Precision Test of Standard Model from High Energy Colliders

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On behalf of the ATLAS, CMS and LHCb experiments

Introduction

Lord Kelvin at British Association for the Advancement of Science in 1900:

"There is nothing new to be discovered in physics now.

All that remains is more and more precise measurements."

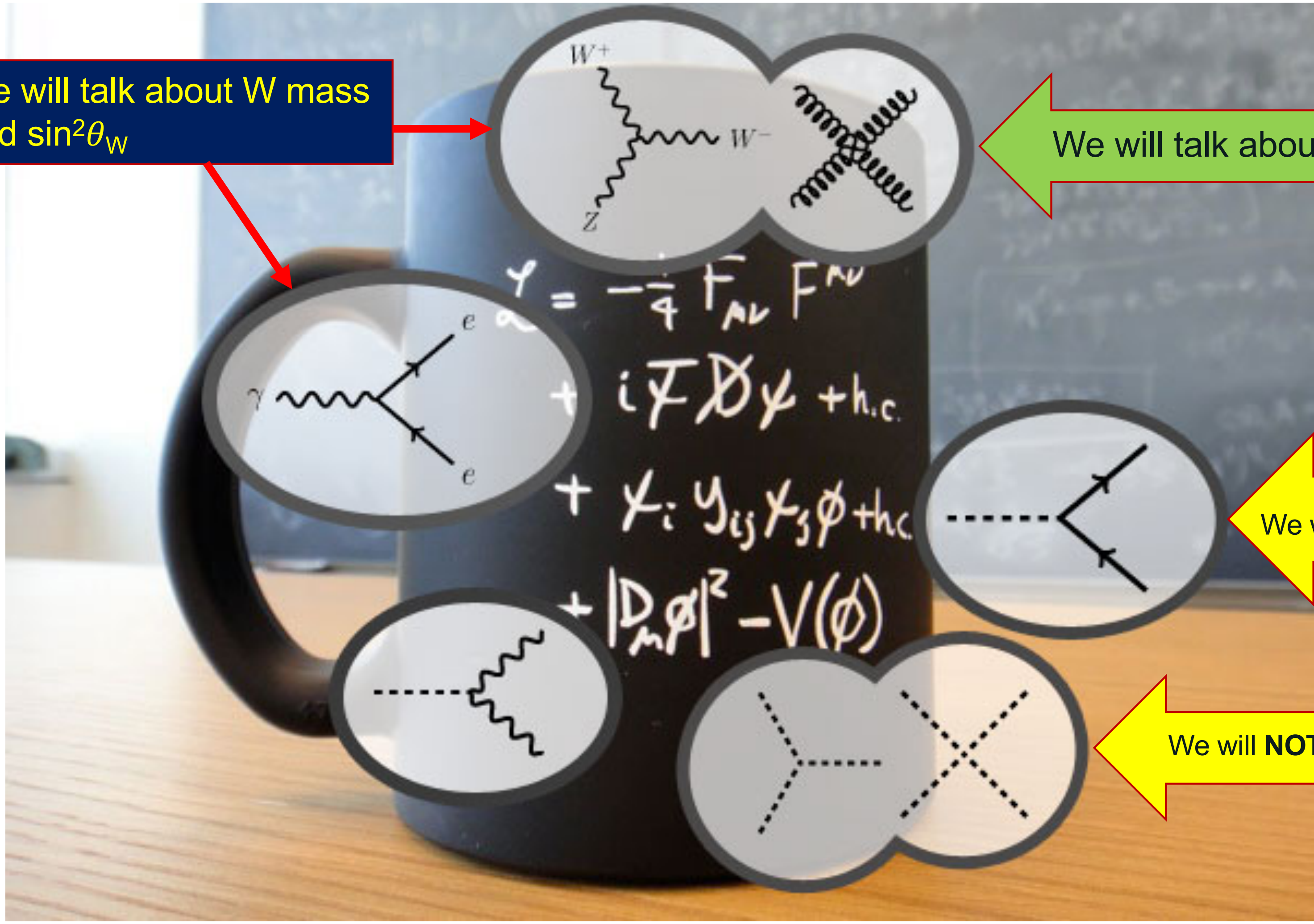
(actually Kelvin never pronounced this sentence. Something similar was said by Michelson six years earlier)

Let's follow the road pointed by "Kelvin/Michelson" in the hope to be wrong as well

What kind of precise measurements?

- The Standard Model in a nutshell (actually in a coffee mug)

We will talk about W mass and $\sin^2\theta_W$



We will talk about this coupling

We will **NOT** talk about top

We will **NOT** talk about Higgs

Standard Model Predictions

- The SM needs three input variables to derive all other quantities. The most precise: α_{em}; G_F; m_Z

Tree Level

$$\begin{cases} m_W^2\left(1-\dfrac{m_W^2}{m_Z^2}\right)=\dfrac{\pi\alpha}{\sqrt{2}G_F} \\ \sin^2\theta_W = 1-\dfrac{m_W^2}{m_Z^2}\end{cases}$$

Loop effect

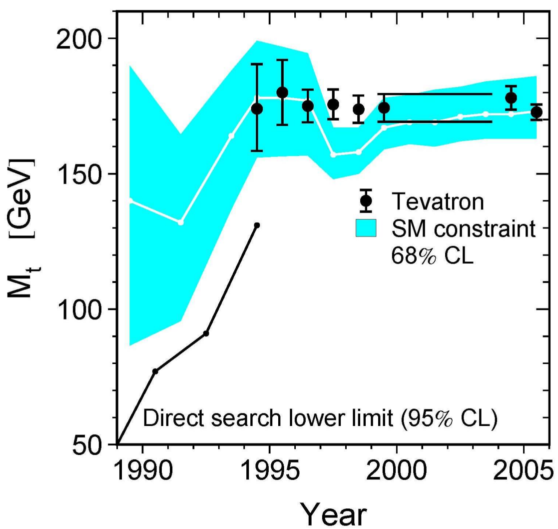
$$\begin{cases} =\dfrac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r) \\ \rightarrow \sin^2\theta^l_{eff} = k^l \sin^2\theta_W\end{cases}$$

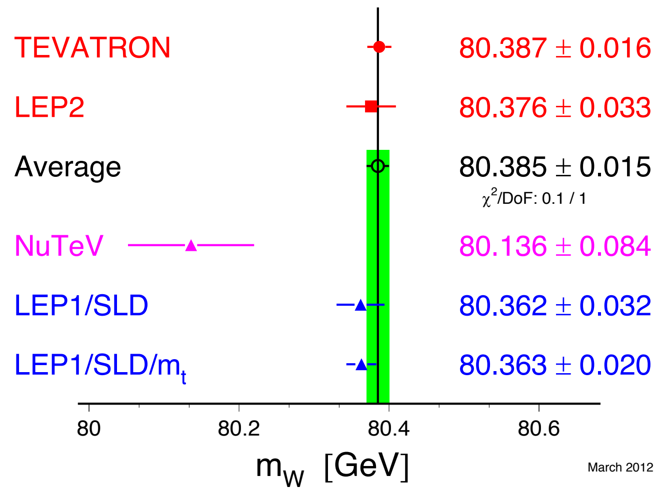
Δr and **k^l** depend on m_t^2 and $\ln(m_H)$

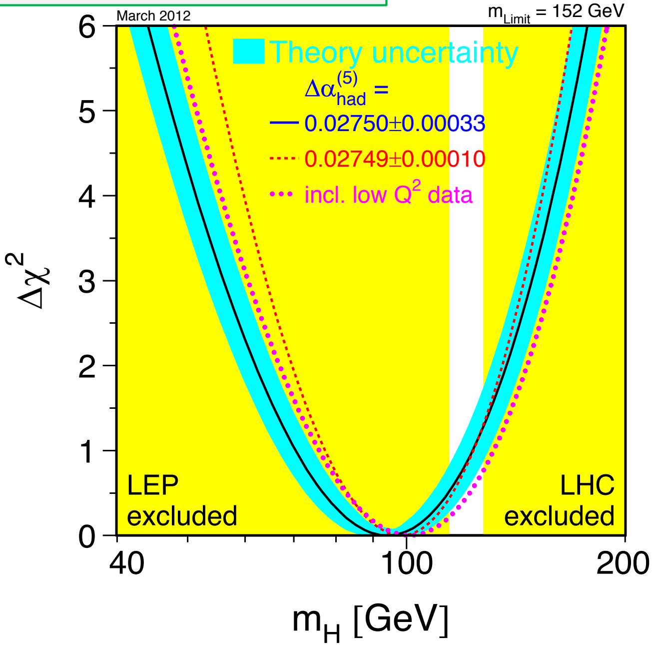
Caveat: in the loop can enter any new and/or unknown particles

A few plots from the LEP electroweak working group page (status at March 2012)

Prediction of the top mass at LEP



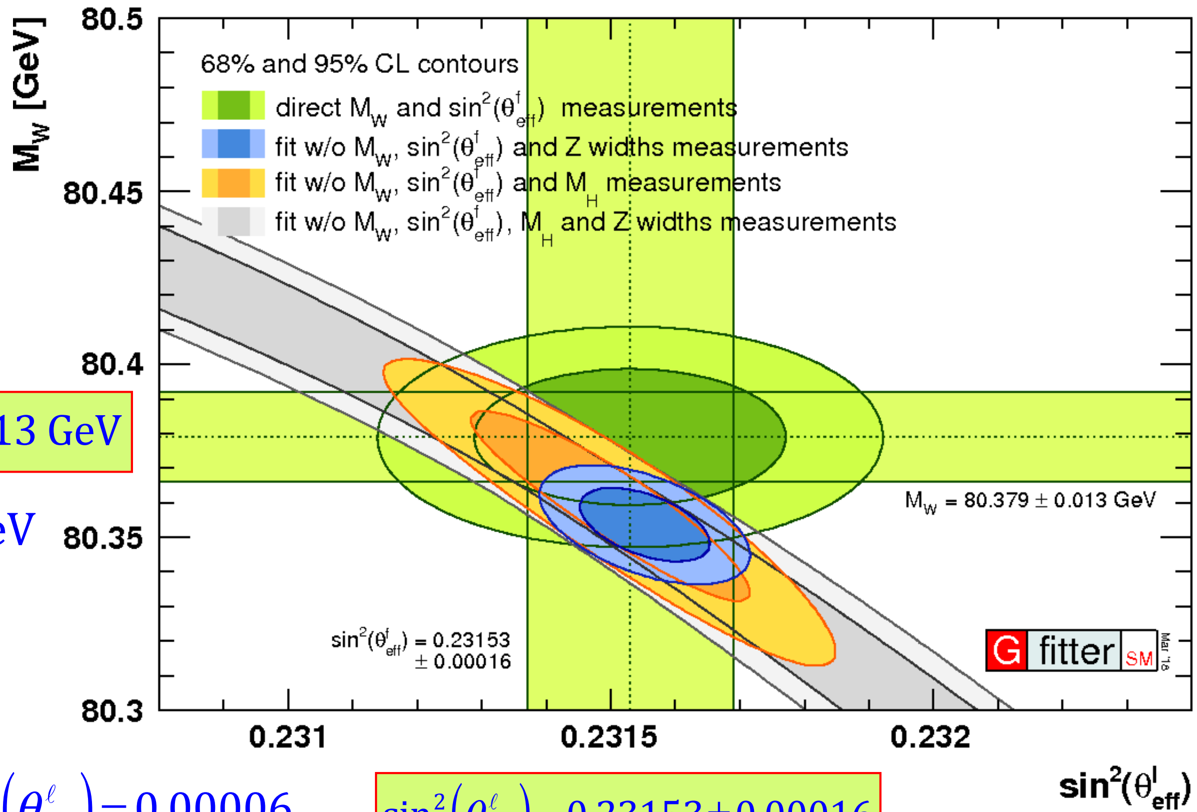




What about LHC?

- With the measurement of M_H the electroweak sector of the SM is **overconstrained**
- Global fits can be exploited to predict W boson mass and the effective electroweak mixing angle, with a precision **exceeding** that of the direct measurements.
- **It is a challenge for the experiments to be (at least) as good as the fit**

Plot taken from the Gfitter working group page



Latest Gfitter paper: arxiv:1803.01853

$M_W = 80.379 \pm 0.013$ GeV

Fit: $\Delta M_W = 8$ MeV

Fit: $\Delta\sin^2(\theta^\ell_{eff}) = 0.00006$

$\sin^2(\theta^\ell_{eff}) = 0.23153 \pm 0.00016$

OUTLINE

- W mass
  - ATLAS (2018): Eur. Phys. J. C 78: 110
- $\sin^2\theta_{eff}$
  - CMS (2018): Eur. Phys. J. C 78: 701 ; ATLAS (2018): ATLAS-CONF-2018-037

--------- Vector Bosons Couplings ---------

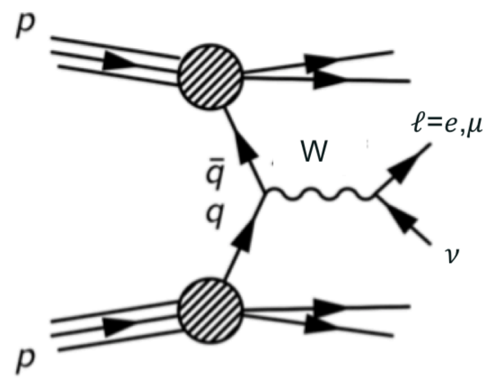
- Vector Boson Scattering
  - Same Sign WW:
    CMS (2018) Phys Rev Lett. 120.081801; ATLAS (2019) arxiv:1906.03203
  - WZ:
    CMS (2019) Phys.Lett. B 795 281-307 ; ATLAS (2019) Physics Letters B 793 469–492
  - ZZ: ATLAS (2019) ATLAS-CONF-2019-033
- Triboson final state
  - WWW: CMS (2019) Phys Rev D 100 012004
  - WWW, WVZ: ATLAS (2019) arxiv:1903.10415

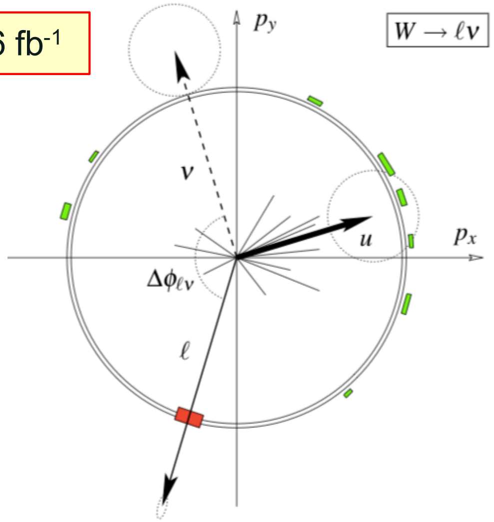
M_W

ATLAS W mass: measurement strategy

Eur. Phys. J. C 78: 110

2011 data set: E_{CM}=7 TeV; $\mathcal{L}$=4.6 fb^{-1}





Due to the neutrino the W invariant mass can not be reconstructed and we are forced to consider other variables sensitive to the W mass, like for instance:

- The lepton transerve momentum: $\vec{p}_T^{\,\ell}$
- The W transvers mass: $m_T^W \equiv \sqrt{2\vec{p}_T^{\,\ell}\vec{p}_T^{\,miss}\left(1-\cos\Delta\phi\right)}$

where $\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$ is the neutrino missing p_T

and u_T is the **recoil**: $\vec{u}_T = \sum_i \vec{E}_{T,i}$ (calorimeter clusters)

Event selection

- Muons: $|\eta|<2.4$
- Electrons : $|\eta|<1.2$ OR $1.8<|\eta|<2.4$
- Lepton isolation
- $p_T^l>30$ GeV
- $p_T^{miss}>30$ GeV
- $u_T<30$ GeV
- $m_T>60$ GeV

Event sample

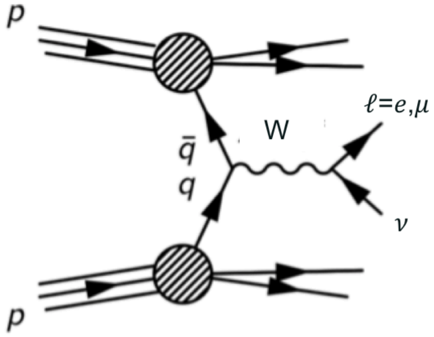
$W^+ \to \mu^+\nu$	4 609 818
$W^- \to \mu^-\bar{\nu}$	3 234 960
$W^+ \to e^+\nu$	3 397 716
$W^- \to e^-\bar{\nu}$	2 487 525

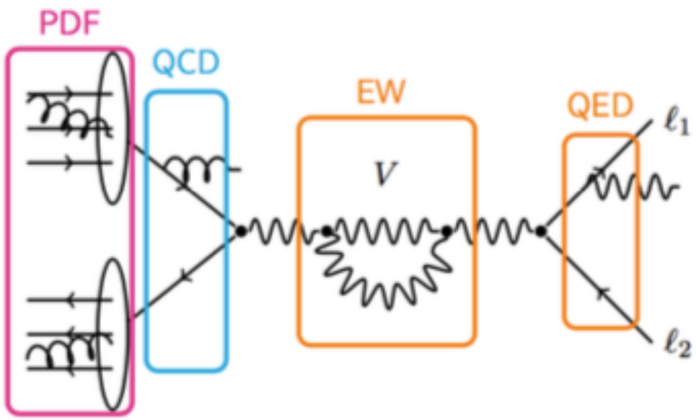
Sample of 13.7 M events: 5 times larger than combined (D0 + CDF) Tevatron sample

Statistics is not an issue; the challenge is the control of systematics (theoretical and experimental) to aim at 10 MeV error

Z→ l^+l^- is valuable to controll the systematics (MC tuning and cross checks)

W mass: effects of p_T^W, PDF and pile up





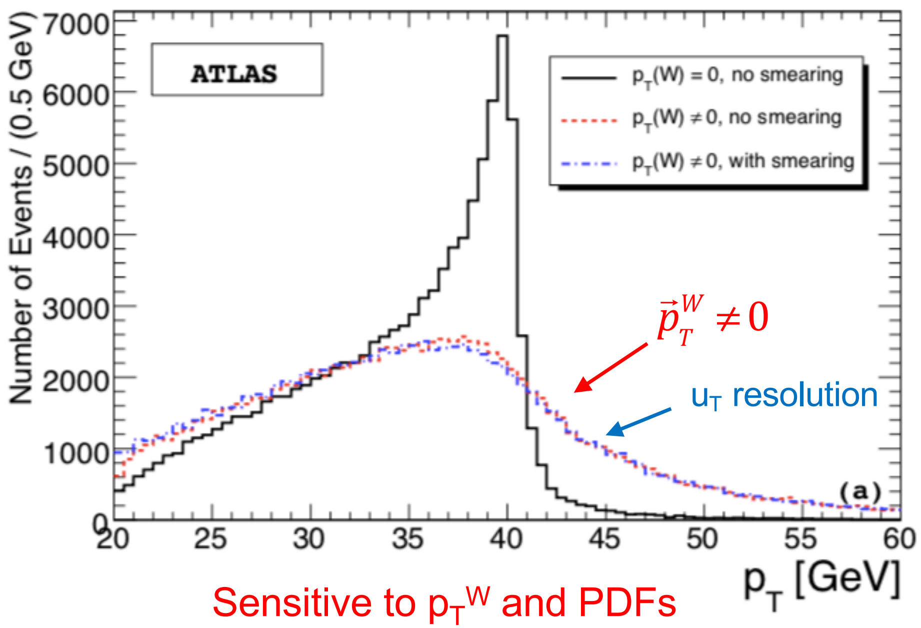
- At Leading Order the W is emitted along the beam pipe:

$$\vec{p}_T^{\,W} = 0$$

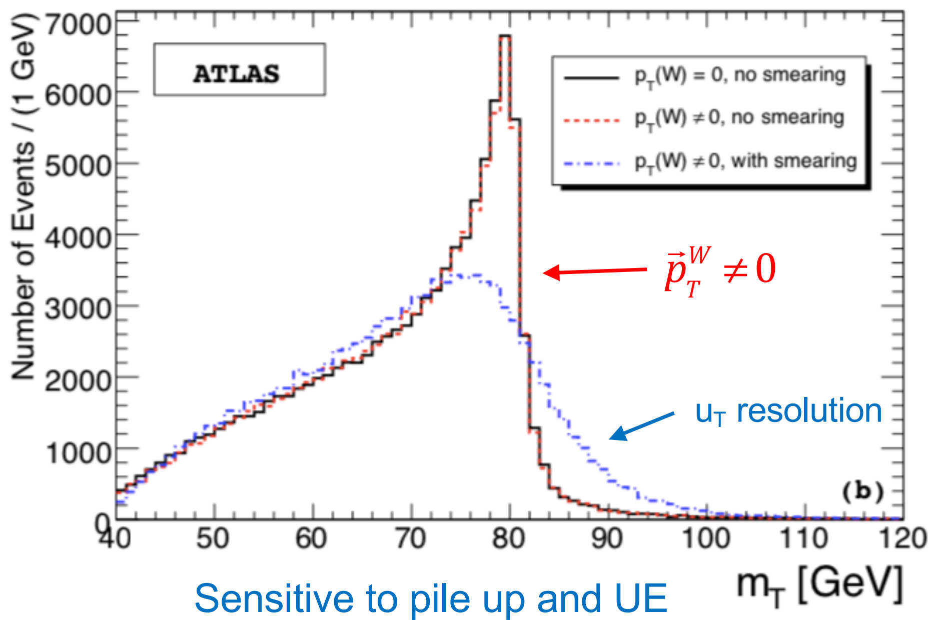
- HO corrections modify the spectrum:

$$\vec{p}_T^{\,W} \neq 0$$

Example taken from an ATLAS note (2008) arxiv:0901.0512



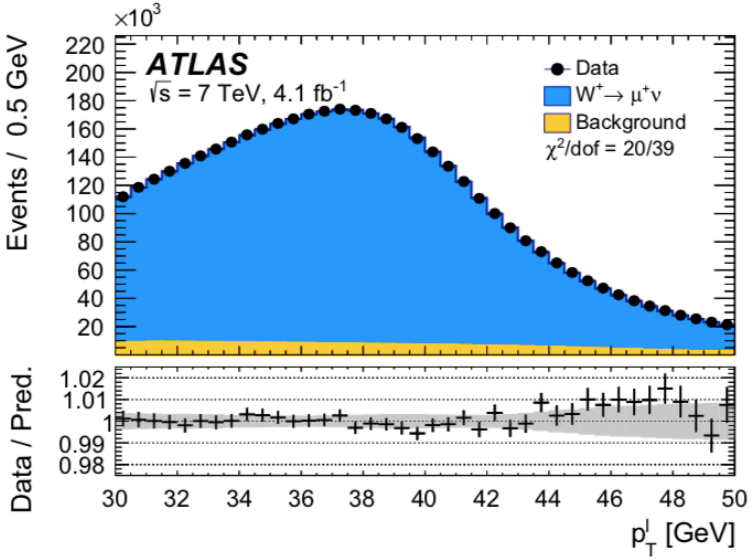
Sensitive to p_T^W and PDFs

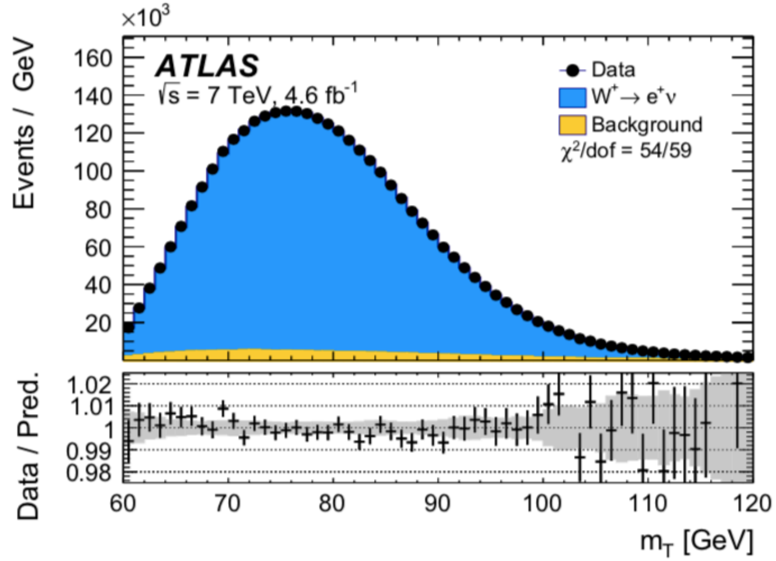


Sensitive to pile up and UE

W Mass Fits

- Fit from MC templates with different mass generated in steps of 1 - 10 MeV
- 28 χ^2 fits, separeted for lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e) and fit variable (**m_T**, **p_T^l**).
- Many other fits were performed as consistency checks by varying fit range, etc …





