
Measurement of electroweak parameters by ATLAS and CMS: status and plans

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Outline

The Electroweak Model: quick overview

Limits with a new boson

$\sin^2\theta_W$ measurement

M_W measurement

Conclusion

Tree level: What a wonderful world

Simple relations after BEH mechanism with $\phi = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

Fondamental parameters can be written...

... and linked to coupling "constants"

- ▶ W mass: $M_W = \frac{gv}{2}$
- ▶ Z mass: $M_Z = \frac{\sqrt{g^2 + g'^2}v}{2}$
- ▶ Mixing angle: $\sin\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$
- ▶ Electric charge: $e = g\sin\theta_W$
- ▶ Fermi constant: $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$
- ▶ g, g' constant of $SU(2)_L$ and $U(1)$

Comparing computations and measurements

Using $\sin^2\theta_W$ and G_F measurements from ν -DIS and τ_μ (independent of $M_{W/Z}$)

	Tree computation	World average
M_W	78.54 ± 0.35 GeV	80.385 ± 0.015 GeV
M_Z	89.26 ± 0.29 GeV	91.1876 ± 0.0021 GeV

Higher-order effect seems needed to make these computations compatible with measurements

Higher orders: introducing dependences

Need to take into account radiative corrections

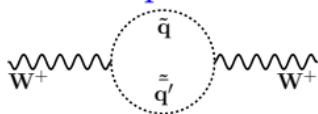
- ▶ QED ones: photon lines (real or virtuals)
- ▶ Weak ones: (γ , Z , W) propagators, vertex corrections, box-diagrams...
- Renormalise divergences, running coupling constant and effective parameters

M_W example:

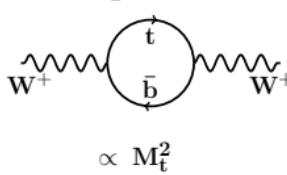
$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1 - \Delta r}}$$

$\Delta r \equiv$ radiative corrections

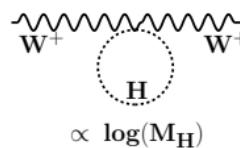
BSM dependences



SM dependences



$$\propto M_t^2$$



$$\propto \log(M_H)$$

Get a precise M_W

→ make equal M_W and M_t contribution M_H uncertainty

$$\Rightarrow \Delta M_W \approx 0,006 \Delta M_t$$

$$\Leftrightarrow \begin{cases} \Delta M_t = 0.9 \text{ GeV} \\ \Delta M_W \approx 6 \text{ MeV} \end{cases}$$

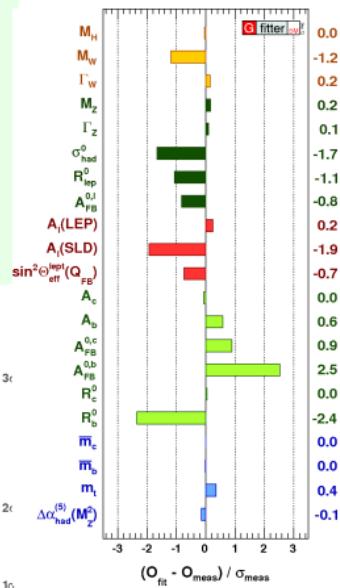
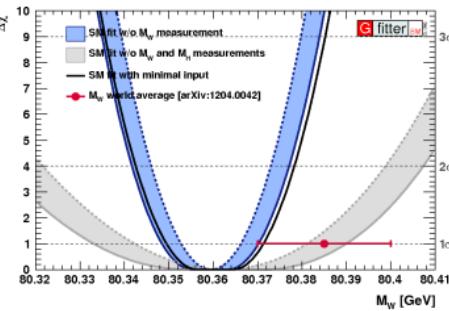
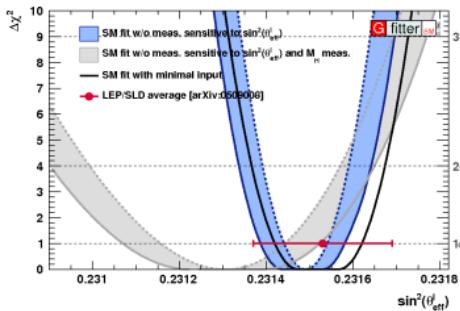
First order correction changing 78.54 to 80.40 for M_W

