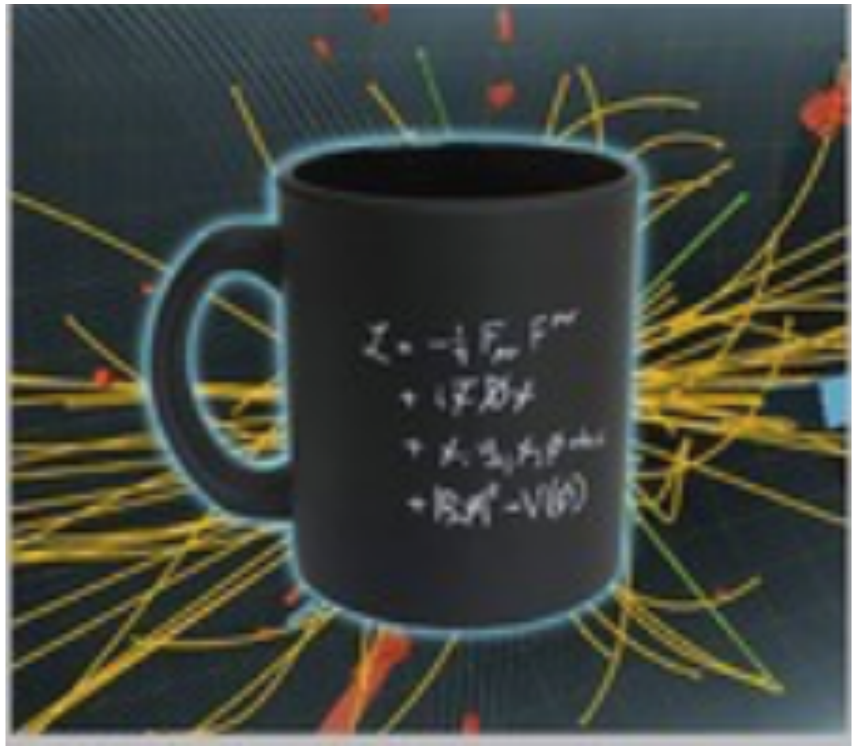
Verifiche del modello standard: stato e prospettive



Gigi Rolandi CERN e Scuola Normale

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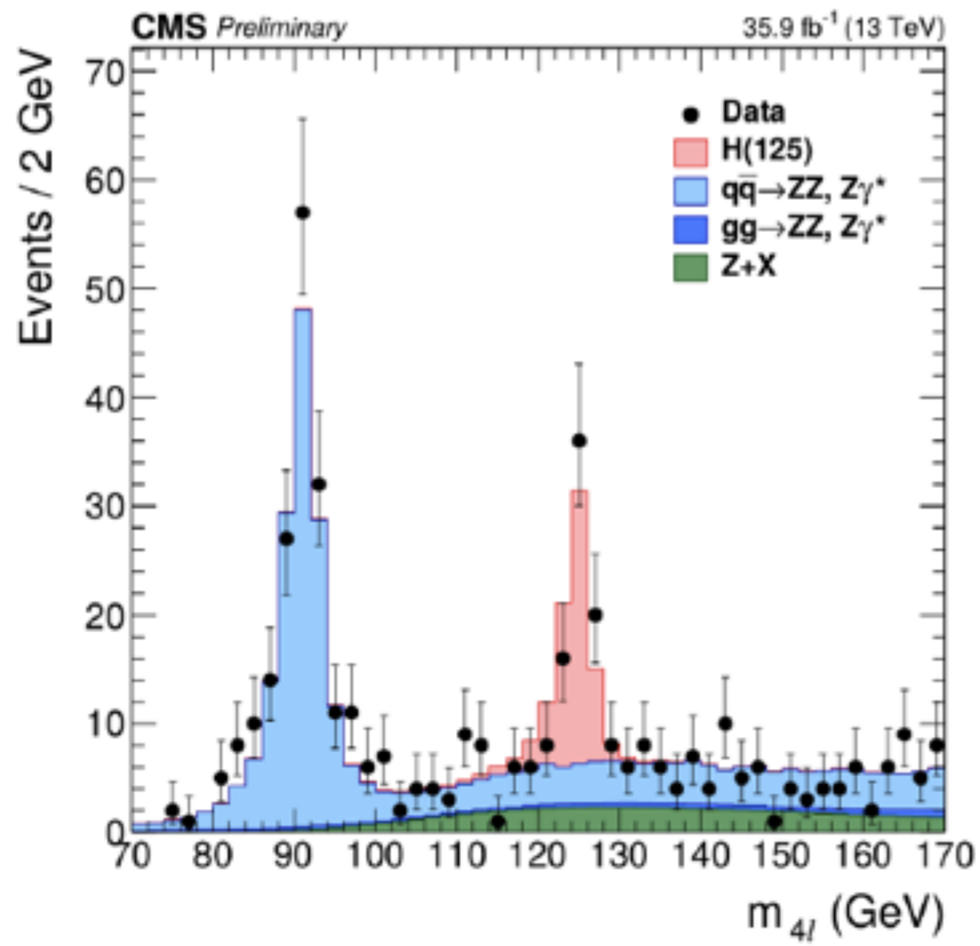
With the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) all the input parameters of the SM have been experimentally measured. The Electro-Weak fit tests the validity of the theory and provides constraint on New Physics.



See e.g. J.Erler and A.Freitas RPP2016

J.de Blas, M.Ciuchini,E.Franco,S.Mishima,M.Pierini,L.Reina,and L.Silvestrini

JHEP 1612 (2016) 135 1608.01509

Experimental input quantities

$\alpha_{EM}(Q^2=0) = 1/137.035999139(31)$ electron g-2

$G_F = 1.1663787(6)\ 10^{-5}\ \text{GeV}^{-2}$ muon lifetime

$M_Z = 91.1875 \pm 0.0021$ GeV

measured at LEP precise energy calibration of beam energy

$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.2324 ± 0.0012
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	0.1465 ± 0.0033
Γ_Z [GeV]	2.4952 ± 0.0023
σ_h^0 [nb]	41.540 ± 0.037
R_ℓ^0	20.767 ± 0.025
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
$\mathcal{A}_c$	0.670 ± 0.027
$\mathcal{A}_b$	0.923 ± 0.020
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016
R_c^0	0.1721 ± 0.0030
R_b^0	0.21629 ± 0.00066

Z pole observables

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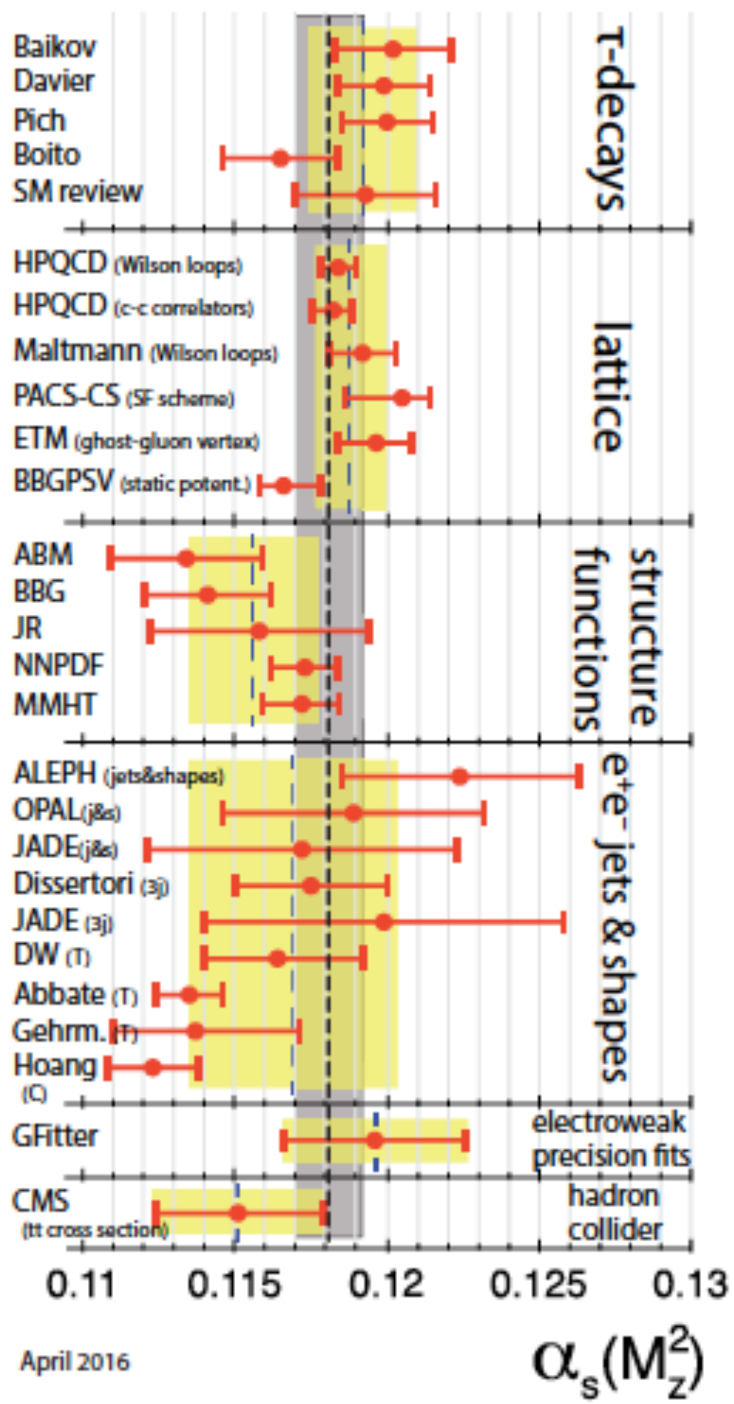
The strong coupling constant α_s

Precision 1 %



RPP 2016 Bethke Dissertori Salam

New method from lattice (ALPHA Collaboration)

Phys.Rev. D95 (2017) no.1, 014507

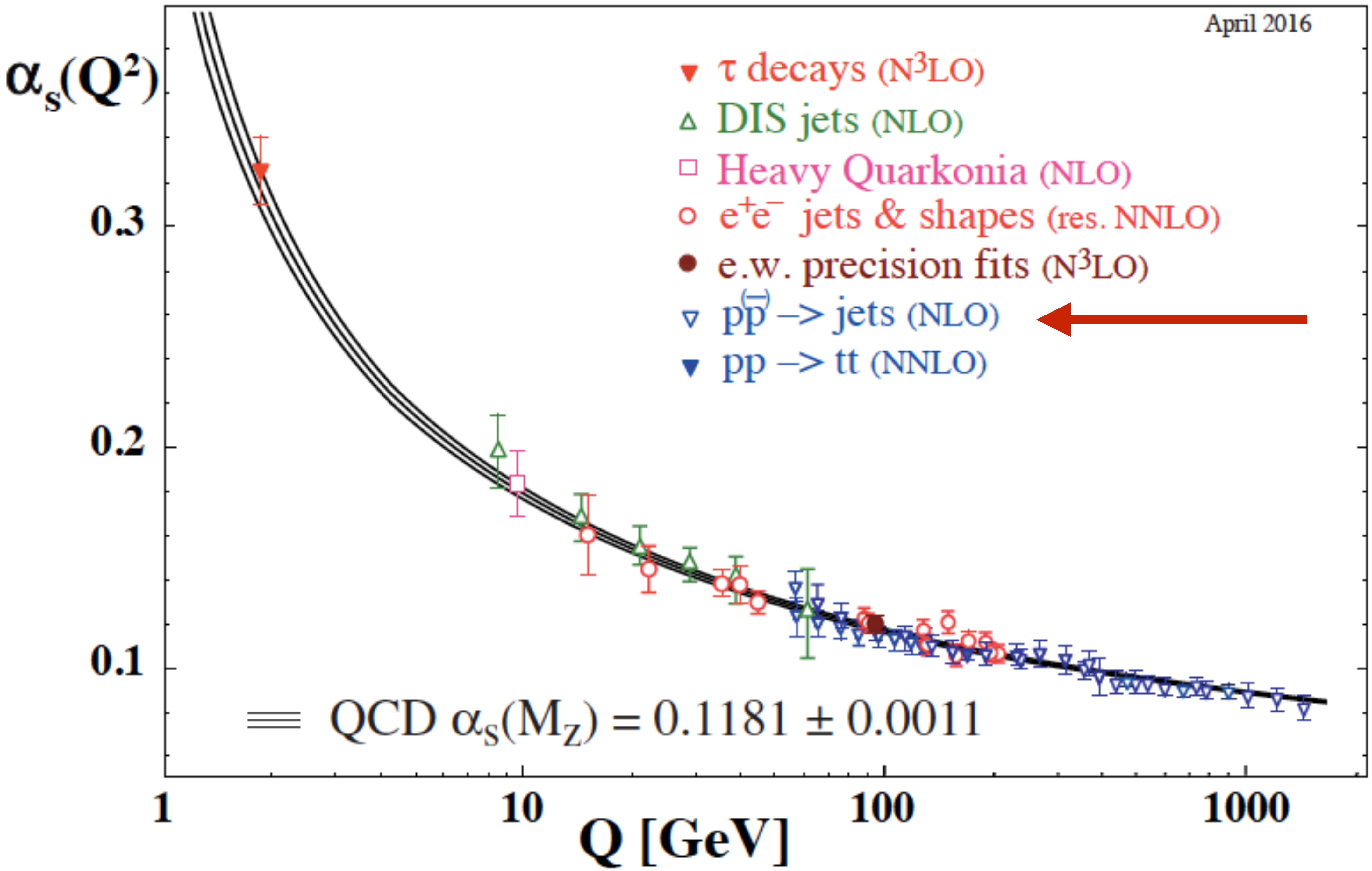
Called gradient flow- based on the addition of an extra “time” coordinate

