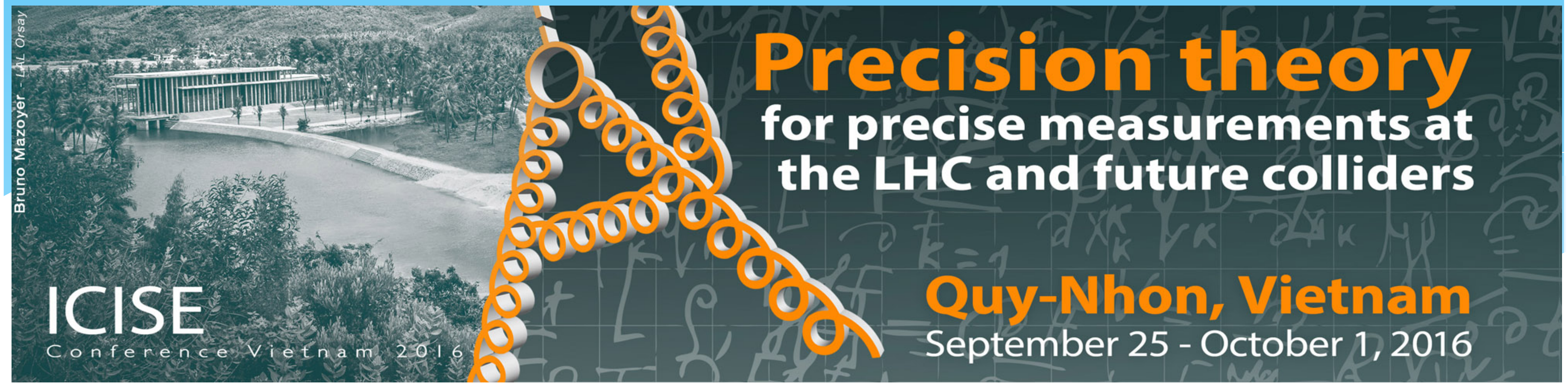
Experimental Status of EW physics

Paolo Azzurri – INFN Pisa

Quy-Nhon September 28, 2016

RENCONTRES DU VIETNAM

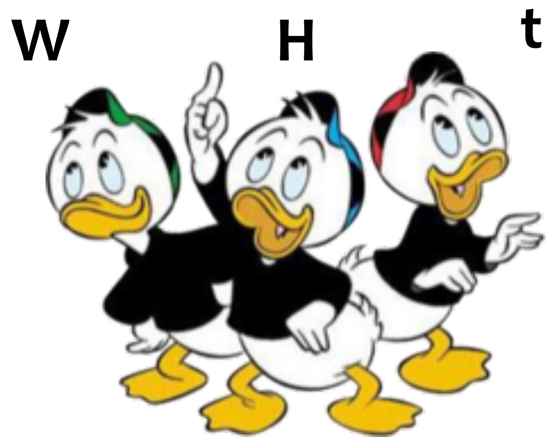


Outline

a biased and incomplete review

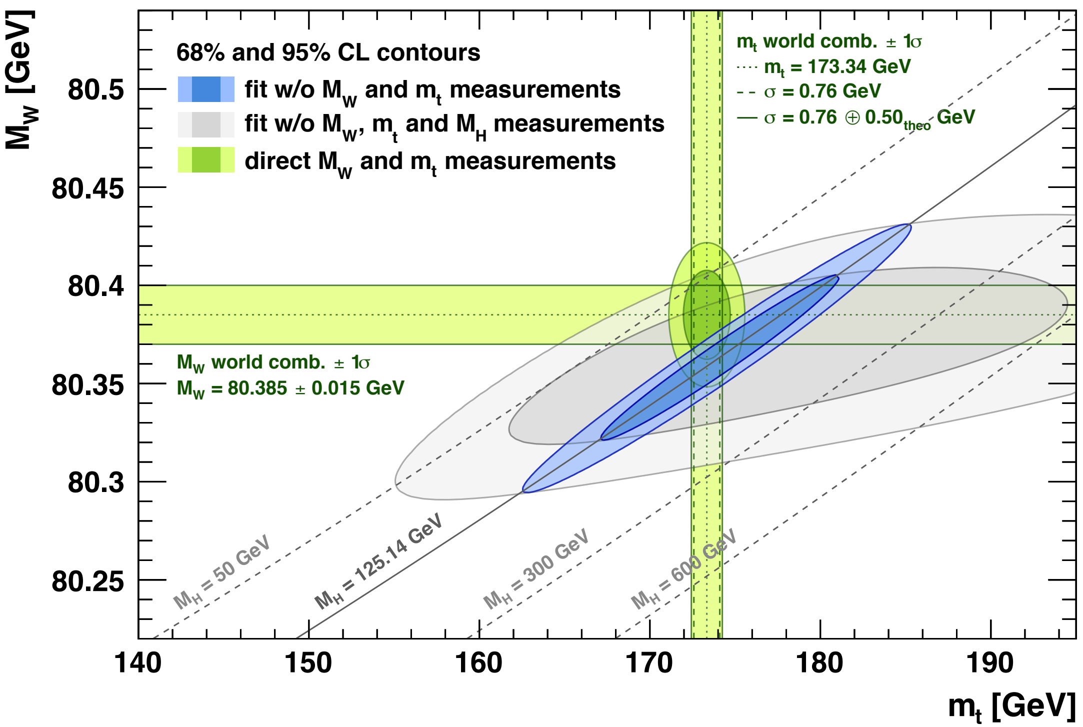
of EW measurements <u>and prospects</u>

* focus on mass (& width) of W, Higgs boson and top quark
* and their couplings



* apologies for overlaps with other presentations
* not covering $\sin^2\theta_W$

