HL-LHC and challenges for CEPC Electroweak Physics

Paolo Azzurri
INFN Pisa

CEPC Workshop
November 7th 2017 IHEP Beijing

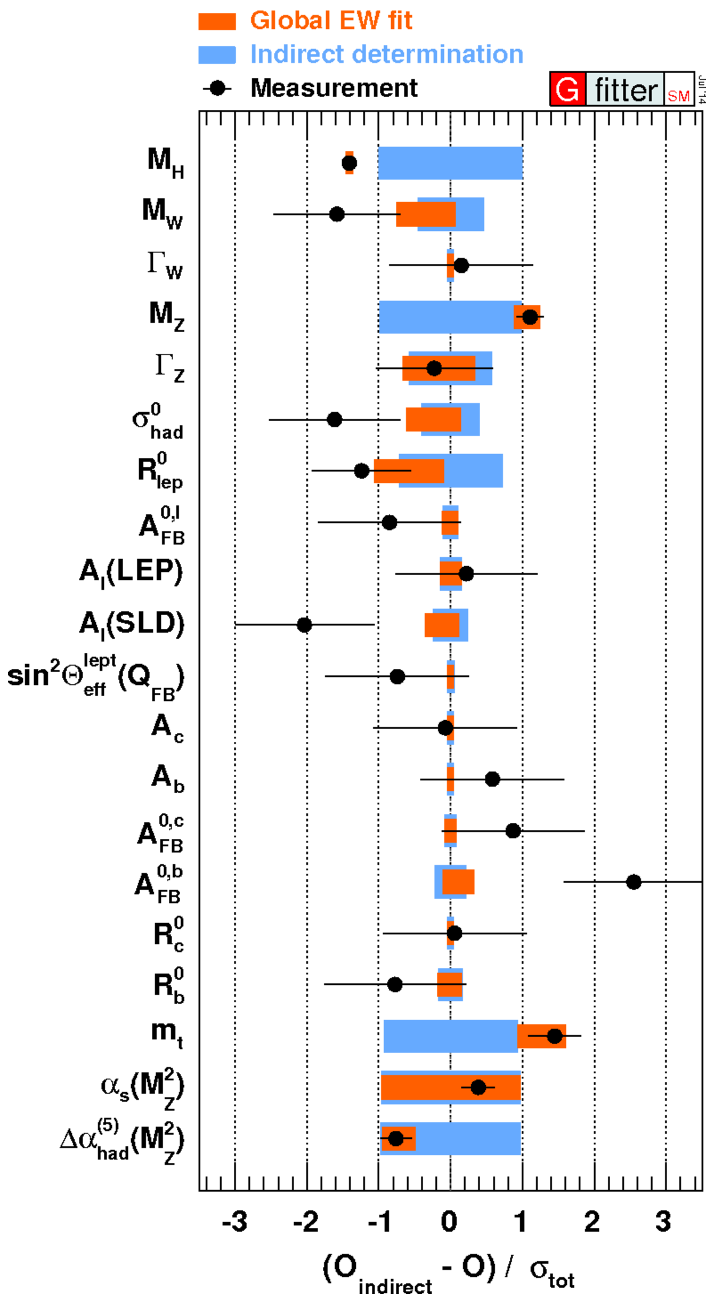
outline

- global EW fit status

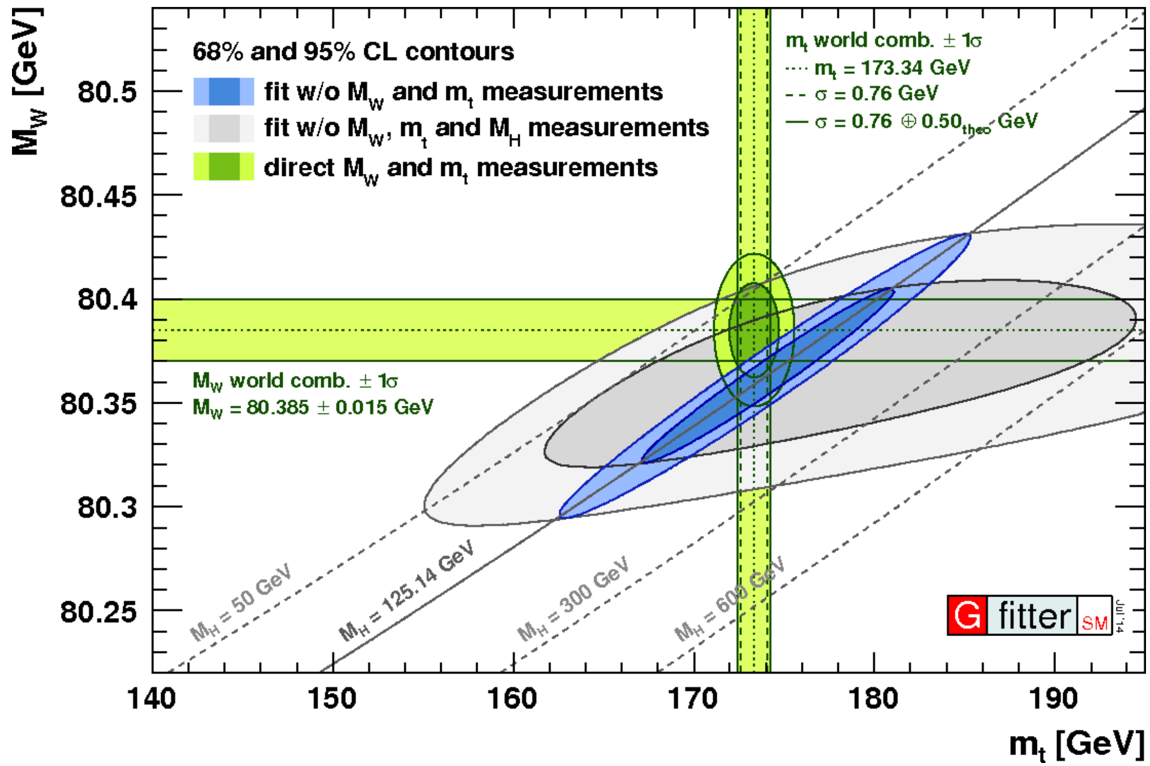
status and perspectives of

- W mass, width, decay couplings
- Z pole A, $\sin^2\theta_W$, couplings, α_{QED}
- EW gauge self couplings