preliminary result Moriond

$$\alpha_s(M_Z) = 0.1179(10)(2)$$

$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

The strong coupling constant α_s



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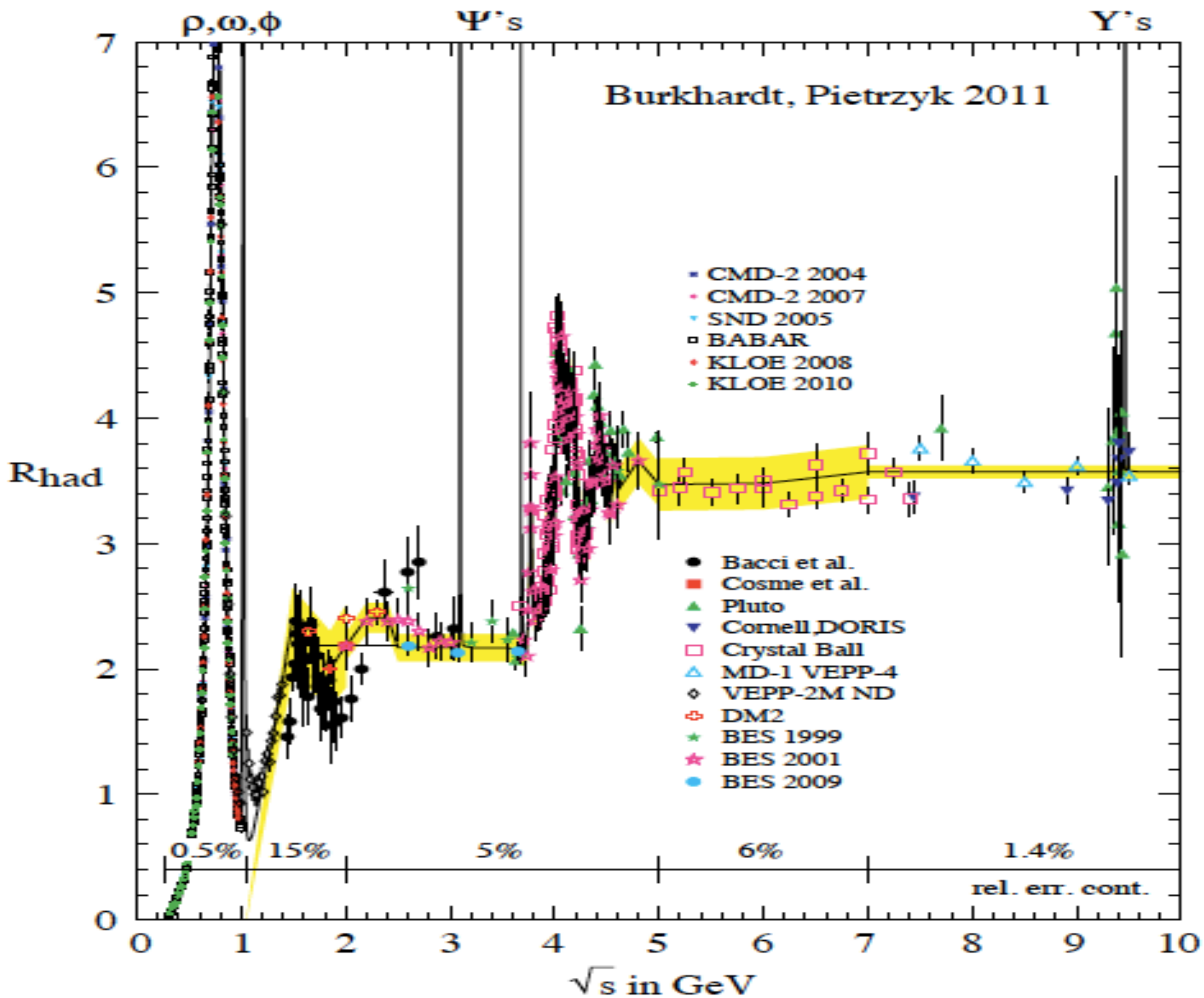
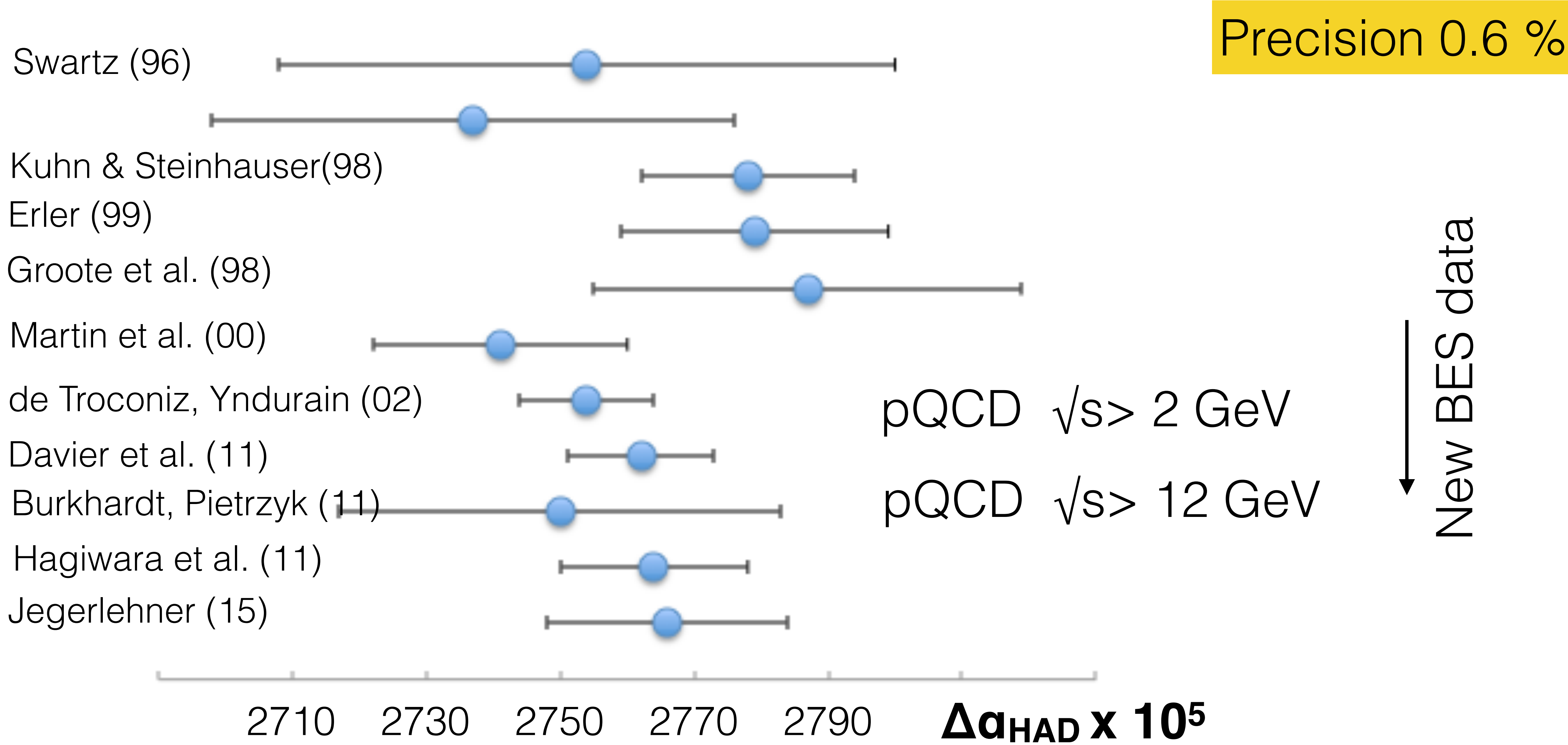
The hadronic contribution to vacuum polarization : $\Delta\alpha_{HAD}$

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)} \qquad \Delta\alpha(s) = \Delta\alpha_{lep}(s) + \Delta\alpha^{(5)}_{had}(s) + \Delta\alpha_{top}(s)$$

$$\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



The hadronic contribution to vacuum polarization : $\Delta\alpha_{HAD}$



$$\Delta\alpha^{(3)}_{\rm had}(2.0\ \ {\rm GeV}) = (58.04 \pm 1.10) \times 10^{-4}$$

The hadronic contribution to vacuum polarization : $\Delta\alpha_{HAD}$

Measurement of the running of the fine structure constant
below 1 GeV with the KLOE detector

Physics Letters B 767 (2017) 485–492

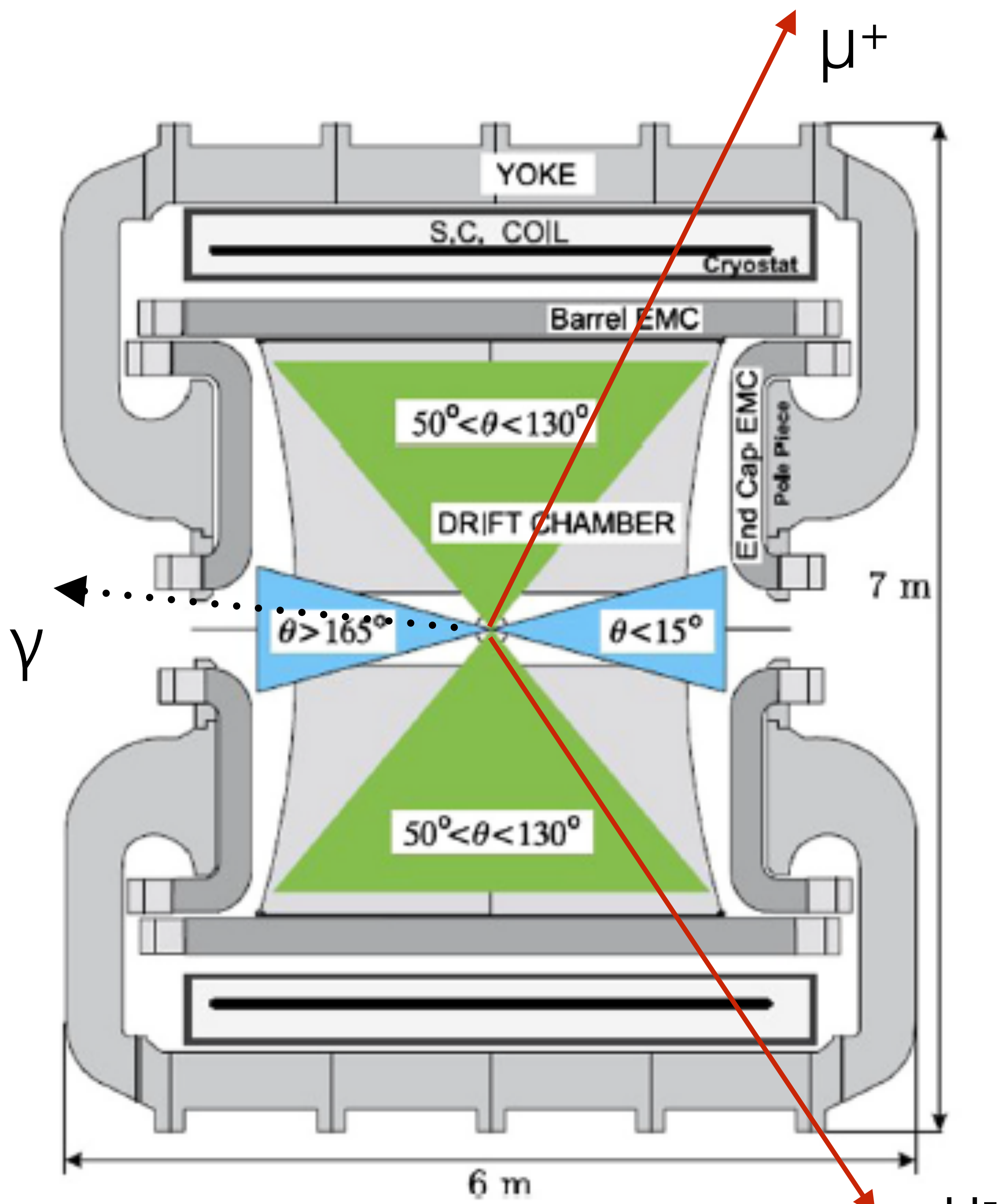
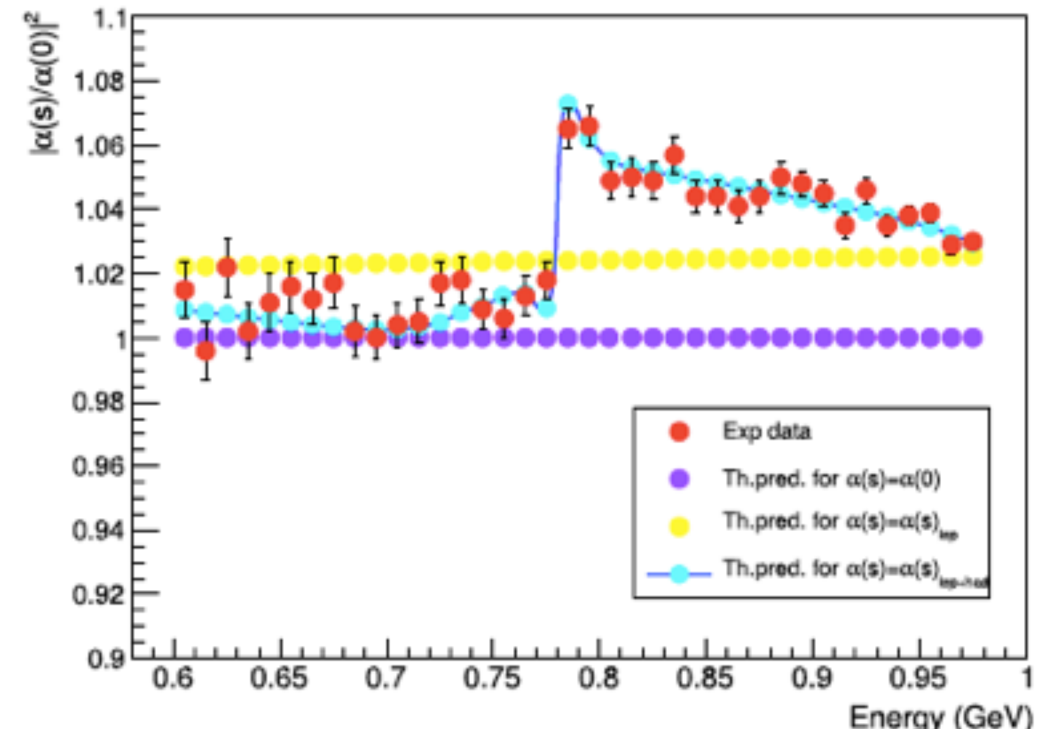
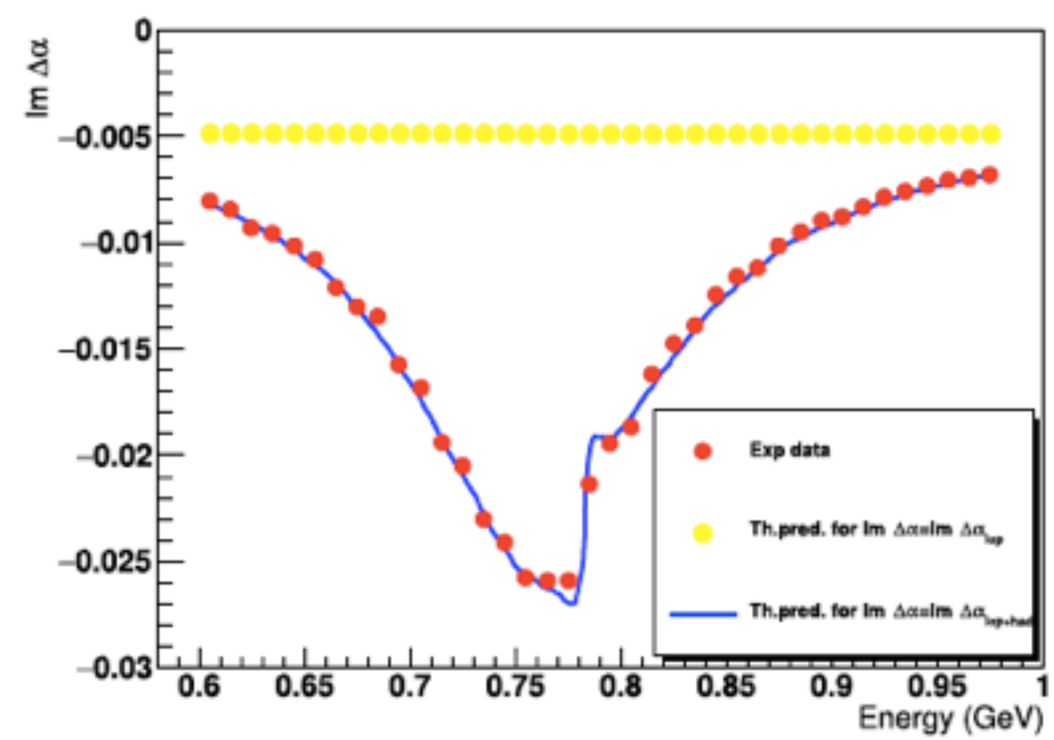