Global fits with/without the new boson

Using Higgs mass from ATLAS and CMS ($M_H = 125.7 \pm 0.4$ GeV)

Fit of EW parameters (mostly at Z pole) by GFitter

- First time the SM is overconstrained at EW scale
- Biggest discrepancy between $A_{FB}^{0,\ell}$ (LEP) and A_ℓ (LSD)
- Significant prediction improvement (surpassed only for M_t)
 $M_W: 28 \rightarrow 11$ MeV; $\sin^2 \theta_W: (2.3 \rightarrow 1.0) 10^{-5}$, $M_t: 6.2 \rightarrow 2.5$ GeV
- $\sin^2 \theta_W$ and M_W uncertainty dominated by M_t and higher order EW corrections



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State of the art

Analysis at the LHC

M_W measurement

Conclusion

How to access $\sin^2\theta_W$

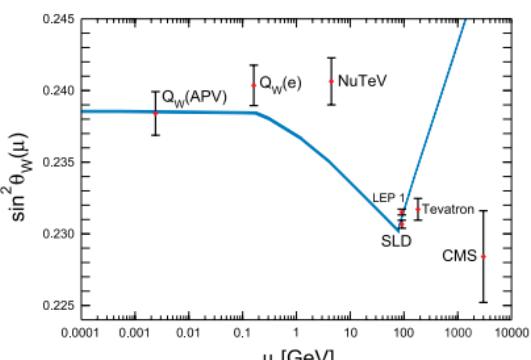
What is $\sin^2\theta_W$

Quantify γ/Z interference in $SU(2) \times U(1)_{\text{em}}$.

Many definition exist among which

- ▶ On-shell: $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$
- ▶ Effective: $\sin^2\theta_{\text{eff}}^{\ell} = 1/4(1 - \frac{g_V^{\ell}}{g_A^{\ell}})$ (LEP)
- ▶ Equivalent at tree-level (depend on other parameter with HO corrections)

	g_V	g_A
$\gamma \rightarrow ee, \mu\mu, \tau\tau$	-1	0
$\gamma \rightarrow u\bar{u}, c\bar{c}, t\bar{t}$	+2/3	0
$\gamma \rightarrow d\bar{d}, s\bar{s}, b\bar{b}$	-1/3	0
$Z \rightarrow ee, \mu\mu, \tau\tau$	$\frac{-3+12\sin^2\theta_W}{6\sin(2\theta_W)}$	$\frac{-1}{2\sin(2\theta_W)}$
$Z \rightarrow u\bar{u}, c\bar{c}, t\bar{t}$	$\frac{+3-8\sin^2\theta_W}{6\sin(2\theta_W)}$	$\frac{+1}{2\sin(2\theta_W)}$
$Z \rightarrow d\bar{d}, s\bar{s}, b\bar{b}$	$\frac{-3+4\sin^2\theta_W}{6\sin(2\theta_W)}$	$\frac{-1}{2\sin(2\theta_W)}$



Measurement of $\sin^2\theta_W$

Can be performed at low energy...

- ▶ ν -DIS experiment ($R^- = \frac{\sigma_{\nu}^{\text{NC}} - \sigma_{\bar{\nu}}^{\text{NC}}}{\sigma_{\nu}^{\text{CC}} - \sigma_{\bar{\nu}}^{\text{CC}}}$)
- ▶ Parity violation (e -deuteron DIS): left-right asymmetry
- ... and at colliders, with asymmetries (forward-backward, left-right...)

Measurement at the LHC

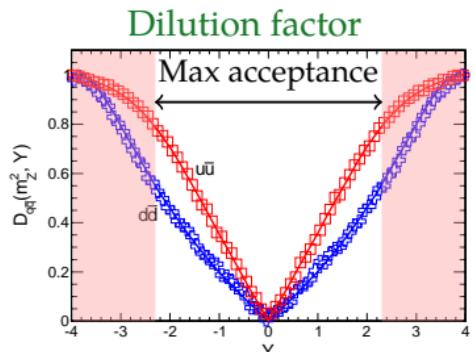
LHC collision conditions

g_A and g_V interference leads to asymmetry in polar angle w.r.t quark ($q\bar{q} \rightarrow Z$)
 → pp collision: where does the quark come from ?