EW fit status



arXiv:1407.3792

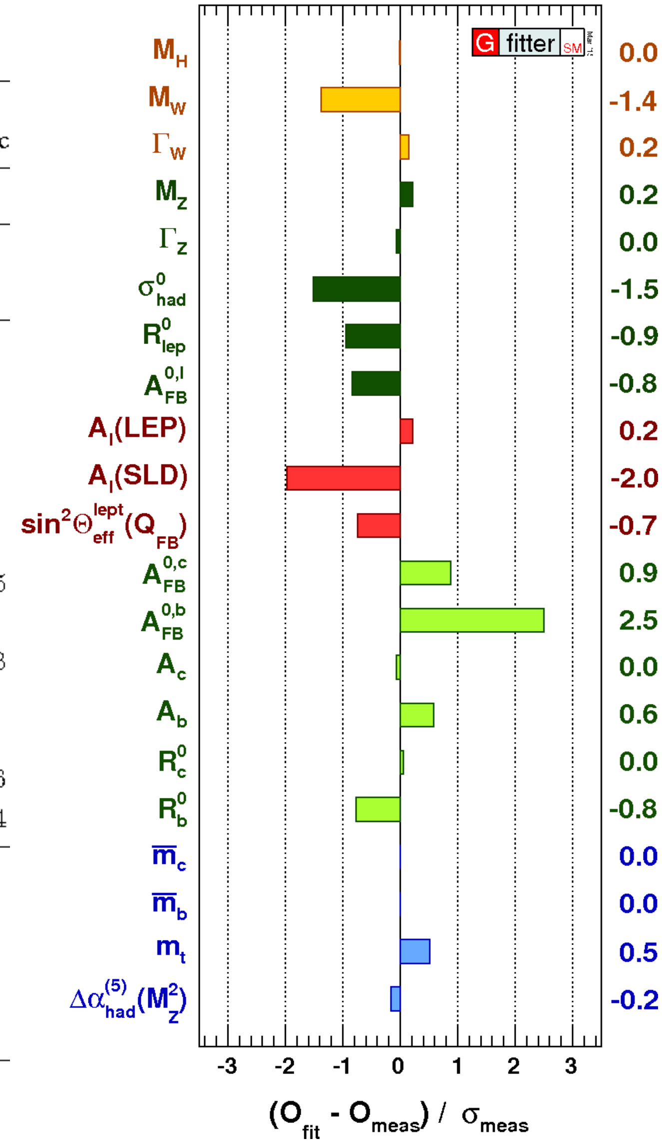


m_W is the loose end of the EW fit

EW fit

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\triangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\triangledown)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M_Z^2)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

$^{(\circ)}$Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.
$^{(\triangledown)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.



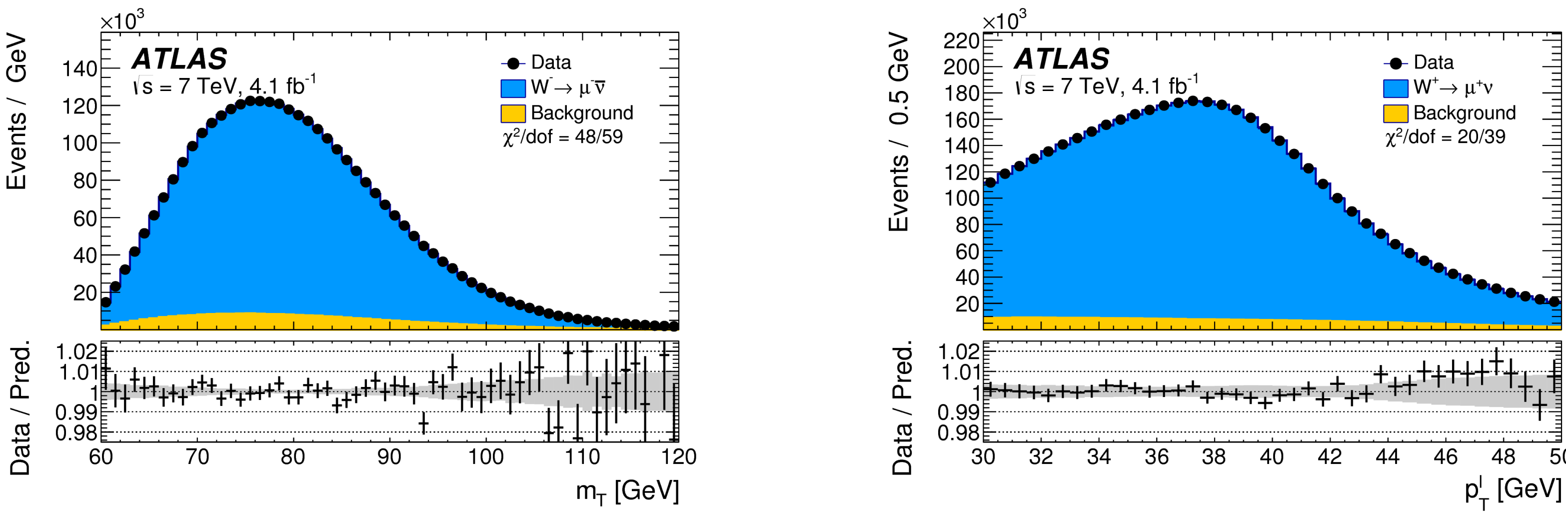
W boson mass : LHC Run1

ATLAS: arXiv:1701.07240 with 4.1-4.6/fb @7 TeV

fit to: p_Tl and m_T

- **Lepton p_T** → affected by pT(W) uncertainties (PDF/QCD)
- **Missing E_T** → affected by detector resolution effects
- **m_T** → compromise between TH and EXP

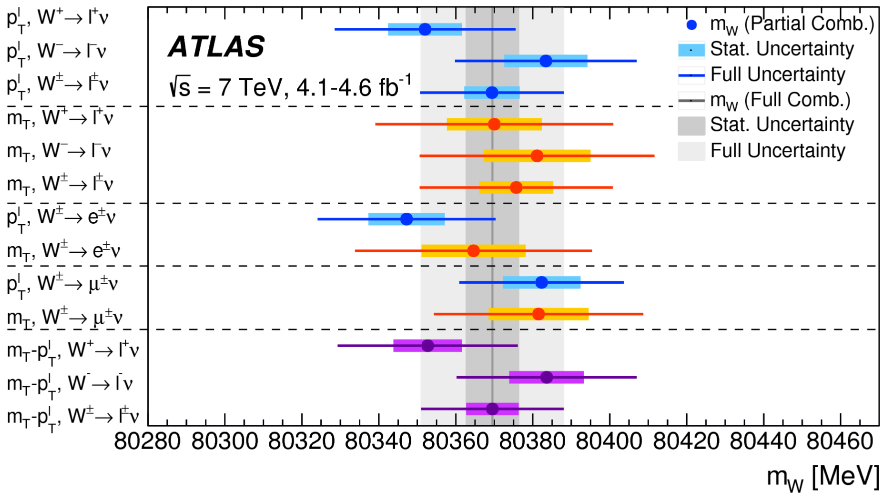
$p_T^\ell > 30$ GeV $p_T^{miss} > 30$ GeV $u_T < 30$ GeV $m_T > 60$ GeV