Fig. 1. Detector section with the acceptance region for the charged tracks (wide cones) and for the photon (narrow cones).





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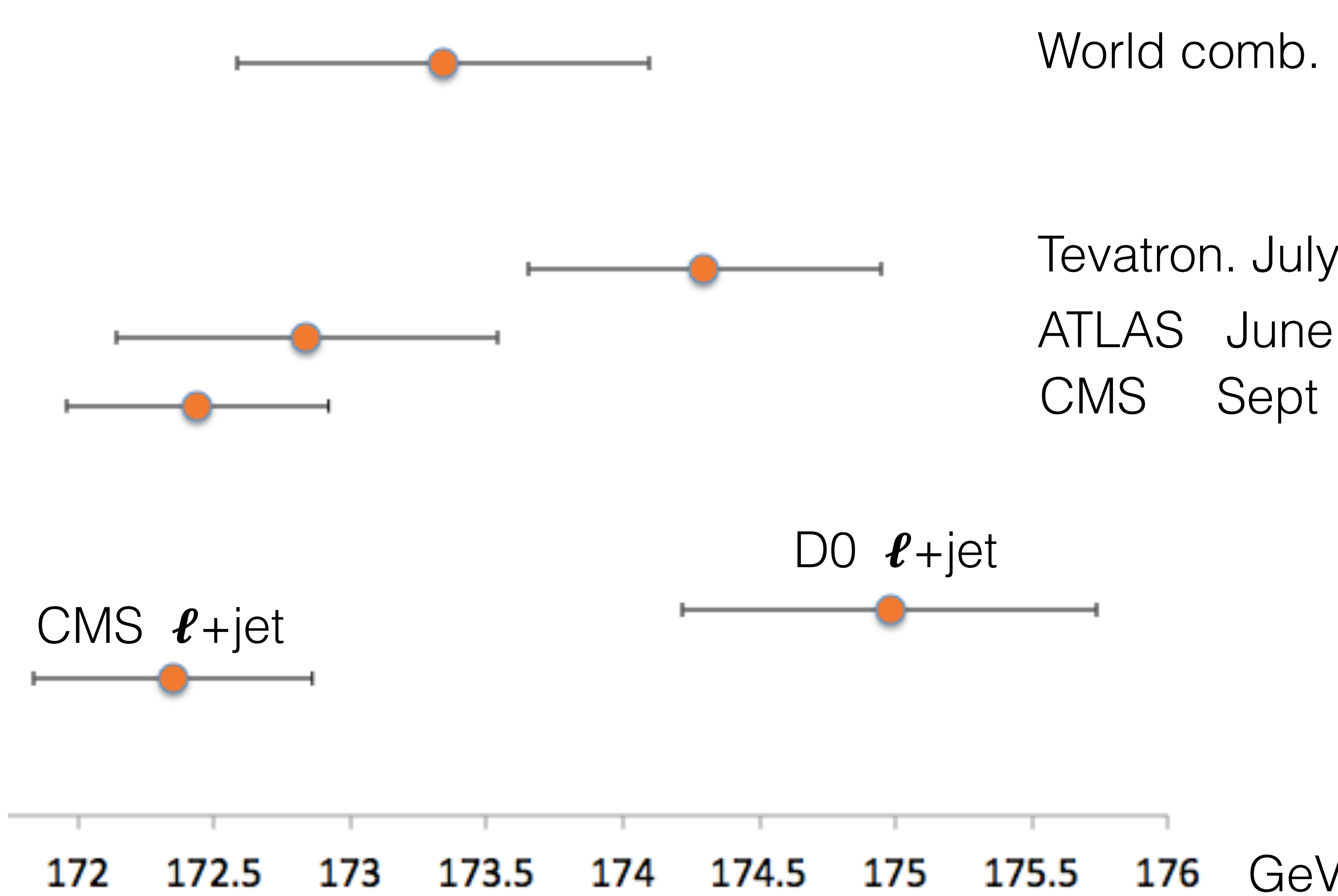
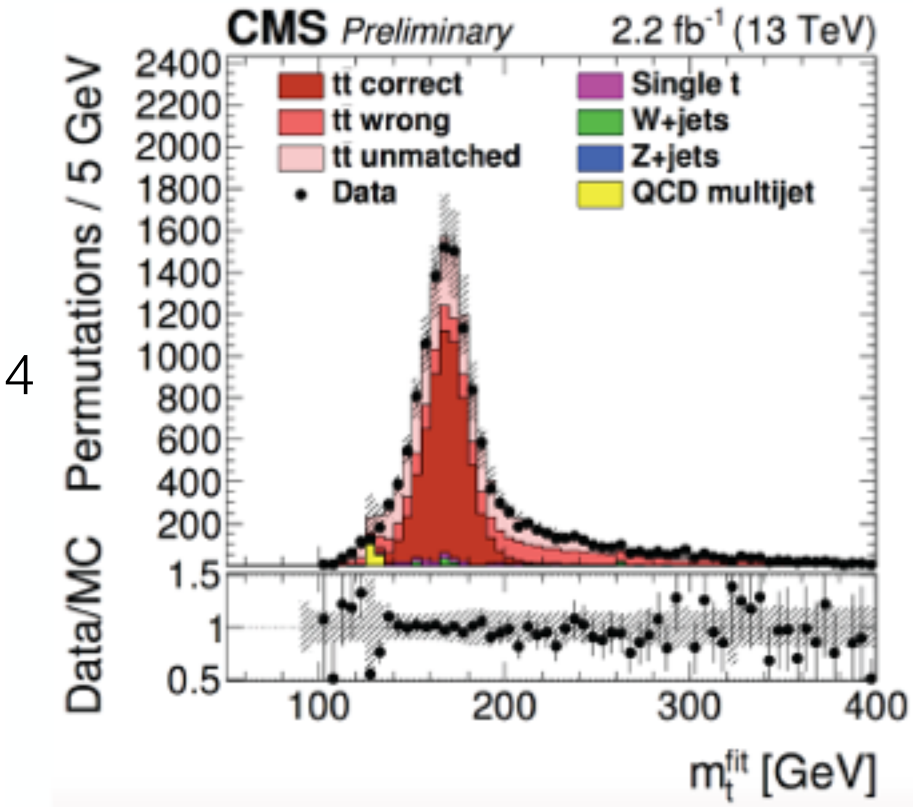
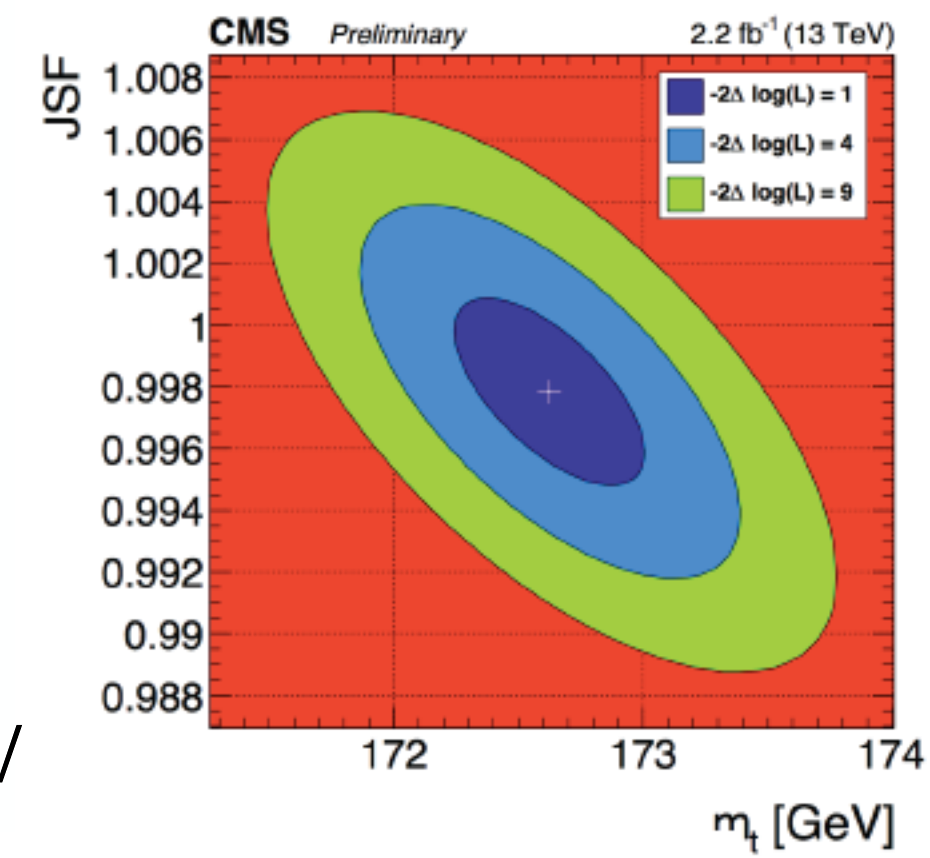
The top quark mass : m_t

Precision 0.4 %







RPP review of EW fit uses 173.34±0.64±0.5 GeV

The top quark mass : m_t

1605.03609 Beneke, Marquard, Nason, Steinhauser

Top quark **pole** mass is an ambiguous definition. When computing the pole mass from the $\overline{MS}$ mass there is an uncertainty of 250 MeV due to missing orders and an ambiguity of 70 MeV due to the definition.

1412.3649 Hoang

The reconstructed top invariant mass distribution calculated by the MC generator is determined by the value of the MC top mass, the parton shower (perturbative) and the hadronization model (non perturbative QCD). Perturbative and non perturbative effects change the shape and the peak position at the 1 GeV level.These effects are process independent (but not PS tuning independent) and can be calibrated.

1608.01318 Butenschoen,Dehnadi, Hoang,Mateu,Preisser,Stewart

Show in their use case a shift of ~600/900 MeV between the pole mass and the MC mass. The RMS(1 GeV) mass agrees within uncertainty with the MC mass.

