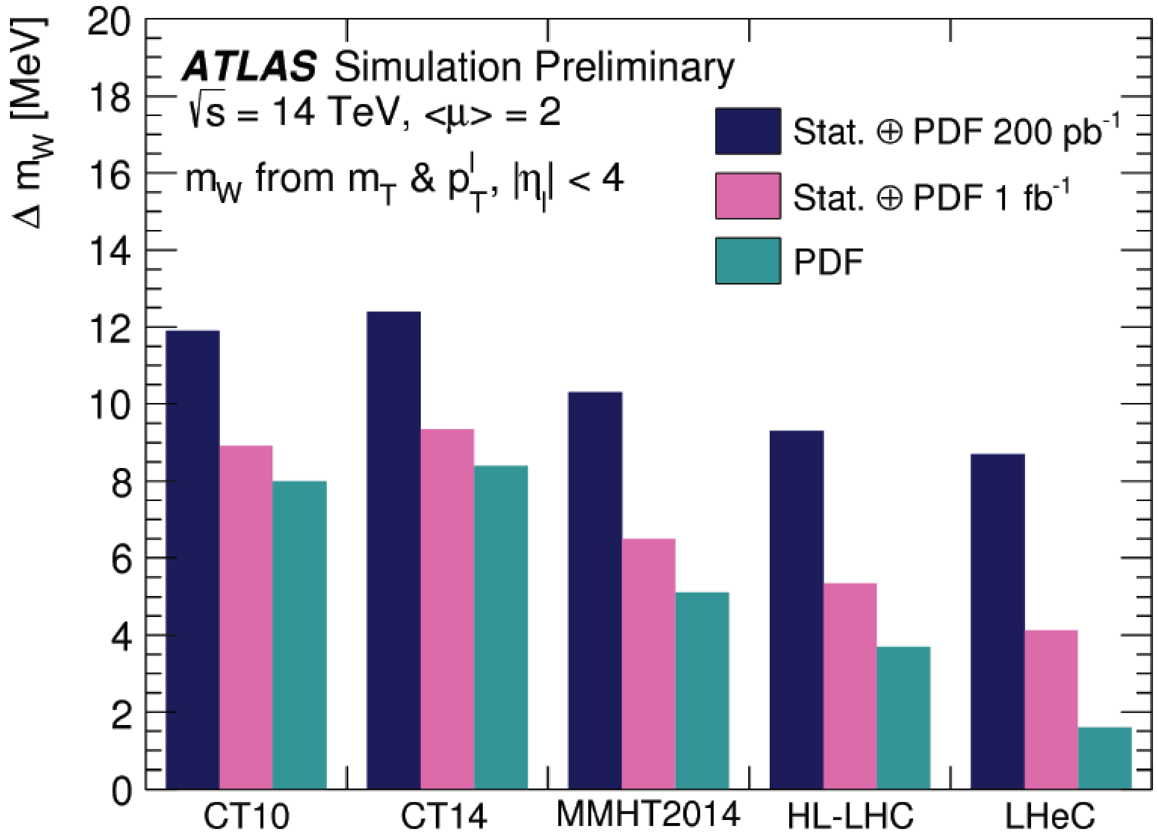


Prospects at the HL-LHC

Potential low pile-up runs at HL-LHC (14 TeV) and HE-LHC (27 TeV): 200 pb-1 per week, yielding ~1M candadite/week

Extended coverage with new tracking detector: $|\eta| < 4$ —> 30% reduction of PDF uncertainties.

PDF uncertainties can be reduced to about 4 MeV using HL-LHC PDF sets, and to 2 MeV using inputs From a possible LHeC.