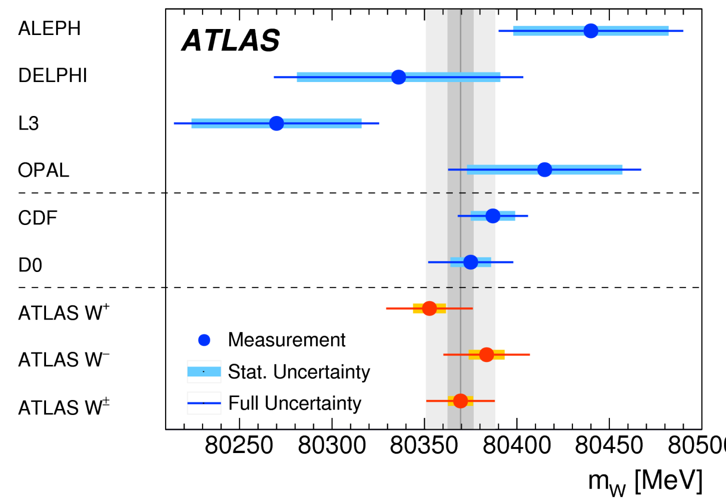


$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \quad = 80370 \pm 19\ \text{MeV}$$

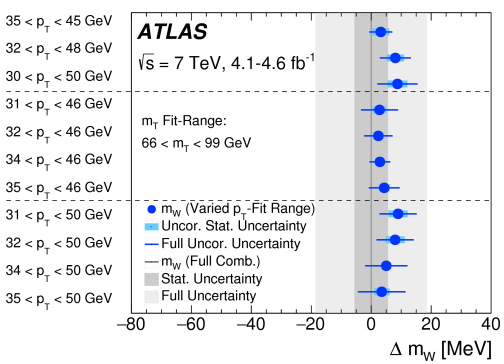
ATLAS: [arXiv:1701.07240](https://arxiv.org/abs/1701.07240)
with 4.1-4.6/fb @7 TeV

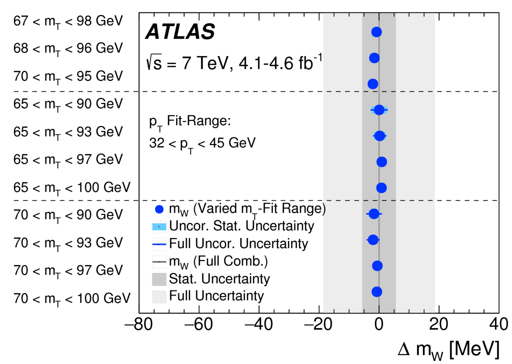
W mass LHC Run1

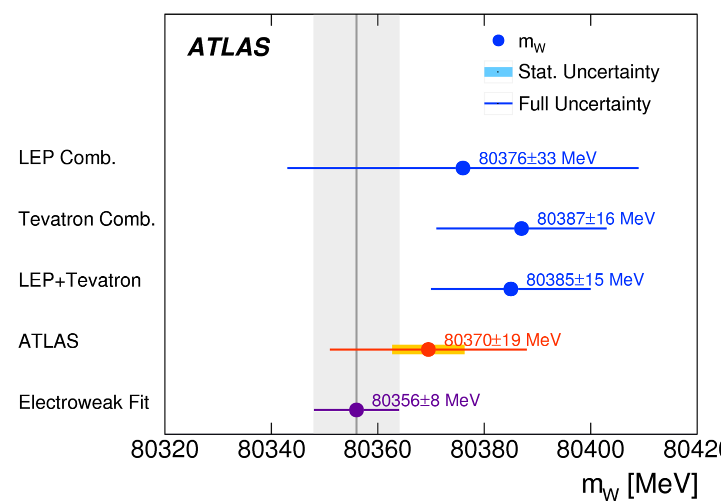




stability per channels, fitted distributions and kinematic ranges







W mass at Run2-3 &HL-LHC

Combined categories	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.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

will go down !

improve e,μ energy calibration

W pT spectrum

higher order corrections

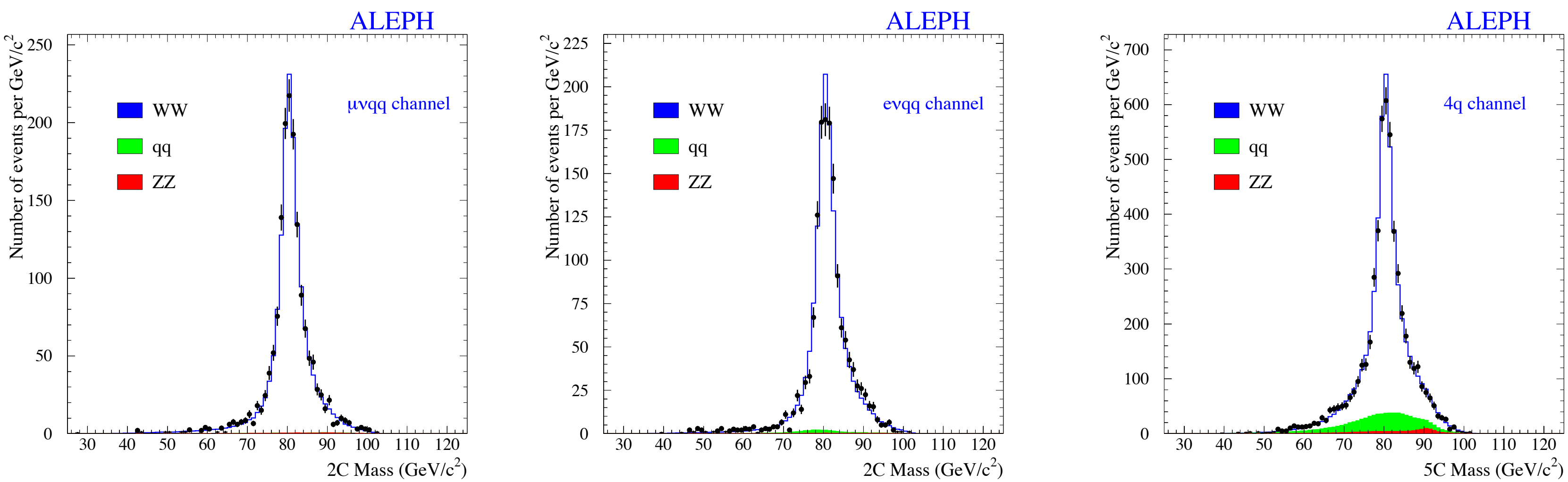
improve PDF uncertainty

~ XX MeV ?