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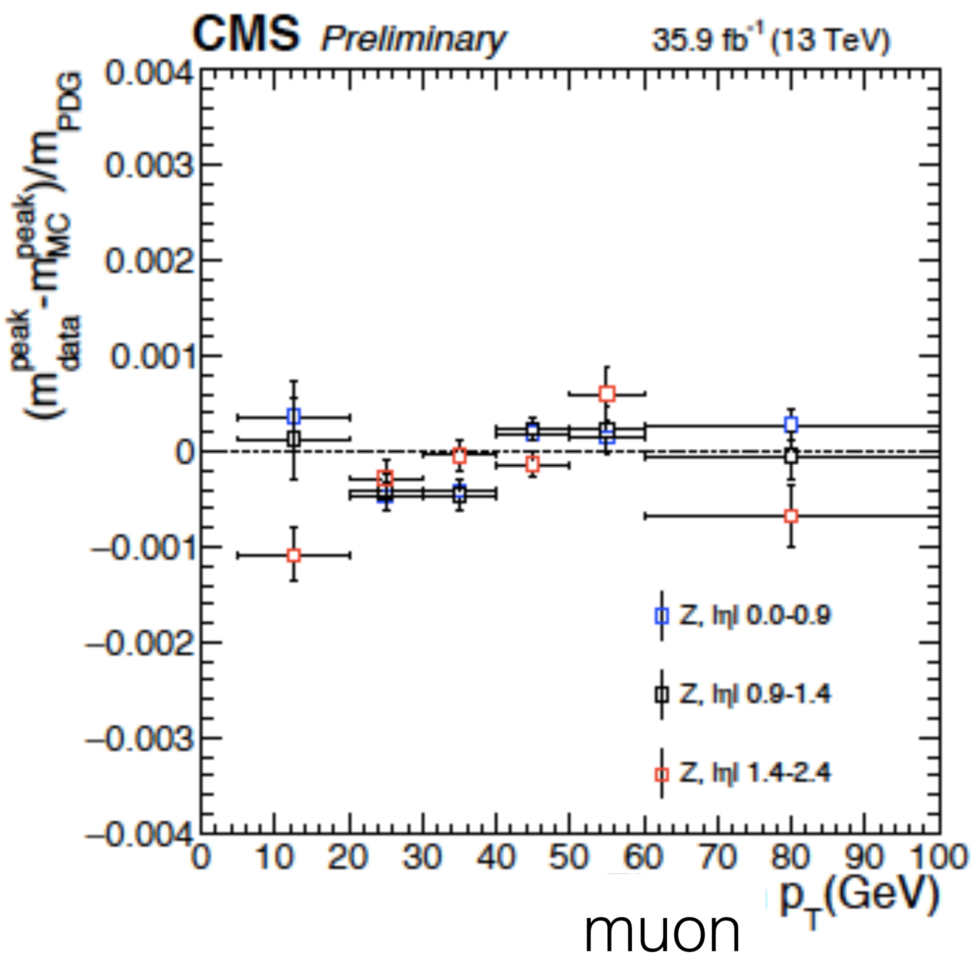
Higgs Boson Mass

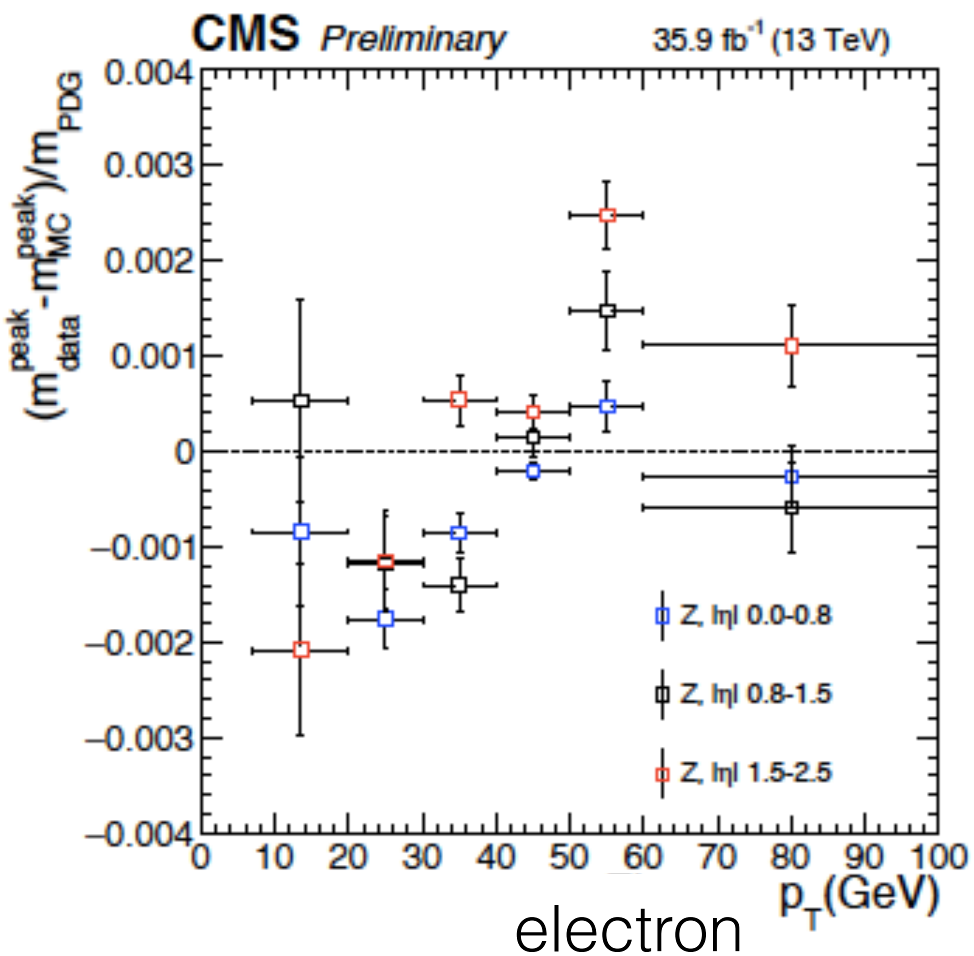
Precision 0.2 %

Use per event mass uncertainty + ME-based kinematic discriminant + Z_1 mass constraint:

125.26 ± 0.20 (stat.) ± 0.08 (sys.) GeV

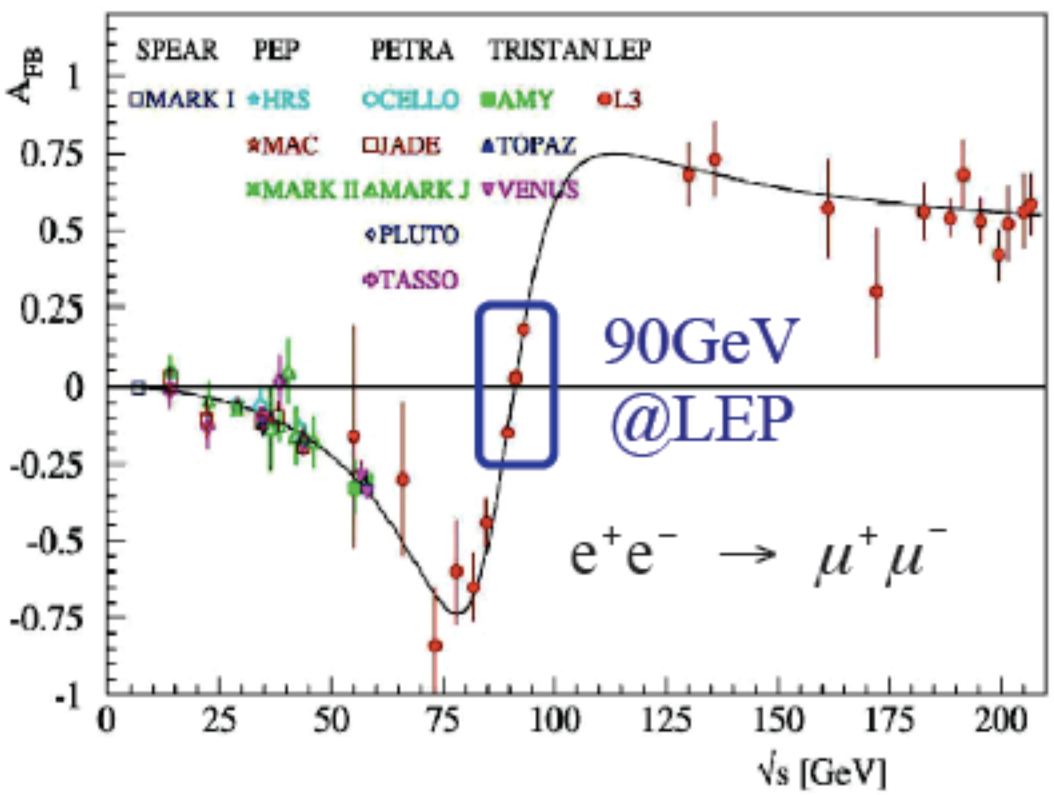
Run I ATLAS+CMS (4l, γγ) combination: 125.09 ± 0.21(stat.)± 0.11(sys.) GeV