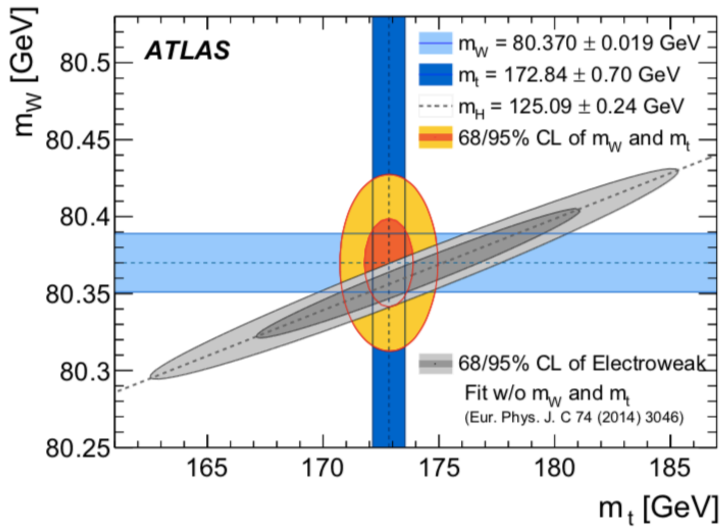
Combined result

Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

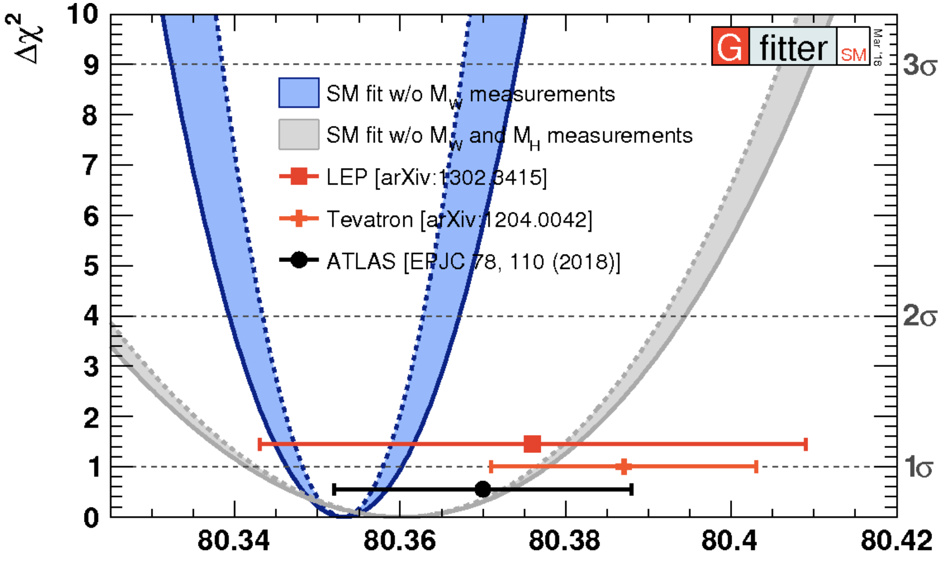
M_W = 80370 ± 19 MeV

Comparison with previous results and SM



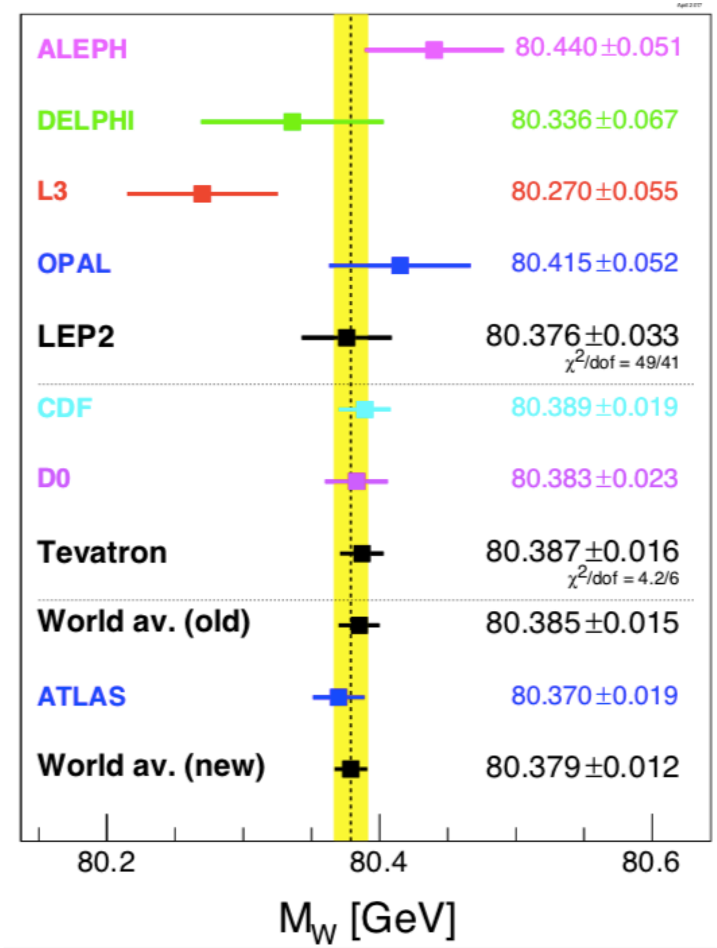
The ATLAS measurement has the same precision of the previous most precise single measurement (CDF) and is consistent with previous results.

Good agreement with SM EWK fits (Gfitter)



From the fit: M_W=80356 ±8 MeV M_W [GeV]

From PDG 2019



Prospects for M_W measurements

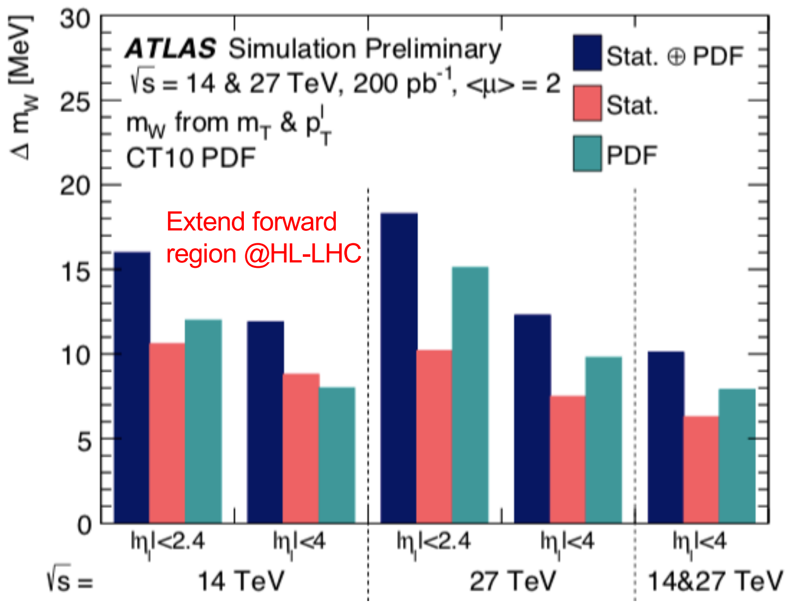
Major source of uncertainties are p_T^W (from QCD and PDF) and recoil (from pile-up)

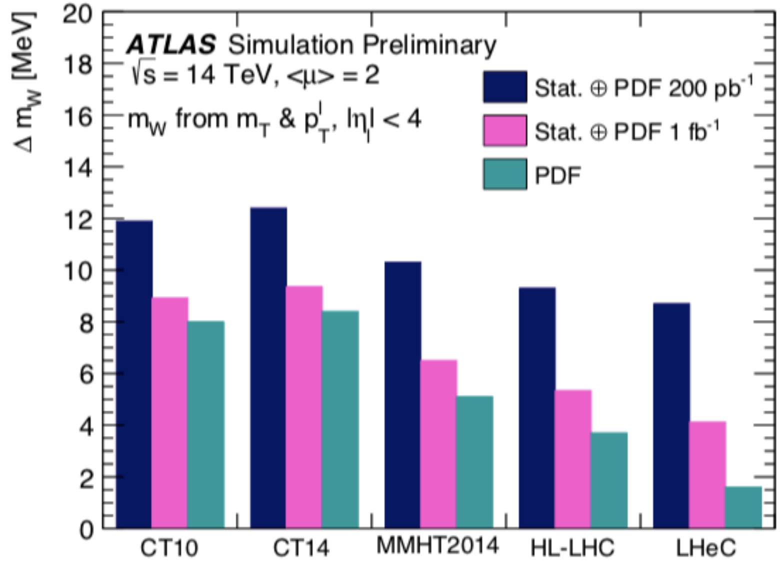
➡ exploit dedicated low pile up runs ($<\mu>\simeq2$) to get p_T^W from data

ATLAS: ATL-PHYS-PUB-2017-021

Low-mu datasets: ATLAS/CMS 380/200 pb^{-1} at 13 TeV; 260/300 pb^{-1} 5 TeV

ATLAS-CMS High_Lumi perspective arxiv:1902.10229





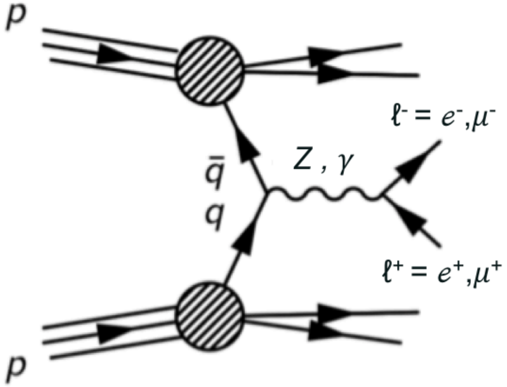
Different set of PDF functions

- Total uncertainty of **~11 MeV** with 200 pb-1 of data at each energy (~one week of data taking)
- With HL-LHC PDF and 1 fb^{-1} we could reach of precision of **6 MeV**
- With Future LHeC PDF set from DIS data we could aim at a precision of **4 MeV**

CAVEAT: experimental systematics are not included, but they are of statistical nature and could be reduced

$\sin^2\theta_{eff}$

Measurement strategy

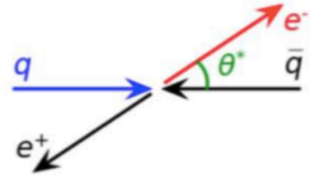


Measurement is based on the cos(theta) dependence of the Drell-Yan cross-section (using **ee/μμ** events)

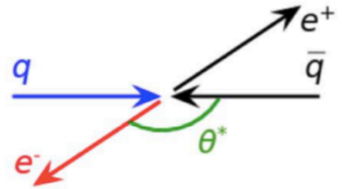
At LO SM

$$\frac{d\sigma}{d\cos\theta^*} = A\left(1+\cos^2\theta^*\right) + B\cos\theta^*$$

Parity-violating term; B ~ A_{FB} is a function of $\sin^2\theta_W$



(Forward event)



(Backward event)

2012 data set: E_{CM}=8 TeV; $\mathcal{L} \approx 20\ fb^{-1}$

ATLAS: 7.5 x 10^6 di-muons and 7.5 x 10^6 di-electrons
CMS: 8.2 x 10^6 di-muons and 4.9 x 10^6 di-electrons

A_{FB}= Forward-Backward asymmetry

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

PROBLEM: how do we distinguish a quark from an antiquark in the initial state?

a) The antiquark is picked up from the sea; b) at high rapidity is more likely that the Z follows the quark direction.

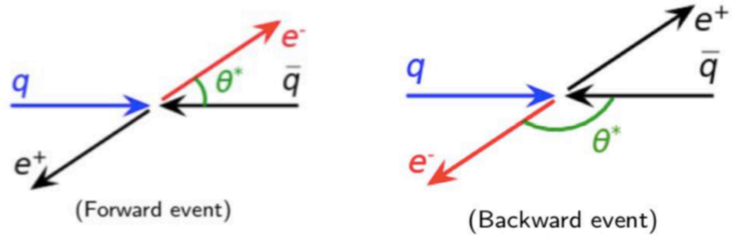
$y_Z \approx 0$ u(x) ≈ ū(x) → maximal dilution

$y_Z >> 0$ u(x) >> ū(x) → anambiguous

This measurement is best done in the high rapidity region of the detector

PDF effects on the A_{FB} measurement

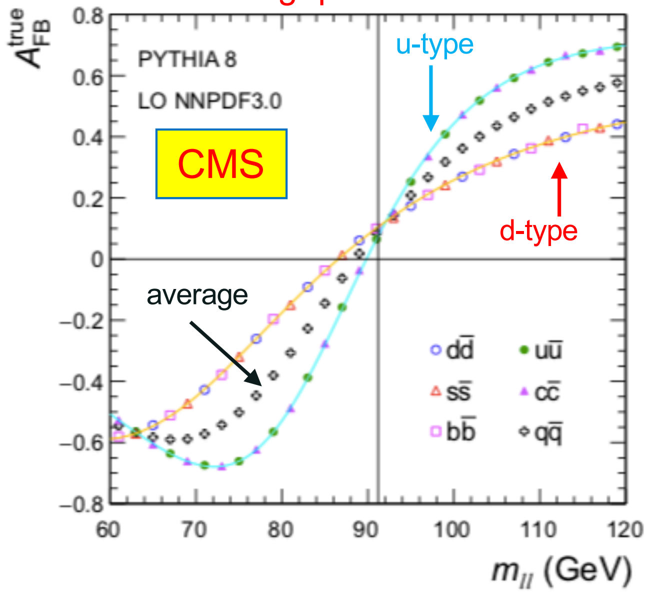
- A_{FB} is sensitive to PDF for two reasons:
  - different couplings of u- and d-type quarks
  - y_{ll} direction depends on the relative content of valence and sea quarks



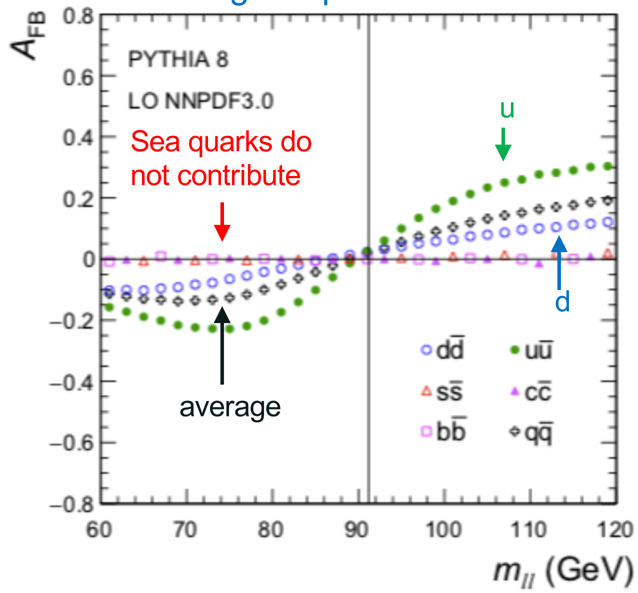
$$v_f = T_3^f - 2Q_f \sin^2\theta_W$$
$$a_f = T_3^f$$

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

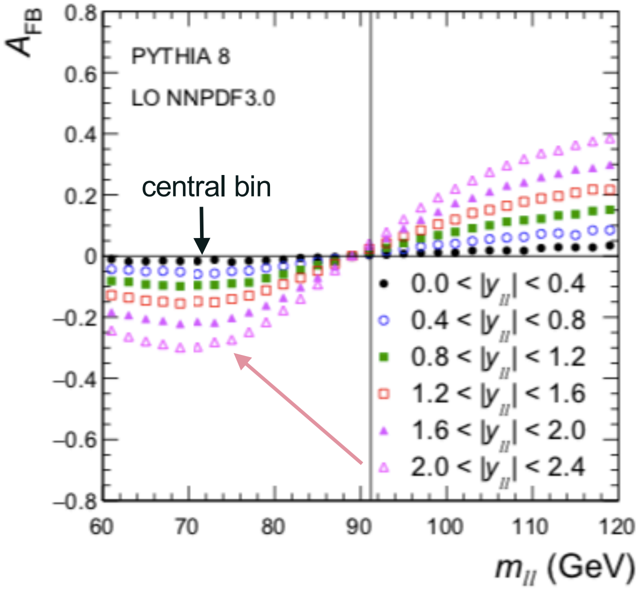
Using quark direction



Using di-lepton direction



A_{FB} for different rapidity bin

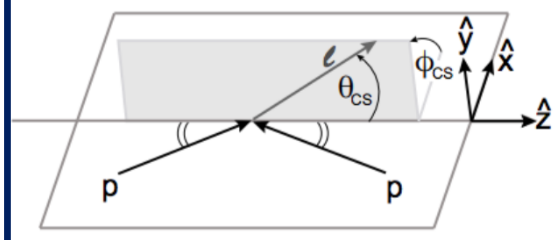


PDF uncertainty is the major source of systematic error and require particular care in the $\sin^2\theta_W$ extraction

CMS: A_{FB} methodology Eur. Phys. J. C 78: 701

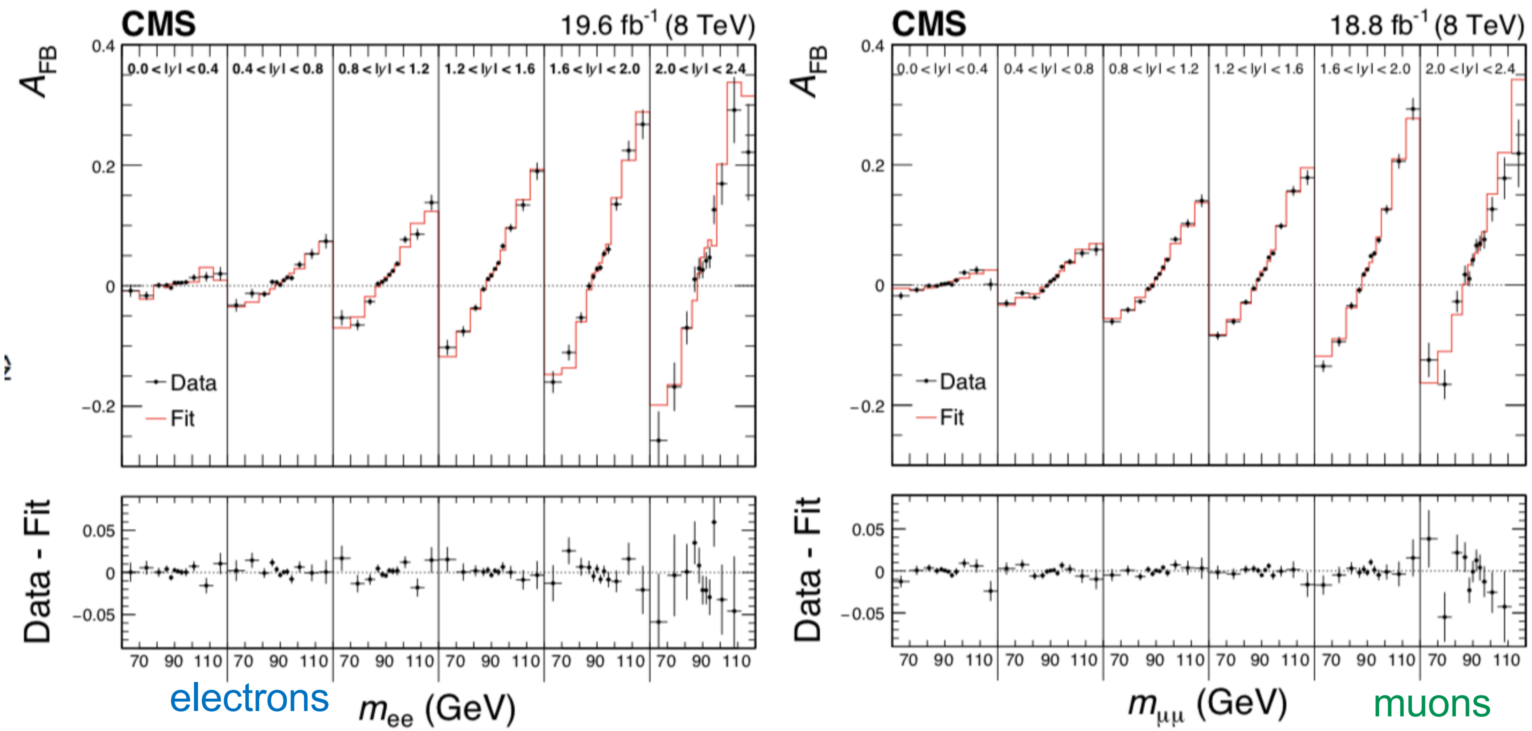
- Measure A_{FB} asymmetry in Collin-Soper frame in reconstructed m_{ll}, y_{ll} bins
- $Sin^2\theta_{eff}$ extracted from template fit to A_{FB} in data using theoretical predictions
  (Powheg v2 event generator using NNPDF3.0 PDFs)