W boson mass : e^+e^-

full m_W reco with kinematic fit. main ingredients :
E_{CM} – jet/lepton angles – (jet boost)

$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$



ALEPH Eur.Phys.J.C47:309 (2006) : 683 /pb ~10k WW events

ignoring low energy particles in the qqqq channel

m_W = 80440±43(stat.)±24(syst.)±9(FSI)±9(LEP) MeV

Γ_W = 2140 ±90(stat.) ±45(syst.) ±46(FSI) ± 7(LEP) MeV

mass of the W boson : e^+e^-

CEPC 5/ab@240GeV
➔ 80M W-pairs:
LEP2 x 2000

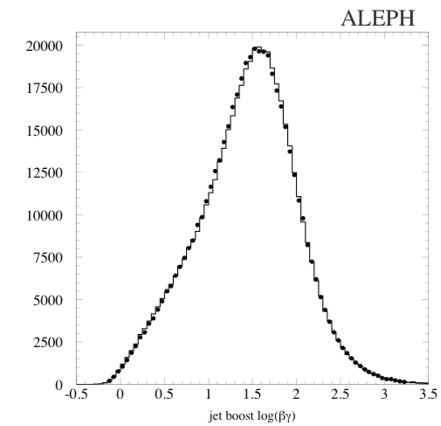
➔ Δm_W (stat)= 0.5 MeV
➔ Δm_W (syst) ≤ X MeV ?

Is ΔE_{beam}~ 1MeV at E_{CM}=240 GeV possible ?

With Zγ events ?
ΔE_{beam}~15MeV(stat) @LEP

Table 9: Summary of the systematic errors on m_W and Γ_W in the standard analysis averaged ove
183-209 GeV for all semileptonic channels. The column labelled $\ell\nu q\bar{q}$ lists the uncertainties in m_W use
in combining the semileptonic channels.

	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7



lepton and jet uncertainties from (Z) calibration data

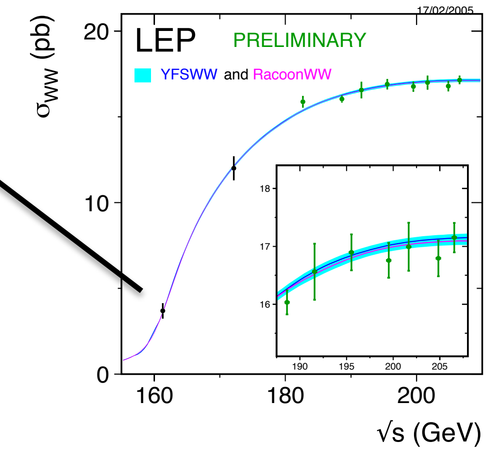
mass of the W boson : e^+e^- threshold

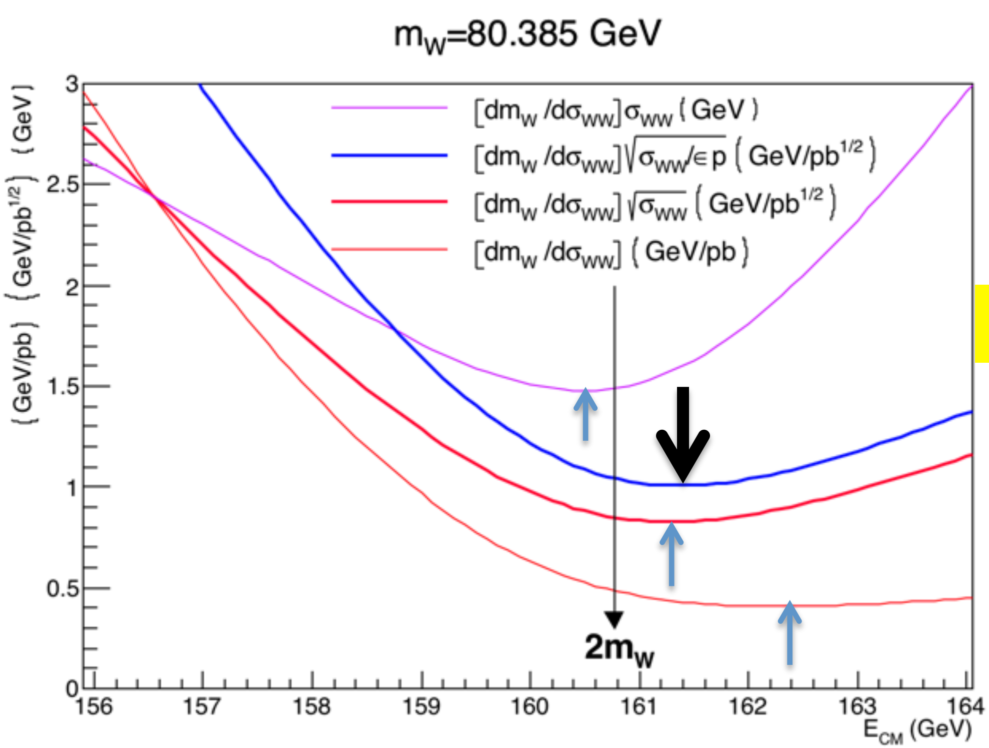
$$m_W = \sigma^{-1}(E)$$

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

LEP2 : 4x10/pb   ~4x30 events
➔ m_W = 80.40±0.21 GeV

$$\Delta m_W(stat) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{L}} \frac{1}{\sqrt{\varepsilon p}}$$





Max stat sensitivity at $\sqrt{s}$~2m_W+400MeV

CEPC: X/ab ➔ Δm_W(stat)= 1 MeV /√X

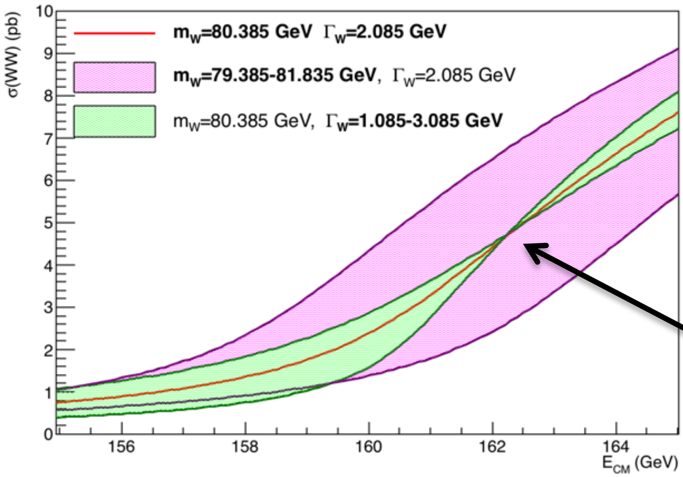
Δmw≈1 MeV would require

ΔE(beam)<1 MeV (10^{-5})