the W,t,H masses & the EW fit



Indirect determinations

$M_t = 177.0^{+2.3}_{-2.5}$ GeV

$M_H = 93^{+25}_{-21}$ GeV

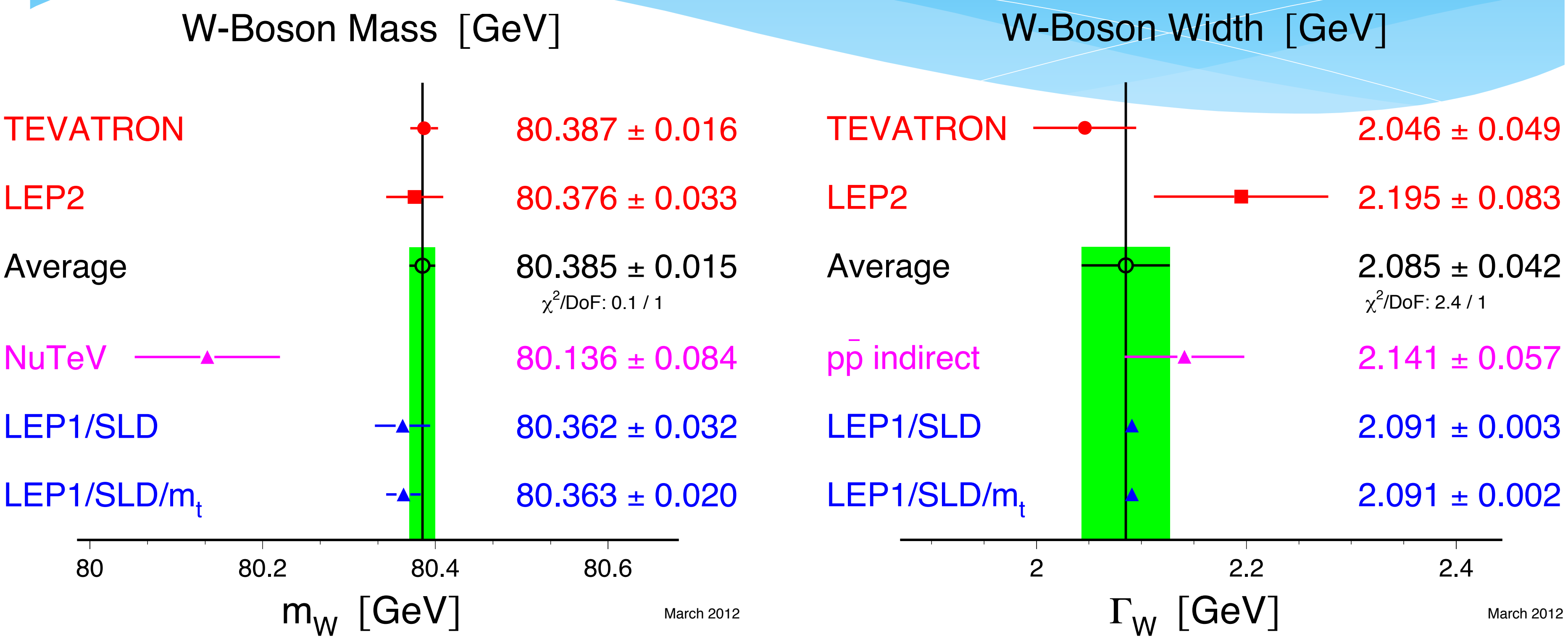
$M_W = 80358 \pm 8$ MeV

the ball is in the W court

➔ **Thomas Peiffer (Mon 11:00)** Eur . Phys. J. C **74,** 3046 (2014)

mass of the W boson

mass & width of the W boson

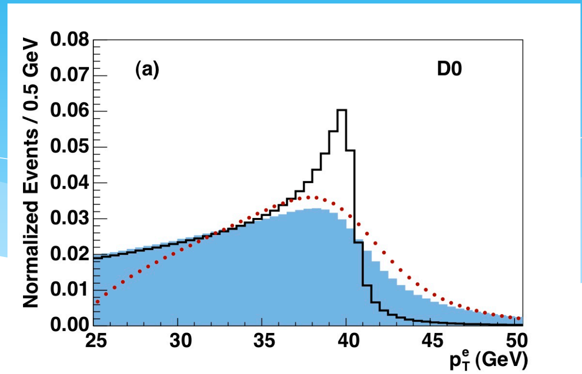


mass of the W boson : Tevatron

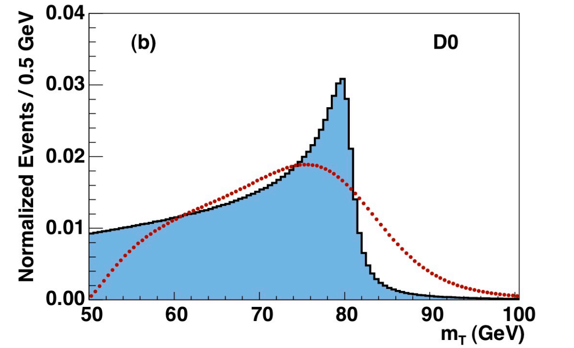
➔ Young Do Oh (Mon 13:30)

CDF 2.2/fb Phys. Rev. D 89, 072003 (2014)
~1M $W \rightarrow e\nu / \mu\nu$ decays
M_W = 80 387 ± 12(stat) ± **15**(syst) = 80 387 ± 19 MeV
fit of m_T, p^l_T, and p^ν_T MC templates

D0 4.3/fb: Phys. Rev. D **89**, 012005
~1.7 M $W \rightarrow e\nu$ decays
M_W=80 367±13(stat)±**22**(syst) MeV=80367±26 MeV



$p^W{}_T$=0 $+p^W{}_T$ +det



- **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

mass of the W boson : Tevatron uncertainties

CDF

TABLE XIV: Uncertainties in units of MeV on the final combined result on M_W.

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	19

Do

TABLE VI. Systematic uncertainties on M_W (in MeV). The section of this paper where each uncertainty is discussed is given in the table.

Source	Section	m_T	p_T^e	E_T
Experimental				
Electron energy scale	VIIC4	16	17	16
Electron energy resolution	VIIC5	2	2	3
Electron shower model	VC	4	6	7
Electron energy loss	VD	4	4	4
Recoil model	VIID3	5	6	14
Electron efficiencies	VIIB10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$ (Experimental)		18	20	24
W production and decay model				
PDF	VIC	11	11	14
QED	VIB	7	7	9
Boson p_T	VIA	2	5	2
$\sum$ (Model)		13	14	17
Systematic uncertainty (experimental and model)		22	24	29
W boson statistics	IX	13	14	15
Total uncertainty		26	28	33