Collins and Soper reference
PhysRevD.16.2219



$70 \leq M_{\ell\ell} \leq 110$ GeV

$0.0 \leq |y| \leq 2.4$



CMS: uncertainties and result

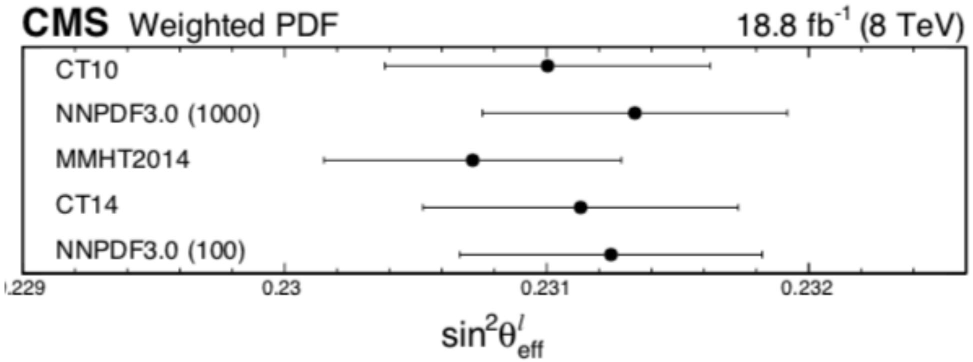
Channel	Statistical uncertainty
Muons	0.00044
Electrons	0.00060
Combined	0.00036

Experimental systematic uncertainties

Source	Muons	Electrons
Size of MC event sample	0.00015	0.00033
Lepton selection efficiency	0.00005	0.00004
Lepton momentum calibration	0.00008	0.00019
Background subtraction	0.00003	0.00005
Modeling of pileup	0.00003	0.00002
Total	0.00018	0.00039

systematic uncertainties from PDF

Channel	Not constraining PDFs	Constraining PDFs
Muons	0.23125 ± 0.00054	0.23125 ± 0.00032
Electrons	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030



systematic uncertainties from theory

Modeling parameter	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
μ_R and μ_F scales	0.00011	0.00013
POWHEG MINLO Z+j *vs.* Z at NLO	0.00009	0.00009
FSR model (PHOTOS *vs.* PYTHIA 8)	0.00003	0.00005
Underlying event	0.00003	0.00004
Electroweak $\sin^2\theta^\ell_{eff}$ *vs.* $\sin^2\theta^{u,d}_{eff}$	0.00001	0.00001
Total	0.00015	0.00017

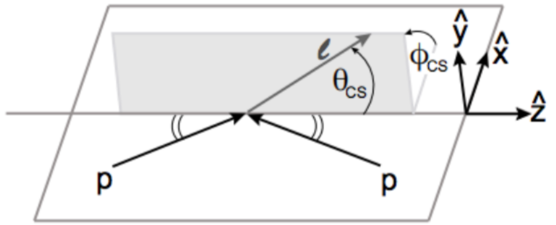
$$\sin^2\theta^\ell_{eff} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

$$\sin^2\theta^\ell_{eff} = 0.23101 \pm 0.00053$$

2.3 ‰ precision

ATLAS: A_i methodology ATLAS-CONF-2018-037

The differential cross section pp → Z → ℓℓ can be parametrized at EW LO and all order QCD as:



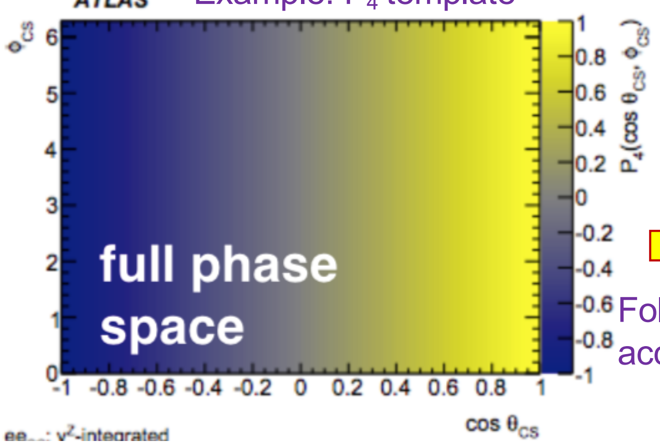
$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}.$$

$$A_{FB} = \frac{3}{8}A_4$$

- 9 harmonic polynomials $P_i(\cos\theta_{CS},\Phi_{CS})$ describe the lepton angular distribution in the Z rest frame
- 8 $A_i(m^{\ell\ell}, p_T^{\ell\ell}, y^{\ell\ell})$ coefficients and total unpolarised cross section σ^{U+L} $(m^{\ell\ell}, p_T^{\ell\ell}, y^{\ell\ell})$ describe the Z dynamics
- **Parity-violating A_4 term is sensitive to $\sin^2\theta_{eff}$**

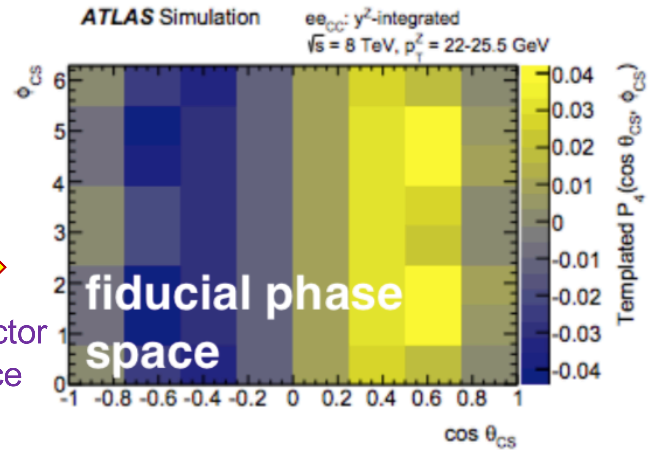
- A_i obtained from templates binned in $(m^{\ell\ell}, y^{\ell\ell})$
  (method here: J. High Energ. Phys. (2016) 2016: 159)

Example: P_4 template

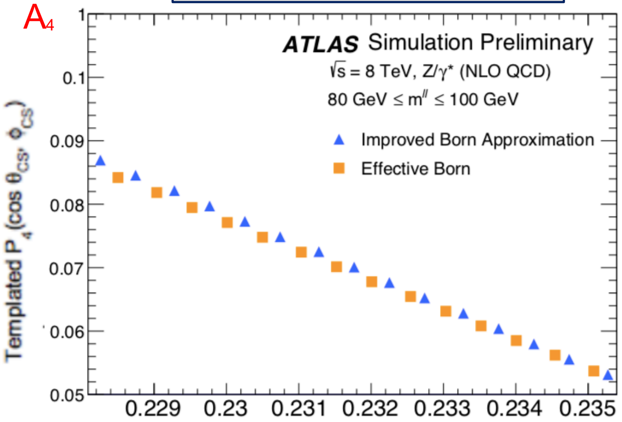


Fold detector acceptance

Fit A_i to the data

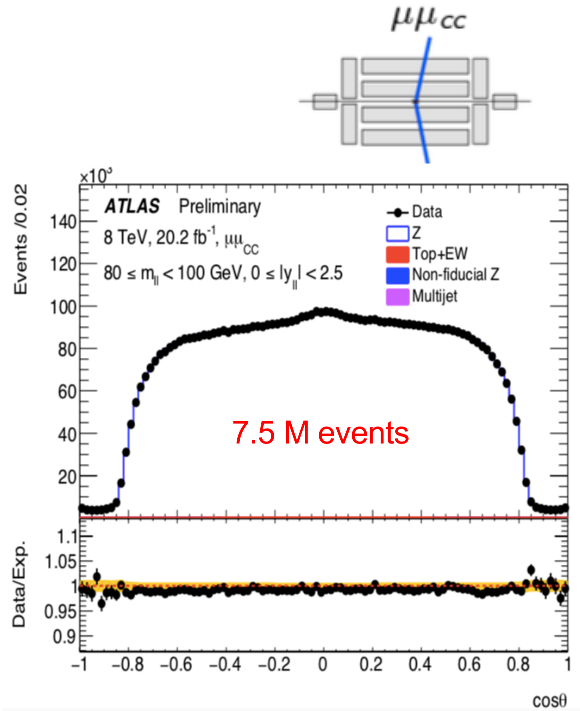


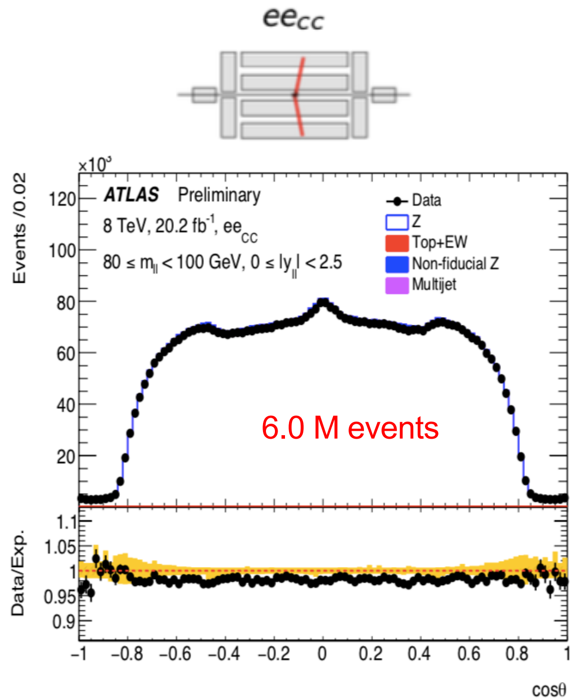
From A_4 we get $\sin^2\theta_{eff}$

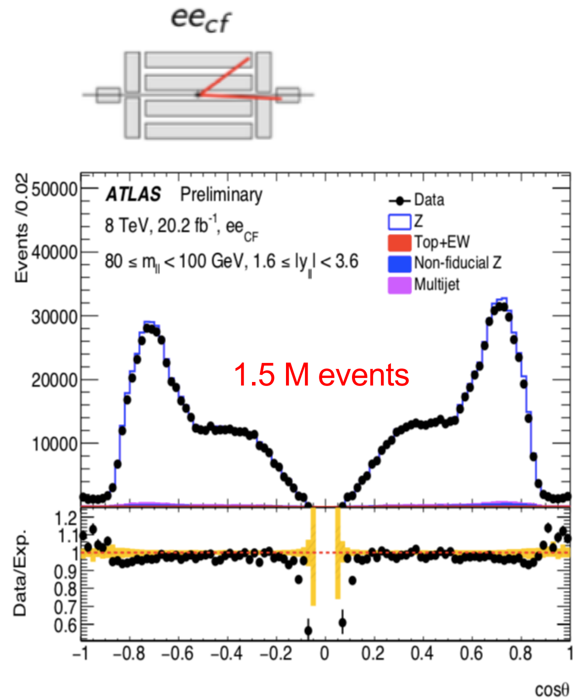


ATLAS: data sample

- ATLAS can exploit also the Forward Region for the electron channel, unlike CMS





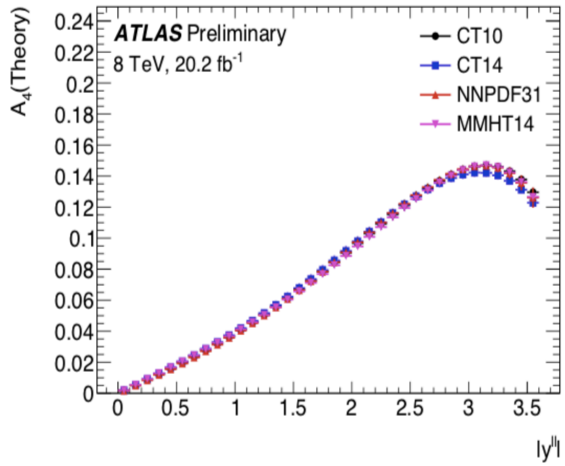


$70 \le M_{\ell\ell} \le 125$ GeV

$0.0 \le |y| \le 2.5$

$1.6 \le |y| \le 3.6$

- Forward region is very important because:
  - Smaller dilution effect
  - Higher sensitivity to A_4 and $\sin^2\theta_{eff}$
  - Smaller PDF uncertainties



ATLAS: uncertainties and result

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				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

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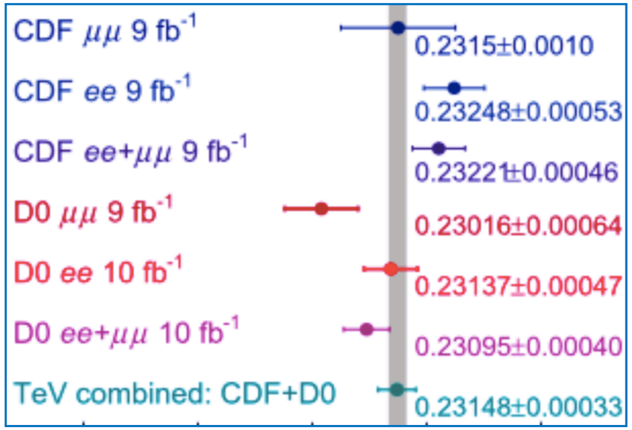
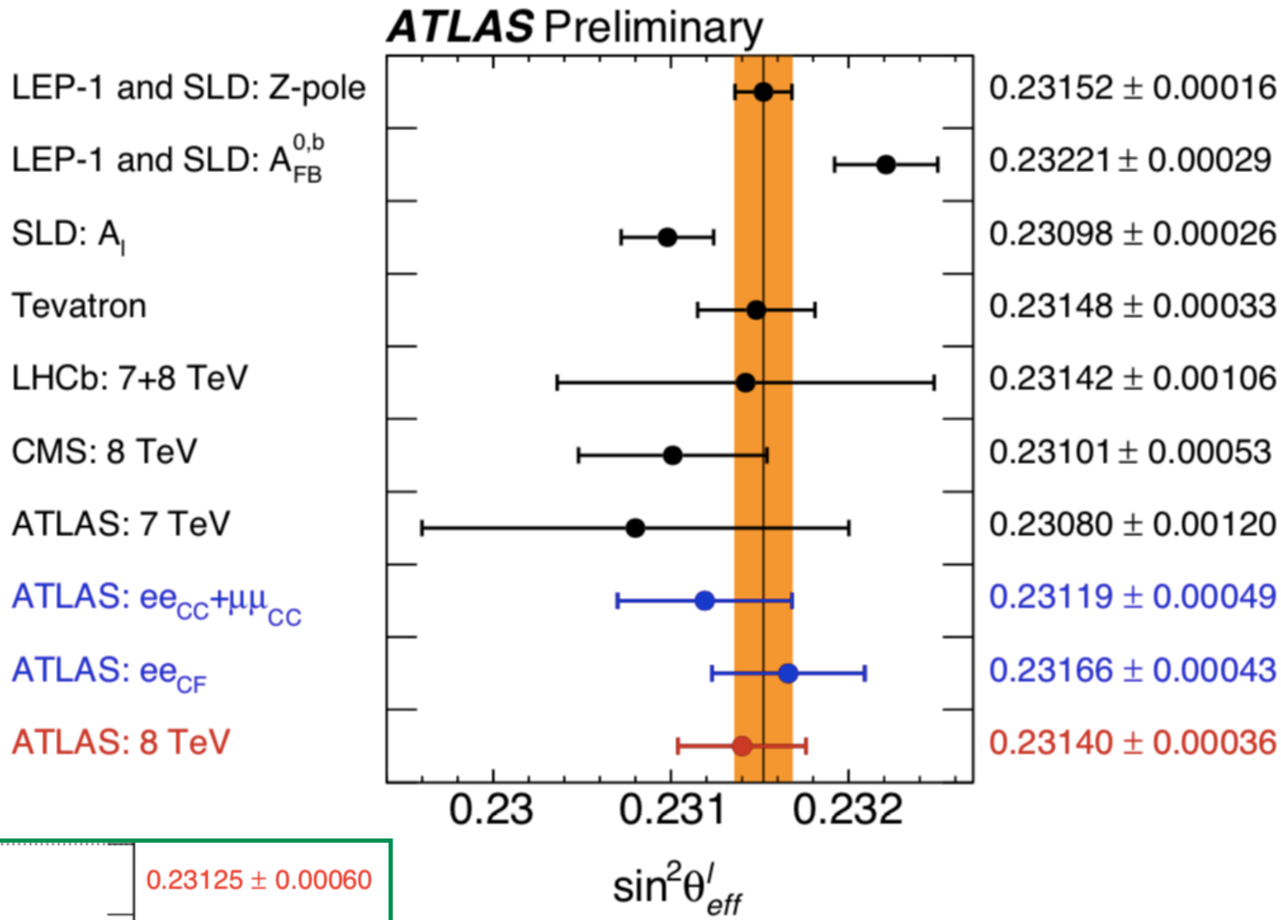
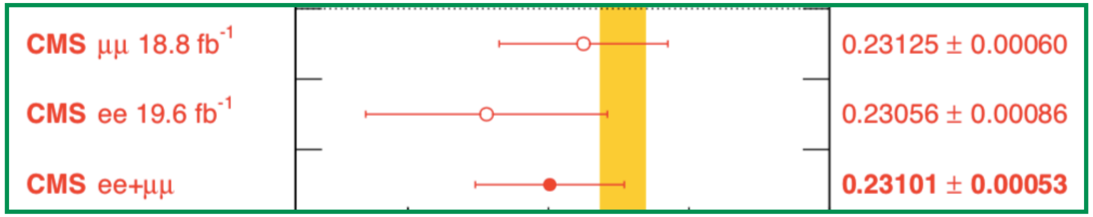
$$\sin^2 \theta^{\ell}_{\rm eff} = 0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.}),$$

$Sin^2\theta_{eff}$: comparison among results







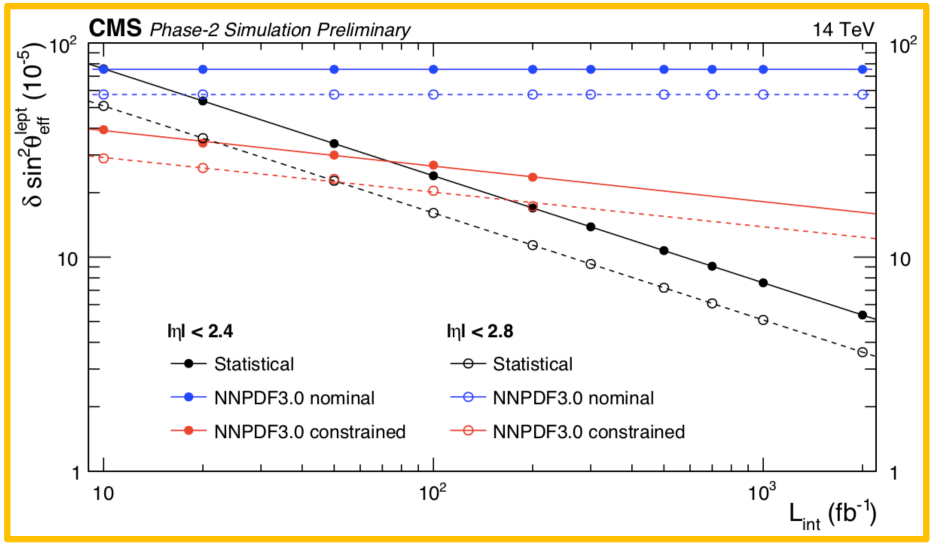
- ATLAS error is similar to the Tevatron one
- ATLAS and CMS errors are comparable in the central region

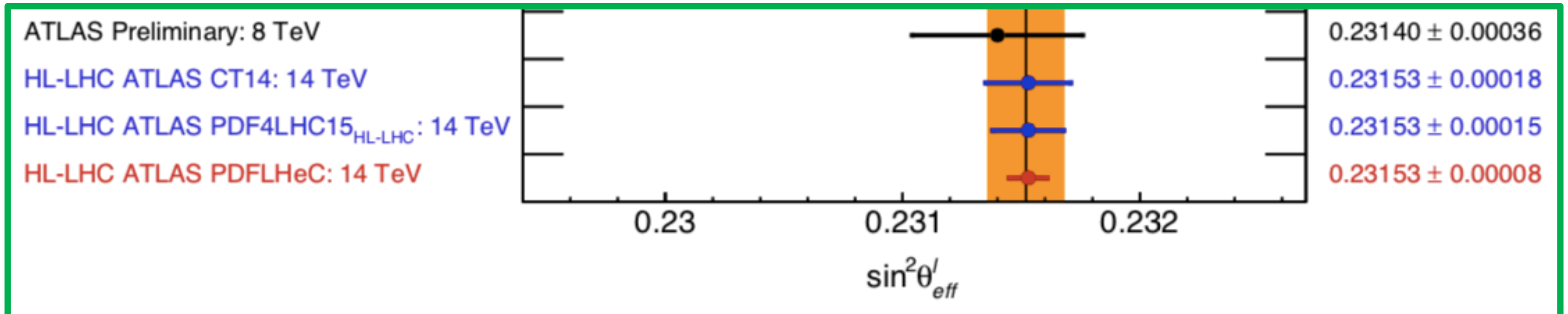
The measurement is still dominated by the ''old'' LEP and SLD done at the Z-pole

$\sin^2\theta_{eff}$: what next?

- ATLAS and CMS measurements can not be combined as they are because they use different analysis methods (the LHC electroweak working group will take care of it)
- They plan to use the same approach (most likely Ai coefficients) for future measurements (Run2 onwards). LHCb will also play an important role (see next slide).
- A common note describes what could be obtained in HL-LHC (arxiv:1902.10229).

