Electroweak physics in *ep* and *pp*

Complementarity of LHC and LHeC

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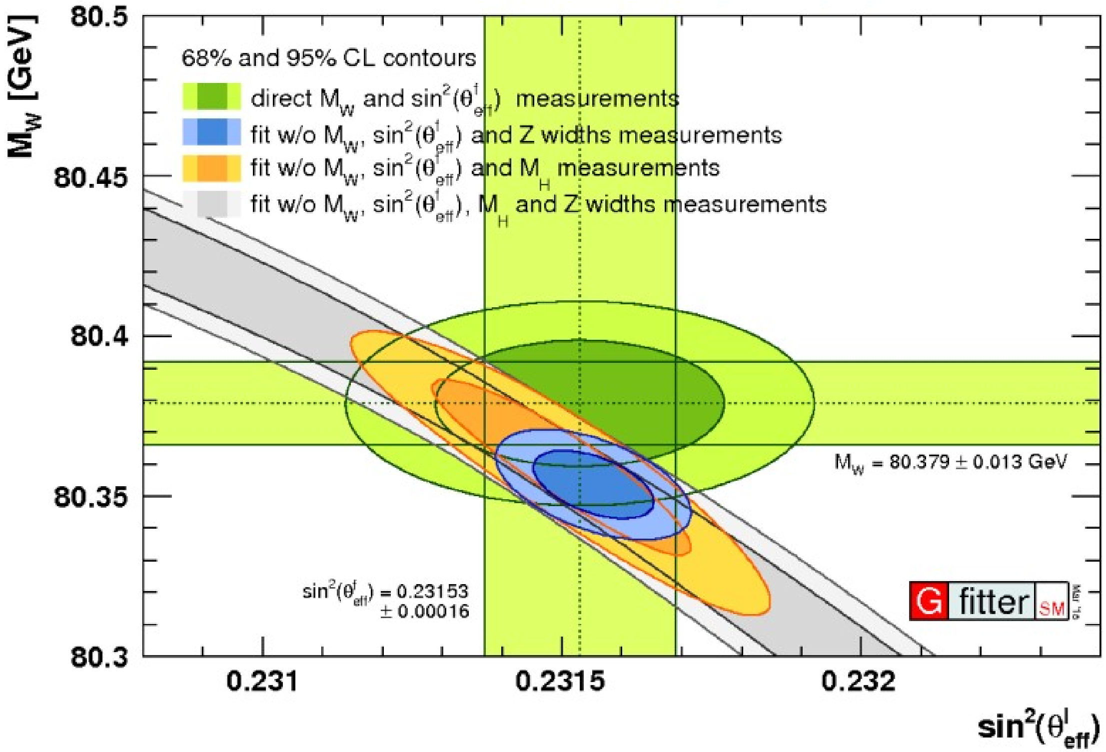
Outline

- Masses
  - M_W and $\sin^2\theta_{eff}$ – follow up
  - M_Z
- Couplings and coupling constants
- High-energy probes
  - High-mass tails in neutral- and charged-current Drell-Yan production
  - On-shell vector-boson scattering at high energies
- Conclusions

W-boson mass and the weak mixing angle

- Two PDF-dominated measurements as we just saw
- How correlated are these measurements under PDF uncertainties?



M_W and $\sin^2\theta_{eff}$ essentially uncorrelated this far (different colliders). Won't remain so when LHC gradually takes over.

Matters for interpretation downstream

W-boson mass and the weak mixing angle

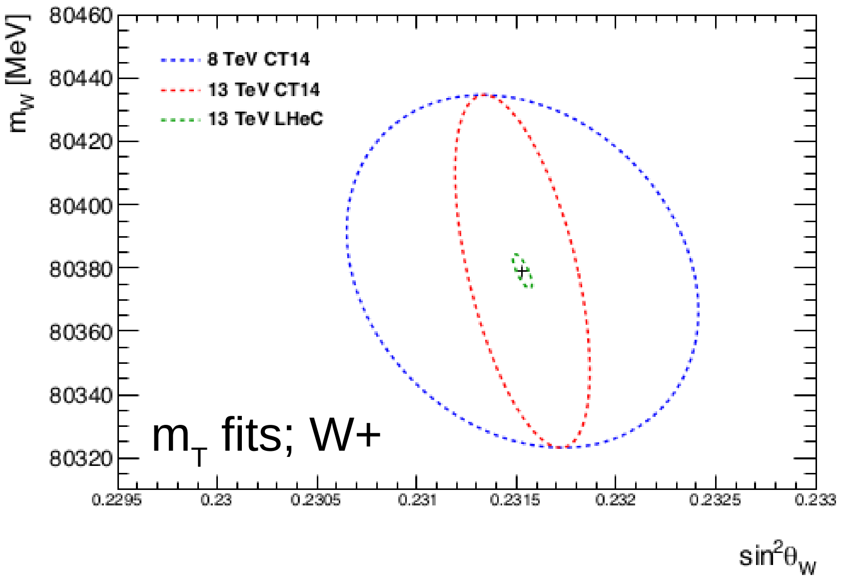
- Two PDF-dominated measurements as we just saw
- How correlated are these measurements under PDF uncertainties?

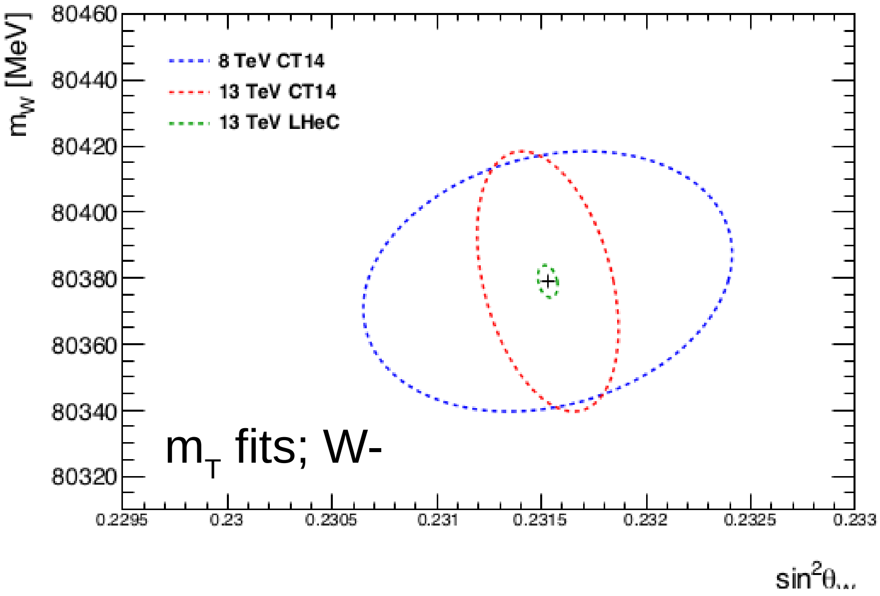
  - References for m_W :
    - 13 TeV : HL-LHC reports. Inclusive in pseudo-rapidity, separate fits for W+, W-
    - PDF sets: CT10, CT14, MMHT, HL-LHC, and LHeC
  - References for $\sin^2\theta_W$:
    - 8 TeV : ATLAS-CONF-2018-037
    - 13 TeV : HL-LHC reports): CT14, NNPDF, HLLHC, LHeC

W-boson mass and the weak mixing angle

- Two PDF-dominated measurements as we just saw
- How correlated are these measurements under PDF uncertainties?