$\sin^2\theta_W$ measurement by CMS (1.1fb $^{-1}$)

Use $\mu\mu$ boost (valence q more momentum than \bar{q})

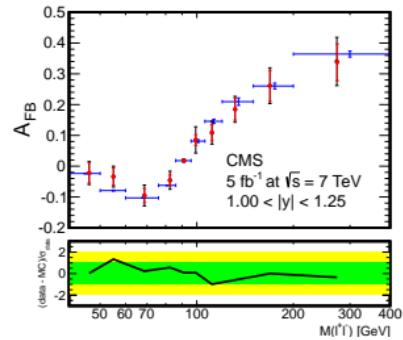
- ▶ Dilution: probability of that being true
- ▶ Make θ^* distribution in CS frame
- ▶ Extract $\sin^2\theta_{\text{eff}}^\ell$ from likelihood
- $\sin^2\theta_{\text{eff}}^\ell = 0.2287 \pm 0.0020 \pm 0.0025$



A_{FB} measurement by CMS using $ee/\mu\mu$ (5fb $^{-1}$)

Not focusing on Z mass, searching for NP

- ▶ 10 bins in $M_{\ell\ell}$ for $M_{\ell\ell} > 40$ GeV
- ▶ 4 bins in rapidity
- Results consistent with SM



Measurement at the LHC

LHC collision conditions

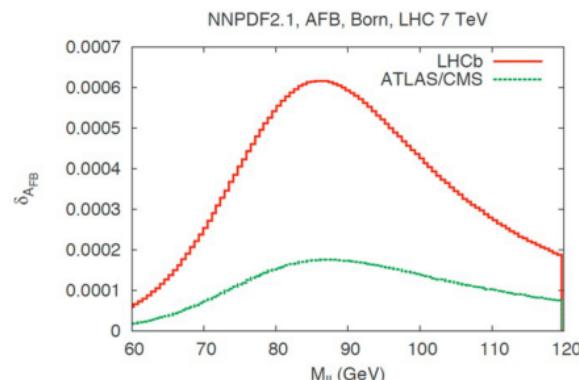
g_A and g_V interference leads to asymmetry in polar angle w.r.t quark ($q\bar{q} \rightarrow Z$)
→ pp collision: where does the quark come from ?

Possible improvements

- ▶ Using more statistics
- ▶ Looking at forward region (more sensitive)

Inputs from LHCb

- ▶ Bigger sensitivity to $\sin^2\theta_W$ variation than CMS/ATLAS
- ▶ Design for forward region (dilution factor is bigger there)



Precision reached at LEP ($\sim 2.10^{-4}$) would be difficult to reach at the LHC

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Principle at hadron colliders

Energy scale determination

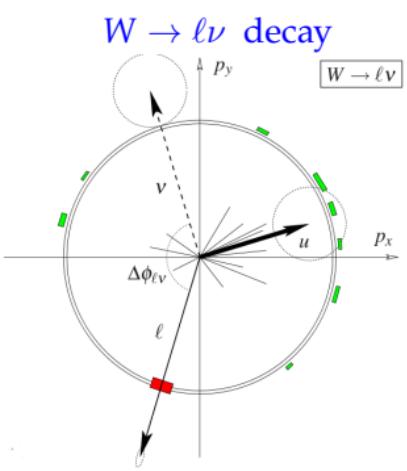
Impact of PDF uncertainties

W/Z transverse momentum

Polarisation study

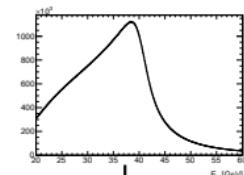
Conclusion

M_W measurement at hadron colliders



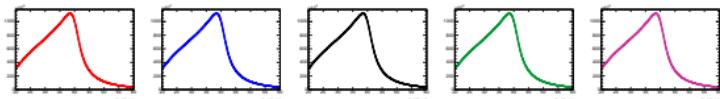
Variables used to perform the measurement:

$$p_T^\ell, M_T^W = \sqrt{p_T^\ell E_T(1 - \cos \phi_{\ell\nu})}, E_T$$



Data

χ^2 computations and minimisation



Difficult measurement that need understanding of many parameters

Theoretical

- ▶ W transverse momentum
- ▶ Lepton angular distribution
- ▶ Parton density function
- ▶ Higher order corrections