	ATLAS $\sqrt{s}$ = 8 TeV	ATLAS $\sqrt{s}$ = 14 TeV	ATLAS $\sqrt{s}$ = 14 TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14 [18]	CT14 [13]	PDF4LHC15$_{\text{HL-LHC}}$ [19]
$\sin^2\theta_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

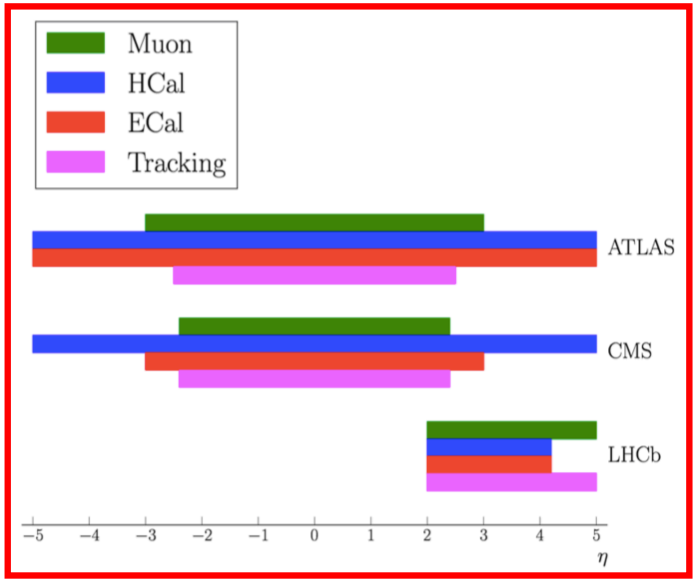


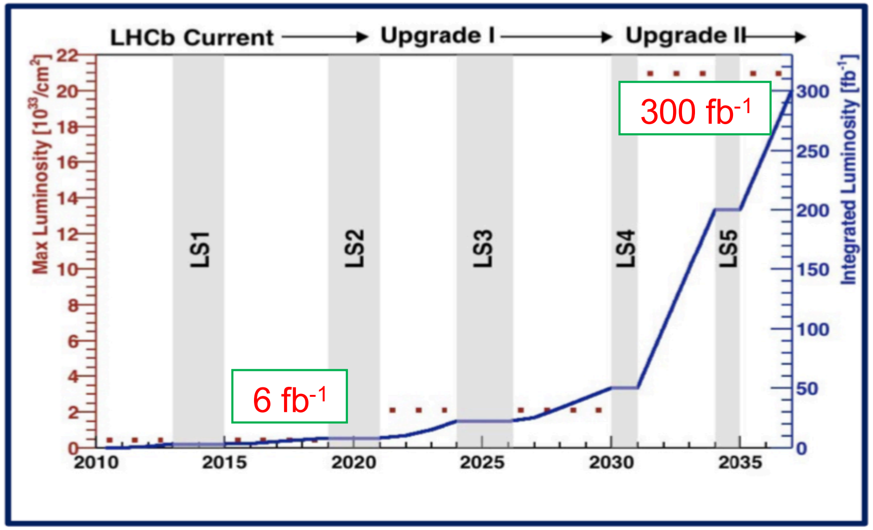


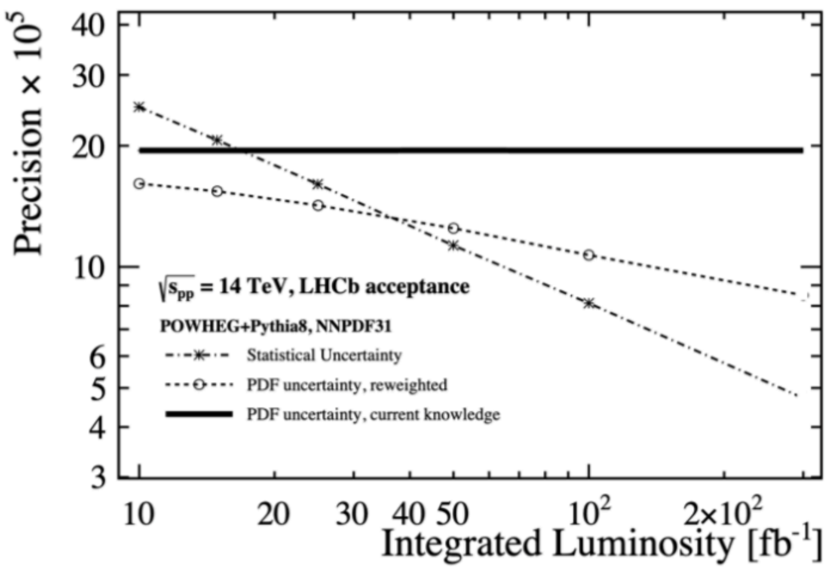
The dominant error will be PDF uncertainties

Prospects for $\sin^2\theta_{eff}$ at LHCb

- LHCb is designed for flavour physics but it is also able to act as general purpose forward detector





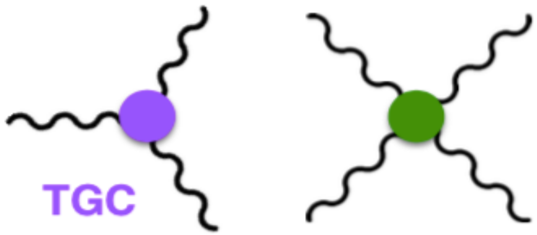


- PDF uncertainty at LHCb is similar to ATLAS and CMS: ~ 20×10^{-5} [ATLAS ~ 24×10^{-5} and CMS ~ 31×10^{-5}]
  J. High Energ. Phys. (2015) 2015: 190
- Statistical uncertainty at LHCb negligible for Upgrade II
- With 300 fb-1 the PDF uncertainty could be reduced below ~10×10^{-5} using PDF reweighting method
  LHCb-PUB-2018-013.pdf

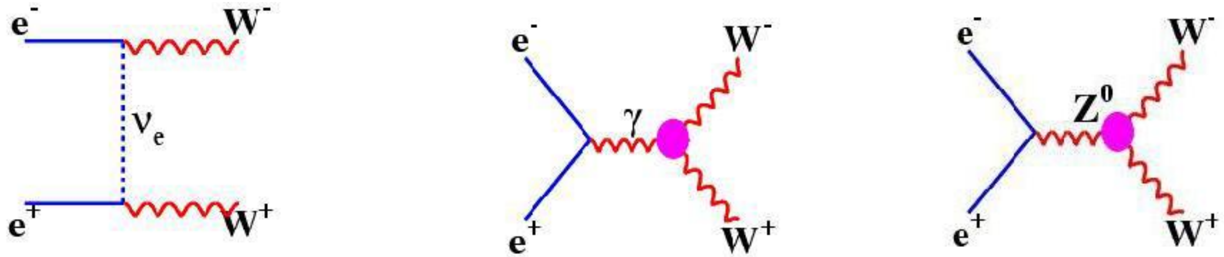
Gauge Boson Couplings

Motivations for the measurement

- The non-Abelian gauge nature of the Standard Model predicts, in addition to the trilinear WWZ and WWγ couplings (TGV), also Quartic Gauge Boson Couplings (QGC)



- TGC and QGC probe different aspects of the weak interactions cds:9505252
- TGC test the non-Abelian gauge structure of the Model; they have been tested at LEP:

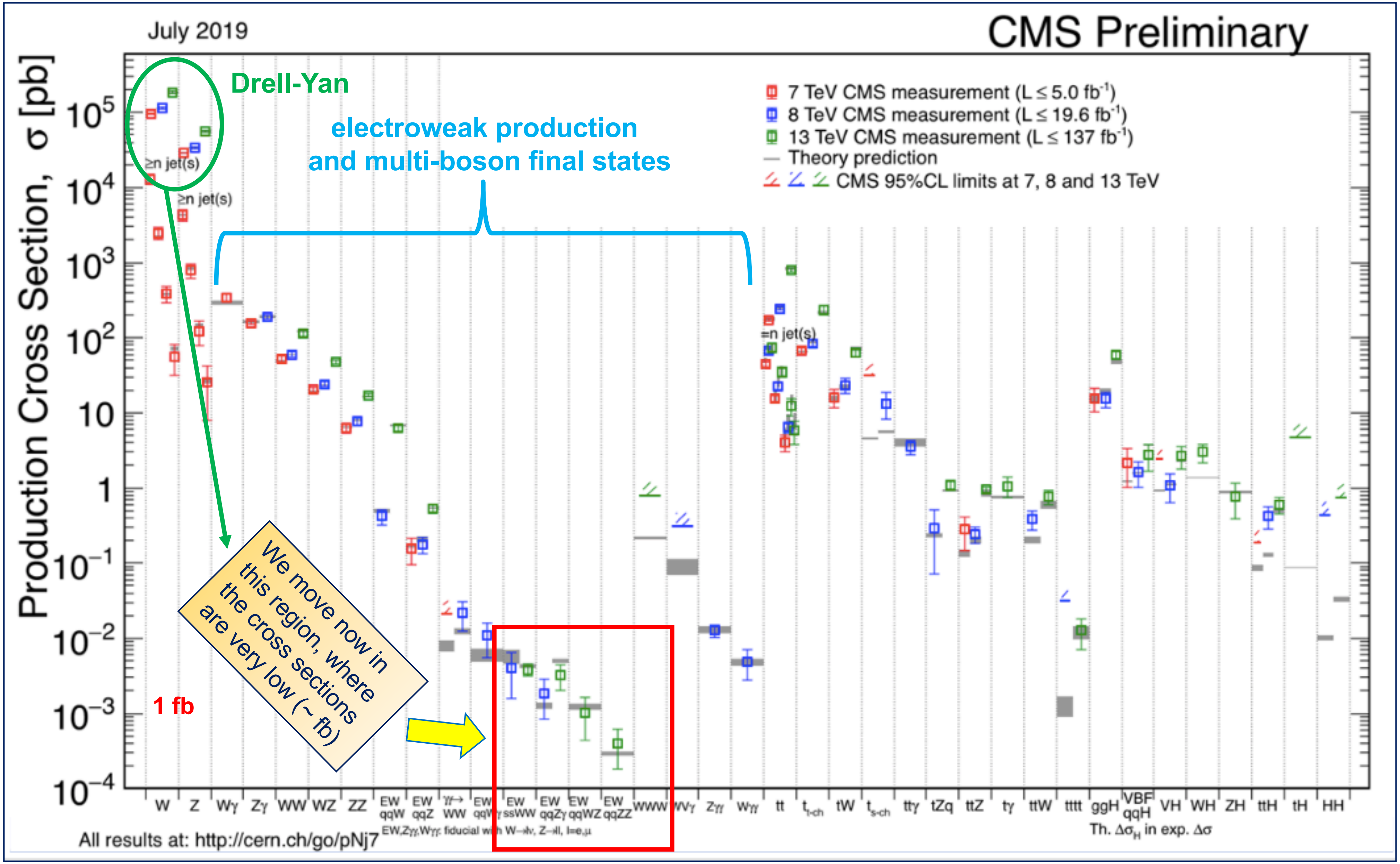


- QGC are accessible to LHC. They can be regarded as a window on the electroweak symmetry breaking mechanism and they represent a connection to the scalar sector of the theory.
- Anomalous couplings are handled by the Effective Field Theory approach:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j + \cdots$$

dim-6 dim-8

Production cross sections

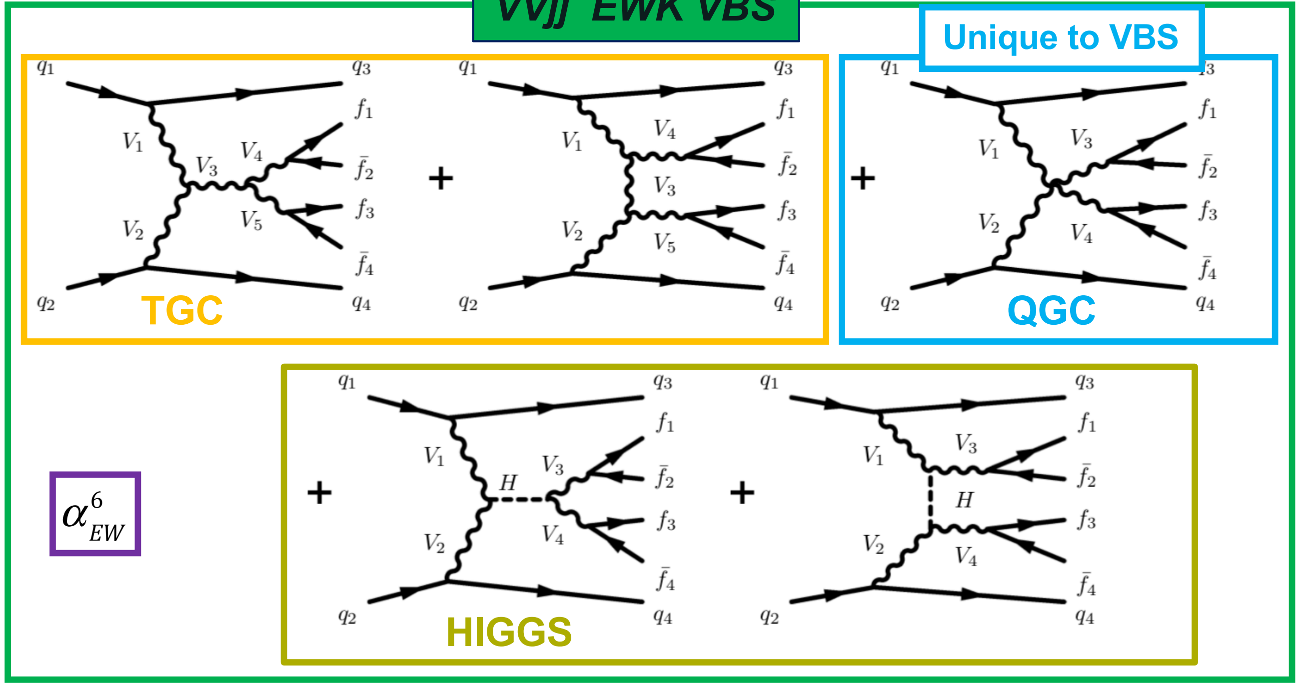


Vector Boson Scattering (VBS)

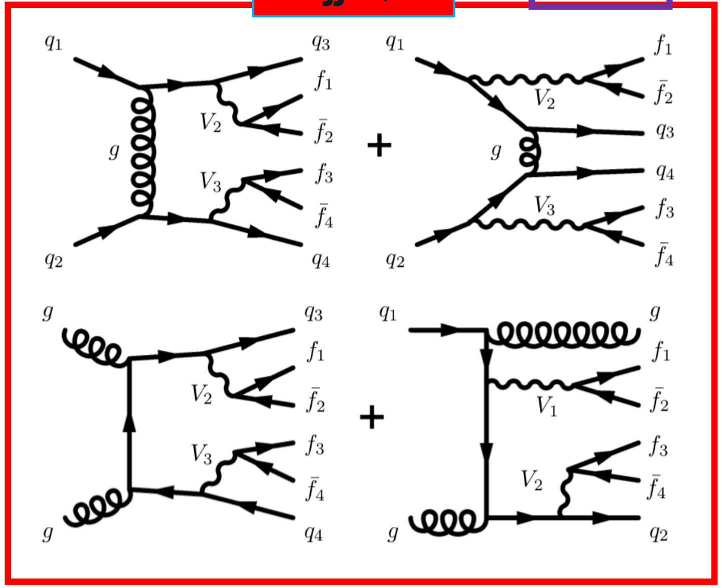
VBS: Feynman diagrams

Final state: 2 Vector Bosons + 2 jets

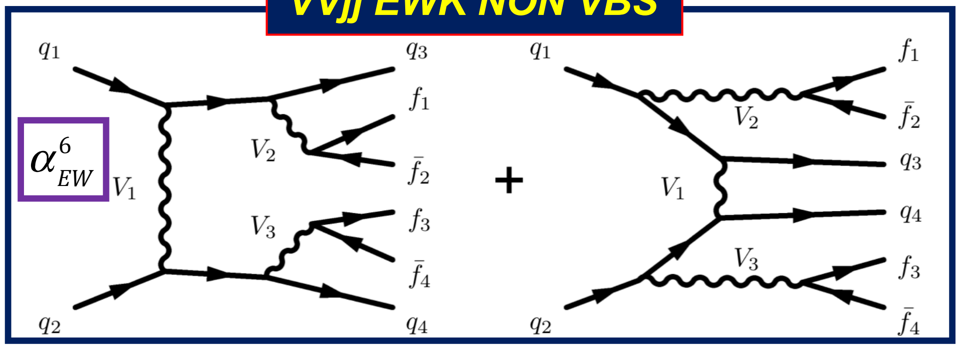
VVjj EWK VBS



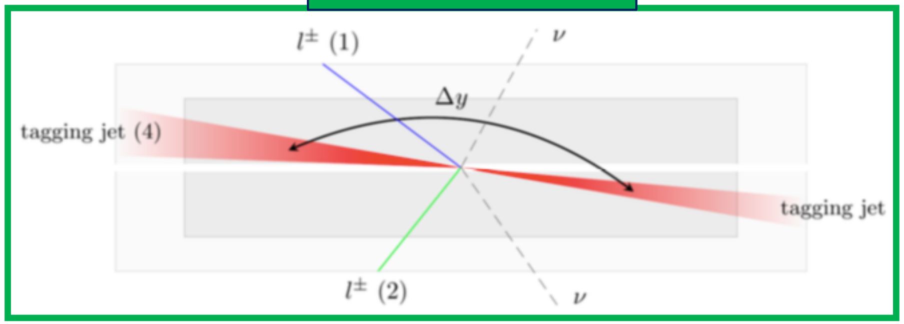
VVjj QCD $\alpha_S^2\alpha_{EW}^4$



VVjj EWK NON VBS

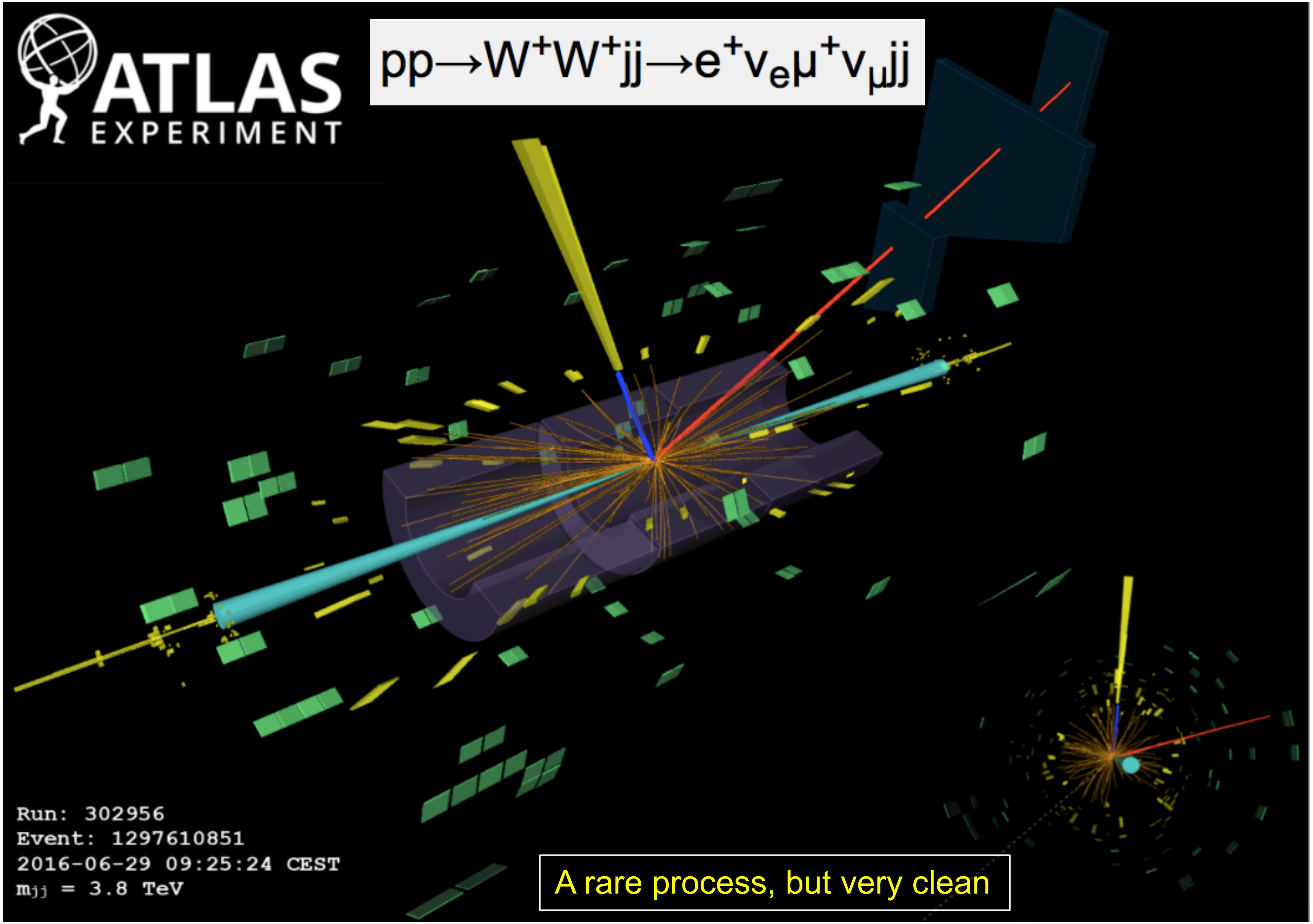


Event topology



Several final states depending on the nature of the Vector Bosons

VBS: Same Sign WW

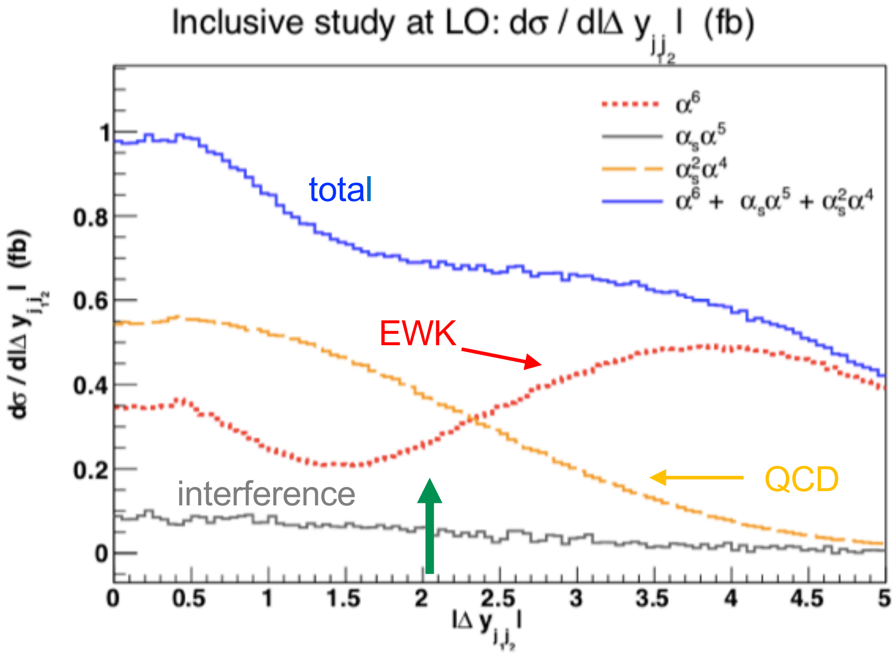


Phenomenology highlights for VBS W±W±jj

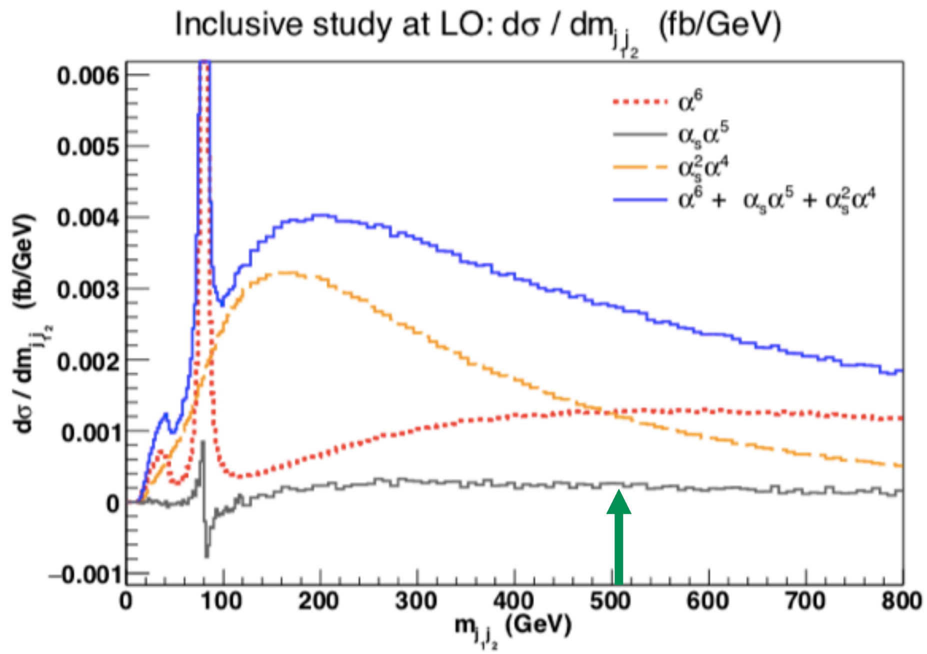
- Two hadronics jets in forward and backward regions with high energy (tagging jets)
- Hadronics activity suppressed between the two jets (rapidity gap) due to absence of colour flow between interacting partons
- Boson pair more central than in non-EWK processed

The VBS process involving two same-sign W bosons has the largest signal-to-background ratio of all the VBS processes at LHC.