N.Andari (work in progress, https://indico.cern.ch/event/776453)





Strong impact of LHeC. Model dependence of observed correlations?

m_W at ~~LHeC~~ HERA

Determination performed in on-shell scheme

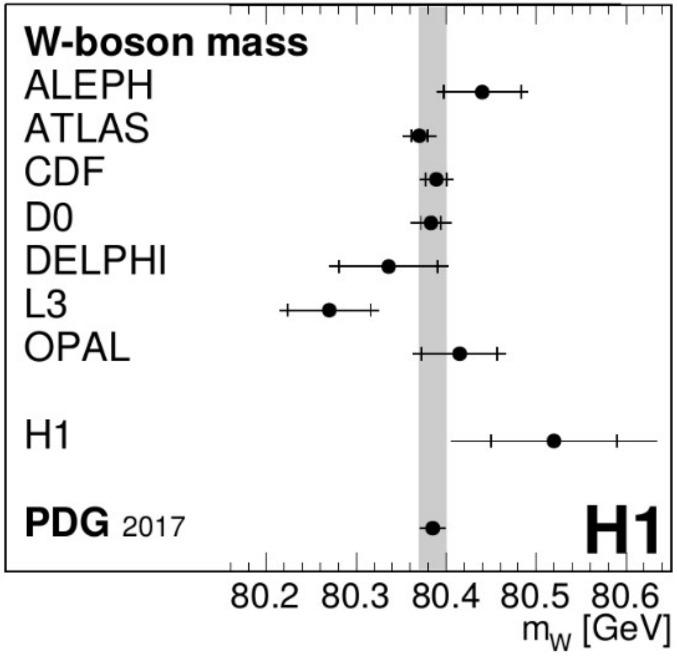
$$m_W = 80.520 \pm 0.070_{\mathrm{stat}} \pm 0.055_{\mathrm{syst}} \pm 0.074_{\mathrm{PDF}} = 80.520 \pm 0.115_{\mathrm{tot}}\,\mathrm{GeV}$$

From D. Britzger, EPS.

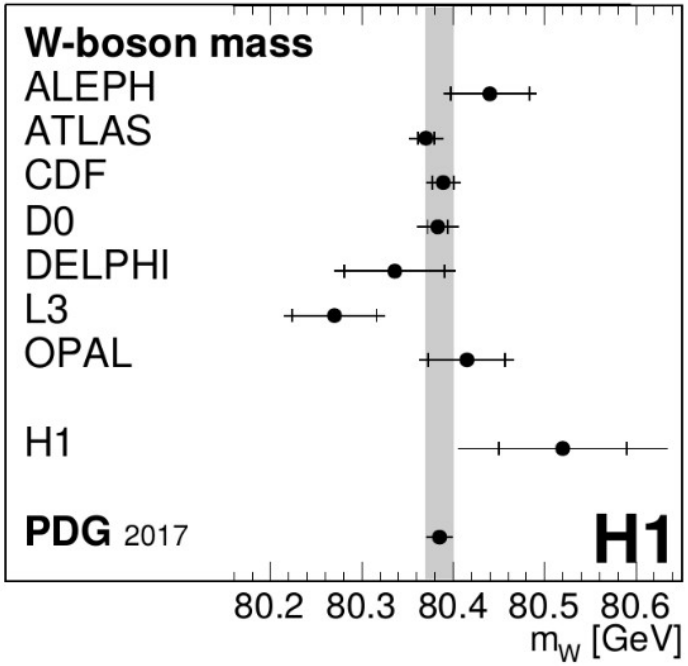
Sensitivity mostly from the normalization of the charged-current cross section :

$$\frac{d\sigma_{CC}^{\pm}}{dQ^2\,dx} = \frac{1 \pm P}{2}\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2 + Q^2}\right]^2 \left(Y_+ \mathbf{W}_2^{\pm} \pm Y_- x \mathbf{W}_3^{\pm} - y^2 \mathbf{W}_L^{\pm}\right)$$

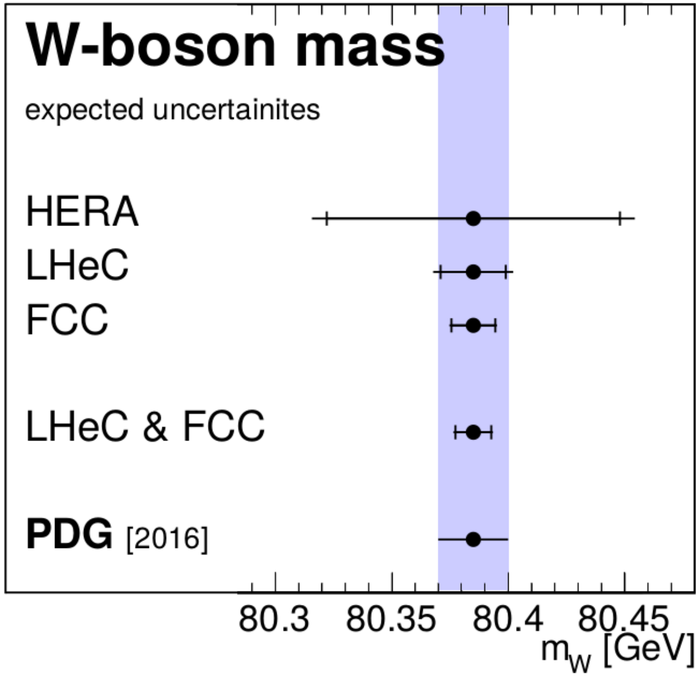
in a scheme where the free input parameters are α_{QED}, m_W, m_Z at Born level (determining G_F)



m_W at LHeC



→



$$\Delta m_W(\text{LHeC}) = \pm 14_{(\text{exp})} \pm 10_{(\text{PDF})}\,\text{MeV}$$

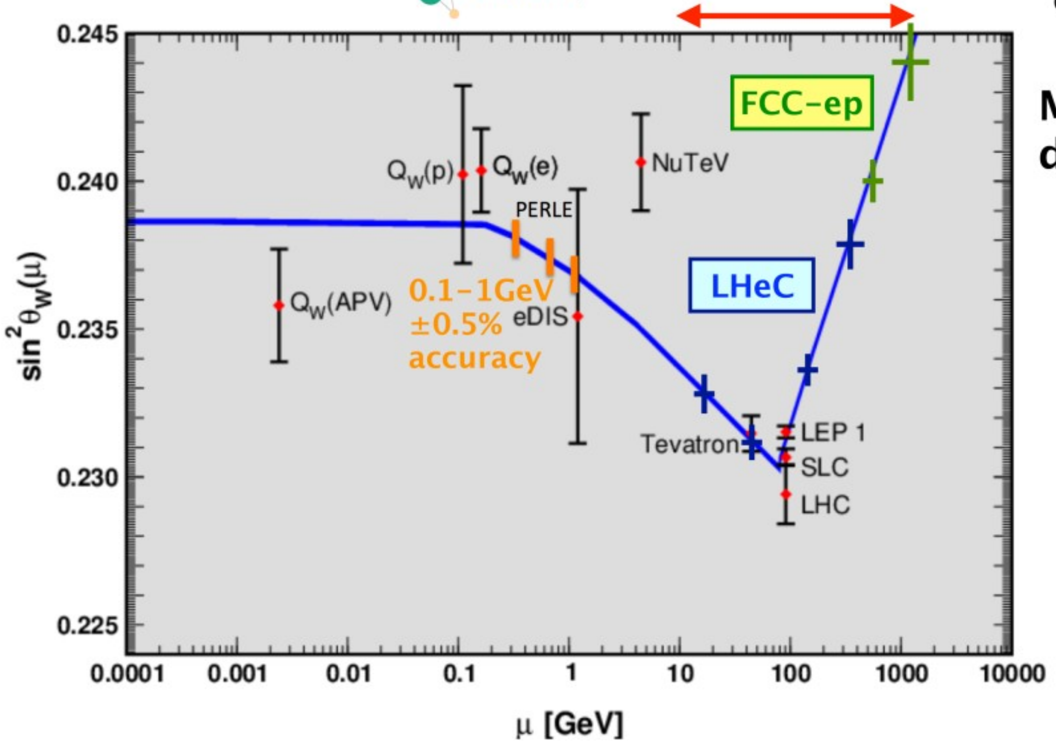
$$\Delta m_W(\text{FCC-eh}) = \pm 9_{(\text{exp})} \pm 4_{(\text{PDF})}\,\text{MeV},$$