Δε/ε, ΔL/L < 10^{-3}

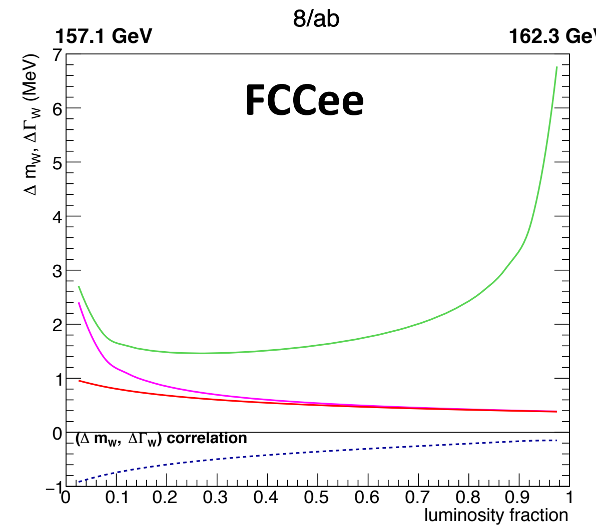
$\Delta\sigma_B$<2 fb (~10^{-2})

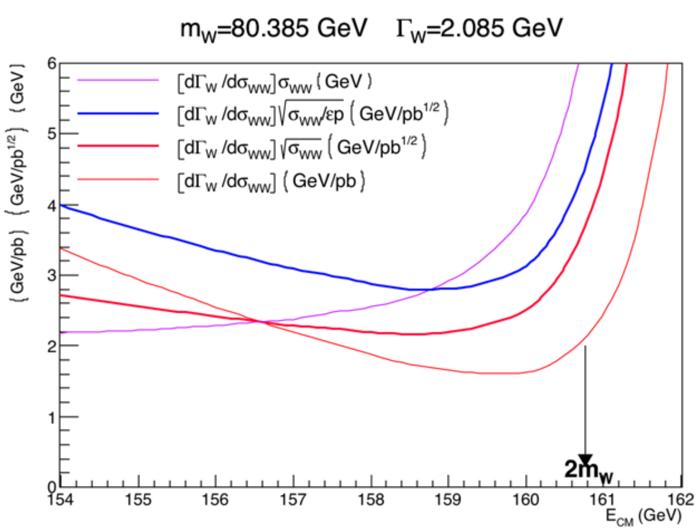
mass & width of the W boson : e^+e^-



Measure σww in two energy points E_1, E_2 with a fraction f of lumi in E_1
➔ extract both m_W & Γ_W

$d\sigma_{WW}/d\Gamma_W = 0$
at E_{CM}~**162.3 GeV**

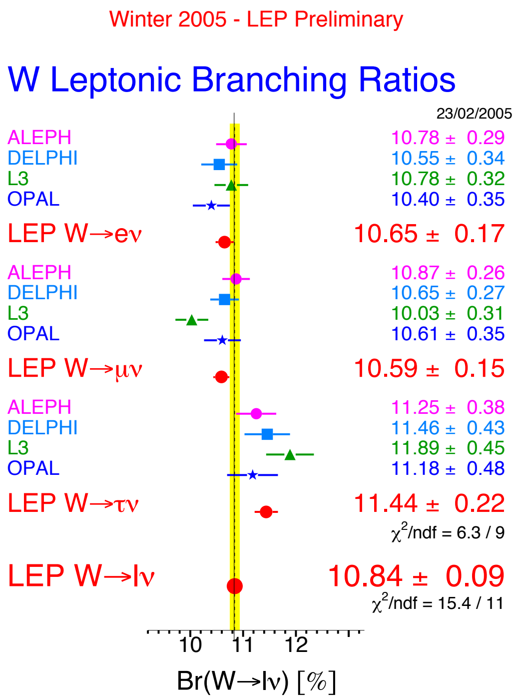


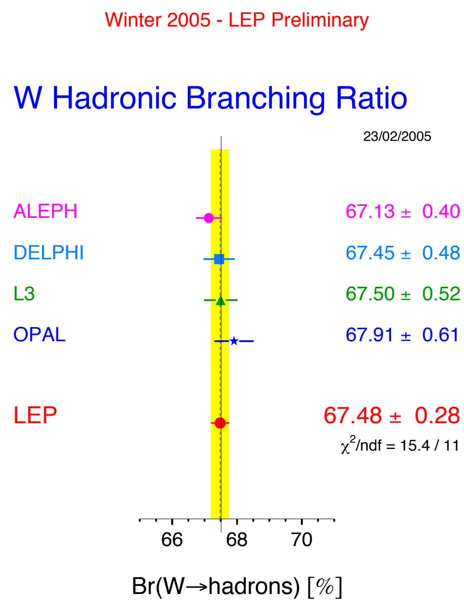


with E_1=**157.1** GeV E_2=**162.3** GeV f=**0.4**
Δm_W=0.62 $\Delta\Gamma_W$=1.5 Δm_W=0.56 (MeV)
[FCC ee]

➔$\Delta\alpha_S \approx (3\pi/2)\Delta\Gamma/\Gamma \approx$ 0.003

W decay BR





5/ab@240GeV
➔ 80M W-pairs

➔ ΔBR(qq) (stat) =[1] 10^{-4} (rel)
➔ $\Delta\alpha_S \approx (9\ \pi/2)\Delta BR \approx 10^{-3}$

➔ ΔBR(e/μ/τν)(stat)=[4]10^{-4} (rel)

q/ l universality at 0.6%
➔ *CEPC @ 10^{-4} level*

Lept universality test at 2% level
tau BR ~2.7 σ larger than e/mu
➔ *CEPC @ 4 10^{-4} level*

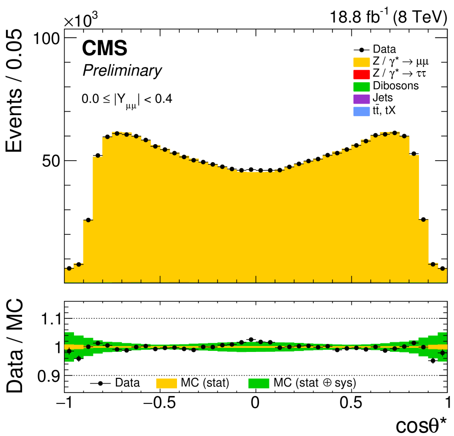
will need very good control of lepton id
i.e. cross contaminations in signal channels
(τ➔e,μ in the e,μ channels and v.v.)

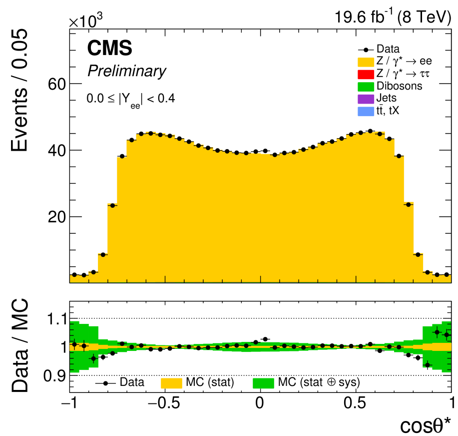
Flavor tagging would allow to measure coupling to c & b-quarks (Vcs, Vcb,..)