Di-jet rapidity difference: arxiv:1803.07943



Di-jet invariant mass: arxiv:1803.07943



The analysis can be cut flow based

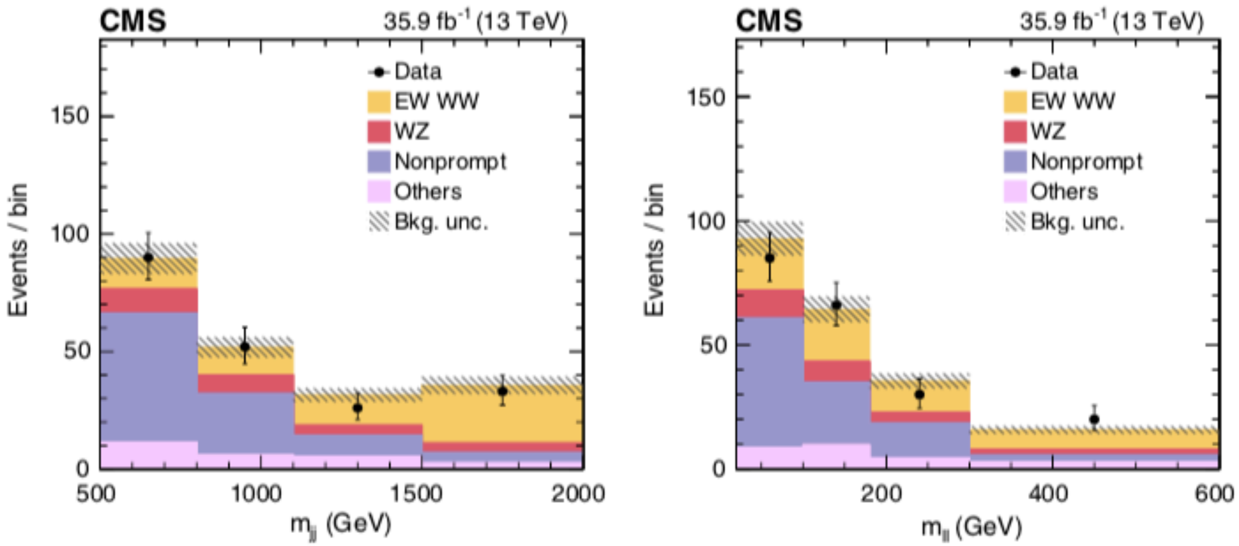
CMS: VBS Same Sign WW

Phys Rev Lett. 120.081801

2016 data: 35.9 fb^{-1} at 13 TeV

- 2 same sign leptons (e or μ) with: p_T > 25/20 GeV and η < 2.5/2.4
- M_{jj} > 500 GeV; $|\Delta\eta_{jj} > 2.5|$

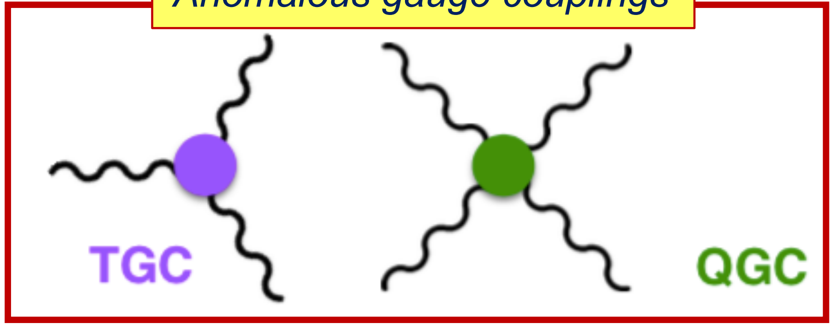
Data	201
Signal + total background	205 ± 13
Signal	66.9 ± 2.4
Total background	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD *WW*	4.8 ± 0.4
Wγ	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1



- Significance: 5.5 σ (obs); 5.7 σ (exp.) → **first observation of EWK $W^\pm W^\pm jj$**
- $\sigma_{fid}(W^\pm W^\pm jj)$ = 3.83 ± 0.66 (stat) ± 0.35 (syst) fb (statistically dominated)
- σ^{LO} = 4.25 ± 0.27 (scale + PDF) fb

CMS VBS WW: aQGC & limits on $H^{\pm\pm}$

Anomalous gauge couplings



handled by → *Effective Field Theory*

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j + \cdots$$

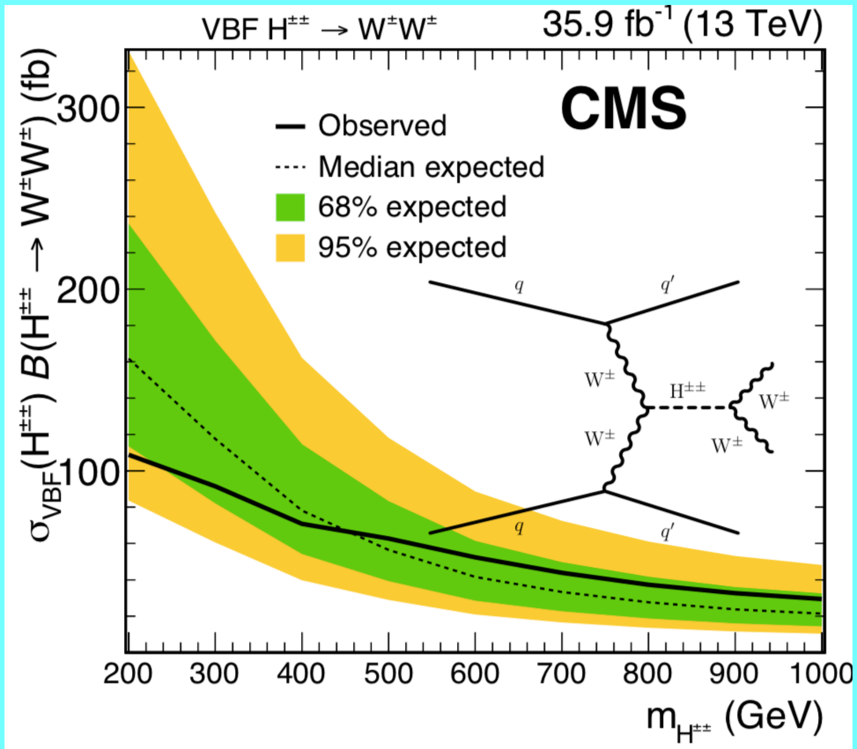
dim-6 dim-8

Focus on dim-8 operators for aQGC

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]

They are all compatible with 0 (SM)

Limits on σ x BR for VBF production of $H^{\pm\pm}$

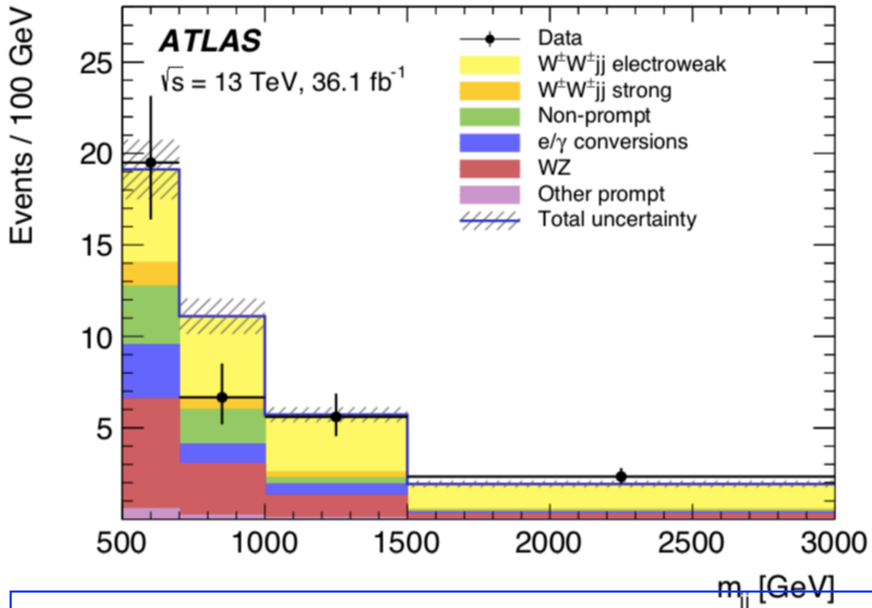


ATLAS: VBS Same Sign WW arxiv:1906.03203

2016 data: 36.1 fb^{-1} at 13 TeV

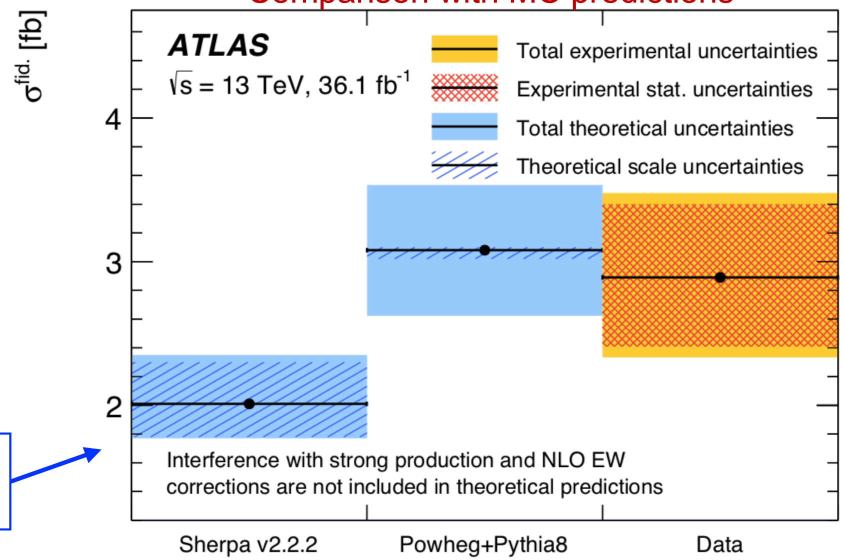
- 2 same sign leptons (e or μ) with: $p_T > 27$ GeV and $\eta < 2.5$
- $M_{jj} > 500$ GeV; $|\Delta\eta_{jj}| > 2.0$

	Combined	
WZ	30	± 4
Non-prompt	15	± 5
e/*γ* conversions	13.9	± 2.9
Other prompt	2.4	± 0.5
$W^\pm W^\pm jj$ strong	7.2	± 2.3
Expected background	69	± 7
$W^\pm W^\pm jj$ electroweak	60	± 11
Data	122	



Sherpa v2.2: non-optimal setting of colour flow for the parton shower
→ excess of central emissions

Comparison with MC predictions



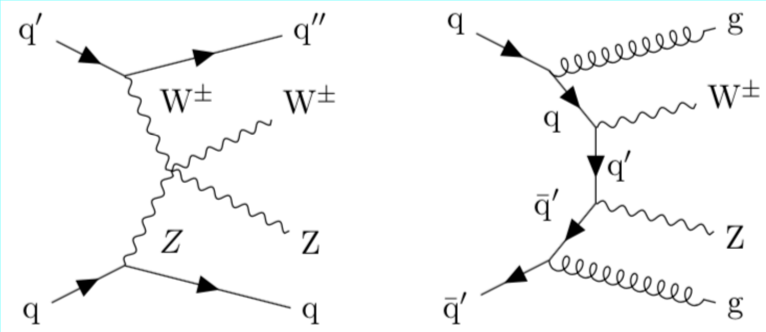
$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\,\text{fb}$$

Significance: 6.5 σ (obs); 4.4 σ (exp. from Sherpa) and 6.5 σ (exp. from Powheg+Pythia8)

CMS: VBS WZ

Phys.Lett. B 795 281-307

We have a Z in the final state

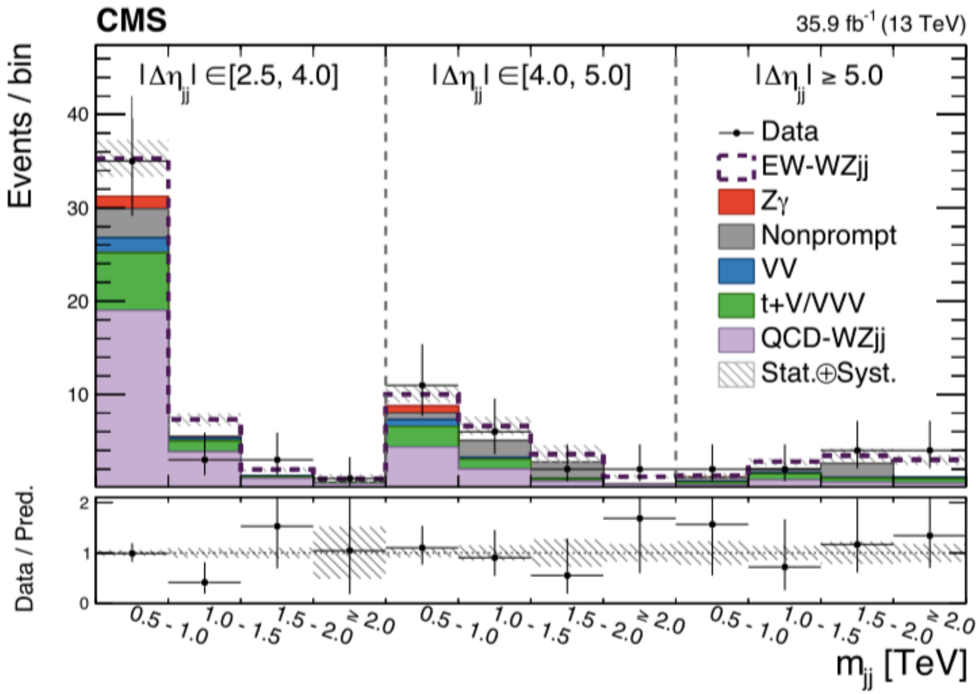


2016: 35.9 fb^{-1}

3 leptons in the final state

Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total yield
QCD WZ	13.5 ± 0.8	9.1 ± 0.5	6.8 ± 0.4	4.6 ± 0.3	34.1 ± 1.1
t+V/VVV	5.6 ± 0.4	3.1 ± 0.2	2.5 ± 0.2	1.7 ± 0.1	12.9 ± 0.5
Nonprompt	5.2 ± 2.0	2.4 ± 0.9	1.5 ± 0.6	0.7 ± 0.3	9.9 ± 2.3
VV	0.8 ± 0.1	1.6 ± 0.2	0.4 ± 0.0	0.7 ± 0.1	3.5 ± 0.2
$Z\gamma$	<0.1	2.1 ± 0.8	<0.1	<0.1	2.1 ± 0.8
Pred. background	25.2 ± 2.1	18.3 ± 1.6	11.2 ± 0.8	7.7 ± 0.5	62.4 ± 2.8
EW WZ signal	6.0 ± 1.2	4.2 ± 0.8	2.9 ± 0.6	2.1 ± 0.4	15.1 ± 1.6
Data	38	15	12	10	75

Less clean signature than W±W±jj



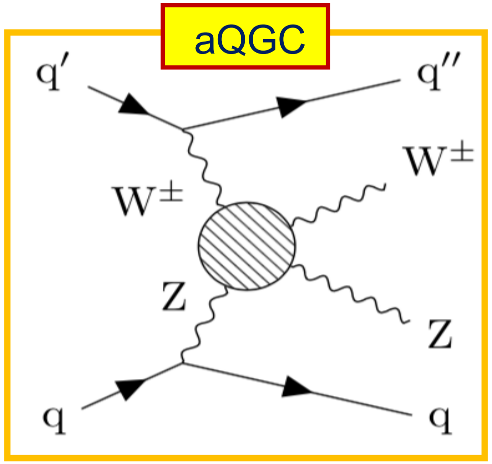
$$\sigma_{WZjj}^{fid} = 3.18^{+0.57}_{-0.52}\,(stat)\,^{+0.43}_{-0.36}(syst)\ \text{fb}$$

$$\sigma_{WZjj}^{LO} = 3.27^{+0.39}_{-0.32}\,(scale) \pm 0.15\,(PDF)\ \text{fb}$$

$$\mu^{EWK} = 0.82^{+0.51}_{-0.43}$$

Significance of EWK WZjj: 2.2 σ (obs); 2.5 σ (exp)

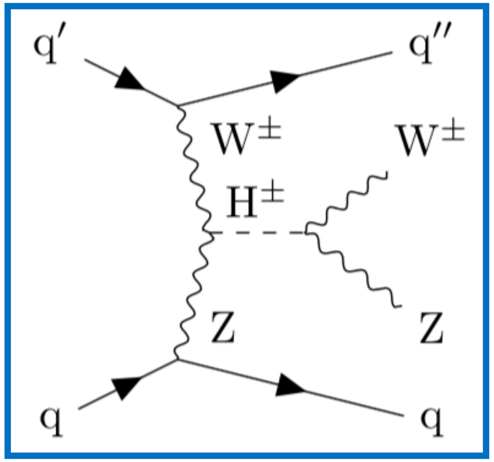
CMS VBS WZ: aQGC & limits on H±



Anomalous gauge couplings

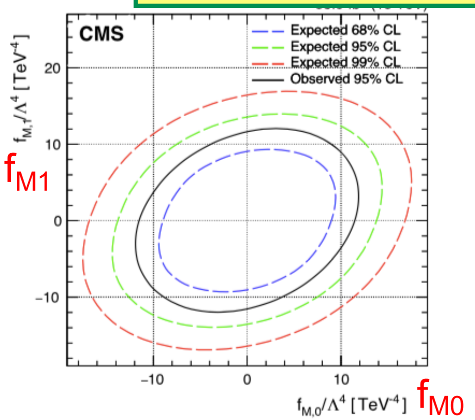
$$\sum_j \frac{f_j}{\Lambda^4} O_j$$

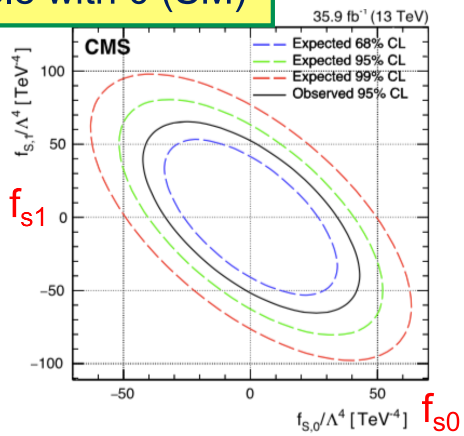
dim-8



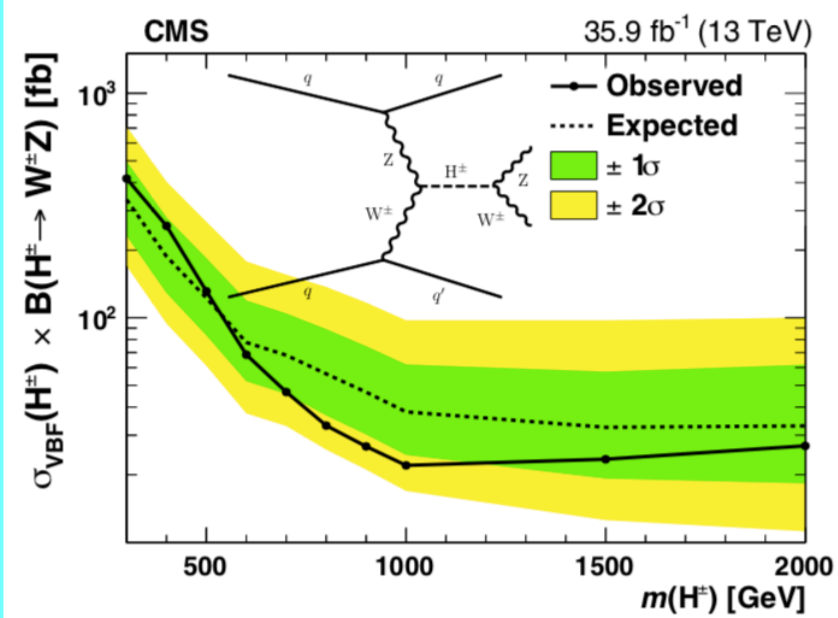
Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	[−11.2, 11.6]	[−9.15, 9.15]
f_{M1}/Λ^4	[−10.9, 11.6]	[−9.15, 9.45]
f_{S0}/Λ^4	[−32.5, 34.5]	[−26.5, 27.5]
f_{S1}/Λ^4	[−50.2, 53.2]	[−41.2, 42.8]
f_{T0}/Λ^4	[−0.87, 0.89]	[−0.75, 0.81]
f_{T1}/Λ^4	[−0.56, 0.60]	[−0.49, 0.55]
f_{T2}/Λ^4	[−1.78, 2.00]	[−1.49, 1.85]

They are all compatible with 0 (SM)





Limits on σ x BR for VBF production of H±



ATLAS: VBS WZ

Physics Letters B 793 469–492

2016 data: 36.1 fb^{-1} at 13 TeV

	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	167 ± 11	204 ± 12	146 ± 11	51.3 ± 7.0
$WZjj$–EW (signal)	44 ± 11	8.52 ± 0.41	1.38 ± 0.10	0.211 ± 0.004
$WZjj$–QCD	91 ± 10	144 ± 14	13.9 ± 3.8	0.94 ± 0.14
Misid. leptons	7.8 ± 3.2	14.0 ± 5.7	23.5 ± 9.6	0.41 ± 0.18
$ZZjj$–QCD	11.1 ± 2.8	18.3 ± 1.1	2.35 ± 0.06	40.8 ± 7.2
tZj	6.2 ± 1.1	6.3 ± 1.1	34.0 ± 5.3	0.17 ± 0.04
$t\bar{t}+V$	4.7 ± 1.0	11.14 ± 0.37	71 ± 15	3.47 ± 0.54
$ZZjj$–EW	1.80 ± 0.45	0.44 ± 0.10	0.10 ± 0.03	4.2 ± 1.2
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.06 ± 0.30