Almost competitive with LHC prospects, and a very complementary measurement (*s* → *t*)

$\sin^2\theta_W$ at LHeC (and PERLE)

PERLE CDR, Arduini et al, to be published
ICFA BeamNewsletter 68 (January 2016)

LHeC CDR,
J.Phys. G39,
075001 (2012)

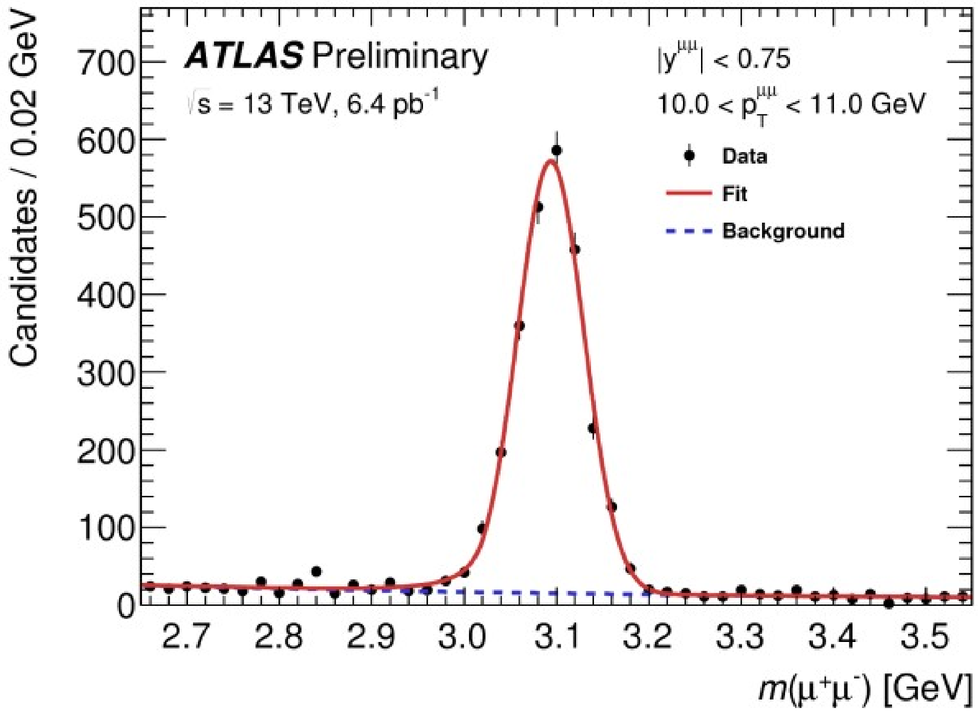


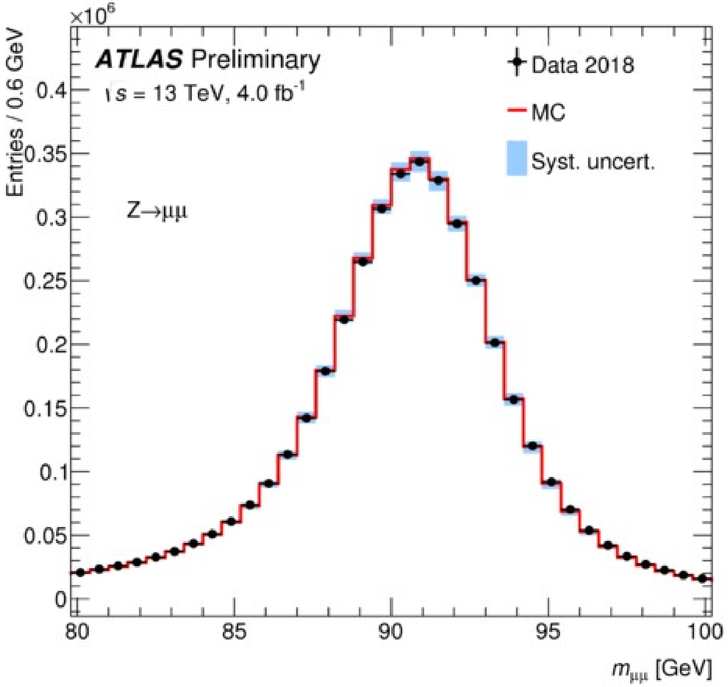
MSbar definition

In contrast to α_{QED}, the evolution of $\sin^2 q_W$ with Q^2 carries ~no uncertainty in the SM, so constitutes a powerful test of BSM, specific to *ep*.

The Z boson mass. Can we do better than LEP?

- Experimental sensitivity : Z and J/psi statistics

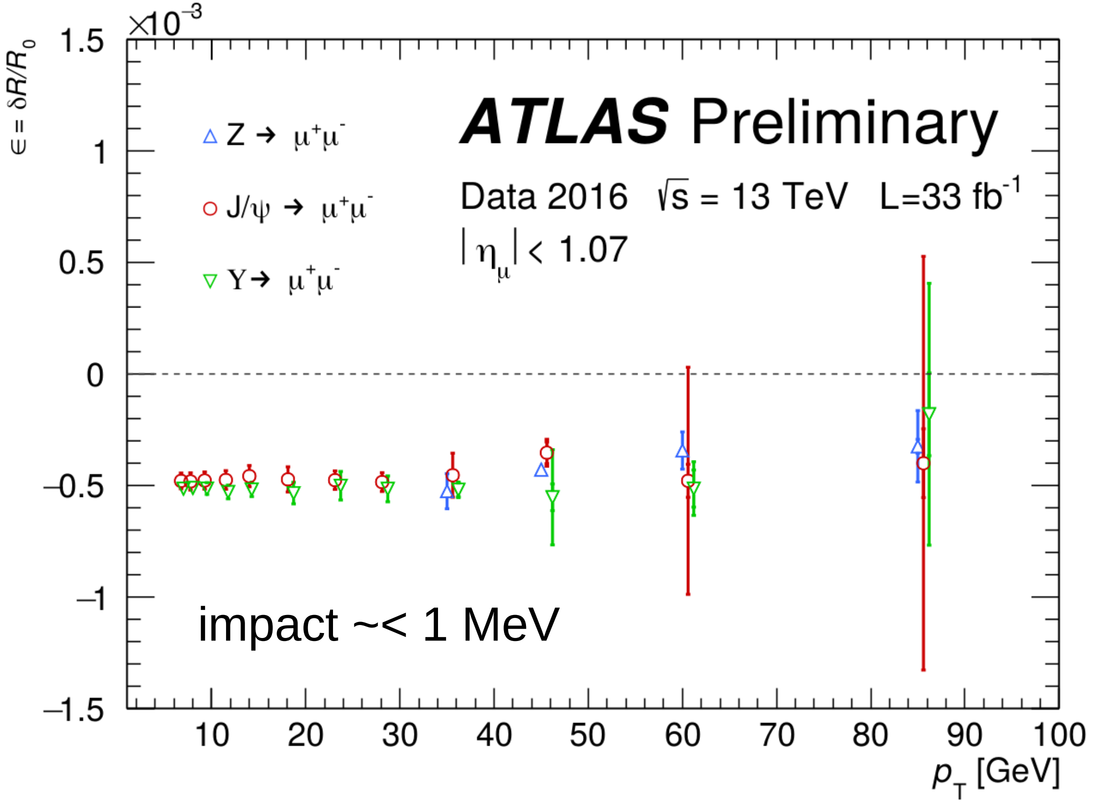




~100M J/psi $\rightarrow \mu\mu$ candidates and ~75M Z $\rightarrow \mu\mu$ per experiment in Run2.
Statistical sensitivity ~0.3 MeV; calibration precision ~0.3 MeV; J/psi mass known to ~10^{-6}