Experimental

Modeling

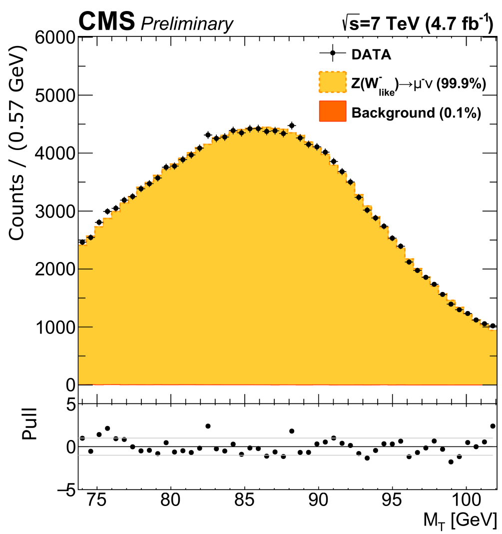
δstat ~ δexp ~ δtheo

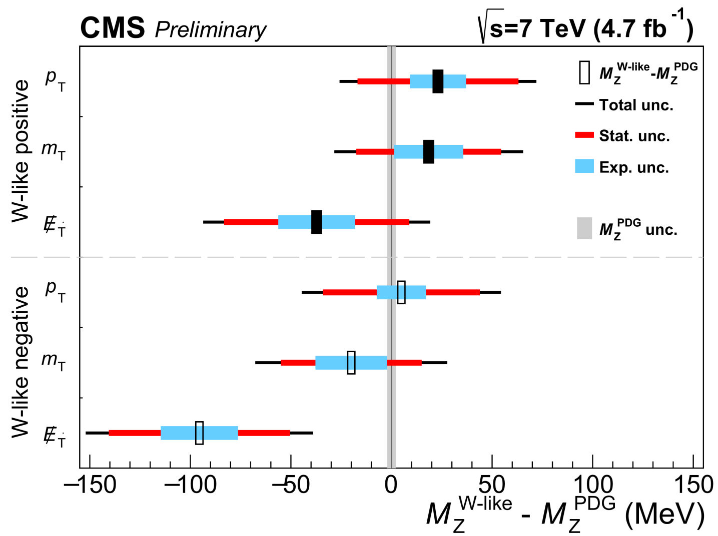
mass of the W boson : LHC

ATLAS/CMS Run1 (~10M W events) : Δm_W (stat) < 5 MeV

- Large coverage & calibration with $Z \rightarrow \mu\mu/ee$ (~1-2 M)
- hadronic recoil resolution and calibration with pileup
- Different energy, larger theoretical uncertainties
- W_+ and W_- asymmetric charge-dependences

CMS Z mass measurement in "W like" $Z \rightarrow \mu\mu$





proof of principle **CMS PAS SMP-14-007**

mass of the W boson : LHC

Sources of uncertainty	$M_Z^{\mathrm{W\,like}+}$ p_T	$M_Z^{\mathrm{W\,like}+}$ m_T	$M_Z^{\mathrm{W\,like}+}$ $\not{E}_T$	$M_Z^{\mathrm{W\,like}-}$ p_T	$M_Z^{\mathrm{W\,like}-}$ m_T	$M_Z^{\mathrm{W\,like}-}$ $\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

CMS PAS SMP-14-007

δstat < δexp < δtheo

precision theory needed :
➔ Fulvio Piccinini Tue 10:00
➔ see also next talks
Stefano Di Vita, Alessandro Vicini