- A boosted decision tree (BDT) is used to exploit the kinematic difference between the WZjj-EW signal and the WZjj-QCD and other background
- A total of 15 variables are combined in one discriminant.

$$\sigma^{fid}_{WZjj-EW} = 0.57\ ^{+0.14}_{-0.13}(stat)\ ^{+0.05}_{-0.04}(\text{exp.}\ syst)\ ^{+0.05}_{-0.04}(\text{mod. exp})\ \pm 0.01\ (lumi)\ \text{fb}$$

$$= 0.57\ ^{+0.16}_{-0.14}\ \text{fb}$$

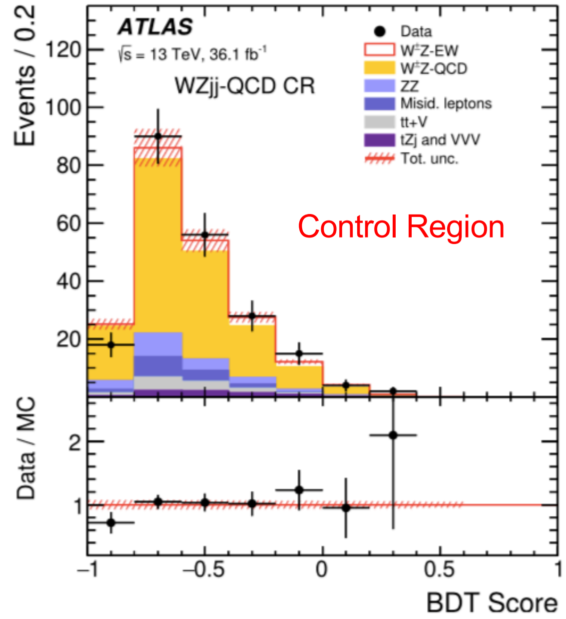
$$\sigma^{fid-Sherpa}_{WZjj-EW}\ 0.321 \pm 0.002(stat) \pm 0.005(\text{PDF})\ ^{+0.027}_{-0.023}\ (\text{scale})\ \text{fb}$$

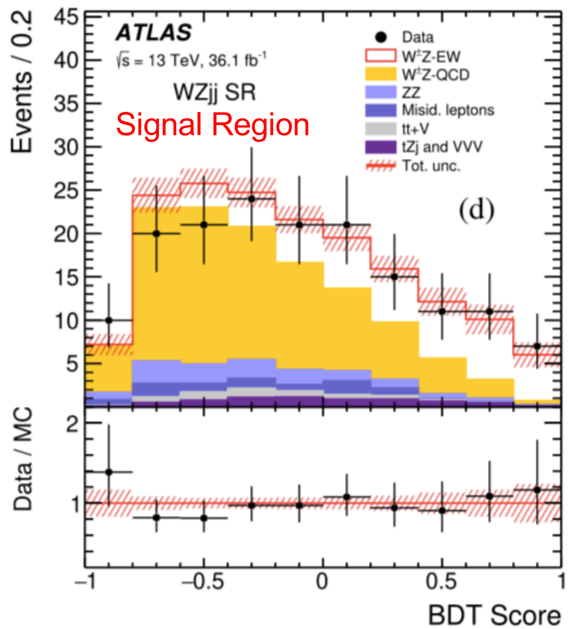
$$\sigma^{fid}_{WZjj} = 1.68 \pm 0.16(stat) \pm 0.12(\text{exp.}\ syst) \pm 0.13(\text{mod. exp}) \pm 0.04\ (lumi)\ \text{fb}$$

$$= 1.68 \pm 0.25\ \text{fb}$$

$$\sigma^{fid-Sherpa}_{WZjj}\ 2.15 \pm 0.01(stat) \pm 0.05\ (\text{PDF})\ ^{+0.65}_{-0.44}\ (\text{scale})\ \text{fb}$$

Significance: 5.3 σ (obs); 3.2 σ (exp.) → **first observation of EWK WZ jj**

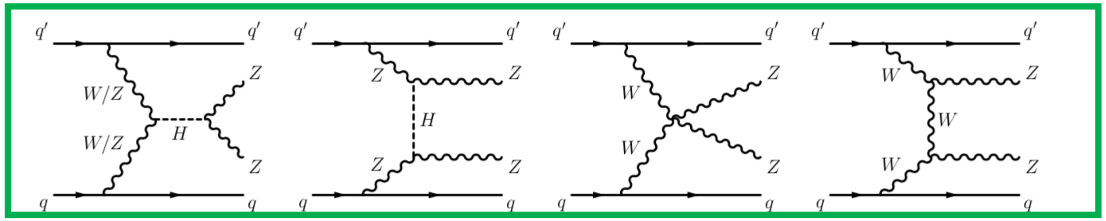




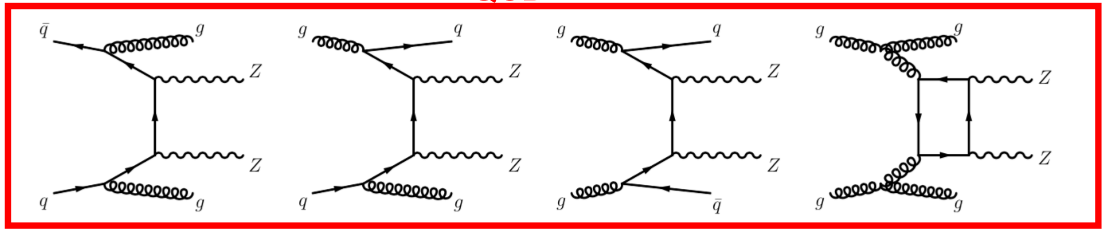
ATLAS: VBS ZZ

ATLAS-CONF-2019-033

EWK



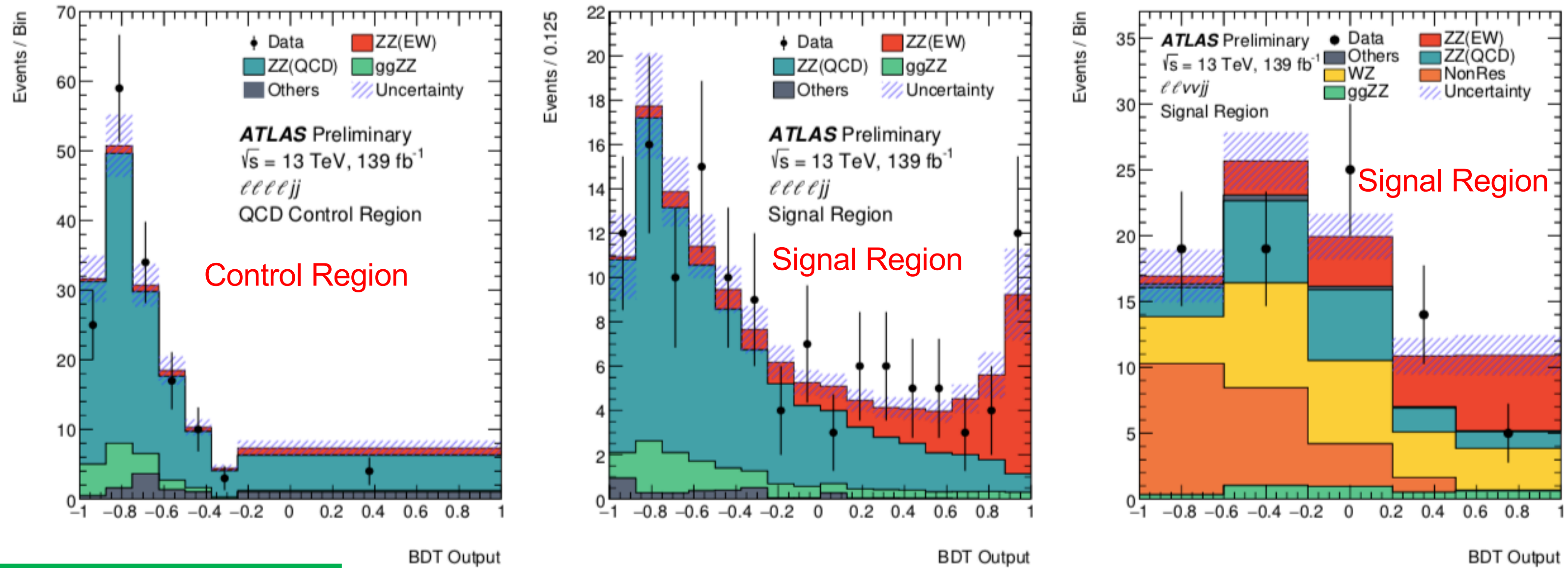
QCD



2015-18 data: 139 fb^{-1} at 13 TeV

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.30 ± 0.65
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.15 ± 0.89
Total	114 ± 26	78.4 ± 6.2
Data	127	82

The electroweak signal is extracted using a BDT with 12 (4ℓ) or 13 (2ℓ 2ν) variables

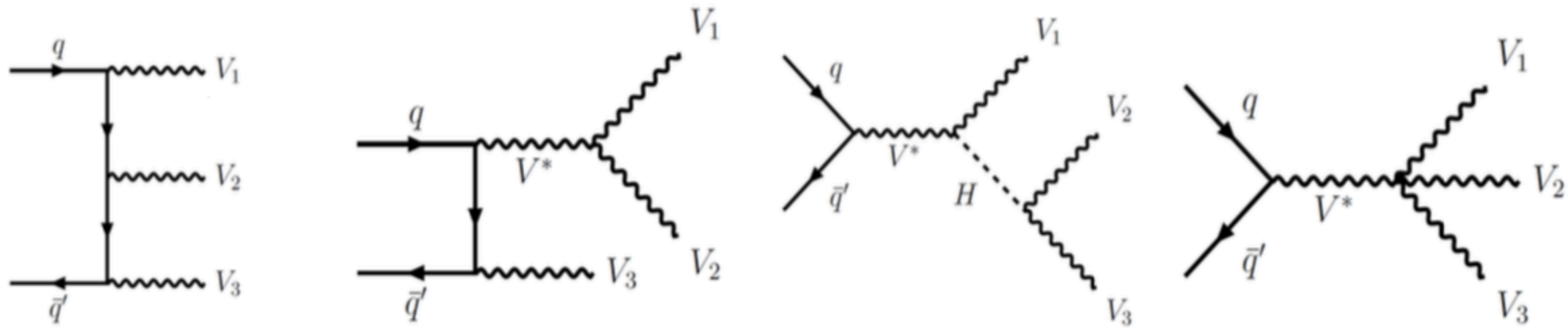


$$\sigma^{fid}_{ZZjj-EW} = 0.82 \pm 0.21\ fb$$

Significance: 5.5 σ (obs); 4.3 σ (exp.) → **first observation of EWK ZZ jj production**

Triboson final state (VVV)

Representative tree level Feynman diagrams



Process never observed at previous colliders

Process sensitive to TGC and QGC

WVV analysis strategy

WWW Analysis — Cutflow Based

WWW

Avoid Z bosons:
- 2ℓ2j Analysis - Two Same Sign leptons
- 3ℓ Analysis - 0 Same Flav. Opposite Sign leptons

2ℓ2j Analysis

- At least 2 jets with b-jet veto.
  - M_{jj} is used as the discriminant
- Specific cuts to veto same sign WW

3ℓ Analysis

- 0 SFOS suppresses majority of backgrounds.
- b-jet veto is additionally applied to veto ttbar events.

WVZ Analysis — BDT Based

WV Z

Categorize according to 3ℓ or 4ℓ end-states

Always reconstruct a Z boson with 2 leptons

3ℓ Analysis

- At least one jet with b-jet veto.
- One BDT is trained per jet category:
  - 1, 2, 3+ jets.

4ℓ Analysis

- 4 leptons with a total charge of 0
- One BDT is trained for each category:
  - Same-flavor on-shell
  - Same-flavor off-shell
  - Different-flavor

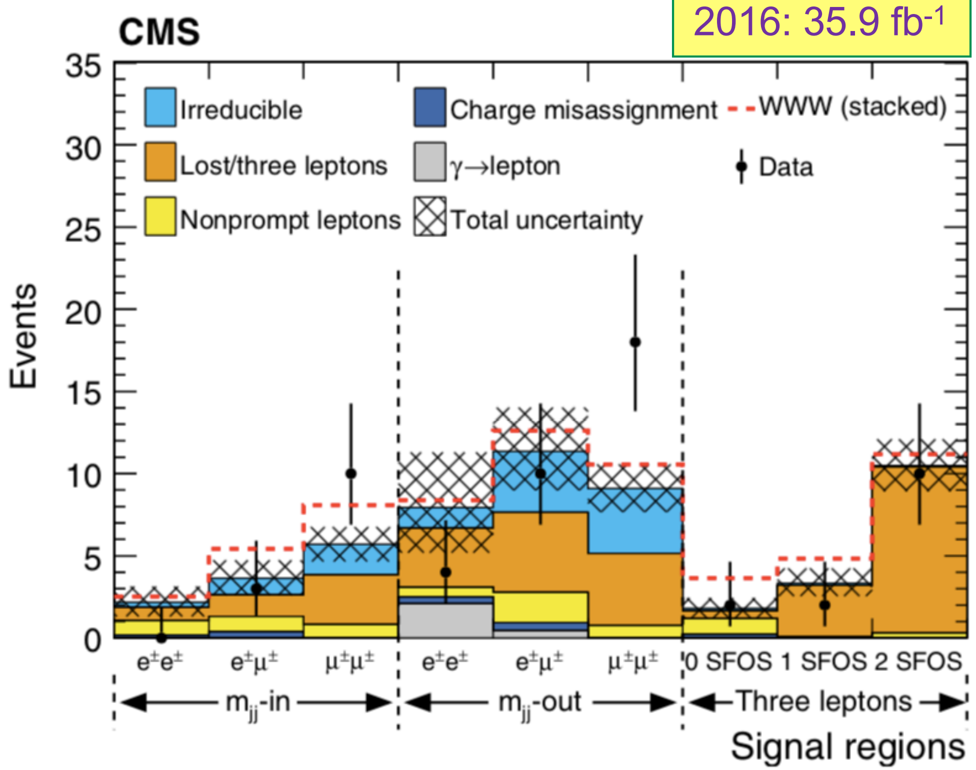
- **Used both data-driven and MC-based background estimates with control region**

CMS: WWW [Phys Rev D 100 012004](#)

2016: 35.9 fb^{-1}

- **9 signal regions**
  - **6 from 2ℓ of same sign, m_{jj}-in consistent as W and m_{jj}-out for other selected events**
  - **3 regions from events with 3ℓ**
- **Measurements:**

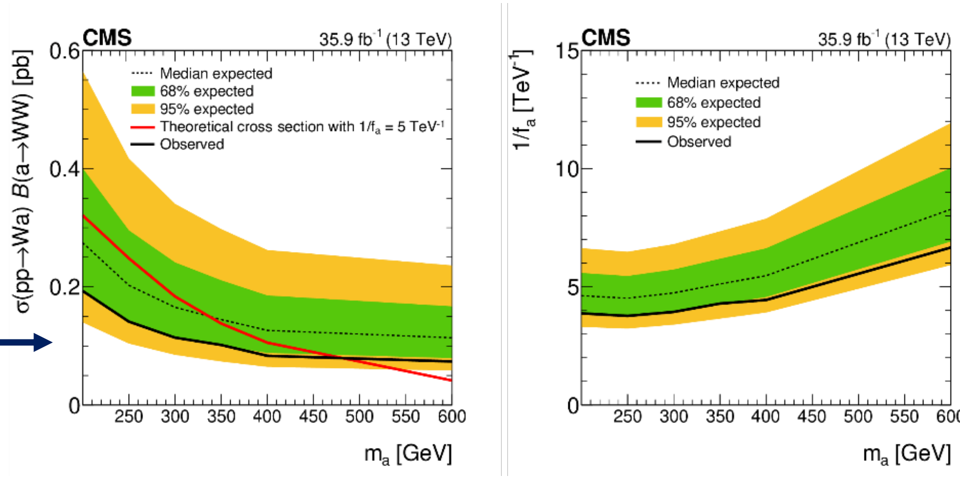
$$\sigma\left(pp \rightarrow W^{\pm}W^{\pm}W^{\mp}\right) = 170^{+320}_{-170}\ fb$$



aQGC limits on 3 most sensitive couplings

Anomalous coupling	Allowed range (TeV^{-4}) Expected	Observed
$f_{T,0}/\Lambda^4$	[−1.3, 1.3]	[−1.2, 1.2]
$f_{T,1}/\Lambda^4$	[−3.7, 3.7]	[−3.3, 3.3]
$f_{T,2}/\Lambda^4$	[−3.0, 2.9]	[−2.7, 2.6]

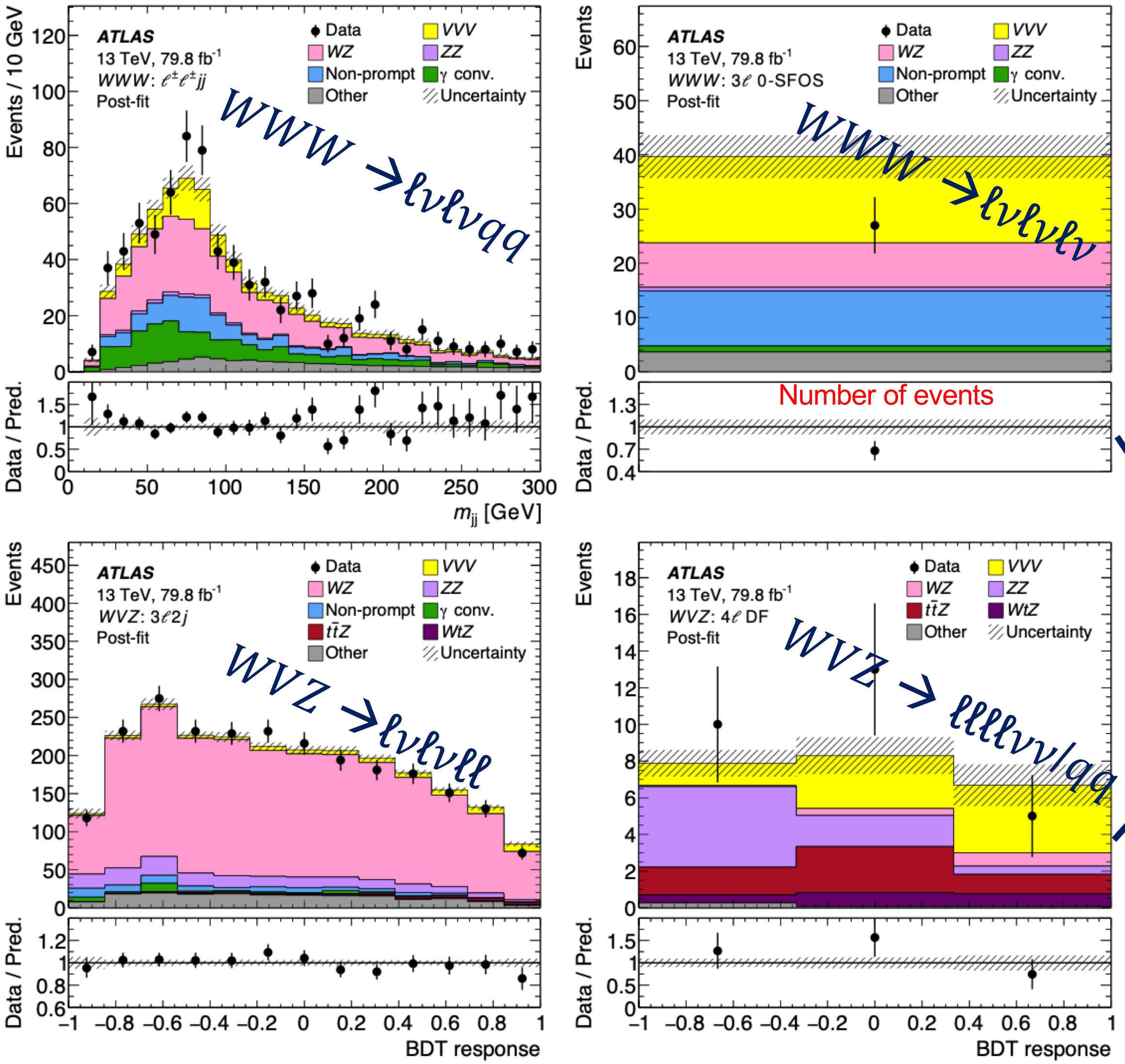
Explore BSM physics based on photophobic axion-like model (ALP: [arxiv:1805.06538](#))
pp → W a (a→ WW) → WWW

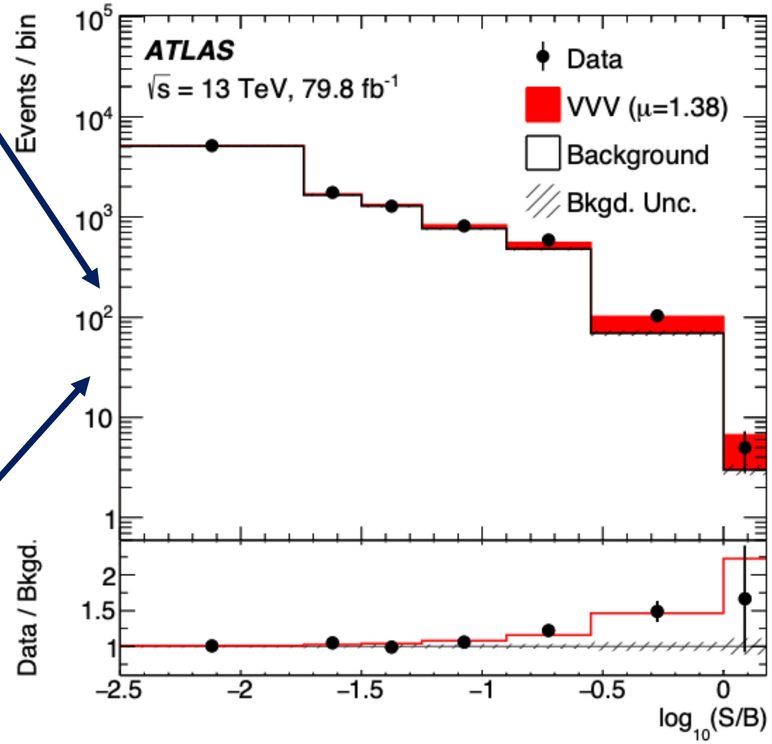


ATLAS: WWW+WWZ+WZZ [arxiv:1903.10415]

2016-2017: 79.8 fb^{-1}

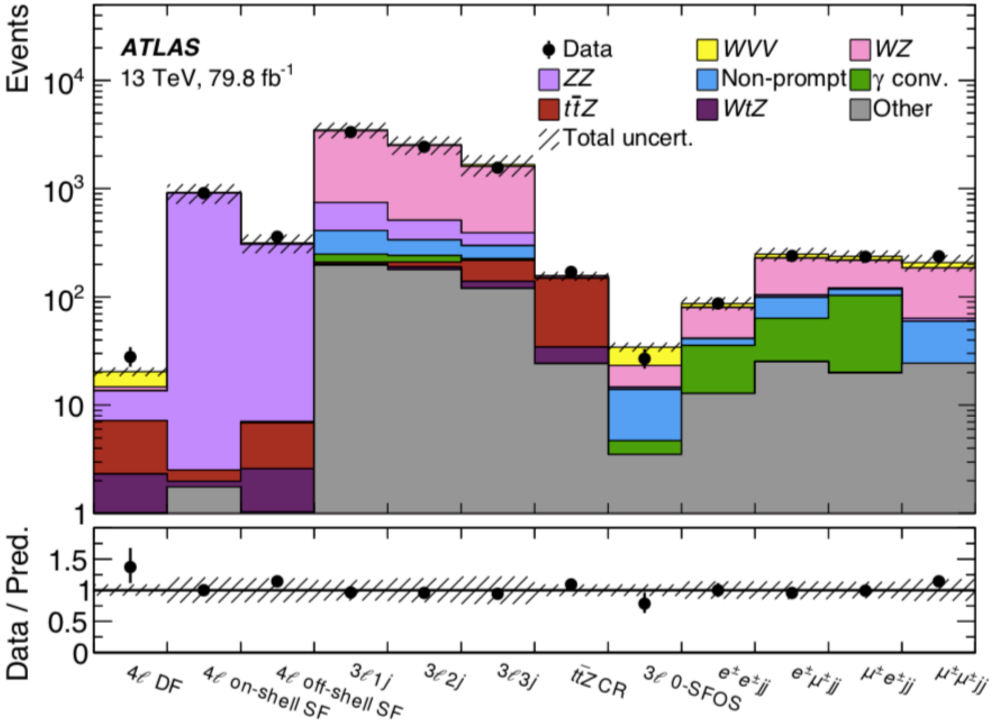
Simultaneous fit to 11 SRs and 1 CR, and combine into a plot of $\log_{10}$(S/B) clearly deviated from BKG only.