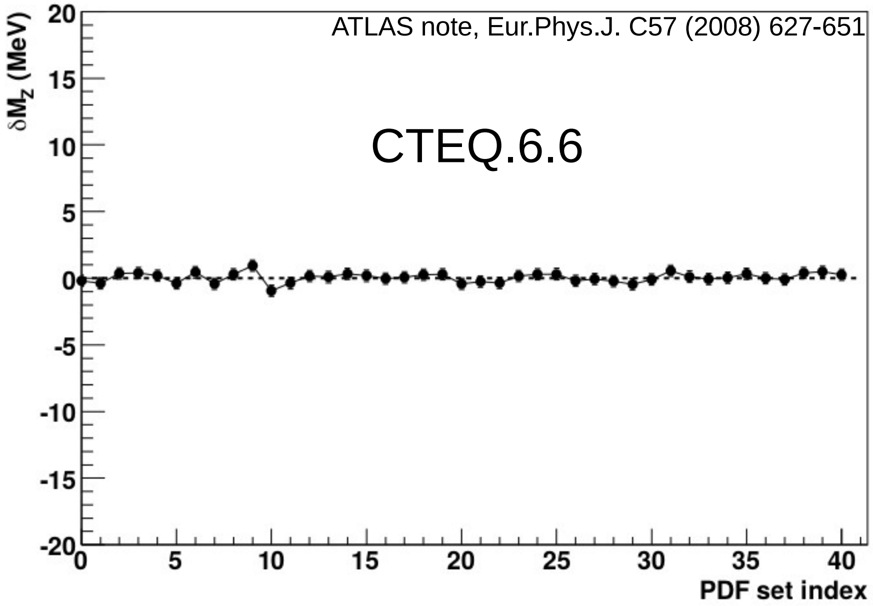
The Z boson mass. Can we do better than LEP?

- Experimental sensitivity
  - Muon momentum linearity



The Z boson mass. Can we do better than LEP?

- Theory / modelling systematics
  - Normalization and QCD uncertainties do not matter; backgrounds small
  - (N)NLO EW corrections needed (especially QED!)
  - PDF uncertainties ~2.5 MeV (from an old study)



A very small effect obviously, but dominant on this scale.
→ LHeC constraints would remove this.

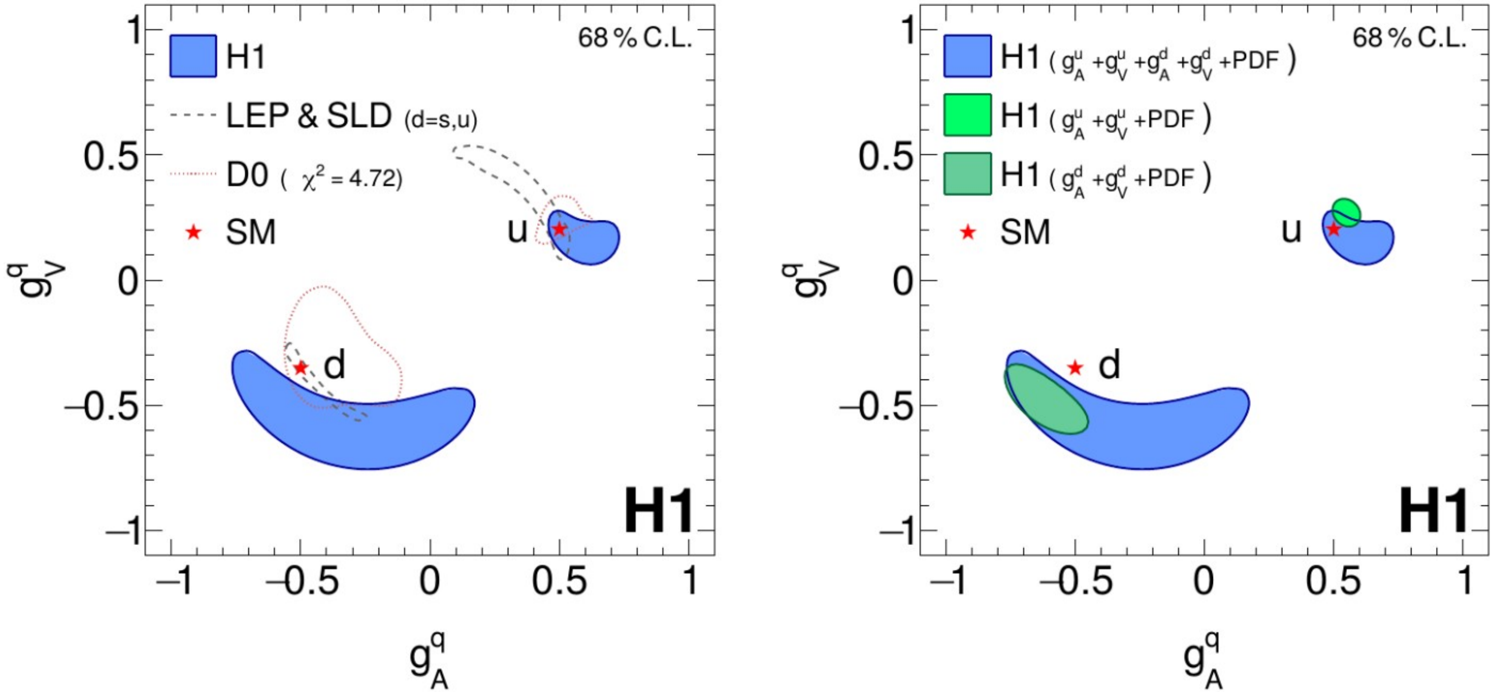
m_Z is relevant when δm_W~few MeV!