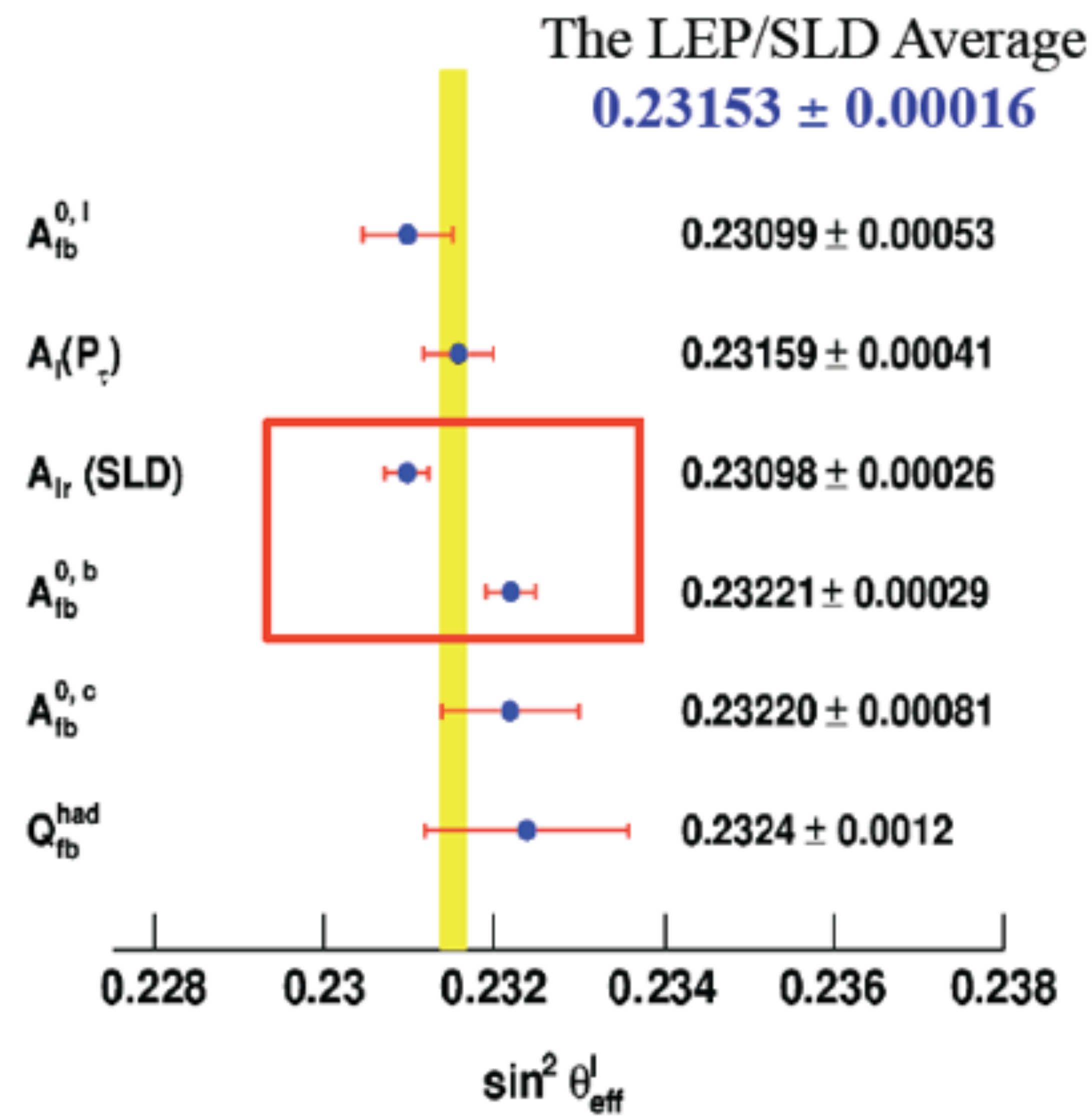


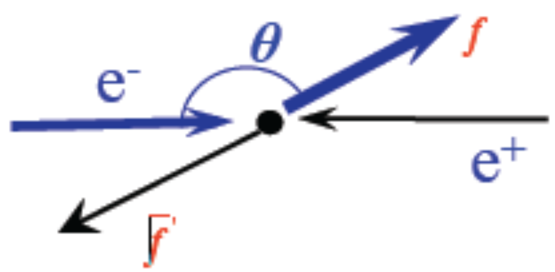


CMS-PAS-HIG-16-041

The Weinberg angle : $\sin^2\theta_{eff}$



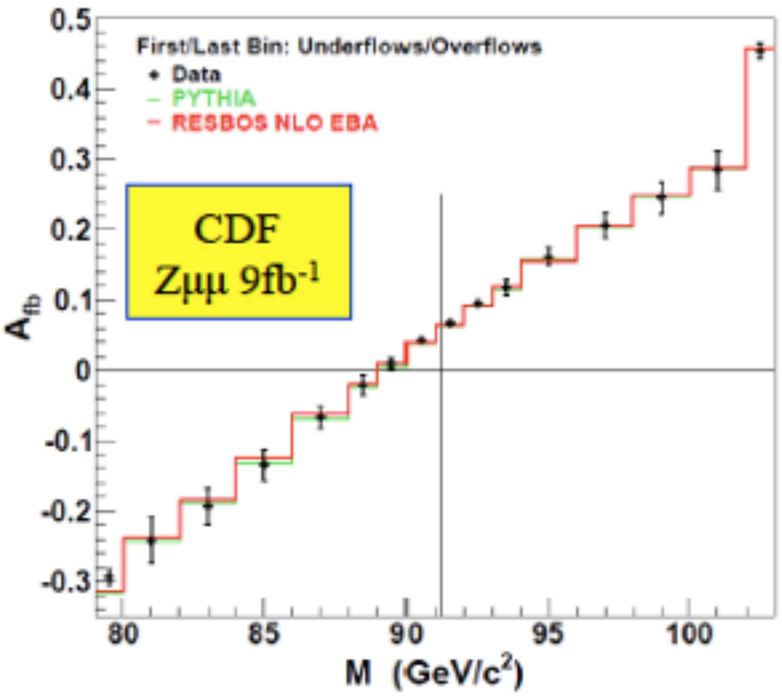




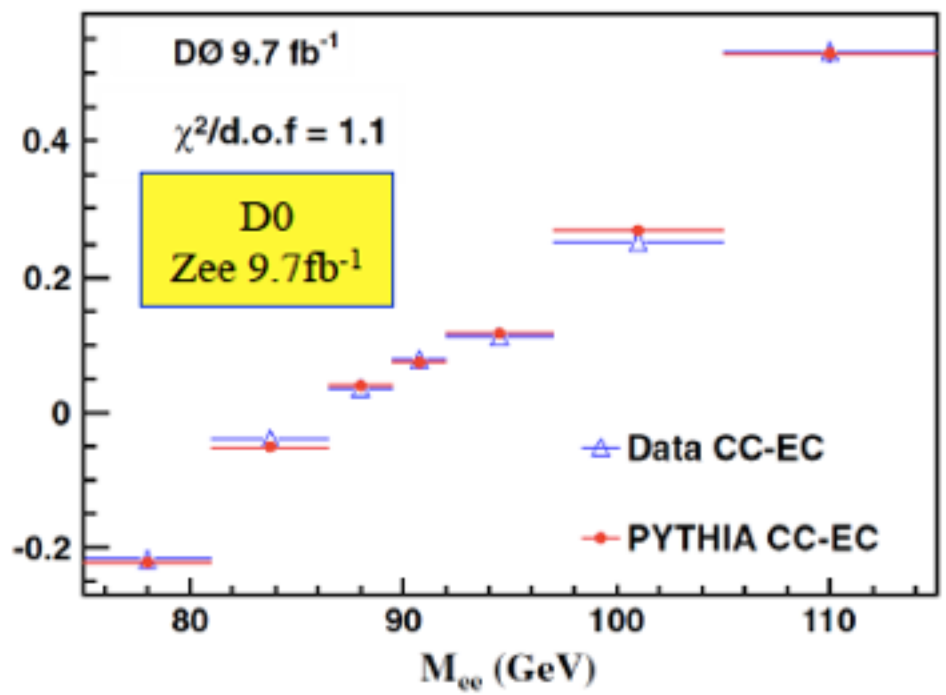
$$\sigma_{F/B} = \int_{0/-1}^{+1/0} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

The Weinberg angle : $\sin^2\theta_{eff}$ Tevatron

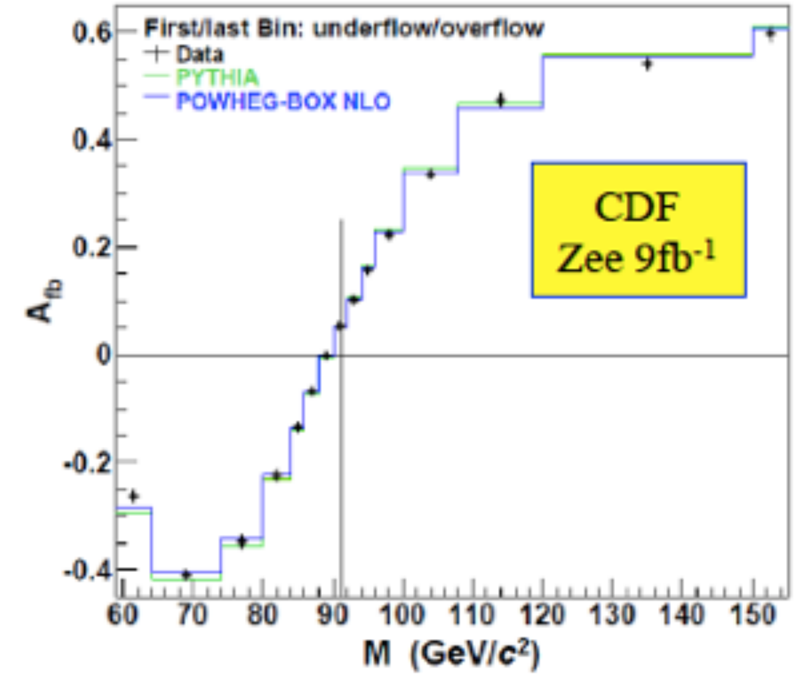
$$\sin^2\theta^u_{\rm eff} \approx \sin^2\theta^l_{\rm eff} - 0.0001,$$
$$\sin^2\theta^d_{\rm eff} \approx \sin^2\theta^l_{\rm eff} - 0.0002.$$



PRD 89(2014)072005

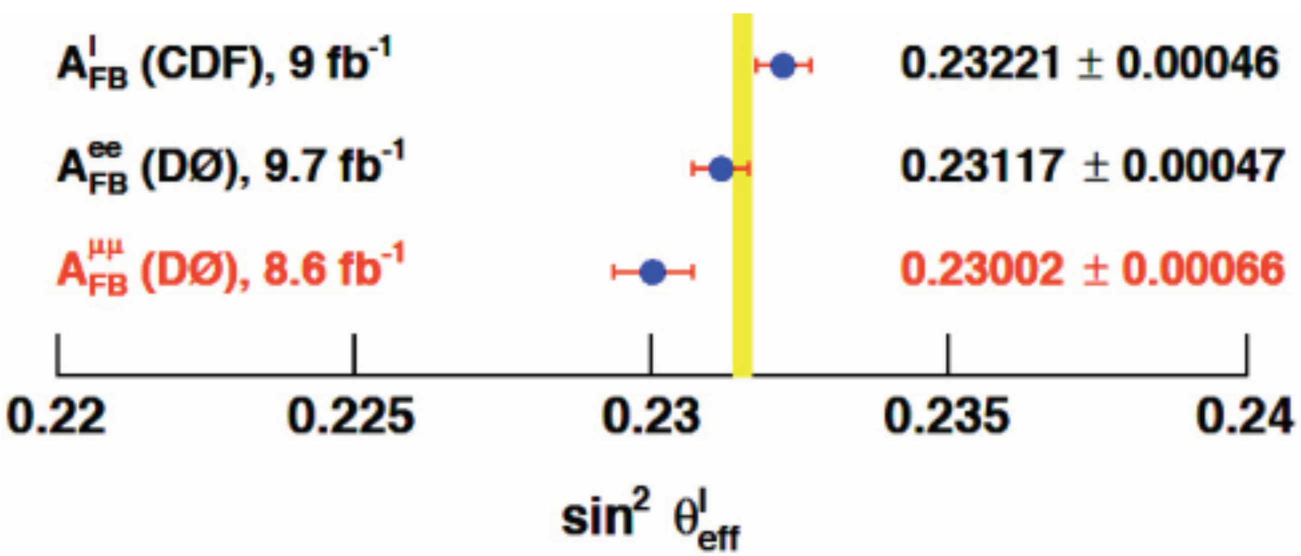


PRL115(2015)041801



PRD 93(2016)112016

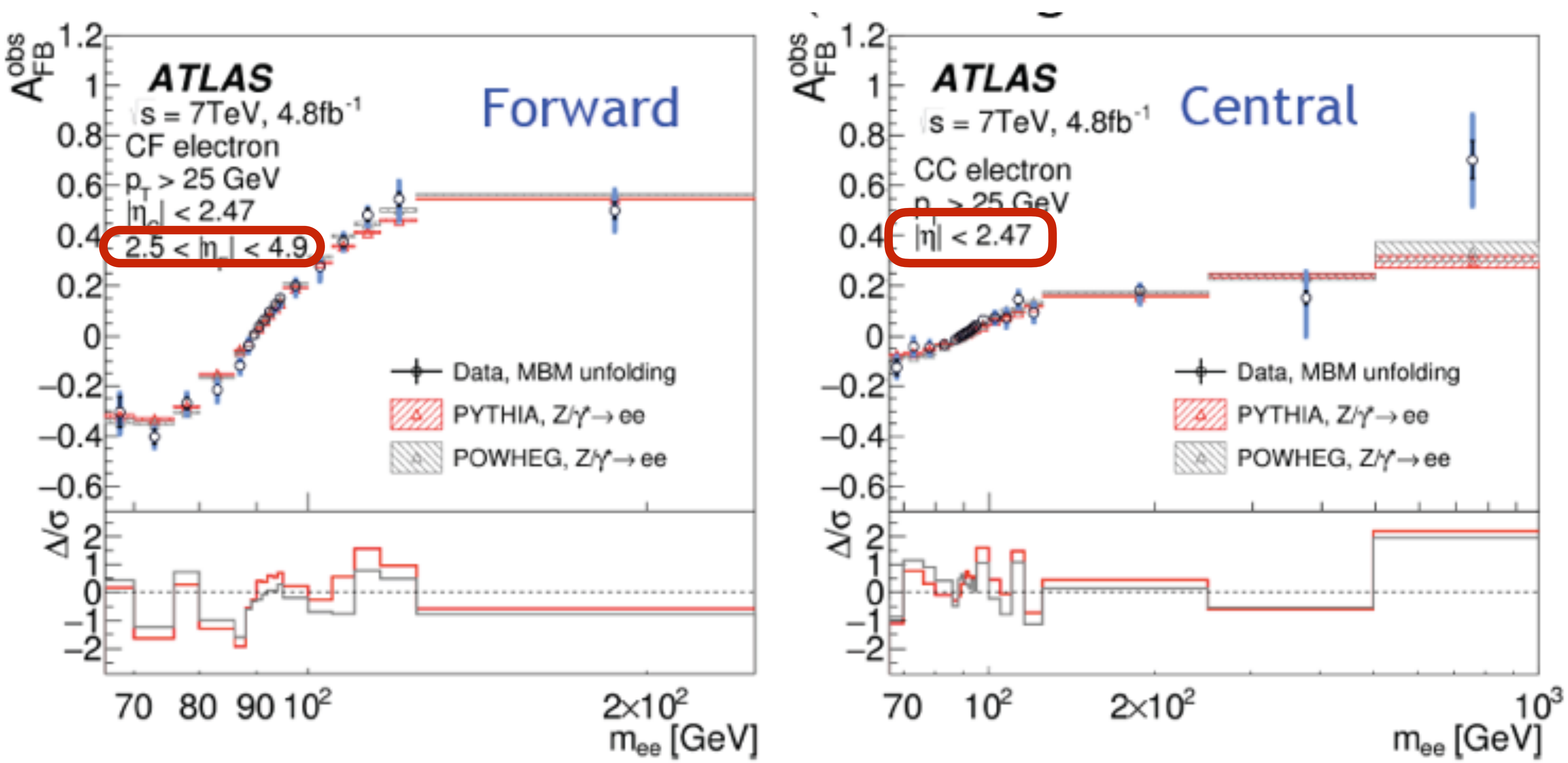
PDF error < 1/3 Statistical error



New D0 conf note 6497/2017

0.23137 ± 0.00029 to be compared to 0.23153 ± 0.00016 LEP/SLD

The Weinberg angle : $\sin^2\theta_{eff}$ LHC



Dilution due to poorly defined Forward vs Backward direction !!

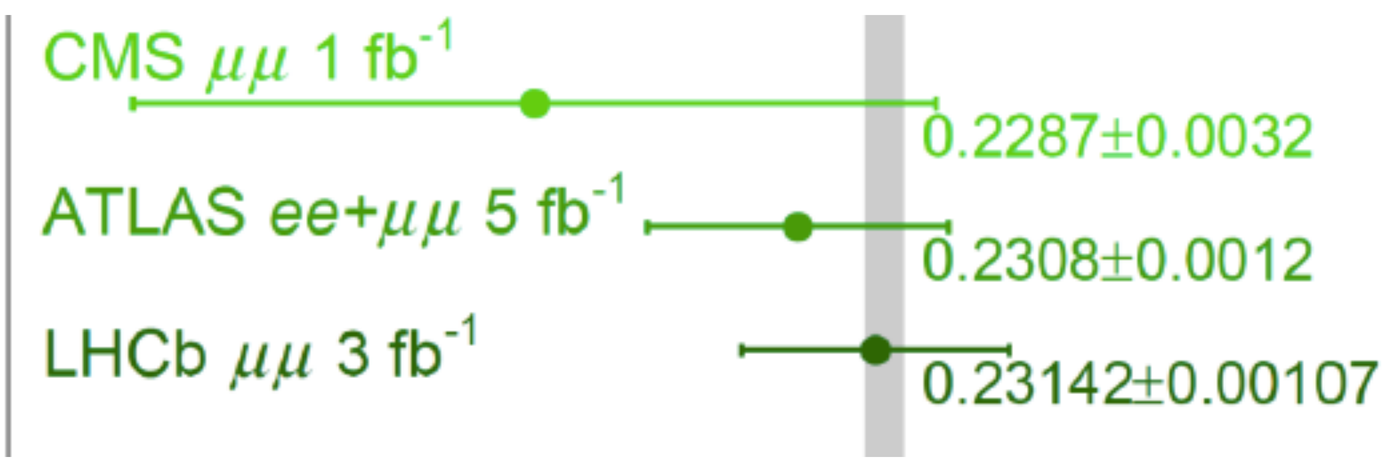
Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

← PDF error dominates

The Weinberg angle : $\sin^2\theta_{eff}$ LHC

LHCb 90% correct assignment in the forward direction

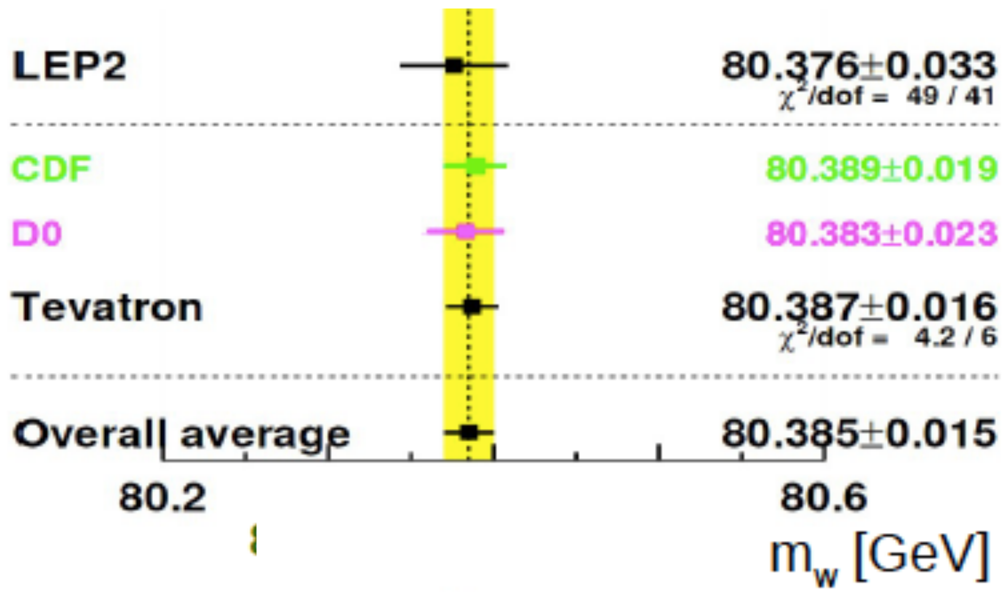
$$\sin^2\theta_W^{eff} = 0.23142 \pm \underset{(stat)}{0.00073} \pm \underset{(exp)}{0.00052} \pm \underset{(theory+pdf)}{0.00056}$$



Possible improvements : New PDF fits, profiling PDFs in the fit ….