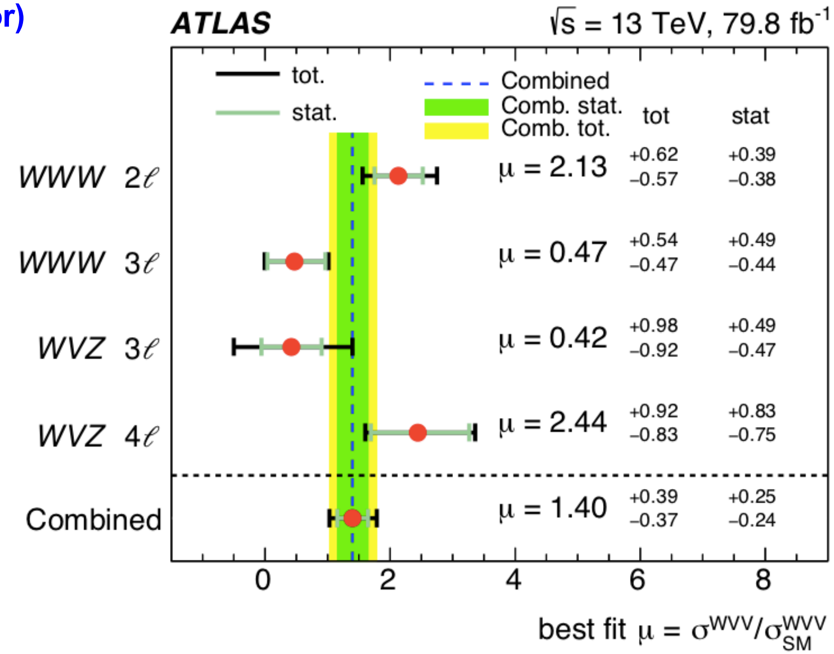




ATLAS: WWW+WWZ+WZZ

12 region distributions after fit (DF=Different ℓ Flavor, SF=Same ℓ Flavor)





First evidence of VVV production in *pp* events has been observed with a significance of 4.1 σ compared to expected 3.1 σ

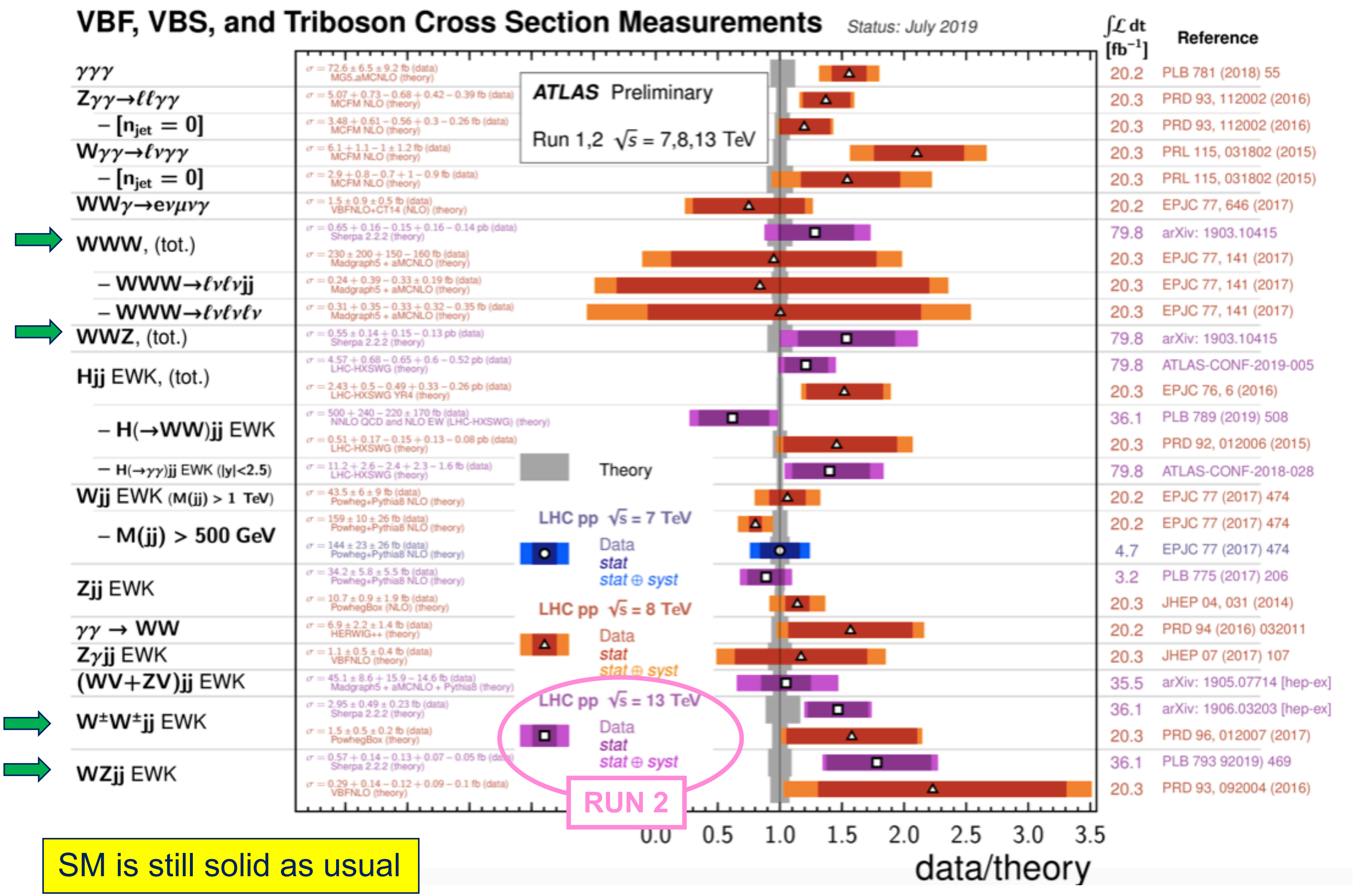
Decay channel	Significance Observed	Significance Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell / qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ

*** WVV cross-section measurements, consistent with SM predictions**

$$\sigma_{WWW} = 0.65^{+0.16}_{-0.15}(stat)\,^{+0.16}_{-0.14}(syst)\;pb$$

$$\sigma_{WWZ} = 0.55 \pm 0.14(stat)\,^{+0.15}_{-0.13}(syst)\;pb$$

Summary on multi boson cross sections



SM is still solid as usual

Conclusions

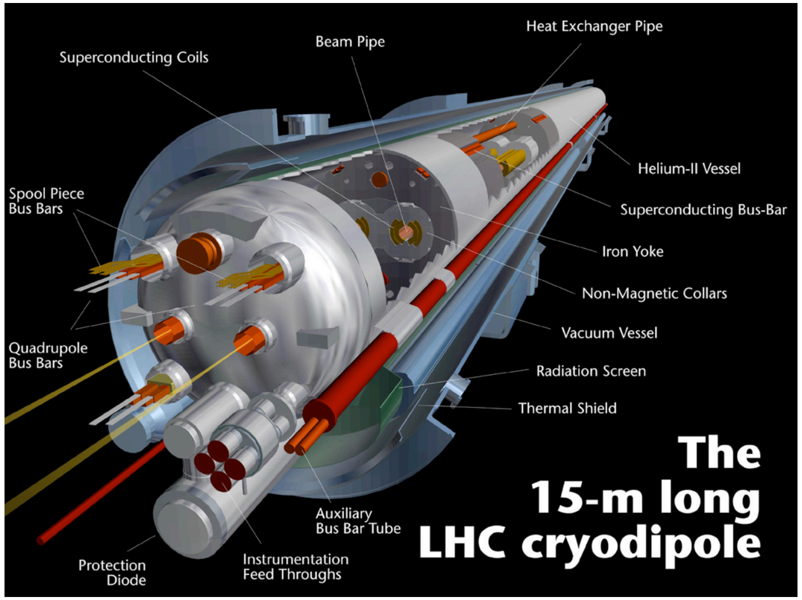
- LHC is a ``discovery'' machine but it can do also precision physics.
- M_W and $\sin^2\theta_W$ are fundamental parameters of the SM, so they have to be measured with the highest precision we can achieve.
- To be noticed: I presented recent results (2018-2019) based mainly on ``old'' data (2011, 2012, 2016) → it takes a lot of time to make accurate measurements.
- In any case the SM is still solid as ever… but we keep trying.
- Gauge Boson Coupling measurements are still limited by statistical uncertainties, so the full statistics available is required

- LHC will restart in 2021 and we expect about 300 fb^{-1} in RUN3.
- The long term goal is the 3 ab^{-1} expected with HL-LHC, but besides the luminosity we need also a major breakthrough in the PDF determinations.

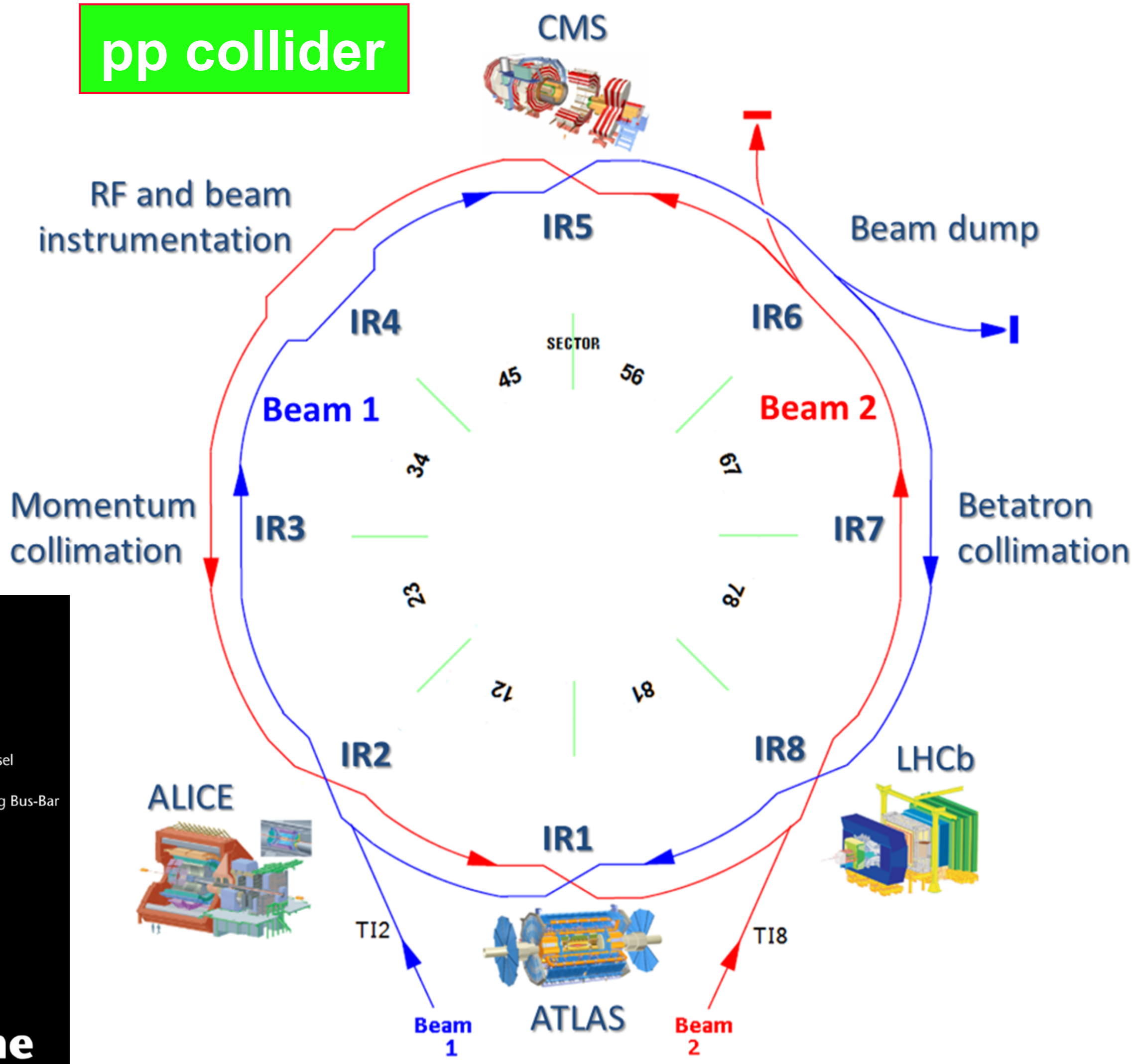
Back-up

The Large Hadron Collider LHC

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each.
- 8 straight sections of 700 m.
- Beams cross in 4 points.
- Design energy 7 TeV obtained with superconducting magnets operating at 8.3 T.
- 2-in-1 magnet design with separate vacuum chambers.
- **2 COUPLED rings**.

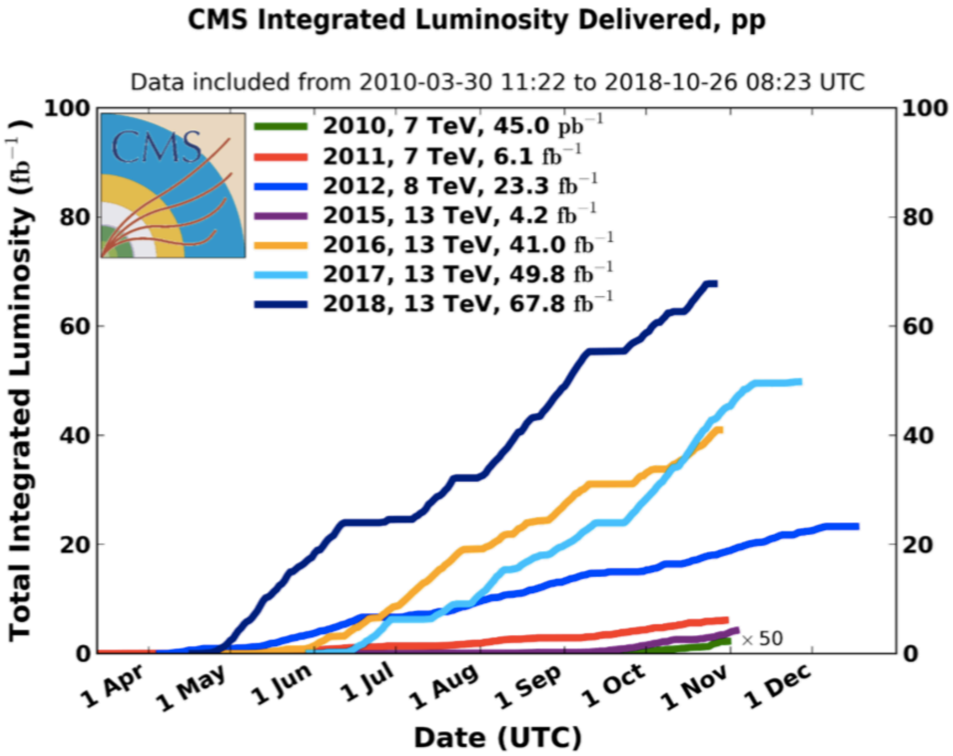


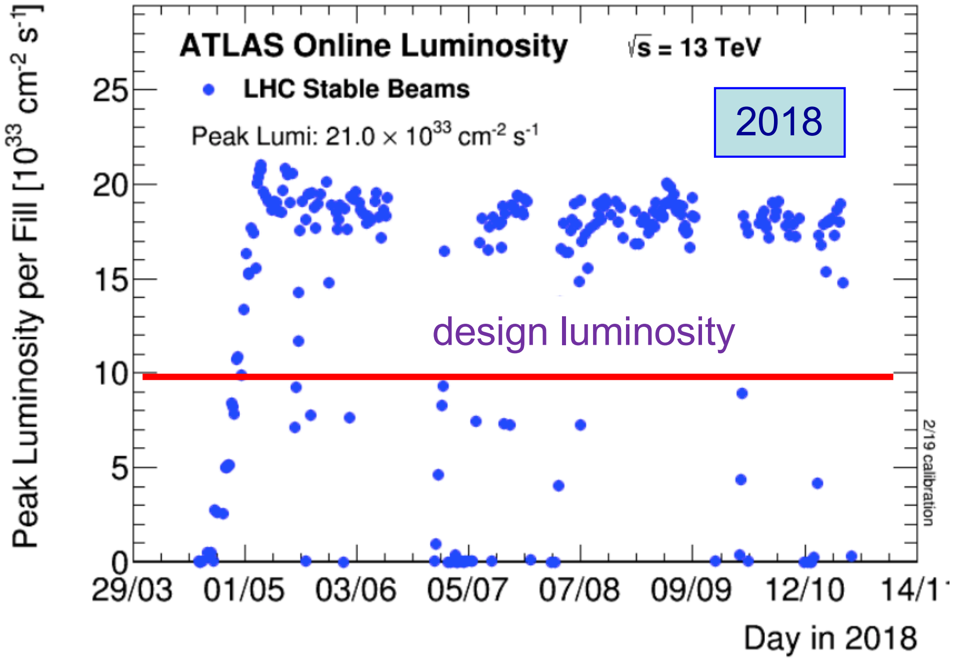
pp collider

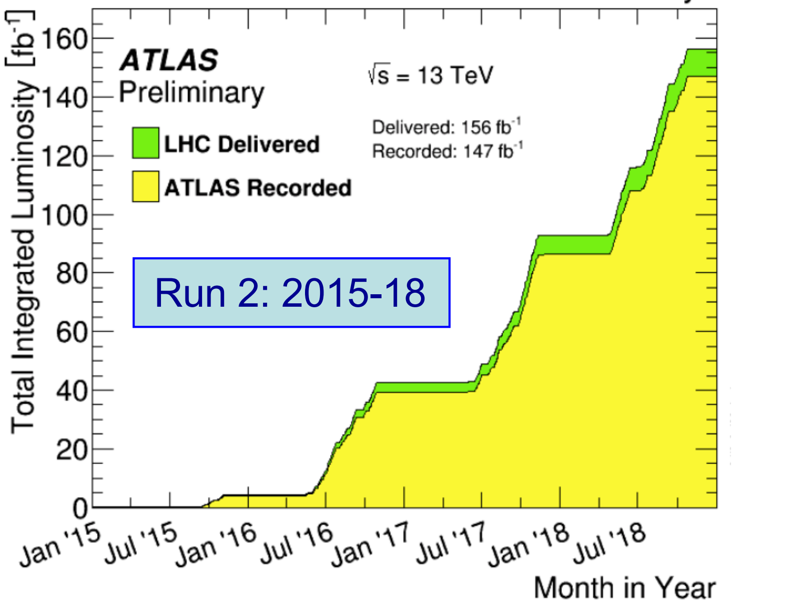


Design √s=14 TeV

LHC Luminosity and Energy: 2010 ÷ 2018



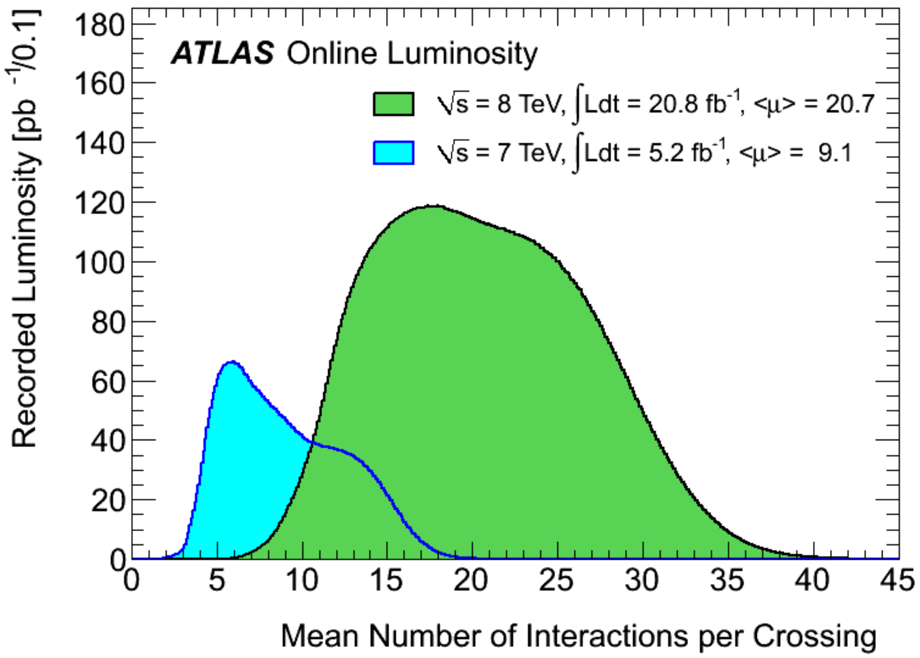




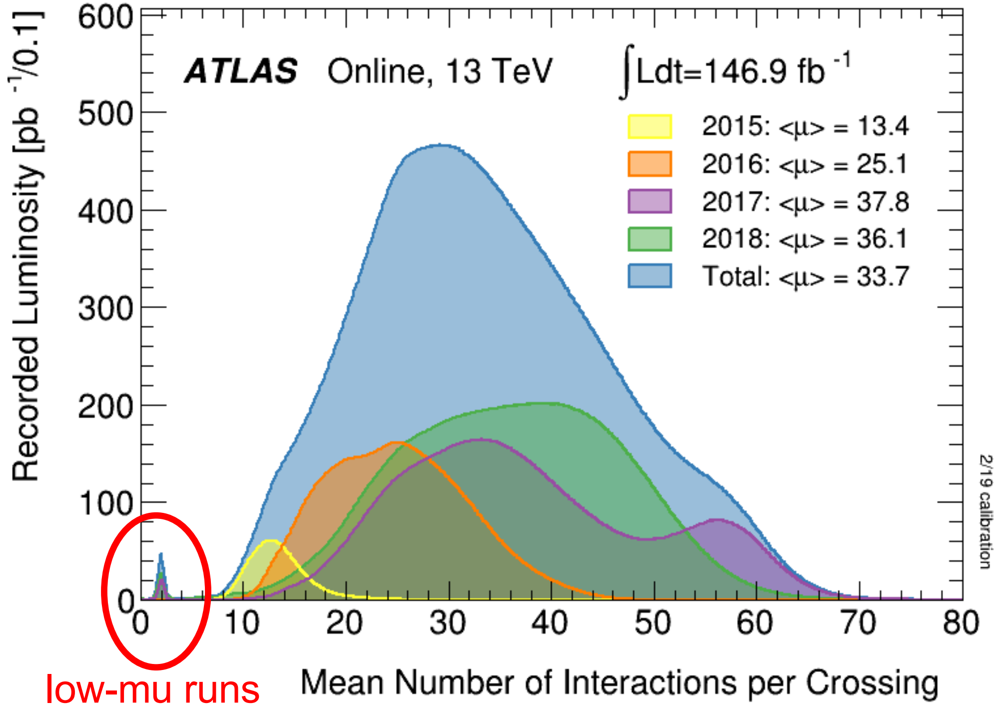
- Run1: 2010- 2012:
  - 2011: 7 TeV; 6.1 fb^{-1}
  - 2012: 8 TeV; 23.3 fb^{-1}
- Run2: 2015-2018
  - CM energy = 13 TeV
  - Total lumi Run2 = 160 fb^{-1}
- Run3 goal: ~ 300 fb^{-1} by 2024
- HL-LHC goal: ~ 3 ab^{-1} by 2035