More on fermion couplings

- Vector and axial couplings to light quarks

$$\boldsymbol{F_2} = F_2^{\gamma} + \kappa_Z(-v_e \mp P a_e) F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm P v_e a_e) F_2^Z$$

$$x\boldsymbol{F_3} = +\kappa_Z(\pm a_e + P v_e) F_3^{\gamma Z} + \kappa_Z^2 \left(\mp 2 v_e a_e - P(v_e^2 + a_e^2)\right) x F_3^Z$$



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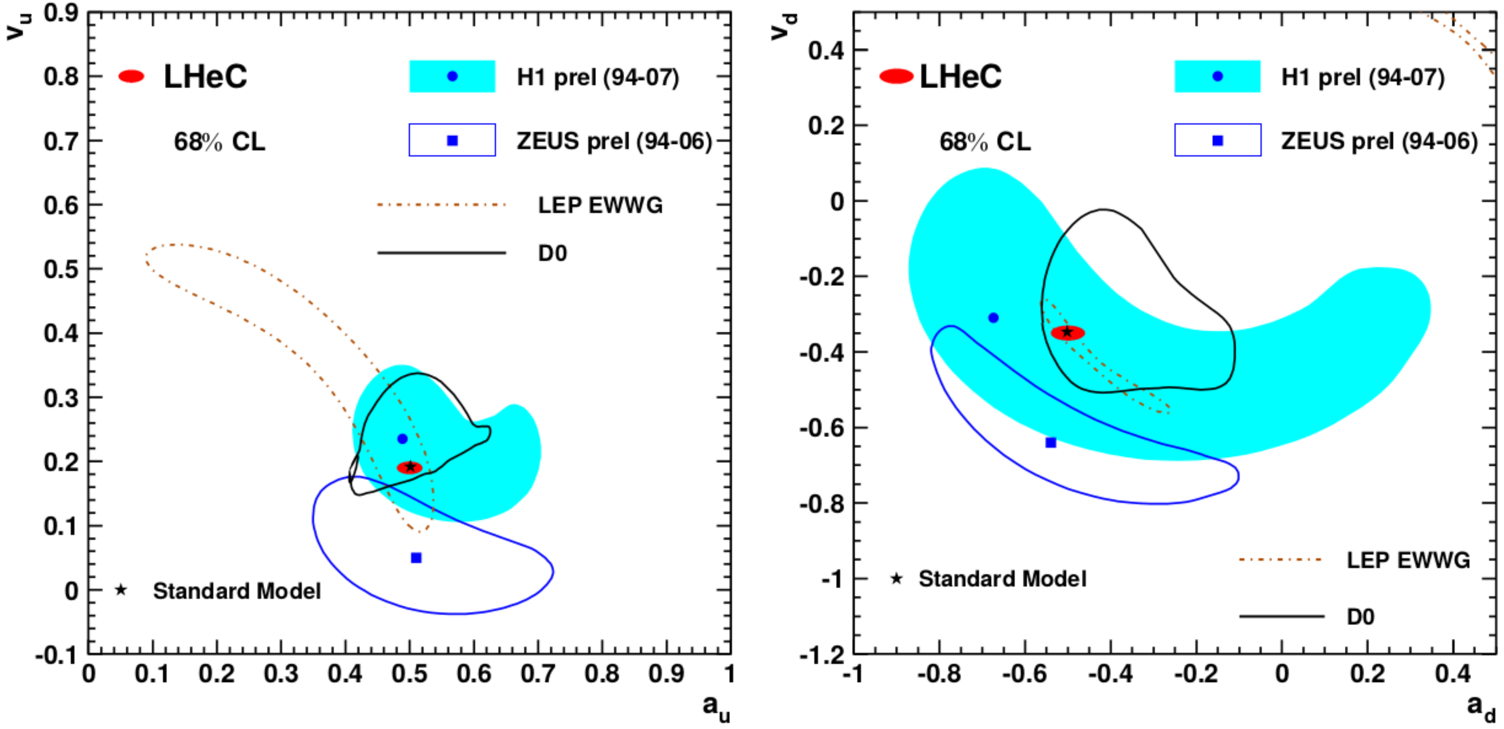

The strong coupling constant : also relevant for the interpretation of electroweak precision data

	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.1180 ± 0.0009	0.1184 ± 0.0028	-0.1
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02750 ± 0.00033	0.02743 ± 0.00025	0.02734 ± 0.00037	0.3
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0021	91.198 ± 0.010	-1.0
m_t [GeV]	$173.1 \pm 0.6 \pm 0.5$	173.43 ± 0.74	176.1 ± 2.2	-1.3
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	100.6 ± 23.6	1.0
M_W [GeV]	80.379 ± 0.012	80.3643 ± 0.0058	80.3597 ± 0.0067	1.4
Γ_W [GeV]	2.085 ± 0.042	2.08873 ± 0.00059	2.08873 ± 0.00059	-0.1
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231454 ± 0.000084	0.231449 ± 0.000085	0.8
$P^{\rm pol}_\tau = A_\ell$	0.1465 ± 0.0033	0.14756 ± 0.00066	0.14761 ± 0.00067	-0.3
Γ_Z [GeV]	2.4952 ± 0.0023	2.49424 ± 0.00056	2.49412 ± 0.00059	0.5
σ^0_h [nb]	41.540 ± 0.037	41.4898 ± 0.0050	41.4904 ± 0.0053	1.3
R^0_ℓ	20.767 ± 0.025	20.7492 ± 0.0060	20.7482 ± 0.0064	0.7
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.01633 ± 0.00015	0.01630 ± 0.00015	0.8
A_ℓ (SLD)	0.1513 ± 0.0021	0.14756 ± 0.00066	0.14774 ± 0.00074	1.6
R^0_b	0.21629 ± 0.00066	0.215795 ± 0.000027	0.215793 ± 0.000027	0.7
R^0_c	0.1721 ± 0.0030	0.172228 ± 0.000020	0.172229 ± 0.000021	-0.05
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	0.10345 ± 0.00047	0.10358 ± 0.00052	-2.6
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07394 ± 0.00036	0.07404 ± 0.00040	-0.9
A_b	0.923 ± 0.020	0.934787 ± 0.000054	0.934802 ± 0.000061	-0.6
A_c	0.670 ± 0.027	0.66813 ± 0.00029	0.66821 ± 0.00032	0.1
$\sin^2\theta^{\rm lept}_{\rm eff}$(Tev/LHC)	0.23166 ± 0.00032	0.231454 ± 0.000084	0.231438 ± 0.000087	0.7

HEPFIT collaboration, arXiv:1710.05402

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R_c^0	0.1721 ± 0.0030	0.172228 ± 0.000020	0.172229 ± 0.000021	-0.05
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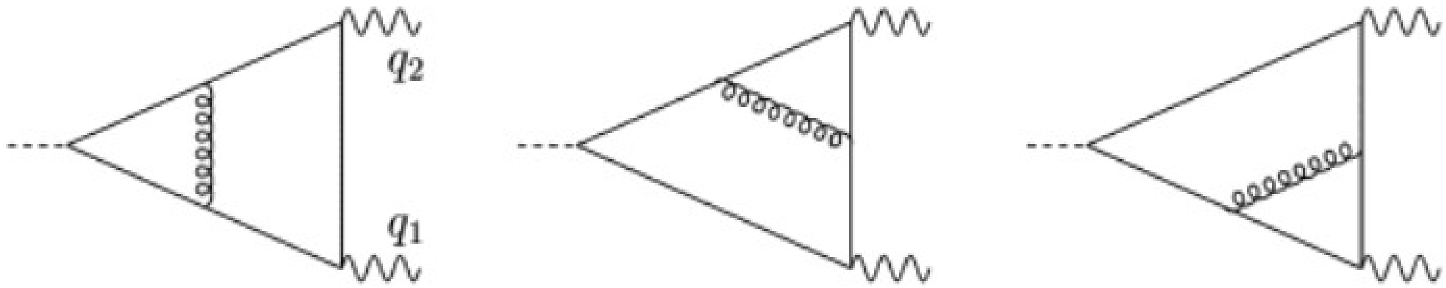