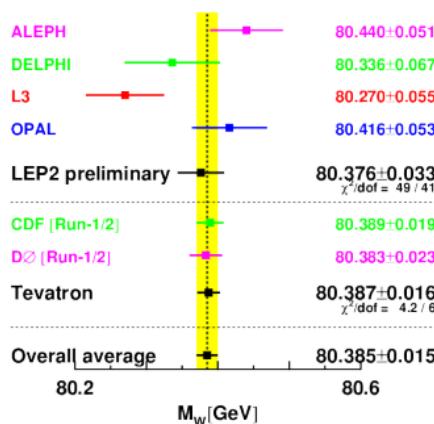
Environmental

- ▶ underlying event
- ▶ pile-up
- ▶ beam angle

Experimental

- ▶ Energy scale
- ▶ Resolution
- ▶ Reconstruction eff.

Status of the measurement



Measurement performed by every experiment

- ▶ Scanning the x-section wrt \sqrt{s} with WW (LEP)
- ▶ Using single-W events and template method at Tevatron

Focuse on Tevatron measurement:

- ▶ Using 4.3 fb^{-1} for D0 (e -only)
- ▶ Using 2.2 fb^{-1} for CDF (e/μ)

Systematic uncertainties are similar for both

→ Will discuss some of them in the following

TABLE II. Systematic uncertainties of the M_W measurement.

Source	$\Delta M_W (\text{MeV})$		
	m_T	p_T^e	\not{E}_T
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

D0 summary

Lepton energy scale and resolution

Importance of lepton scale and resolution

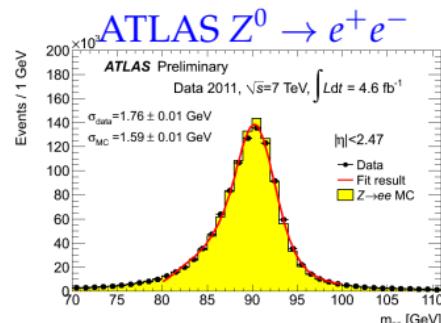
Biggest experimental systematic uncertainty.

→ Need very precise measurements (also for other analysis like Higgs decay)

Work ongoing:

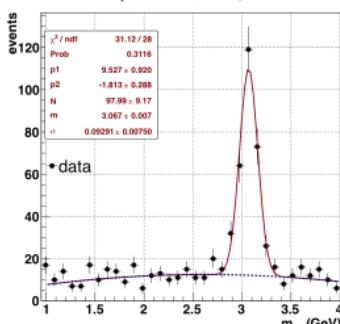
Studies ongoing using Z and J/ψ ($ee/\mu\mu$)

- ▶ Calibration measurement (vs η and p_T)
- ▶ Resolution measurement
- ▶ E/p measurements



CMS $J/\psi \rightarrow e^+e^-$

CMS Preliminary $(s = 8 \text{ TeV}, L = 19.6 \text{ fb}^{-1})$



Expected dependence:

Published scale have precision (0.2-1.5) % (2010).

One can expect significant improvement (~ 20 times)

- ▶ $\frac{\delta M_W}{\delta_{\text{rel}\alpha}} = 800 \text{ MeV} / \%$
- ▶ $\frac{\delta M_W}{\delta_{\text{rel}\sigma}} = 0.8 \text{ MeV} / \%$

Effect of PDF misknowledge

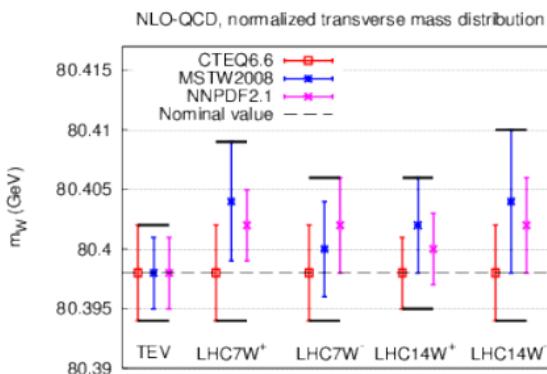
Possibility to have $\delta_{\text{PDF}} < 10 \text{ MeV}$ at LHC: MC study on M_T^W (truth level)