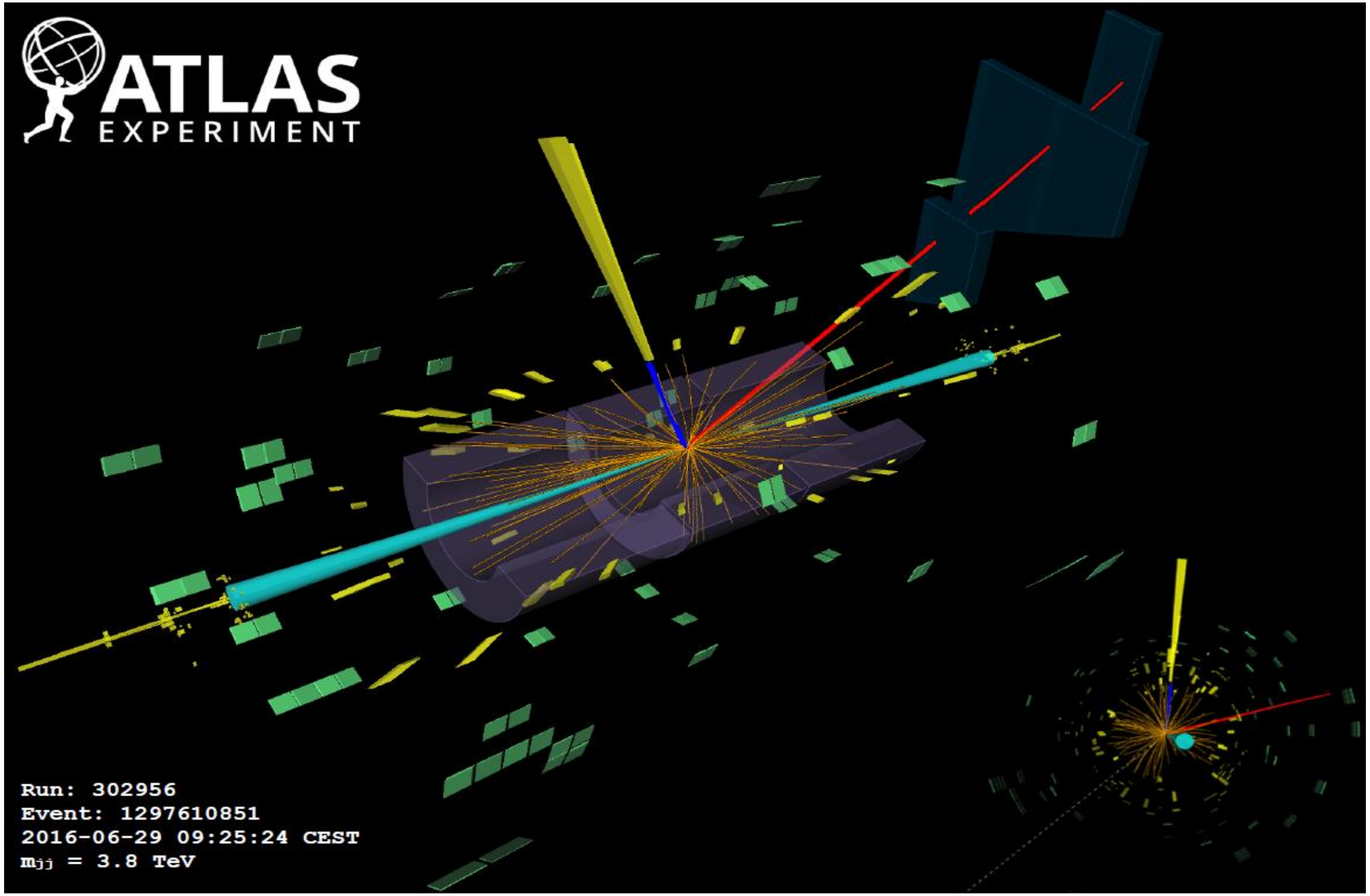


Weak boson interactions at high energy

pp → leptons/neutrinos + jj + X

(following slides courtesy Philip Sommer)

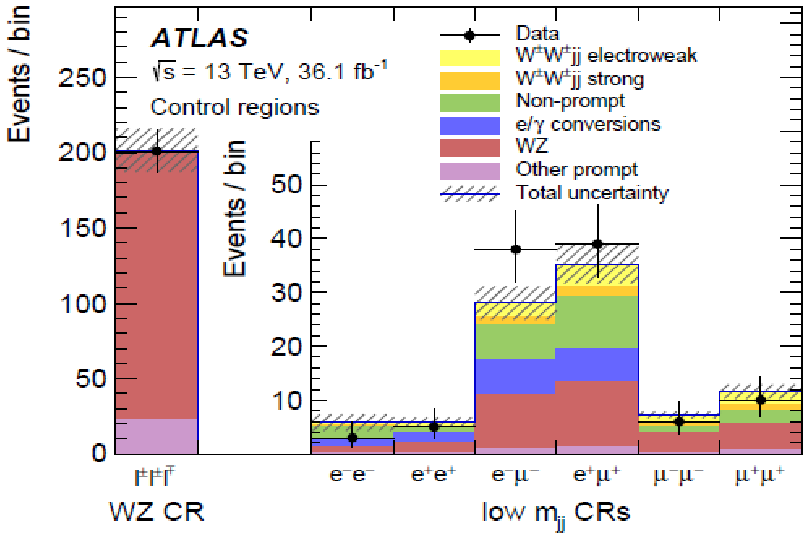
A spectacular signature :
2 or more leptons and two very forward, high-pT jets