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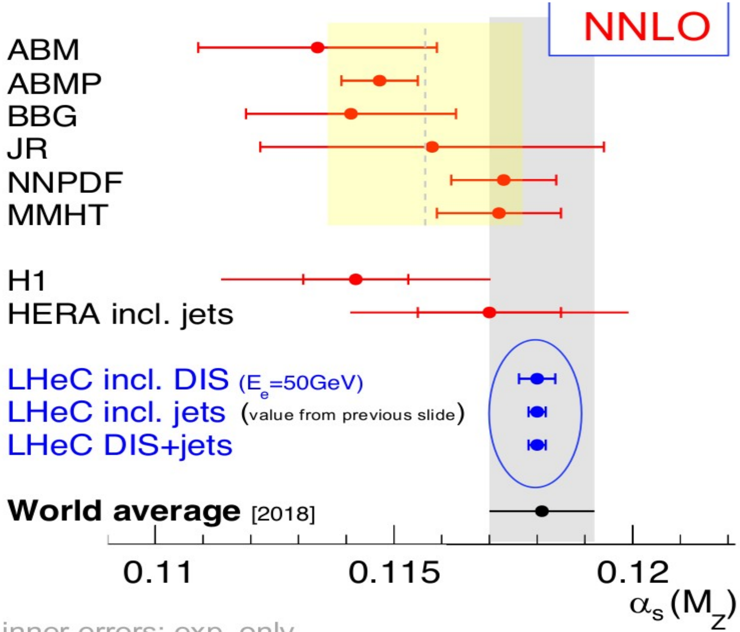
HEPFIT collaboration, arXiv:1710.05402

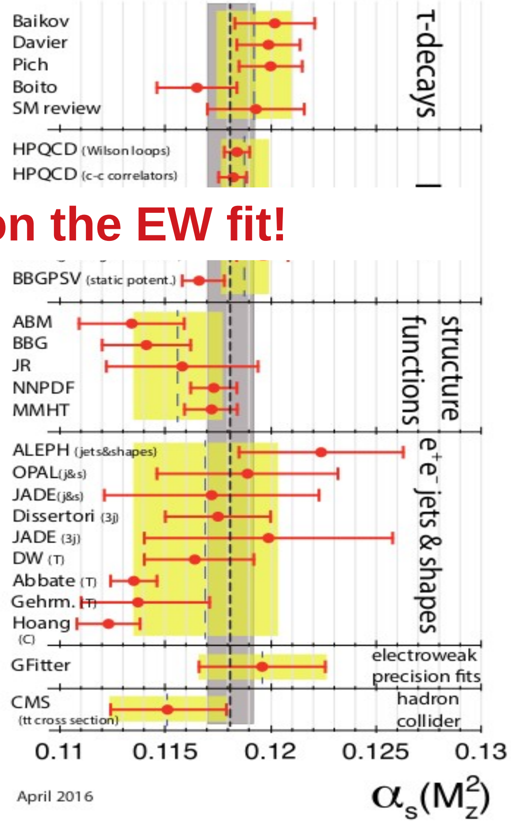
The strong coupling constant : also relevant for the interpretation of electroweak precision data

The least well measured fundamental coupling constant of the SM at $1 \sim 2\%$ precision – beyond the fundamental interest, a significant uncertainty e.g. on $\sigma(gg \to H)$, pp can measure scale dependence only

LHeC measurement with N^{3}LO theory can reach

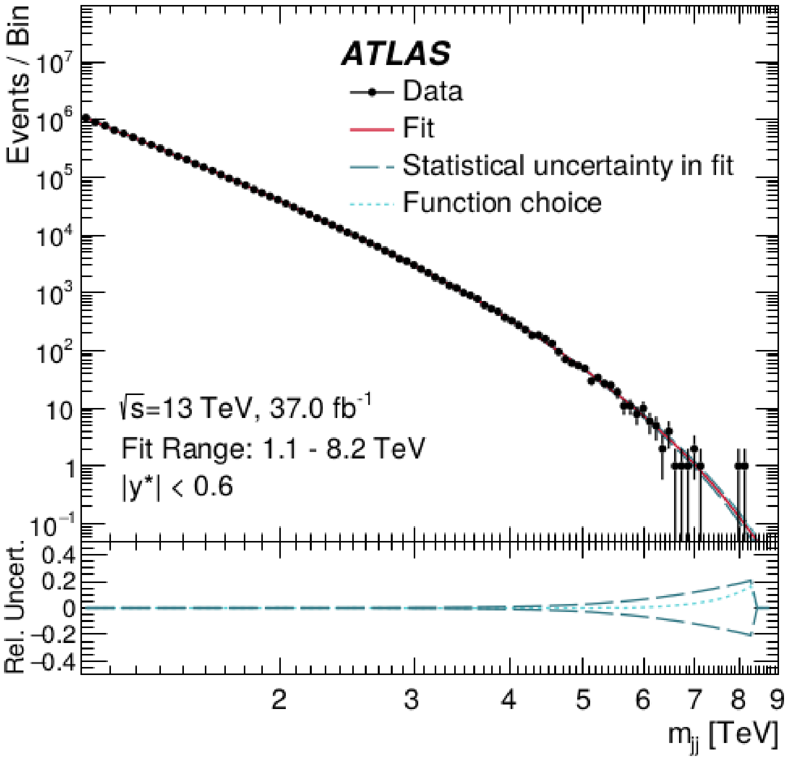
$\pm 0.1\,(\mathrm{exp.}) \pm 0.?\,(\mathrm{theo.})[\%]$ → **constraints on the EW fit!**