Born-level (HORACE) and NLO (DYNNLO) using CTEQ6.6, MSTW2008, NNPDF2.1

- ▶ Check the α_s dependence
- ▶ Investigate effect of quark masses
- ▶ Check consistency of one PDF set versus another

Conclusions:

- ▶ α_s uncertainty are negligible w.r.t PDF ones
- ▶ PDF sets agreed one to another (also from one collider to another)
- ▶ PDFs and related uncertainties (α_s , m_c) estimated smaller than 10 MeV



Improvement using LHC data

- ▶ W charge asymmetry
- ▶ W/Z differential x-section
- ▶ Strange quark PDF
- LHCb constrain forward regions

Strangeness of the proton

Increasing precision on strange density

- Flavour SU(3) suggests equal proportion in sea (u , d and s)
- Higher relevance than at Tevatron \Rightarrow central W^+ 30% (pp) / 10% ($p\bar{p}$)

Use HERA ep -DIS and ATLAS W/Z data (36pb^{-1})

Fit to determine $r_s = 0.5(s+\bar{s})/\bar{d}$ (~ 0.5 if s suppression)

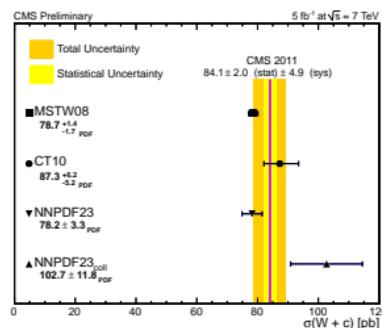
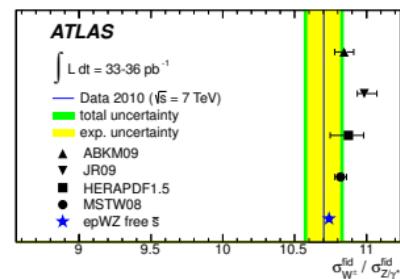
$\rightarrow r_s(0.013, M_Z^2)$ measurement is 1.00 ± 0.10

- \bar{u} and \bar{d} decreased by 10%
- total sea enhanced by 8%

$W + c$ x-section measurement, CMS (5fb^{-1})

Using e/μ in three decay-channels

- Displaced 2nd vertex with N tracks
 - $N=3, D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$
 - $N=2, D^0 \rightarrow K^- \pi^+$ from $D^* \rightarrow D^0 \pi^+$
 - Semileptonic decay of c into μ
- \rightarrow Inclusive and differential x-section measured

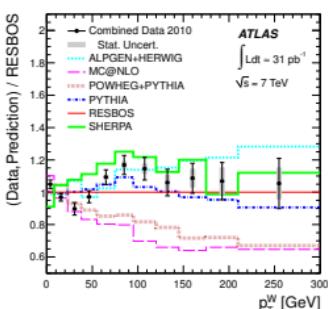
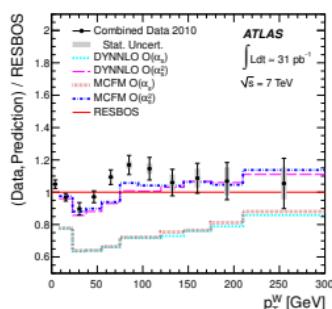


Data and measurements to be used by PDF groups

W/Z transverse momentum

Test multiple models of QCD predictions

- ▶ Low p_T (region of interest for M_W): soft/collinear partons.
- ⇒ Logarithmic resummations up to NNLL in RESBOS
- ⇒ PS (PYTHIA, HERWIG) iterative splitting and radiation of parton
- ⇒ ME+PS (MC@NLO, POWHEG), with ME $O(\alpha_s)$