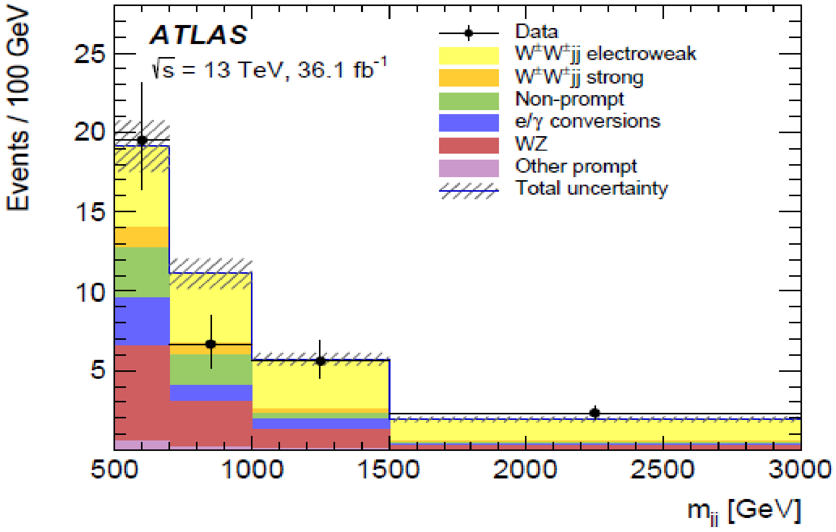


An electroweak $W^{\pm}W^{\pm}jj$ candidate event. The jets have p_T=118 GeV and p_T=104 GeV, with m_{jj}=3.8 TeV and Δy_{jj}=7.1.

Observation of Electroweak $W^{\pm}W^{\pm}jj$ Production

arXiv:1906.03203



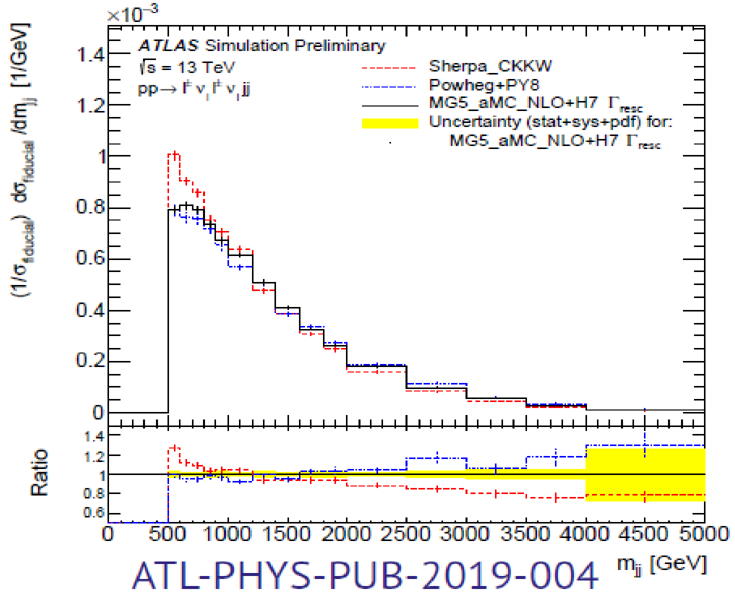


The analysis explores different background compositions in a likelihood fit to five bins in m_{jj}

(by fitting e^+e^+, e^-e^-, $e^+\mu^+$, $e^-\mu^-$, $\mu^+\mu^+$, $\mu^-\mu^-$ separately)

Separate bin to constrain *WZjj* yield

$0.86^{+0.07}_{-0.07}$ (stat.)$^{+0.18}_{-0.08}$ (exp. syst.)$^{+0.31}_{-0.23}$ (mod. syst.)