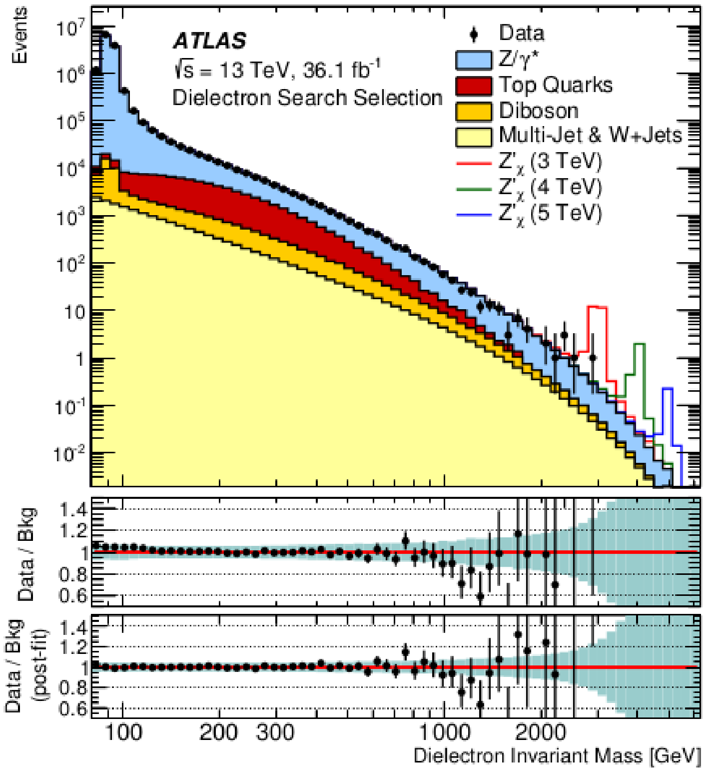




High-mass di-jets and di-leptons at the LHC

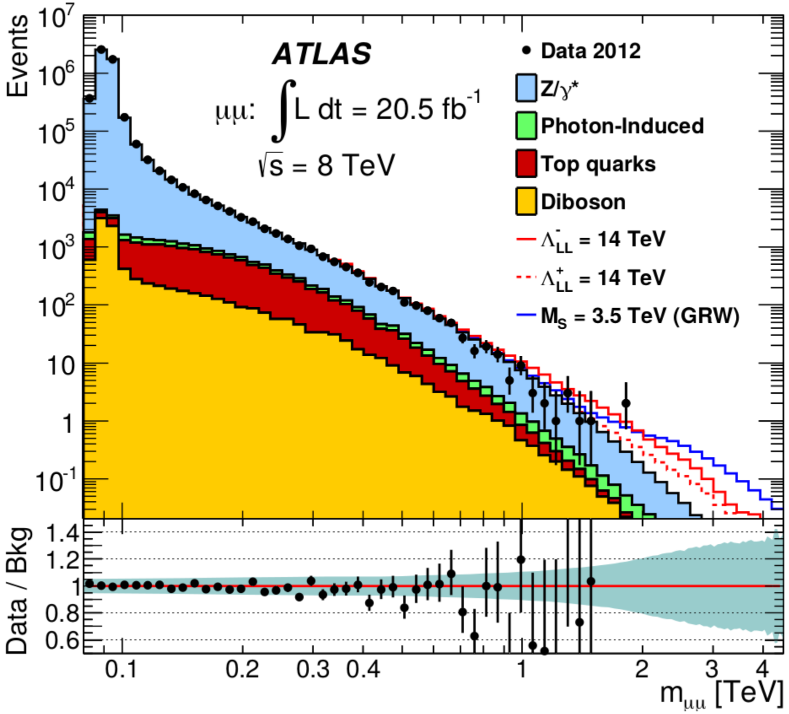
- High-mass final states are primarily a probe of new particles



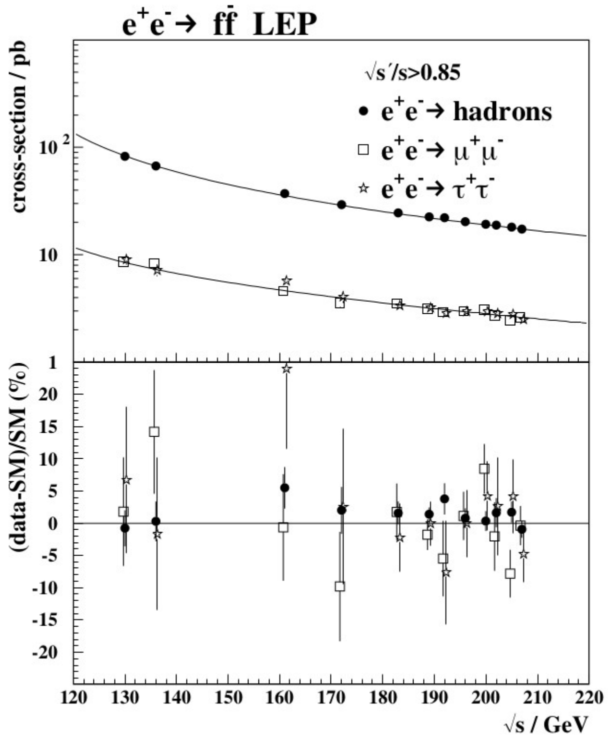


High-mass di-leptons at the LHC

- In absence of resonances, these data can be used to probe for high-mass contact interactions, which reflect eg. heavy gauge bosons beyond the kinematic limit. Reminiscent of LEP2 fermion-pair production analyses



LHC | LEP



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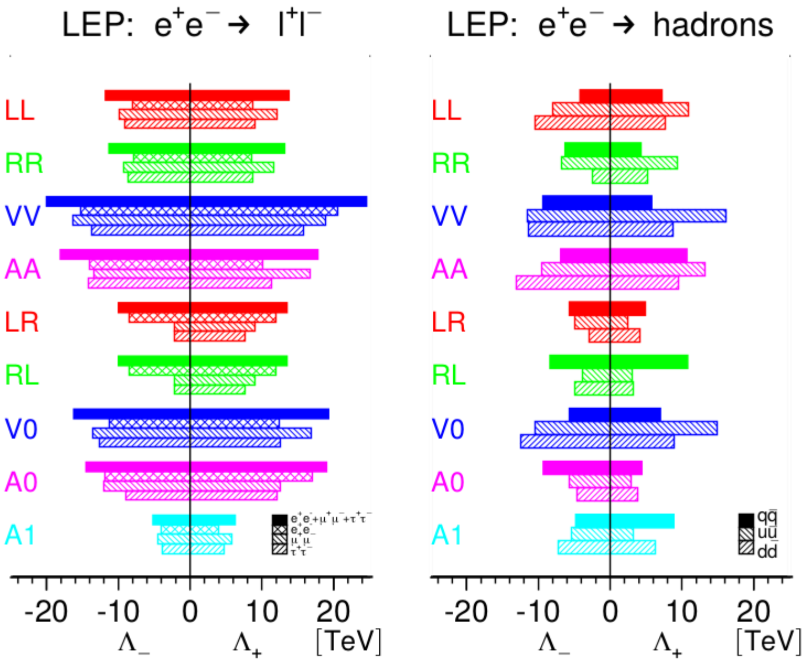
Expected and observed lower limits on Λ [TeV]

Channel	Prior	Left-Left		Left-Right		Right-Right	
		Const.	Destr.	Const.	Destr.	Const.	Destr.
Exp: ee	$1/\Lambda^2$	19.1	14.0	22.0	17.4	19.0	14.2
Obs: ee		20.7	16.4	25.2	19.2	20.2	16.6
Exp: ee	$1/\Lambda^4$	17.4	13.0	20.1	16.3	17.2	13.1
Obs: ee		18.6	14.7	22.2	17.7	18.3	14.9
Exp: $\mu\mu$	$1/\Lambda^2$	18.0	12.7	21.6	16.3	17.7	13.0
Obs: $\mu\mu$		16.7	12.5	20.5	14.9	16.5	12.7
Exp: $\mu\mu$	$1/\Lambda^4$	16.2	12.0	19.8	15.3	16.2	12.1
Obs: $\mu\mu$		15.6	11.8	19.0	14.3	15.4	11.9
Exp: $\ell\ell$	$1/\Lambda^2$	21.4	14.7	24.8	18.5	21.0	15.0
Obs: $\ell\ell$		21.6	17.2	26.3	19.0	21.1	17.5
Exp: $\ell\ell$	$1/\Lambda^4$	19.1	13.8	23.1	17.6	19.1	14.2
Obs: $\ell\ell$		19.6	15.4	23.8	17.8	19.3	15.6