Overall p_T^W range

Agreement within 20 % of

- ▶ RESBOS
- ▶ ALPGEN
- ▶ PYTHIA
- ▶ SHERPA

Improving these analysis using 2011 data

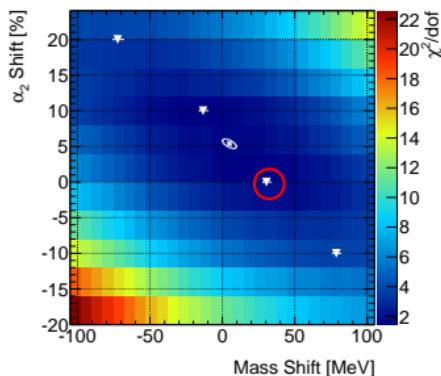
Lots of work to be done (keeping in mind that $\frac{\delta M_W}{\delta \text{rel } p_T^W} = 0.3 \text{ MeV}/\%$)

- ▶ Estimate/constrain pile-up effect
- ▶ Use $Z \phi^*$ to improve the description (see V. Lombardo's talk)
- ▶ Investigate effect of quark b difference between W/Z
- ▶ Expect improvement on precision by 1 order of magnitude

Polarisation effect on M_W measurement at the LHC

MC analysis: variation of α_2 when $d\sigma/d\cos\theta = 1 + \alpha_1 \cos\theta + \alpha_2 \cos^2\theta$

→ Produce templates that depends on (ΔM_W , $\Delta \alpha_2$)



χ^2 distribution example

Signal made with (ΔM_W , $\Delta \alpha_2$) = (0 MeV, 5 %)

Results of 1D template fits:

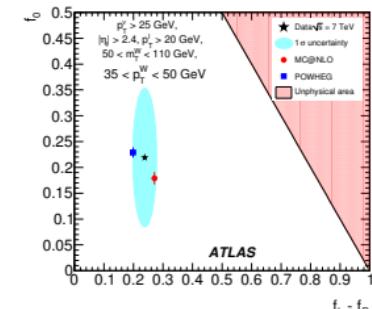
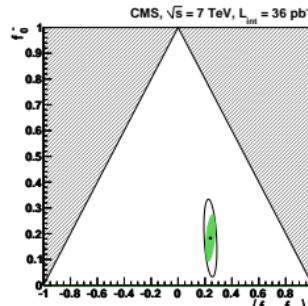
Only mass templates $\Leftrightarrow \Delta \alpha_2$ constant (▼)

→ $\Delta \alpha_2 = 0 \Rightarrow \Delta M_W \sim 25 - 30$ MeV (○)

→ No effect claimed by Tevatron experiments

First measurement performed by CMS and ATLAS (2010 data)

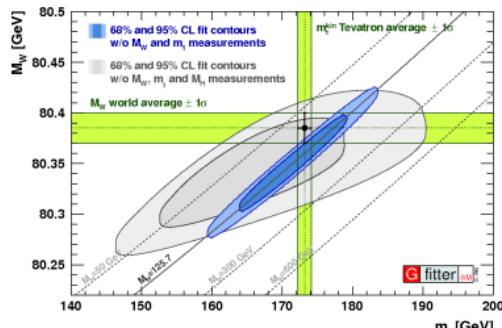
To be redone with 2011



Summary and conclusion

EW precision measurements: are they still useful ?

- ▶ Check the validity of SM
- ▶ Check the performance of the detector used
- ▶ Help preparing future precision measurements on new particle
- ▶ Can be used to detect possible new physics contributions



Many other things to work on

- ▶ Pile-up effect reduction
- ▶ Monte-Carlo tune on LHC results
- ▶ Fast-simulation tests and validations
- ▶ All the previous studies (and many others) to be redone/redefine
- Room for everyone to have original contribution 

Thank you for your attention !

References

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- s5: Eur.Phys.J. C72 (2012) 2205
- s7: PDG 2012
- s8: Phys.Rev. D84 (2011) 112002 ($\sin^2\theta_W$), Phys.Rev. D84 (2011) 112002 (A_{FB})
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- s17: PhD thesis: <https://cdsweb.cern.ch/record/1393392>, Phys.Rev.Lett. 107 (2011) 021802 (CMS), EPJC Volume 72, Number 5 (2012) (ATLAS)
- s18: Eur.Phys.J. C72 (2012) 2205