LHC : A^{FB} and $\sin^2\theta_{eff}$

CMS: PAS SMP_16_007 :

18.8-19.6/fb @8TeV





Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta_{eff}^{lept} - \sin^2\theta_{eff}^{u,d}$)	0.00001	0.00001
Total	0.00015	0.00017

$$\sin^2\theta_{eff}^{lept} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory}) \pm 0.00030(\mathrm{pdf})$$

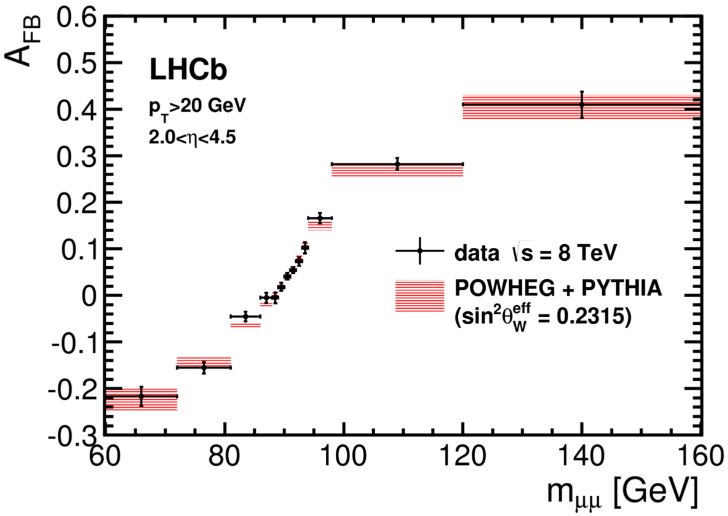
$$\sin^2\theta_{eff}^{lept} = 0.23101 \pm 0.00052.$$

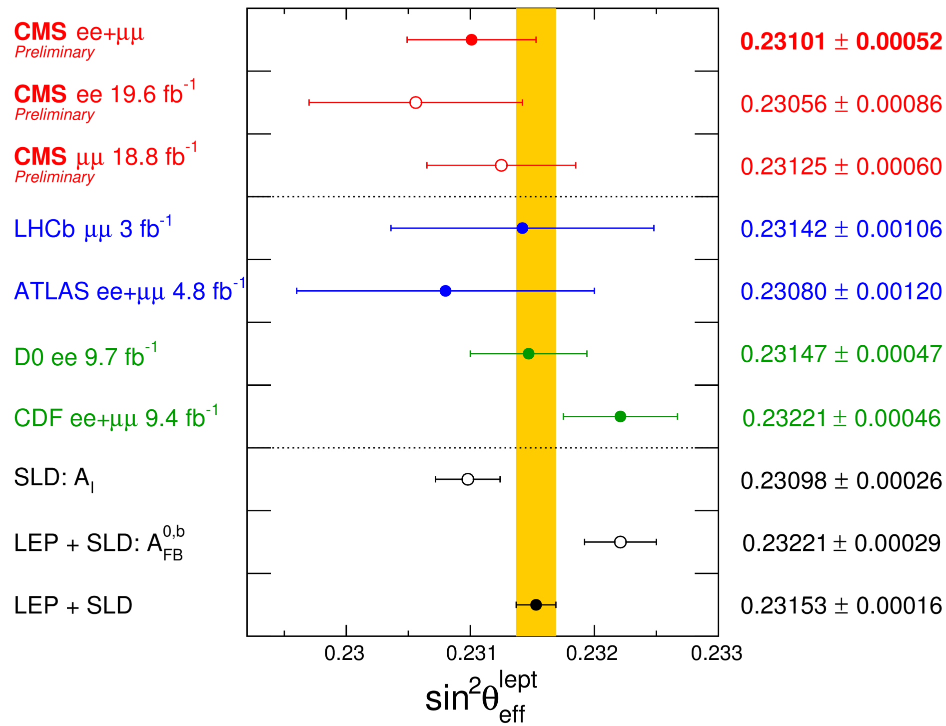
LHC : A^{FB} and $\sin^2\theta_{eff}$

CMS: PAS [SMP-16-007](SMP-16-007)