Hoping to reach a precision of 5 10^{-4}

The W boson mass : M_W



New ATLAS Measurement
december 2016

mW = 80.370 ± 19 MeV

Gigi's Breakdown

ATLAS Numbers

CDF

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total combination	19

$$625,000\ W \to \mu\nu$$
$$470,000\ W \to e\nu$$

ATLAS

Source	Uncertainty	ATLAS Numbers
Lepton energy scale and resolution	9-14	
Recoil energy scale and resolution	2-13	11
Lepton tower removal		
Backgrounds	6-12	
PDFs	8-9	14
$p_T(W)$ model	8-10	
Photon radiation	5-3	
Statistical	7	7
Total combination	19	

$$7.8\,M\ W \to \mu\nu$$
$$5.8\,M\ W \to e\nu$$

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The W boson mass : M_W

CMS Statistics on tape

	Lumi (1/fb)	Pileup	J/Psi	Y	Z	W+	W-
			Million Events				
7 TeV	5	7	3.5	1	1.4	13	9
8 TeV	22	22	5.3	3	6.2	61	45
13 TeV	4+35	13+24	122	49	39	~350	~250

Using 8 TeV only the statistical error is <2 MeV

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The W boson mass : M_W PDF uncertainty Good news from ATLAS

CDF Variation of Mw with CTEQ6.6 and MSTW2008 eigenvect.

$$\delta M_W^{\rm PDF} = \frac{1}{2}\sqrt{\sum_i (M_W^{i+} - M_W^{i-})^2}$$

10 MeV

ATLAS uses CT10nnlo

: profits of strong anti-correlations W^+/W^- and η

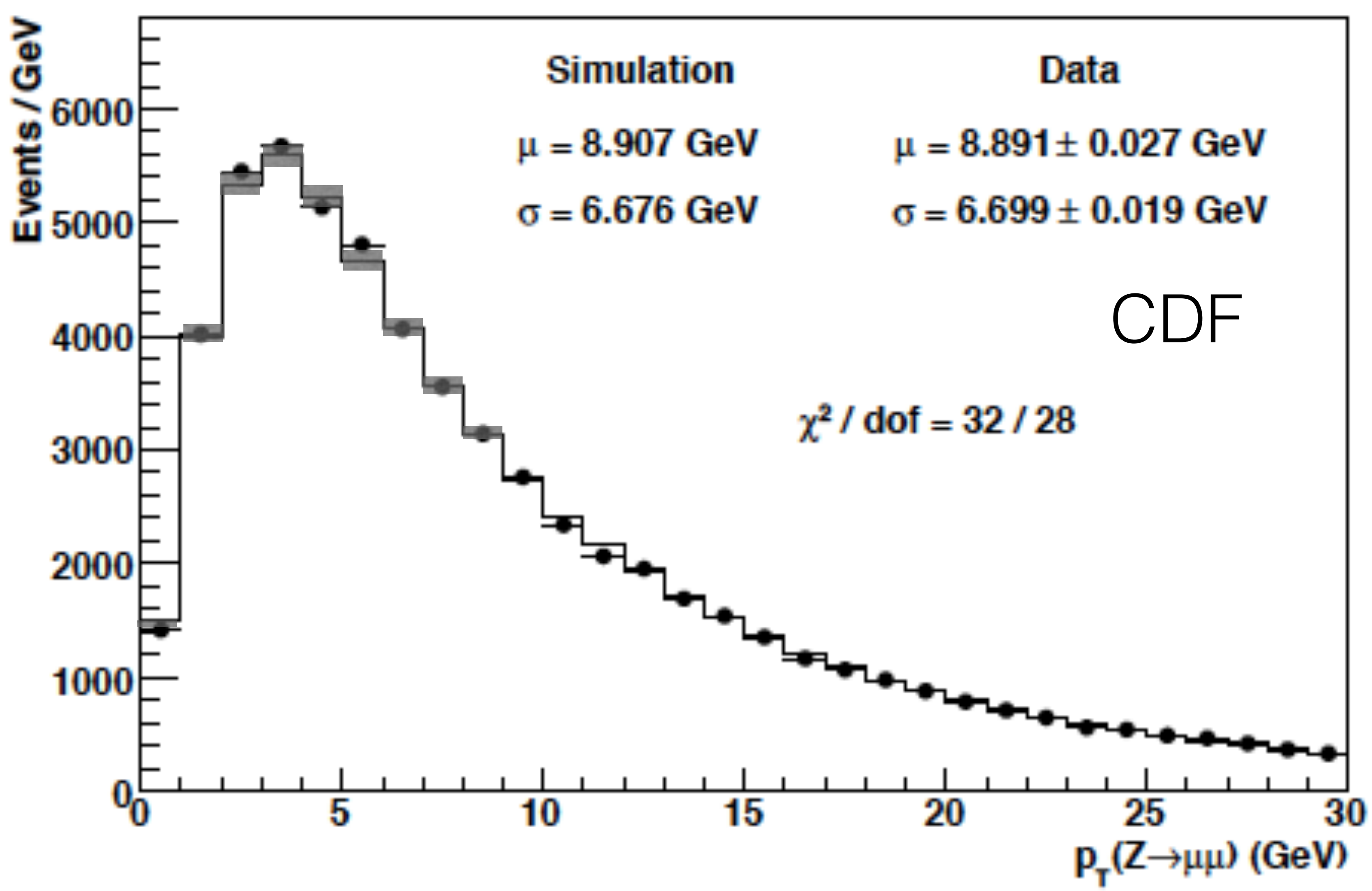
	W+	W-	Combined
PDFs /PT	14.5	13.5	9
PDF/MT	16.9	16.2	10.2

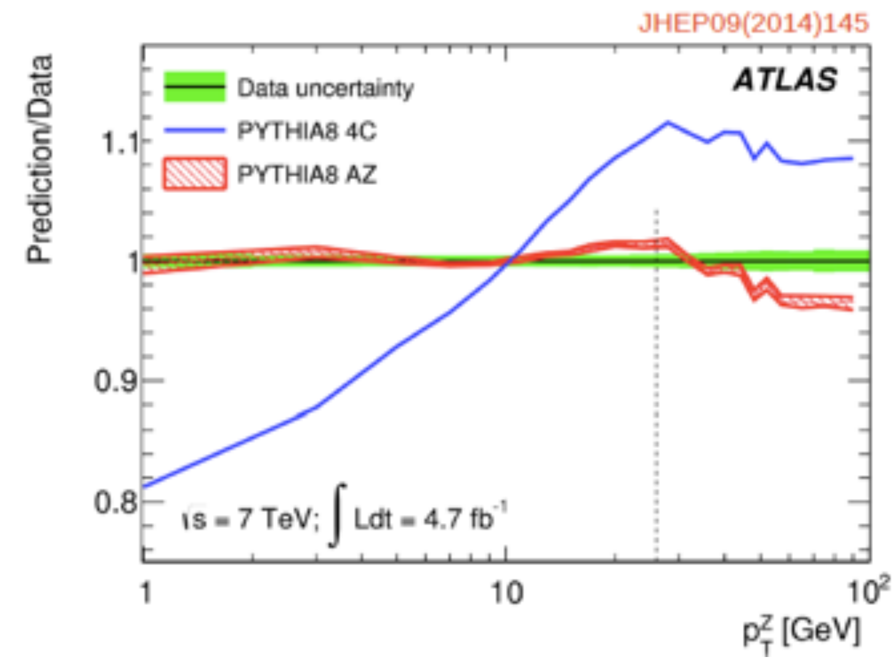
	η -range	0-0.8	0.8-1.4	1.4-2.0	2.0-2.4	Combined
PDF W+ /PT		24.7	20.6	25.2	31.8	14.5
PDF W+/MT		28.4	23.3	27.2	32.8	16.9

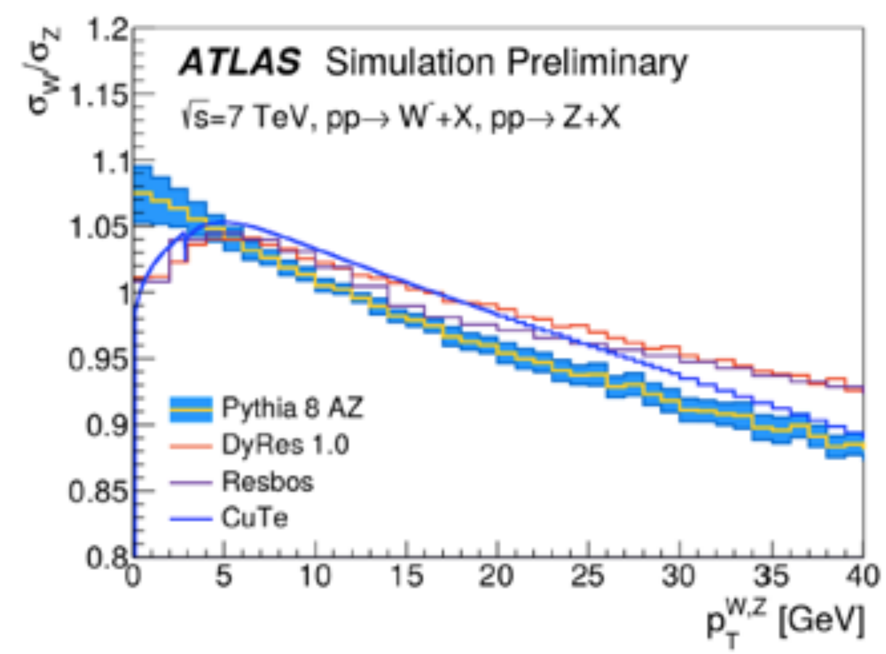
The W boson mass : M_W W pt modeling bad news from ATLAS

CDF : uses RESBOS to fit Z data for g_2 and α_s and determines the variation for M_W 9 and 3 MeV for the P_T and M_T fits