ATL-PHYS-PUB-2019-004

Background-only hypothesis rejected with 6.5σ

(where 4.4σ and 6.5σ expected from Sherpa and PowhegBox+Pythia8, respectively)

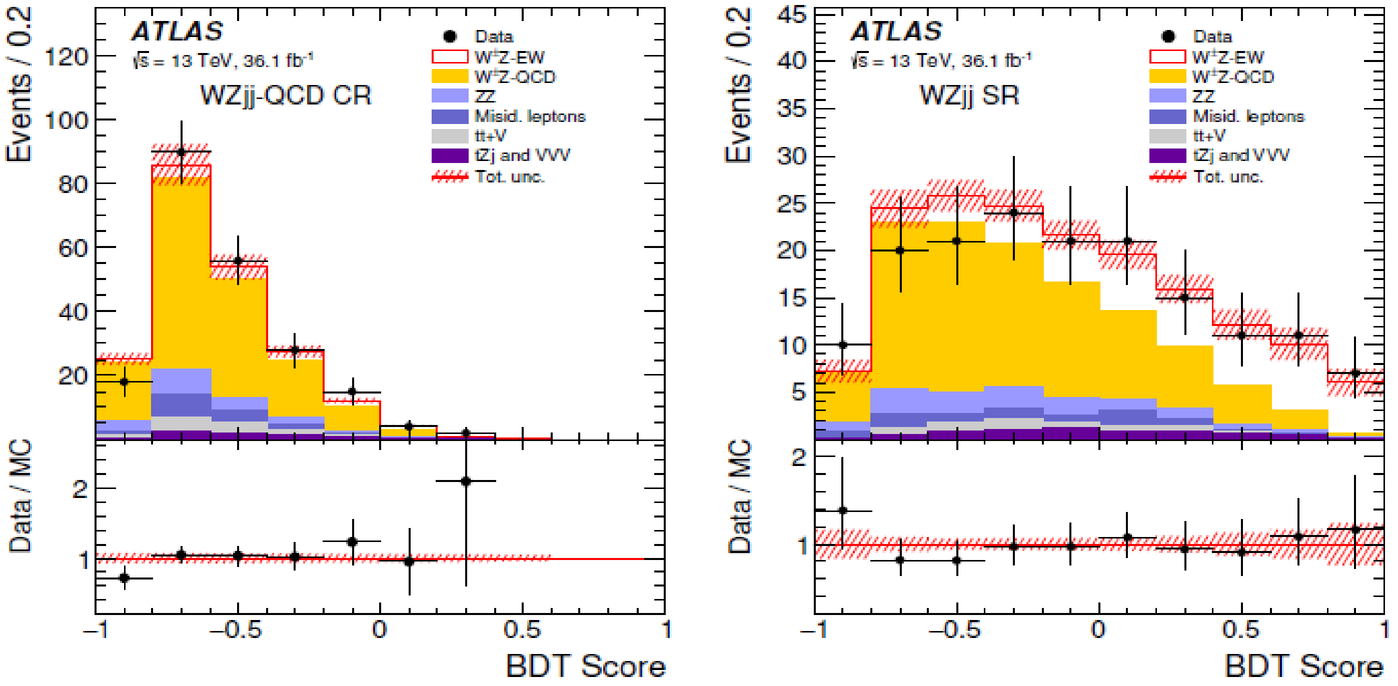
Observation of Electroweak *WZjj* Production

Phys. Lett. B 793 (2019) 469

Signal extracted by fitting a BDT discriminant built from 15 variables

- jet kinematics
  (m_{jj}, p_T^{j1}, p_T^{j2}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, y^{j1}, n_{jets})
- diboson kinematics
  (p_T^W, p_T^Z, η^W, $|y_Z - y_{\ell,W}|$, m_T^W)
- combined jet-diboson
  ($\Delta R(j_1, Z)$, $R_{p_T}^{\text{hard}}$, ζ_{lep})

Background constrained in three control regions



Overestimation of strong *WZjj* production in Sherpa2.2.2, $\mu_{WZ-\text{QCD}} = 0.56 \pm 0.16$

Difference in electroweak *WZjj* between Sherpa2.2.2 and MG5_aMC@NLO

Background only hypothesis rejected with 5.3σ (expected 3.2σ)