ATLAS: JHEP 1509 (2015) 49
4.8/fb @7TeV

LHCb: JHEP 1511 (2015) 190
1/fb+2/fb @7+8 TeV



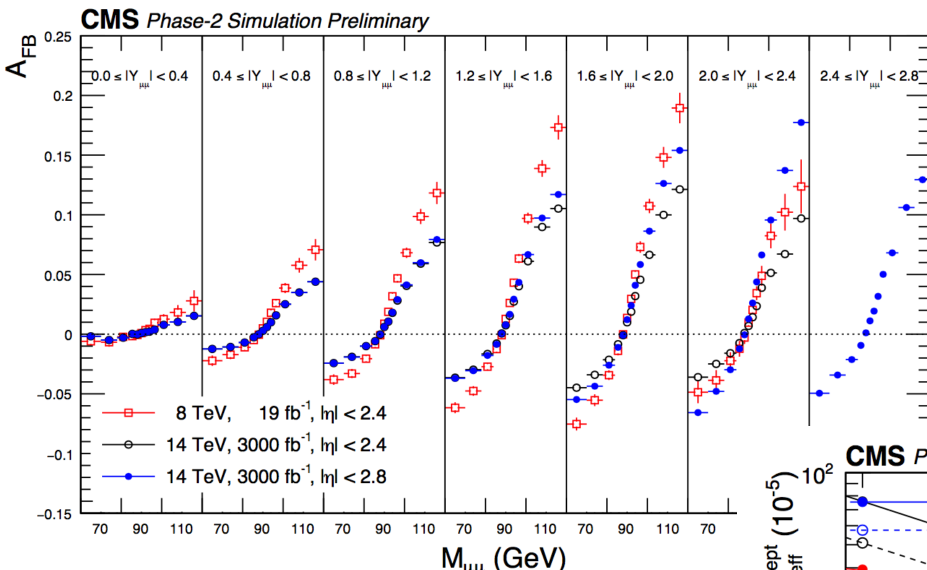


LEP+SLD still ~3 times better

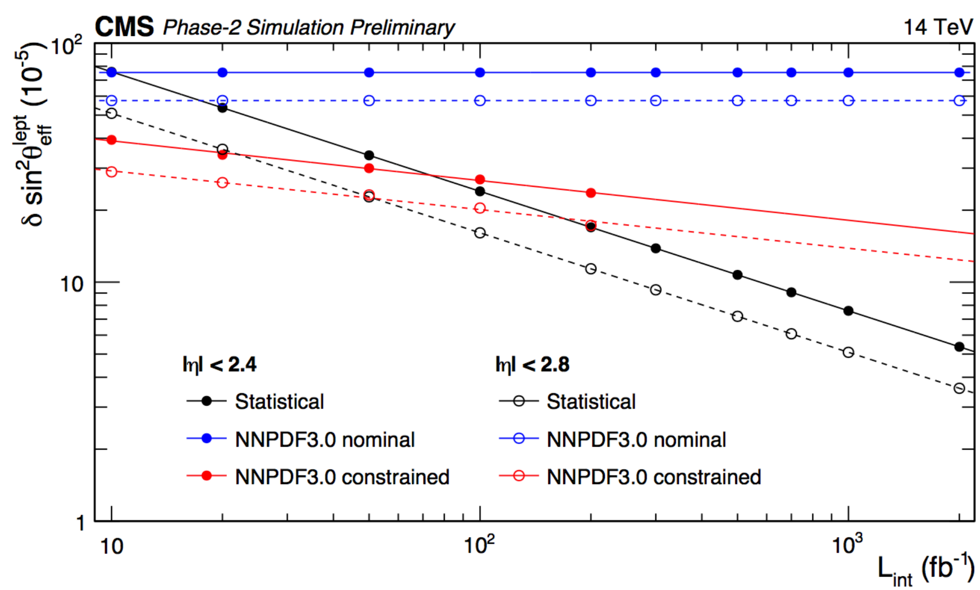
LHCb high rapidity yields less A^{FB} dilution

CMS PAS FTR-17-001

HL- LHC : A^{FB} and $\sin^2\theta_{eff}$



L_{int}	$\delta_{stat}[10^{-5}]$		$\delta^{nominal}_{nnpdf3.0}[10^{-5}]$		$\delta^{constrained}_{nnpdf3.0}[10^{-5}]$	
(fb^{-1})	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$
10	76	51	75	57	39	29
100	24	16	75	57	27	20
500	11	7	75	57	20	16
1000	8	5	75	57	18	14
3000	4	3	75	57	15	12
19	43		49		27	
19 (from [1])	44		54		32	



reach LEP+SLD
precision with 1/ab
(maybe improve with 3/ab)

CEPC Z pole precision

10^9-10^{11} Z decays : **LEP1 x 10^{2-4}**

continuous E_{CM} calibration (resonant depolarization)
Z **mass** and **width** : 500 KeV (syst)

pre CDR
IHEP_CEPC_DR_2015_01

Observable	LEP precision	CEPC precision	CEPC runs	$\int \mathcal{L}$ needed in CEPC
m_Z	2 MeV	0.5 MeV	Z lineshape	> 150 fb^{-1}
m_W	33 MeV	3 MeV	ZH (WW) thresholds	> 100 fb^{-1}
A^b_{FB}	1.7%	0.15%	Z pole	> 150 fb^{-1}
$\sin^2\theta^{\rm eff}_W$	0.07%	0.01%	Z pole	> 150 fb^{-1}
R_b	0.3%	0.08%	Z pole	> 100 fb^{-1}
N_ν (direct)	1.7%	0.2%	ZH threshold	> 100 fb^{-1}
N_ν (indirect)	0.27%	0.1%	Z lineshape	> 150 fb^{-1}
R_μ	0.2%	0.05%	Z pole	> 100 fb^{-1}
R_τ	0.2%	0.05%	Z pole	> 100 fb^{-1}

Z pole acceptance

- @LEP acceptance effects at **10^{-4}** OK for cross sections at **10^{-3}** level. Main effects were due to track losses, angle mis-measurements and knowledge of boundaries.
- @CEPC exploit a statistical uncertainty at some **10^{-5}**

Example from ALEPH, EPJC 14 (2000) 1

Table 13. Exclusive $\mu^+\mu^-$ selection: examples of relative systematic uncertainties (in %) for the 1994 (1995) peak points

Source	$\Delta\sigma/\sigma$ (%)
Acceptance	0.05
Momentum calibration	0.006 (0.009)
Momentum resolution	0.005
Photon energy	0.05
Radiative events	0.05
Muon identification	$\simeq$ 0.001 (0.02)
Monte Carlo statistics	0.06
Total	0.10 (0.11)

@LEP detectors inner edge (**relevant boundary**) was known at the level of up to **20 µm**
The beam displacement (**vertical** and **horizontal**) becomes ineffective by choosing two fiducial regions (**loose and tight**) and **alternating them** in the two sides

@CEPC can **use similar methods for cross sections** measurements (e.g. different and alternating forward and backward fiducial regions), but still need to identify and know well the relevant boundaries (~5µm level)

couplings and R_b

couplings measurements require asymmetry and width ratios

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma_{had}}$$

$$A_{FB}(b) = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_b \text{ (LEP)} \longrightarrow \frac{g_{Vf}}{g_{Af}}$$

$$A_b = A_{FB}^{pol}(b) = 0.921 \pm 0.021 \text{ (SLC)}$$

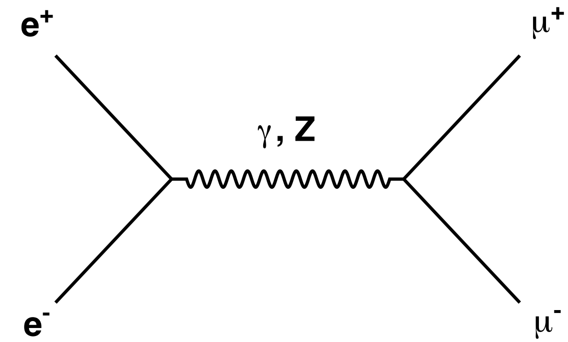
$$R_b = 0.21646 \pm 0.00065 \text{ (LEP+SLC)} \longrightarrow (g_{Af})^2 + (g_{Vf})^2$$

- R_b Very sensitive to rad. vertex corrections due to new particles
- Important to sort out LEP b-couplings issue
- Measurement exploits the presence of two b hadrons and b-tagging.
- **Independent** from **b-tagging efficiency**, but **not** from **hemisphere correlations**
- Higher b-tagging performance (vertex detectors) helps in reducing the correlation
- Correlations sources should be identified and studied with data (done at LEP)

$\Delta R_b \approx$ **5** (**5-20**) 10^{-5} **stat** (**syst**) $\Delta R_c \approx$ **10** (**50**) 10^{-5} **stat** (**syst**)

Direct measurement of $\alpha_{QED}(m_Z^2)$

Patrick Janot: arXiv:1512:05544, JHEP 2016(2) 1



EW high precision will require higher order perturbative calculations : a **bottleneck** will be represented by the hadronic contributions to the vacuum polarization