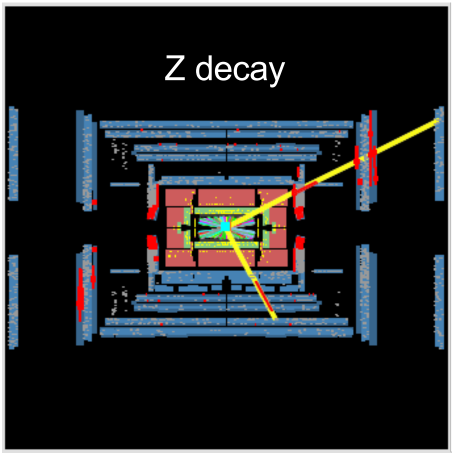
Pile-up

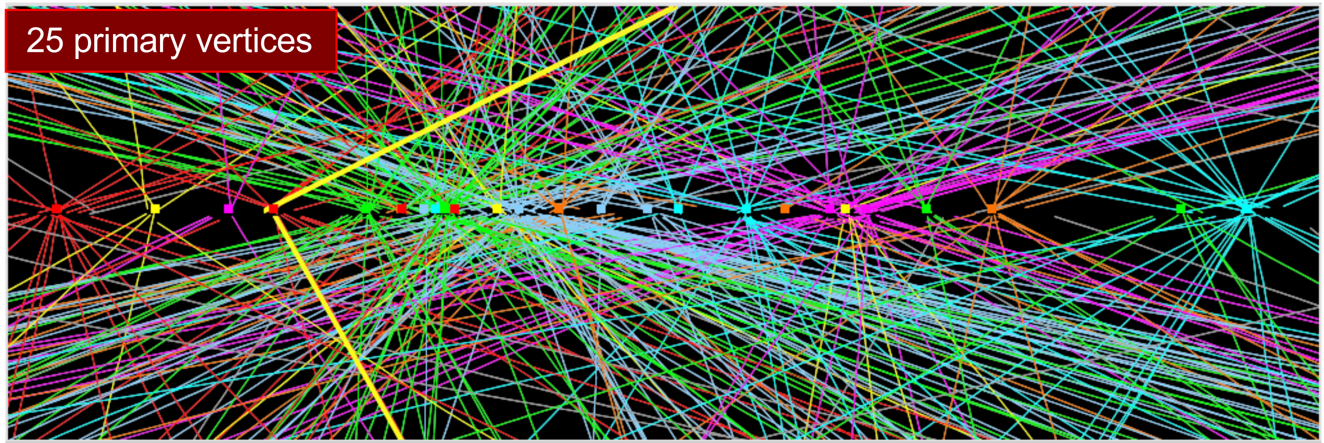
2011-2012: 50 ns bunch spacing



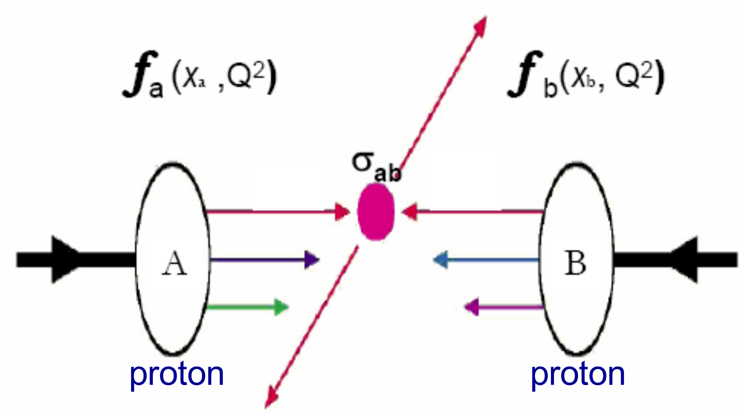
2015-2018: 25 ns bunch spacing



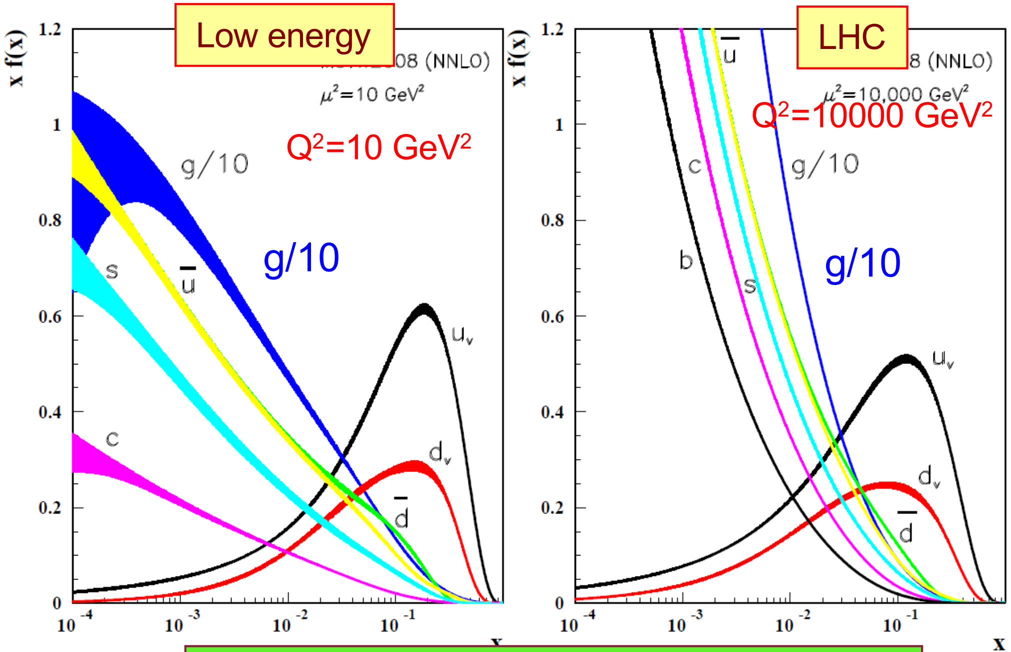




LHC: parton-parton interactions



Interaction between the partons which constitute the hadrons:
not well defined parton energy but energy distribution → pdf



LHC is a gluon machine

PDFs are parameterizations of the partonic content of the proton:
at Hadron Colliders cross-section calculations are a convolution of the cross-section at parton level and PDFs

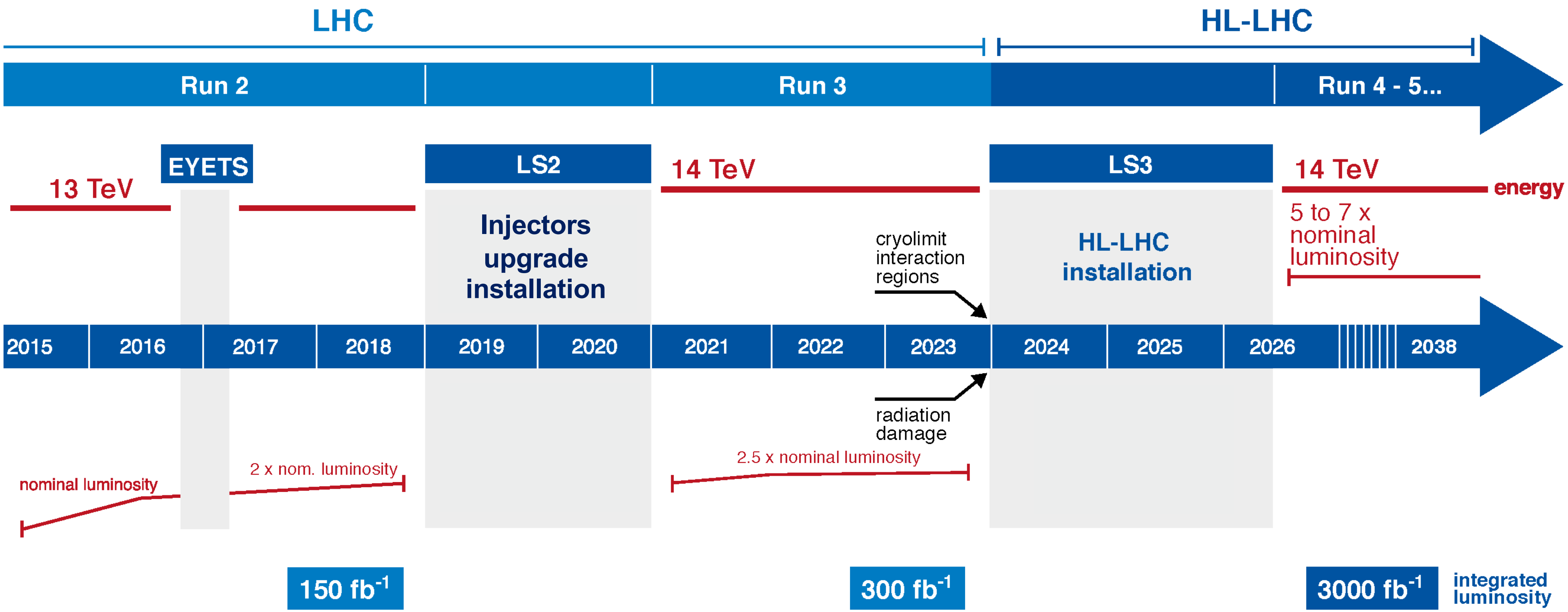
$$\sigma_X = \sum_{a,b} \int_0^1 dx_a dx_b f(x_a, flav_a, Q^2) f(x_b, flav_b, Q^2) \cdot \sigma_{ab \to X}(x_a, x_b, Q^2)$$

Sum over initial partonic states a,b

Parton Density Function

hard scattering cross-section

LHC schedule



In November 2019 there will be a meeting with CERN DG, accelerator and experiments to revisit the schedule

Technical limitation on the Instantaneous Luminosity:

Collider (cryolimit in the triplet region) at 2×10^{34} $cm^{-2}s^{-1}$ twice the nominal design luminosity)

Experiments pile up in the detectors). Designed for peak of 40 they are actually dealing with 60!

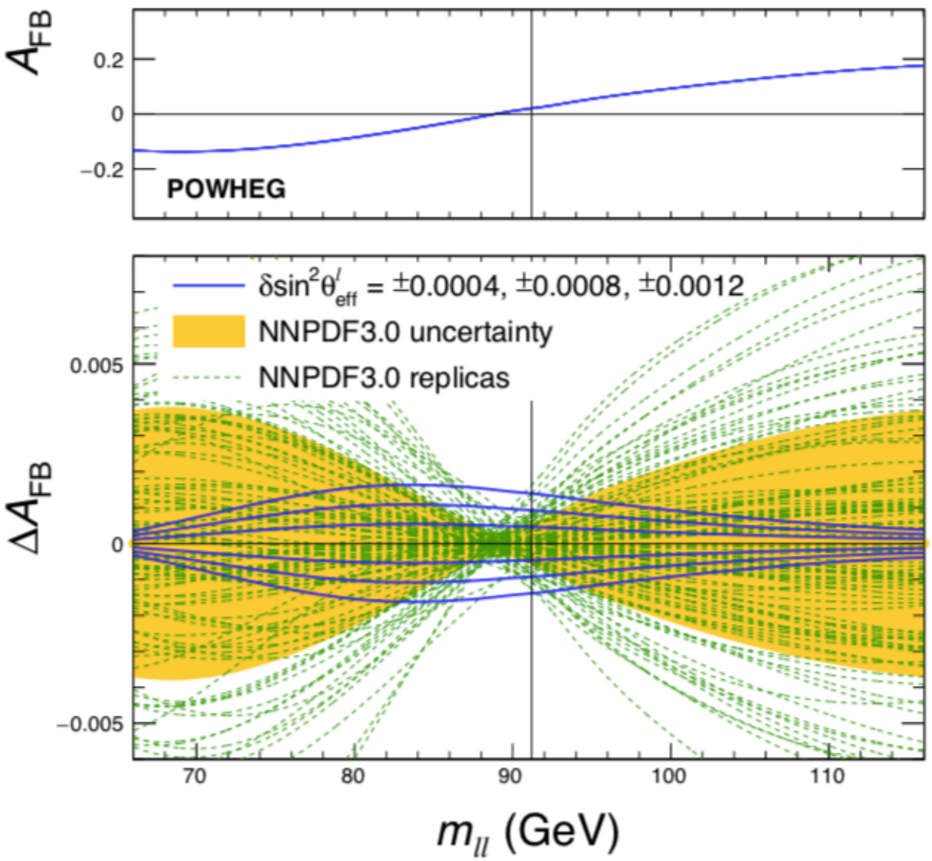
Technical limitation on Integrated Luminosity:

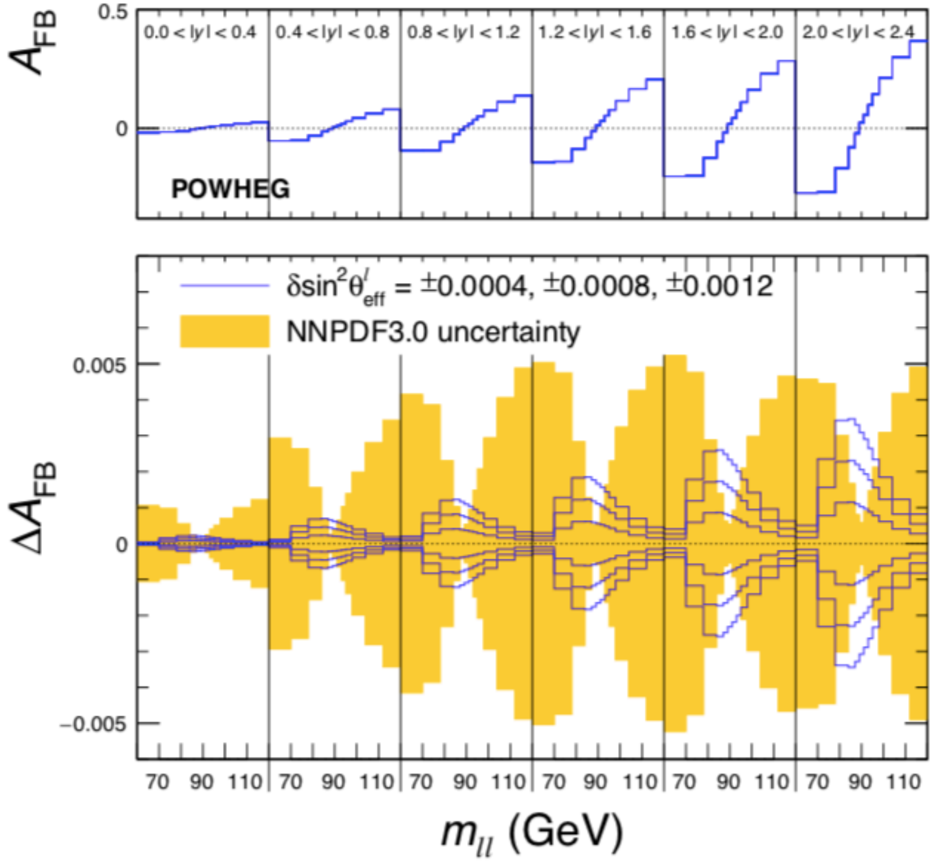
Collider (radiation damage to the IT magnets – correctors and quadrupoles)

Experiments radiation damage in the Inner Tracker)

Constrained PDF uncertainties

- The observed A_{FB} value depend on PDF distributions and on $\sin^2\theta_{eff}$ value.
- Changes in PDFs produce large changes in A_{FB} when the absolute values of A_{FB} are large (away from the Z pole). In contrast, the effect of changes in $\sin^2\theta_{eff}$ are largest near the Z pole.
- Because of this behaviour, we could apply a Bayesian χ^2 reweighting method (arxiv:1310.1089) to constrain the PDF, and thereby reduce their uncertainties in the extracted value of $\sin^2\theta_{eff}$.

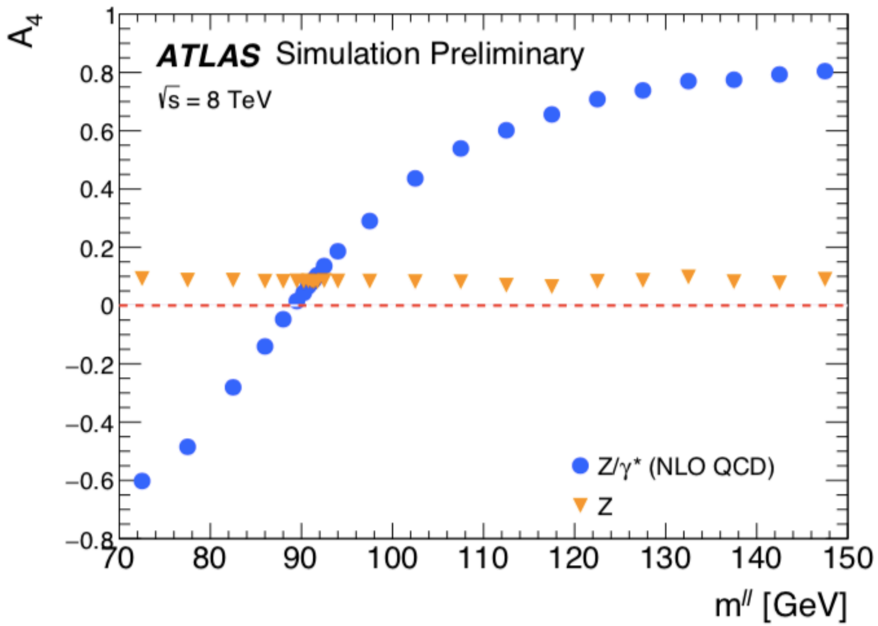


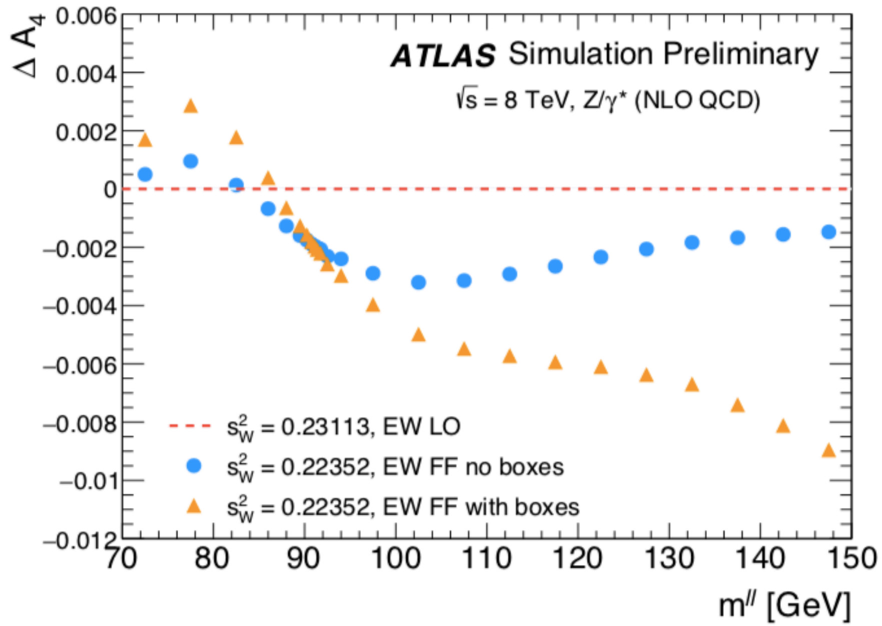


EW corrections impact on A_i decomposition

- The polynomial decomposition of the Drell-Yan differential cross section decouples the angular distribution of the final state from the production variables of the initial state contained in the A_i
- This factorisation is valid as long as we can neglet the higher order box corrections that couple initial and final states.
- We can see that aroud the Z pole the box corrections can be neglegted

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}} \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}.$$





Large Hadron Electron Collider (LHeC)

- A Large Hadron Electron Collider web page http://lhec.web.cern.ch
- Scattering of 60 GeV electron with 7 TeV proton (CDR done on 2012)
- LHeC is designed to have a factor of 10-20 higher cms energy ($s=4E_eE_p$) and a factor of nearly 1000 higher luminosity (L near 1 ab^{-1}) than HERA
- LHeC extends the kinematic range accessed with HERA from a maximum momentum transfer squared, Q^2, of about 0.03 TeV^2 to above 1 and from a maximum Bjorken x of about 0.6 to 0.9. The low x range extends down to 10^{-6}.