Agreement ~ 2%

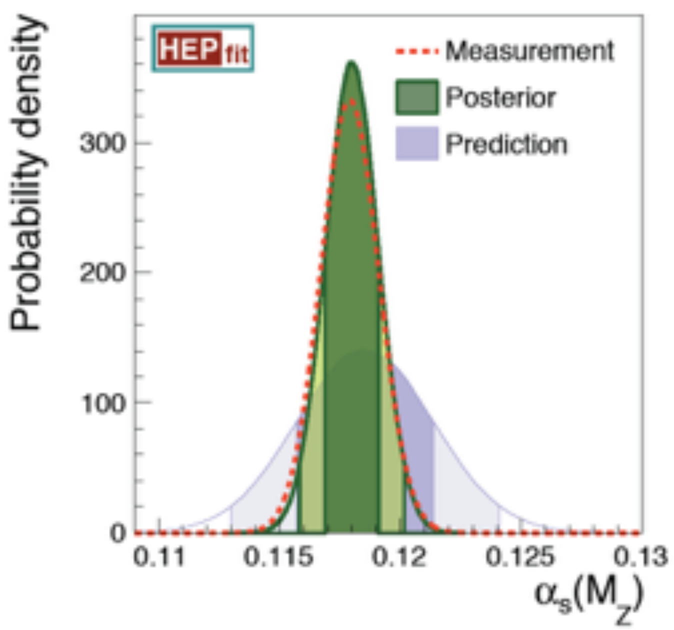


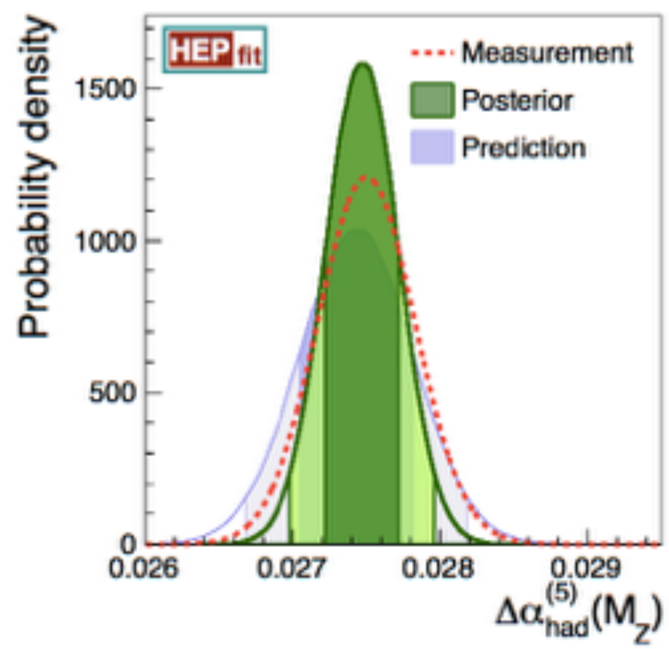


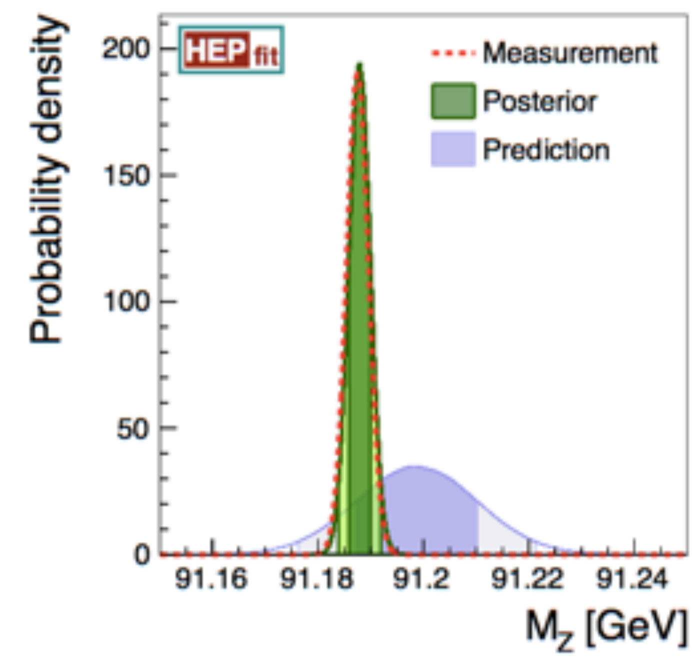


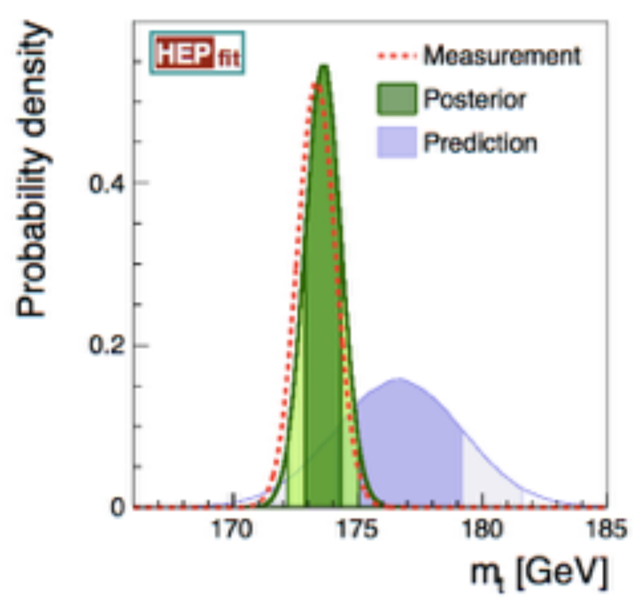
The EW fit   1608.01509

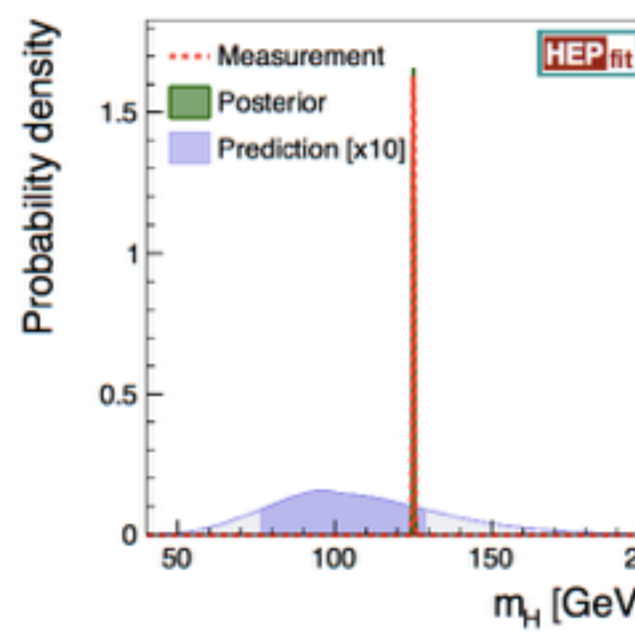
Overall good agreement between measurement and posterior, largest pull is 2 for the known discrepancy between A_{LR} measured at SLAC and the $A_{FB}(b)$ measured at LEP











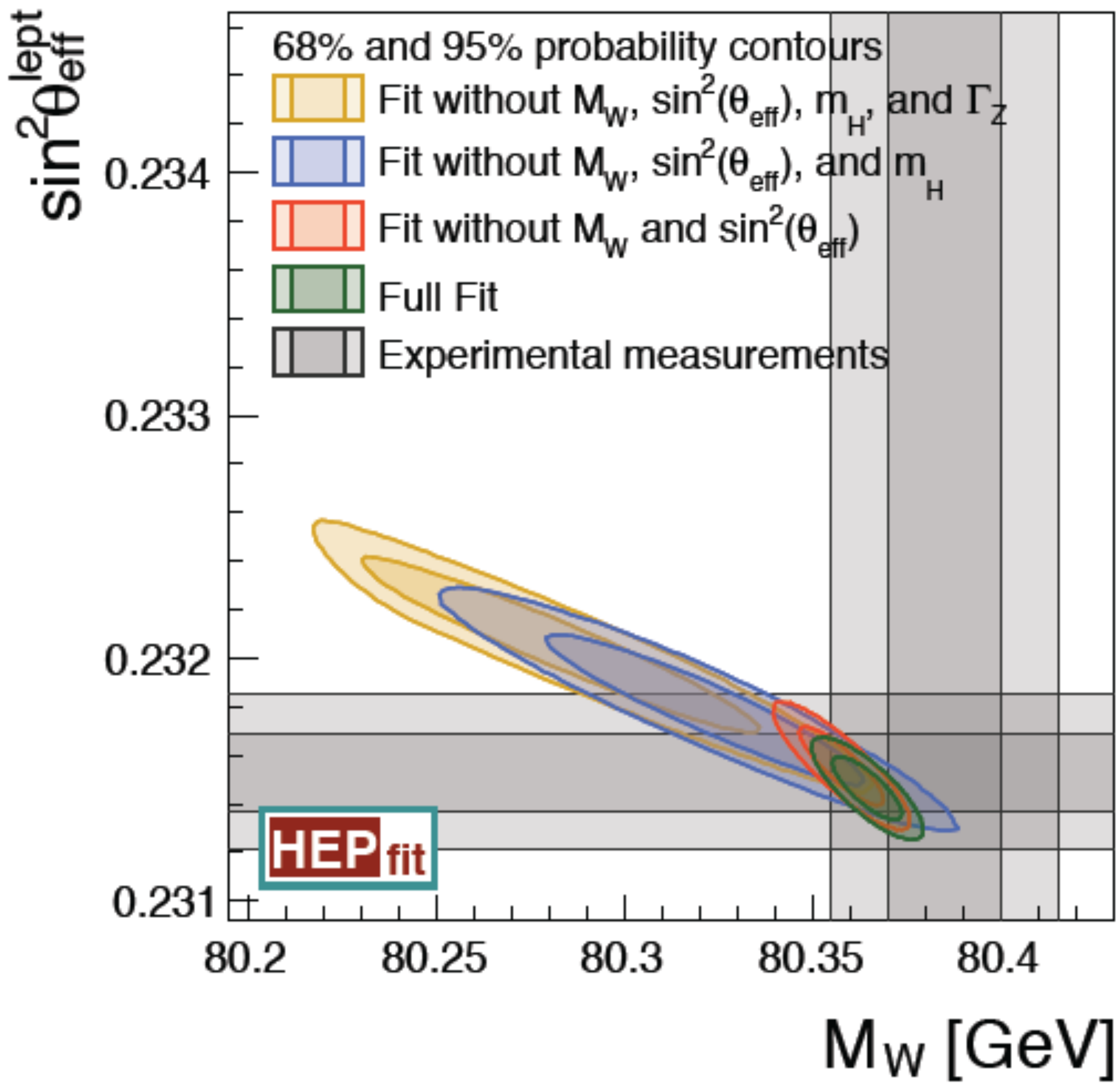
The EW fit   RPP review

This fit includes also other EW observables including a_μ, Higgs decays and W and Z decays

Largest pull 4.2 is the known discrepancy of the anomalous muon momentum. Overall χ^2= 53.6/42   11% probability to obtain a larger χ^2

In this fit the indirect determination of M_H is M_H=126.1± 1.9 GeV because of the strong dependence of the BR (H—>ZZ*) on the Higgs mass.

The EW fit   1608.01509



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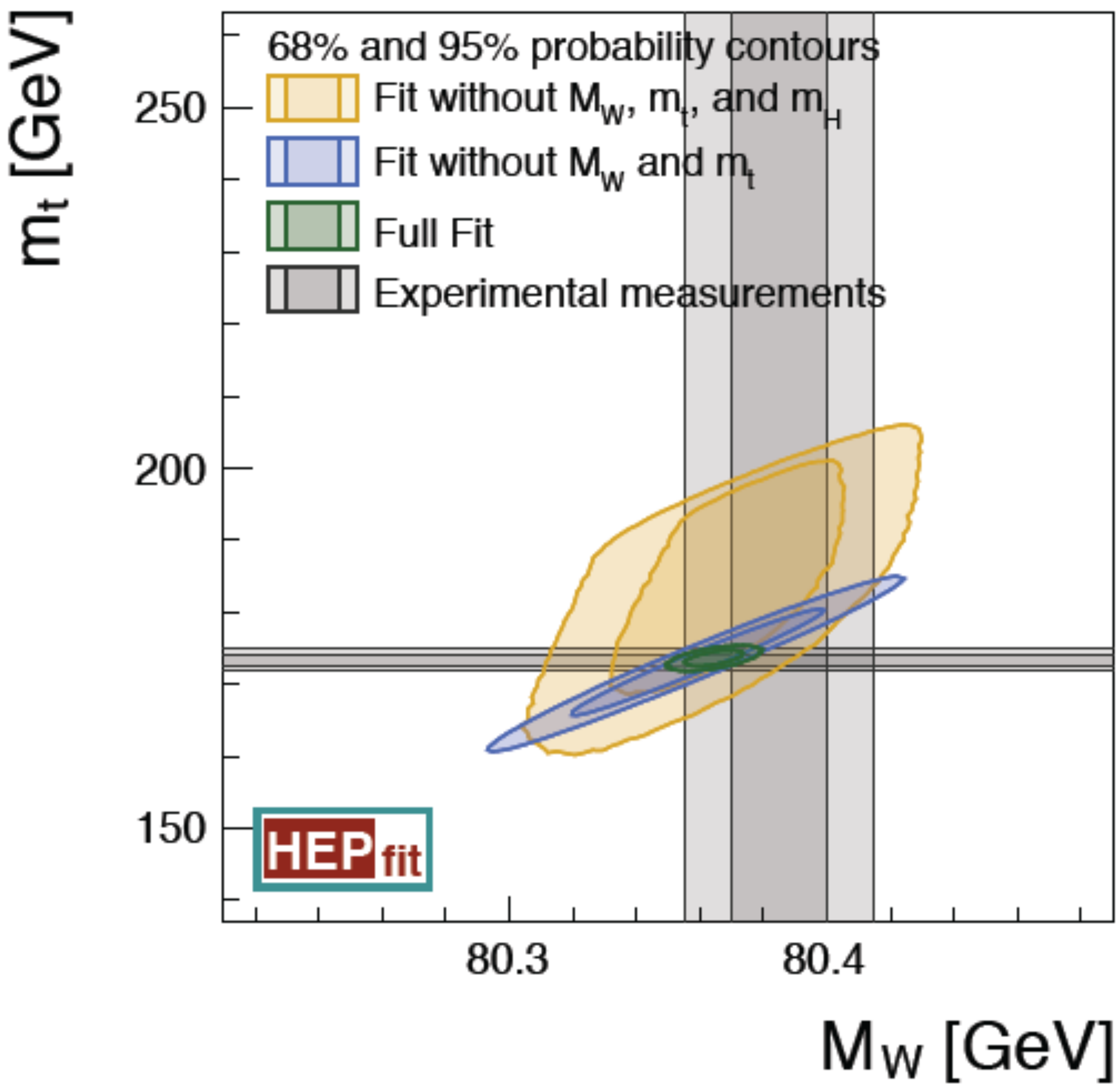
The EW fit 1608.01509 and RPP