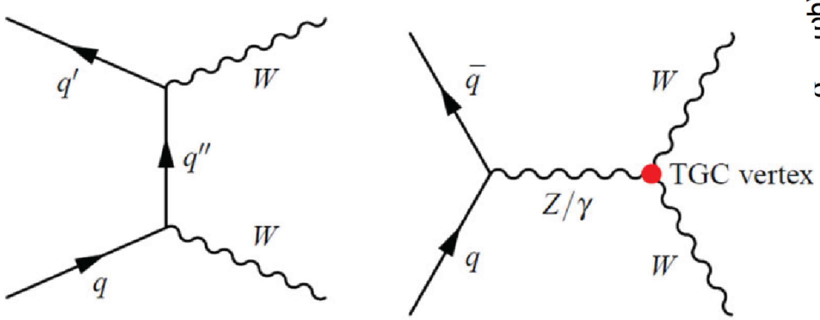
Direct measurement with the forward-backward asymmetry

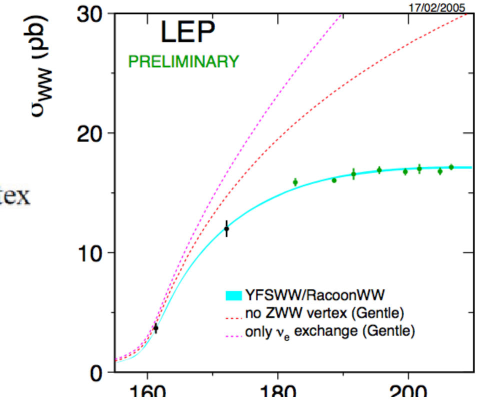
Optimal centre-of-mass energies
$\sqrt{s_-}$ = **87.9 GeV** and $\sqrt{s_+}$ = **94.3 GeV**

Two measurements with possible cancellation of some correlated syst effects

Type	Source	Uncertainty
Experimental	E_{beam} calibration	1×10^{-5}
	E_{beam} spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
Theoretical	QED (ISR, FSR, IFI)	$< 10^{-6}$
	Missing EW higher orders	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

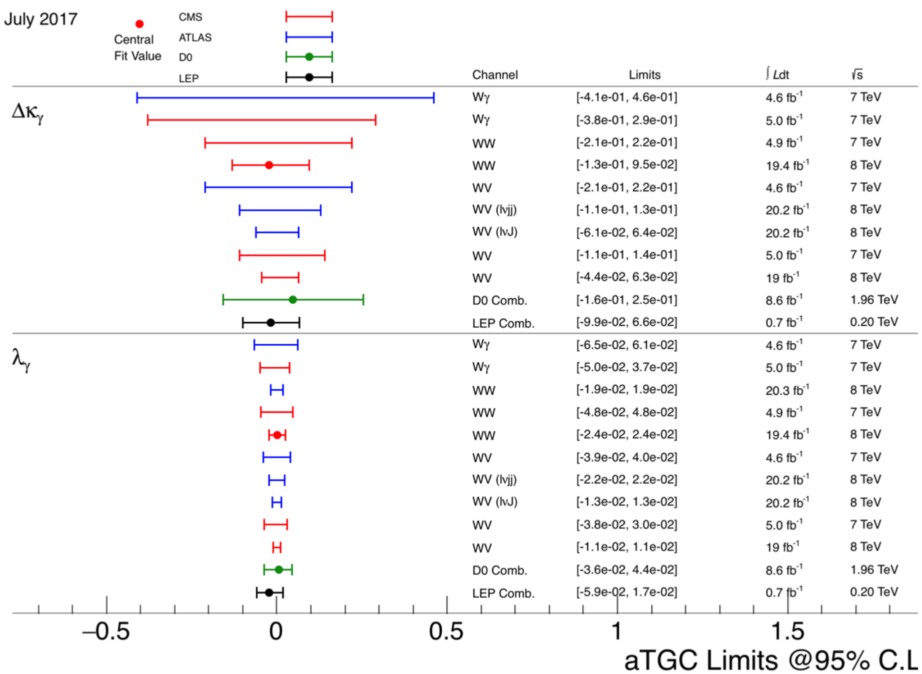
W/Z/γ couplings LEP2/TeV/LHC

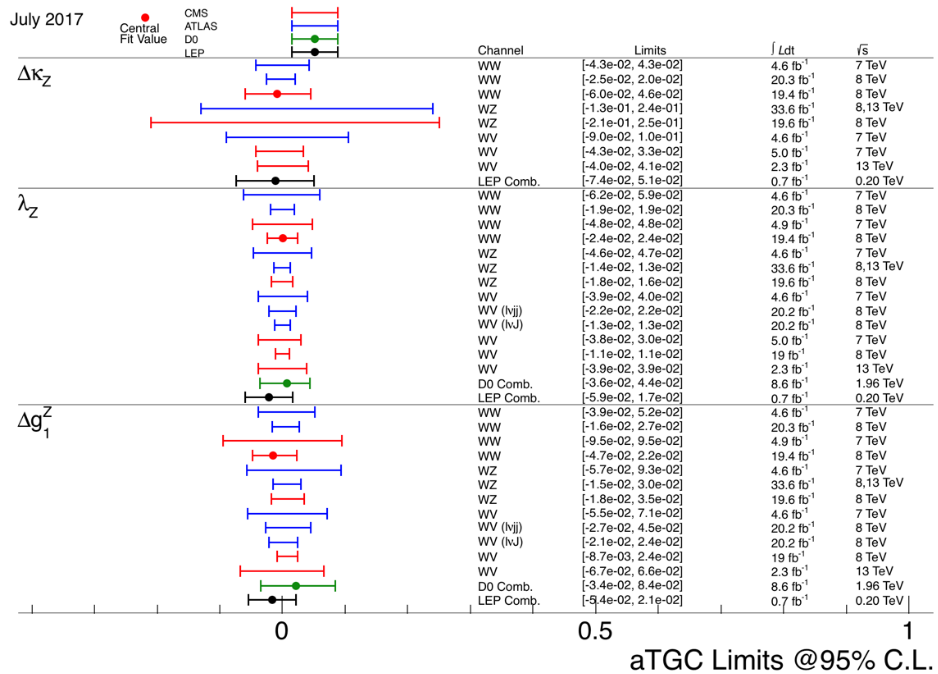




gauge cancellations

Run1 LHC ~ LEP2
HL−LHC ~ Run1 x 10^2
5/ab@240 ~ LEP2 x 2•10^3





summary

- EW physics at the LHC is a challenging business
  - most promising advances with Run2-3 and HL will come in the context of VBF and VBS processes (& quartic couplings)
  - improvements on diboson & TGC limits should be at hand
  - hard work on systs can deliver W mass and $\sin^2\vartheta$ with some improvement over current precision
- CEPC would deliver game changing precision for EW parameters
  - possible x 10-100 improvement factors to LEP1 & 2 precision
  - W mass and width to ~1 MeV (make a visit to the threshold if possible)
  - Z pole physics also very worth to be exploited