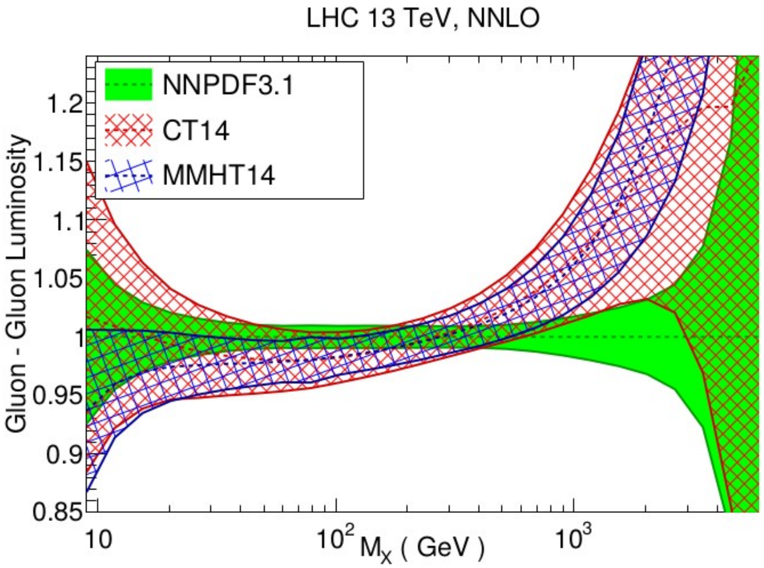
LHC

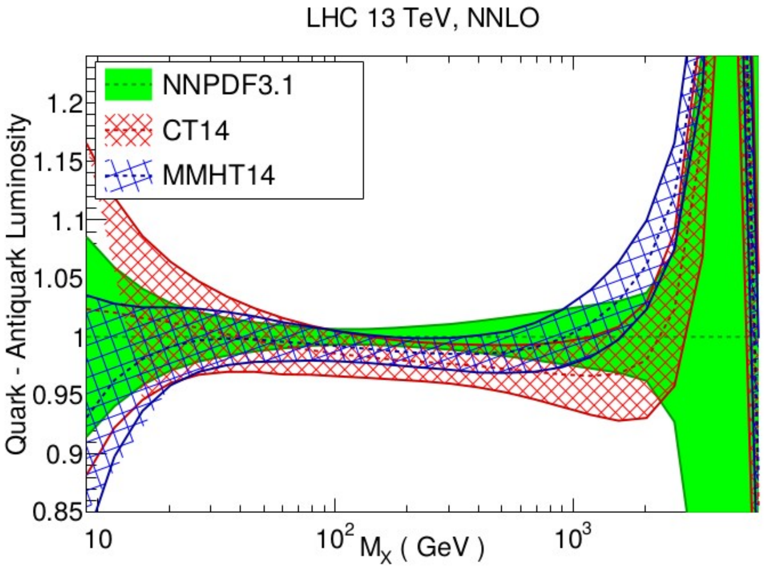
LEP



High-mass di-leptons at the LHC

- In spite of a factor ~5 in invariant mass (at 8 TeV), the LHC limits are only barely better than LEP. Uncertainties in the predictions at high-mass are dominated by PDF uncertainties : LHeC data would remove this, and boost limits to typically 50-100 TeV, depending on models
  - Most useful inputs, when considering the opportunity of a high-energy pp collider



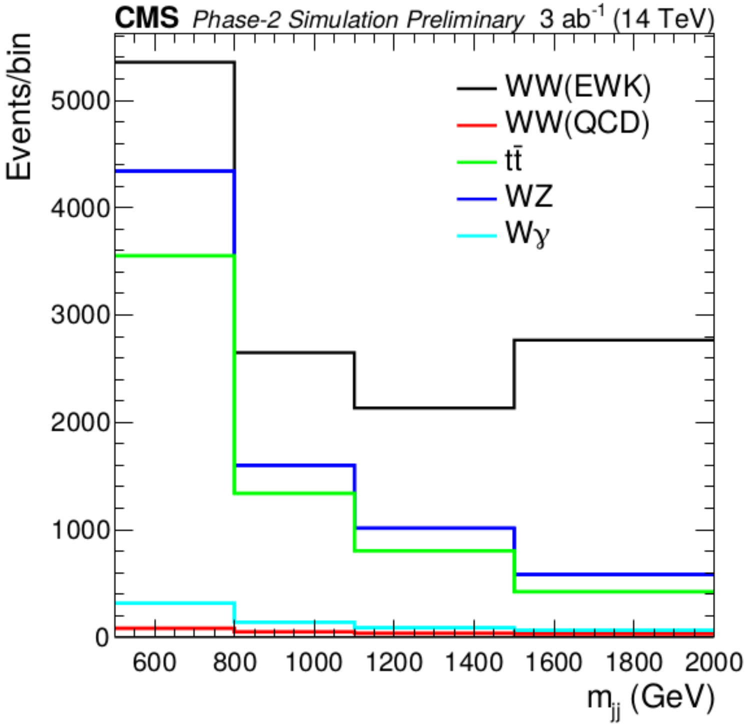


Vector-boson scattering at high energies

- The 3rd summit of the EWSB “triangle” (EWPO – Higgs – VBS). Establishing these signals is one of the main subjects of the HL-LHC

Expected yields for 300 fb^{-1}
CMS PAS FTR-18-005

Process	Expected yield, $\mathcal{L} = 3000\ fb^{-1}$
$W^{\pm}W^{\pm}$ EWK	5368
$t\bar{t}$	5515
WZ	1421
$W\gamma$	406
$W^{\pm}W^{\pm}$ QCD	196
Total background	7538



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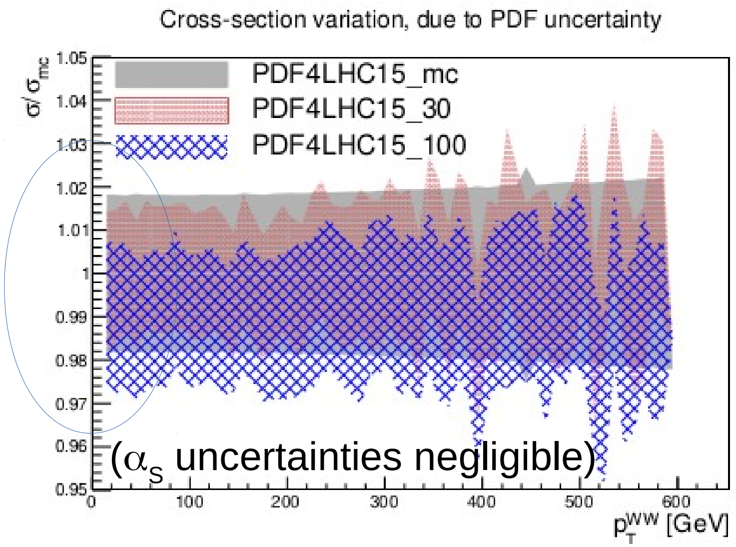
Source of uncertainty	3000 fb^{-1} (10 years)
Statistical uncertainty	1.8%
Trigger efficiency (electron)	0.2%
Trigger efficiency (muon)	0.6%
Electron id + iso. efficiency	0.3%
Muon id + iso. efficiency	0.6%
Jet energy scale	0.4%
b tag (stat. component)	0.3%
b tag misidentification	1.2%
Misidentified lepton from $t\bar{t}$	1.0%
Misidentified lepton from $W\gamma$	0.1%
Stat. accuracy of $W\gamma$ sample	0.1%
Total (stat + experimental syst)	3.2%
Luminosity	1.0%
Theoretical/QCD scale	3.0%
Total (stat + syst + lumi + theory)	4.5%

Measurement



Prediction

So here the case is not so compelling….

Conclusions

- (almost) All LHC pp analyses are or will be limited by the knowledge of proton PDFs. This especially holds for EW precision
  - improvement of PDFs possible using LHC data, but mostly “incremental” (we will always need the HERA “backbone”), or data more precise than theory
  - Next generation ep data from LHeC constitute a quantitative jump in this area, and solve one of the major issues of pp analyses and their interpretation

We need to help the LHC community realize this situation

- In addition, several unique ep analyses help lift remaining ambiguities:
  - precision measurements of the running of $\sin^2\theta_W$
  - Precise measurement of m_W in the *t*-channel
  - Unique power to disentangle vector and axial couplings of the Z to fermions