	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
$WZjj$–EW (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21 ± 0.12
$WZjj$–QCD	144 ± 41	231 ± 60	24.4 ± 1.7	1.43 ± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47 ± 0.21
$ZZjj$–QCD	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18 ± 0.04
$t\bar{t}+V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ± 10.3	2.8 ± 0.61
$ZZjj$–EW	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05 ± 0.30

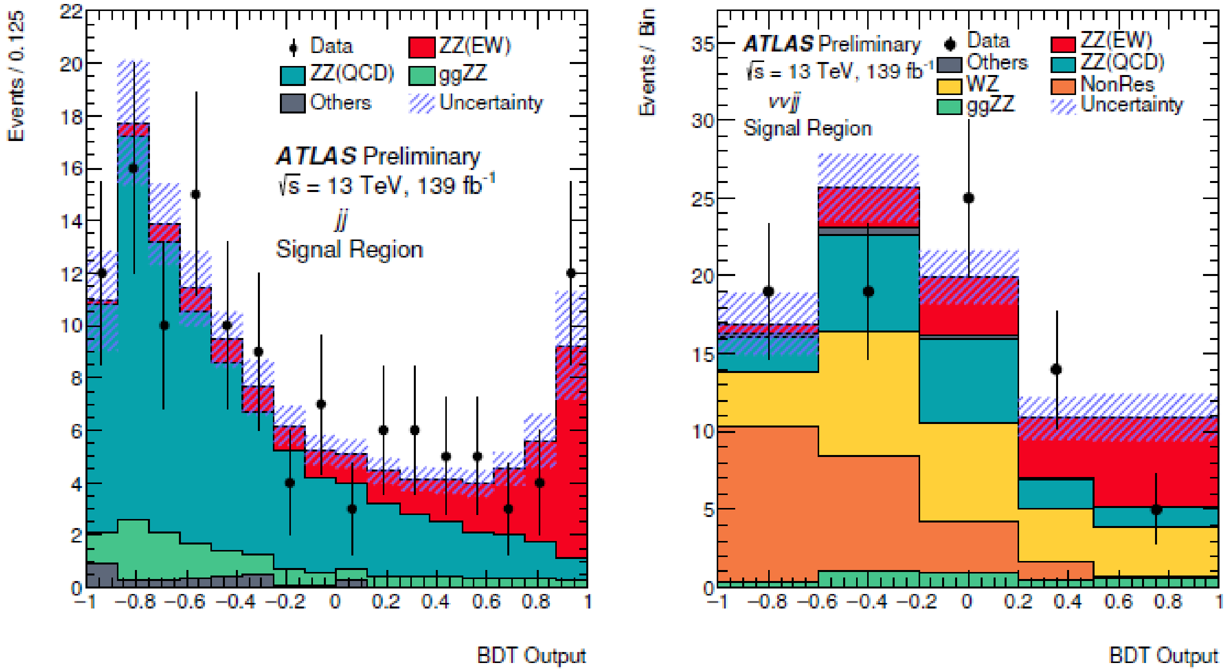
Event yields, pre-fit

Observation of Electroweak *ZZjj* Production

ATLAS-CONF-2019-033

The electroweak signal is extracted using a BDT with 12 (4ℓ) or 13 ($2\ell2\nu$) variables

A fit of the BDT discriminant is performed simultaneously in $4\ell jj$ and $2\ell2\nu jj$ (with a 4ℓ QCD CR defined by events failing Δy_{jj} or m_{jj})



Electroweak *ZZjj* production is observed **for the first time** with the background-only hypothesis rejected with 5.5σ (expected 4.3σ from MG5_aMC@NLO)

The fiducial cross section is measured to be:

$$\sigma^{\text{fid.}}_{ZZjj-\text{EW}} = 0.82 \pm 0.21 \text{ fb}$$

in agreement with the MG5_aMC@NLO prediction of 0.61 ± 0.03 fb

Summary

- After almost ten years of operation, the LHC is competing with the previous machines in electroweak precision.

- First mearuements of m_W and $\sin^2\theta^l_{eff}$ match the earlier best inividual measurements, and show the path for future iterations

- Vector boson interactions at high energy are probed for the first time at the LHC, and will join the set of precision probes of EWSB in the mid term.