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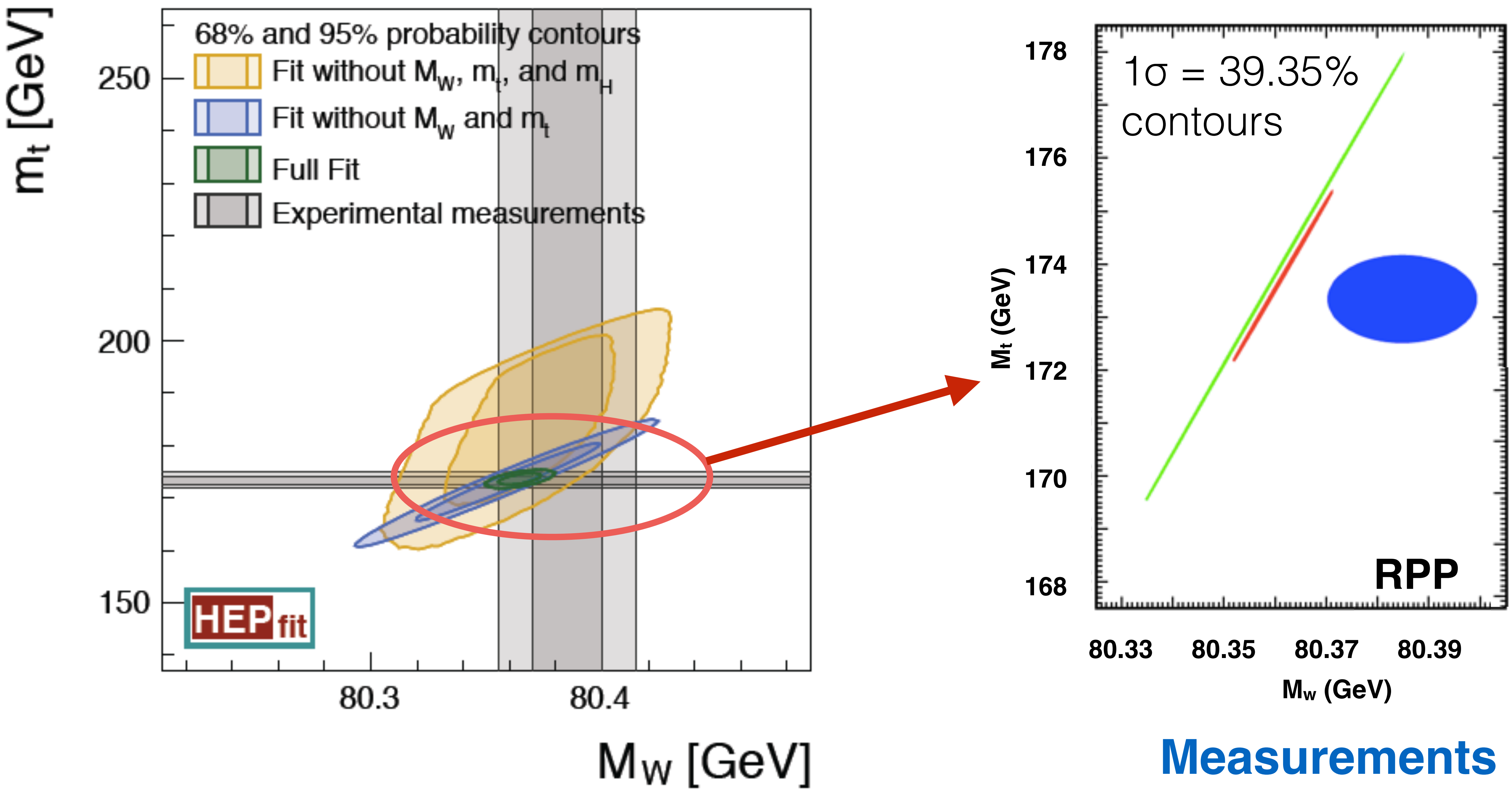
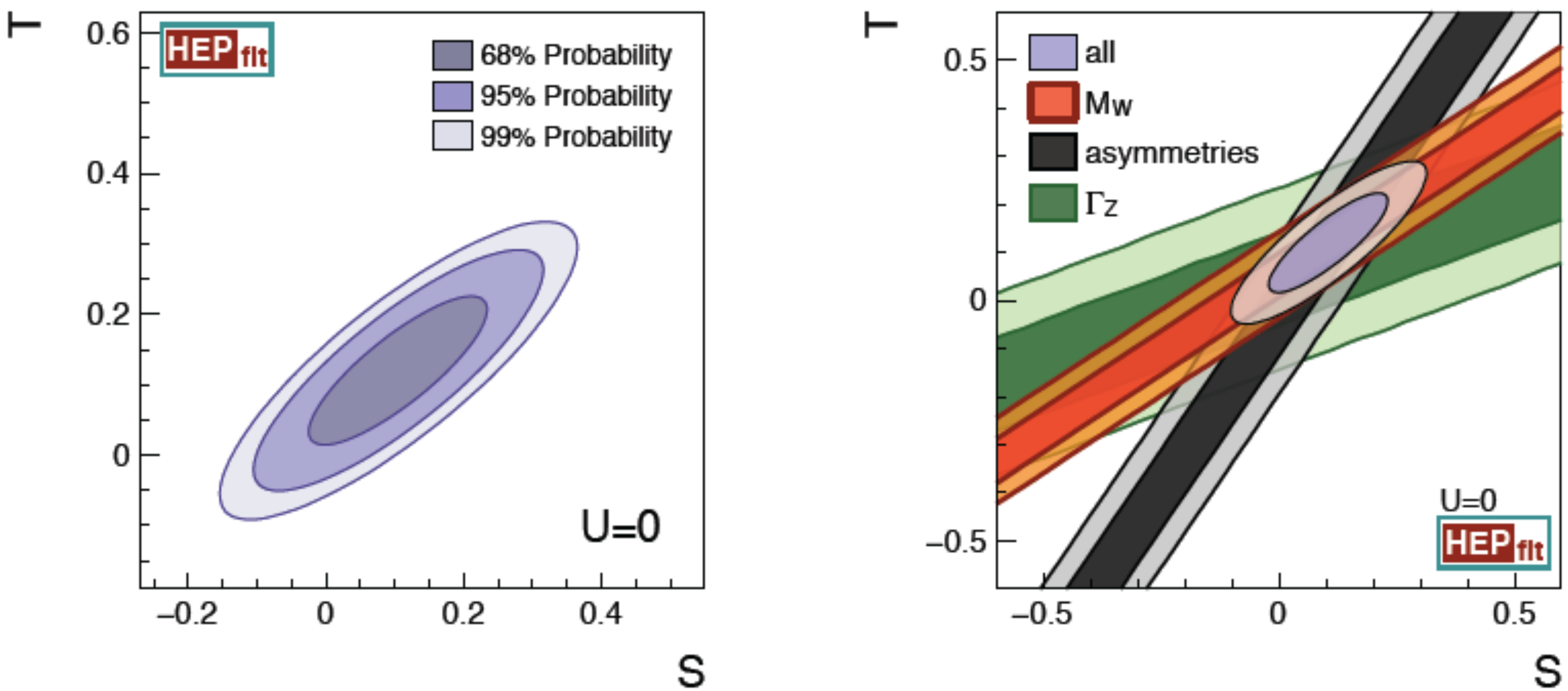
The EW fit 1608.01509 and RPP



Measurements

Fit w/o M_W M_t

The EW fit and new physics



Standard Model —> S=0, T=0 . The ability to exclude 1 gives a measure of sensitivity to new physics.

Eg KK resonances of mass larger than 2-3 TeV are excluded

FCC-ee up to 10^{13} Z decays

FCCee	Z pole	WW threshold	HZ threshold	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^8	2×10^6	2.1×10^5	7.5×10^4

Observable	Current Th. Error	Future Th. Error	Current Exp. Error	ILC	FCC-ee	CepC
M_W [MeV]	4	1	15	$3-4$	1	3
$\sin^2\theta_{\rm eff}^{\rm lept}$ [10^{-5}]	4.5	1.5	16		0.6	2.3
Γ_Z [MeV]	0.5	0.2	2.3		0.1	0.5
R_b^0 [10^{-5}]	15	10	66		6	17

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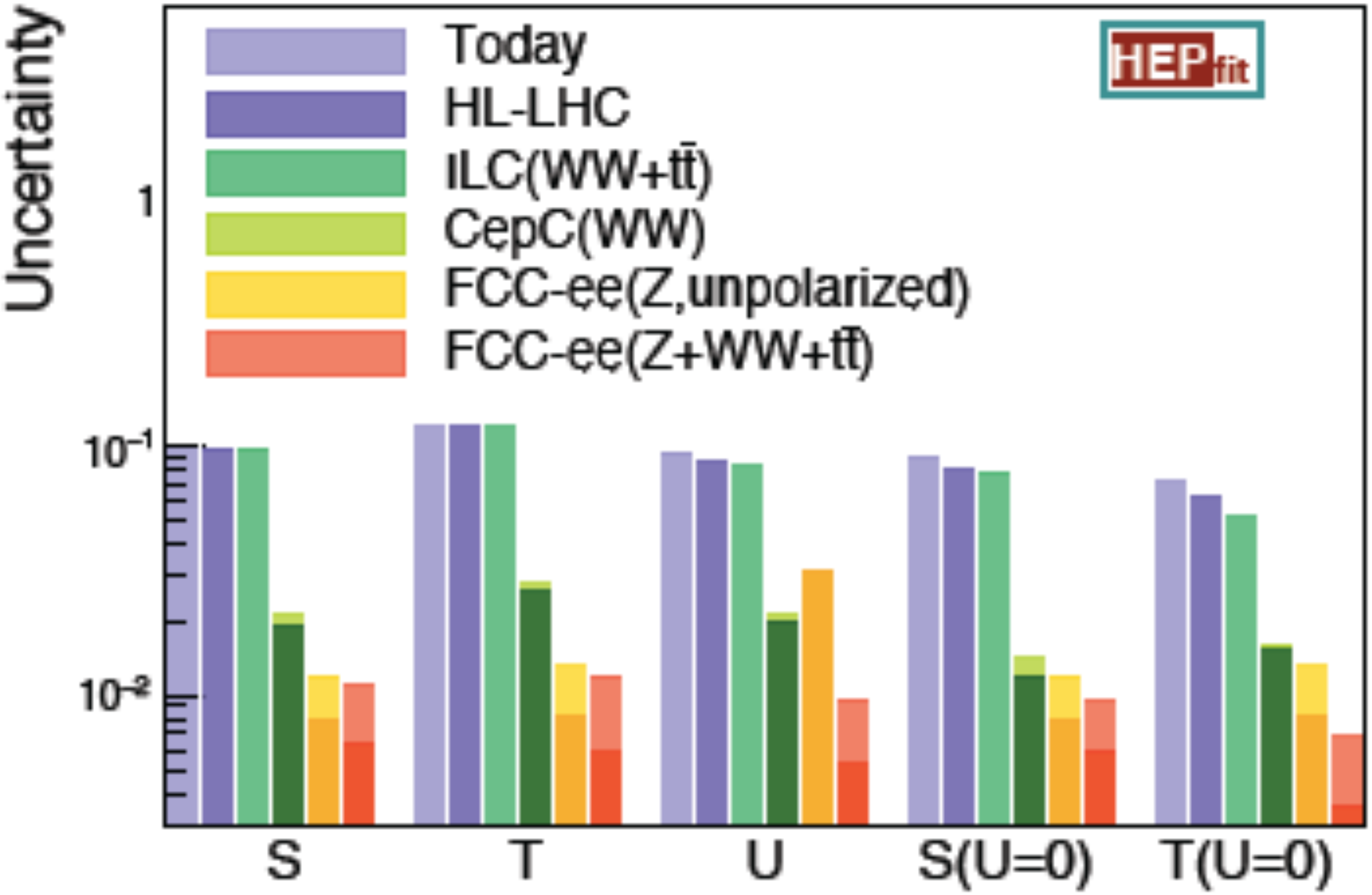
The EW fit up to 10^{13} Z decays



Conclusions

The Electroweak Fit is an excellent tool for discovery

The level of precision of the fit is such that difficult details about the central values and uncertainties of α_s , $\Delta\alpha_{EM}$ and M_{TOP} should be clarified with efforts from experiments and theory.

LHC will provide a more precise value of Mw in the near future and possible quite precise measurements of $\sin^2\theta_l$.

…. waiting for a new accelerator capable to produce 10^{12-13} Z decays

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	Current Data	HL-LHC	ILC	FCCee	(Run)	CepC
$\alpha_s(M_Z)$	0.1179±0.0012					
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	0.02750±0.00033					
M_Z [GeV]	91.1875±0.0021			±0.0001	(FCCee-Z)	±0.0005
m_t [GeV]	173.34±0.76	±0.6	±0.017	±0.014	(FCCee-$t\bar{t}$)	
m_H [GeV]	125.09±0.24	±0.05	±0.015	±0.007	(FCCee-HZ)	±0.0059
M_W [GeV]	80.385±0.015	±0.011	±0.0024	±0.001	(FCCee-WW)	±0.003
Γ_W [GeV]	2.085±0.042			±0.005	(FCCee-WW)	
Γ_Z [GeV]	2.4952±0.0023			±0.0001	(FCCee-Z)	±0.0005
σ_h^0 [nb]	41.540±0.037			±0.025	(FCCee-Z)	±0.037
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2324±0.0012			±0.0001	(FCCee-Z)	±0.000023
$P_\tau^{\rm pol}$	0.1465±0.0033			±0.0002	(FCCee-Z)	
A_ℓ	0.1513±0.0021			±0.000021	(FCCee-Z [pol])	
A_c	0.670±0.027			±0.01	(FCCee-Z [pol])	
A_b	0.923±0.020			±0.007	(FCCee-Z [pol])	
$A_{\rm FB}^{0,\ell}$	0.0171±0.0010			±0.0001	(FCCee-Z)	±0.0010
$A_{\rm FB}^{0,c}$	0.0707±0.0035			±0.0003	(FCCee-Z)	
$A_{\rm FB}^{0,b}$	0.0992±0.0016			±0.0001	(FCCee-Z)	±0.00014
R_ℓ^0	20.767±0.025			±0.001	(FCCee-Z)	±0.007
R_c^0	0.1721±0.0030			±0.0003	(FCCee-Z)	
R_b^0	0.21629±0.00066			±0.00006	(FCCee-Z)	±0.00018