missing syst: PDFs in W production, Z → W extrapolation , Background

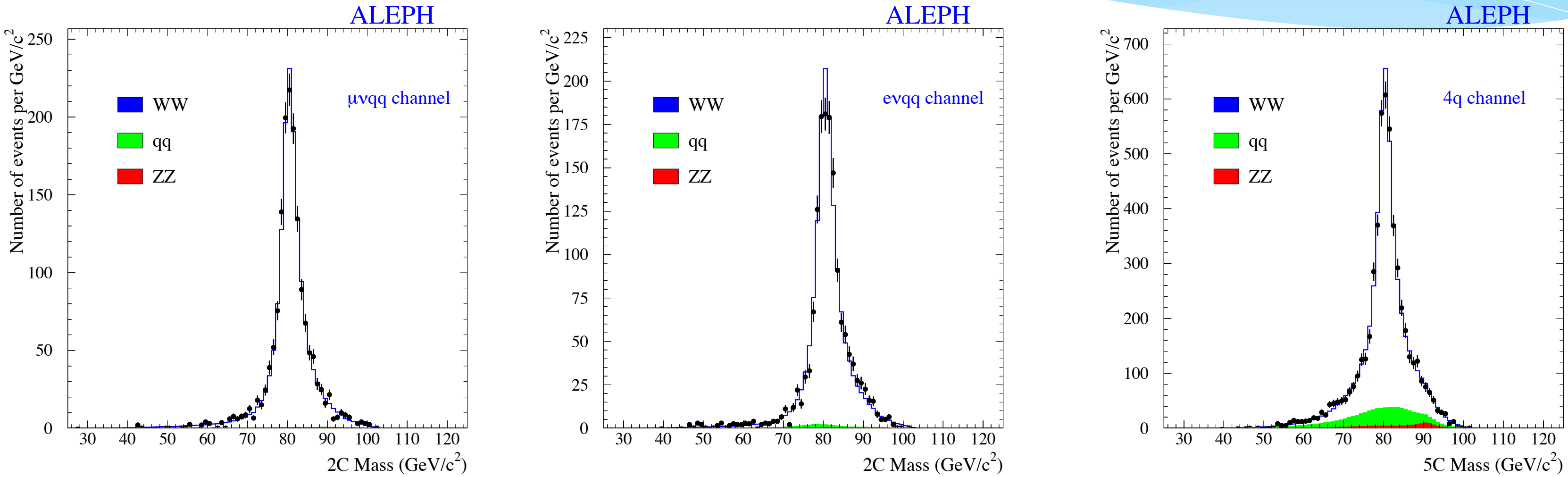
ATL-PHYS-PUB-2014-015
detailed study of theoretical uncertainties
quark PDF / low W pT (polarization)

aiming to achieve Δm_W (syst) ≈ 10 MeV : currently ~30-→ 20 MeV (-QED)

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

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

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



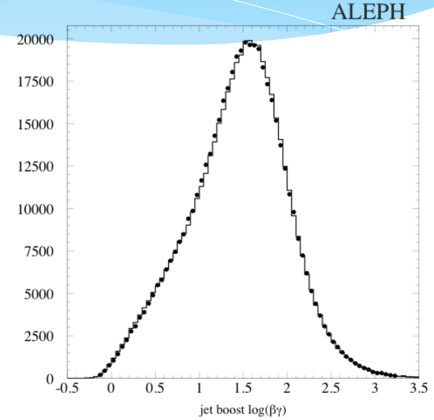
ALEPH Eur.Phys.J.C47:309 (2006) : 683 /pb ~10k WW events
ignoring low energy particles in the qqqq channel
m_W = 80440±43(stat.)±24(syst.)±9(FSI)±9(LEP) MeV
Γ_W = 2140 ±90(stat.) ±45(syst.) ±46(FSI) ± 7(LEP) MeV

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

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

jet boost



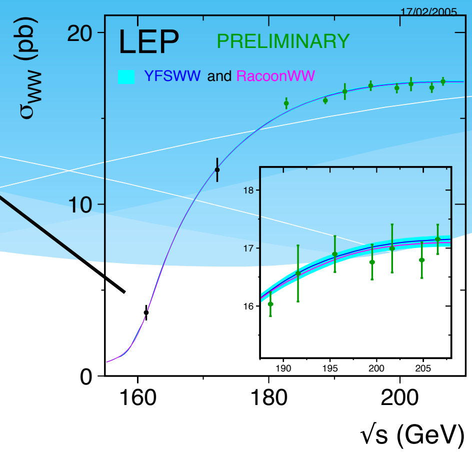
lepton and jet uncertainties from (Z) calibration data

FCC ee 1/ab@240GeV ➔ 10M W-pairs ➔ Δm_W (stat)= 1-2 MeV
➔ Δm_W (syst) < 5 MeV ?
Similar prospects for ILC 1/ab @500GeV

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

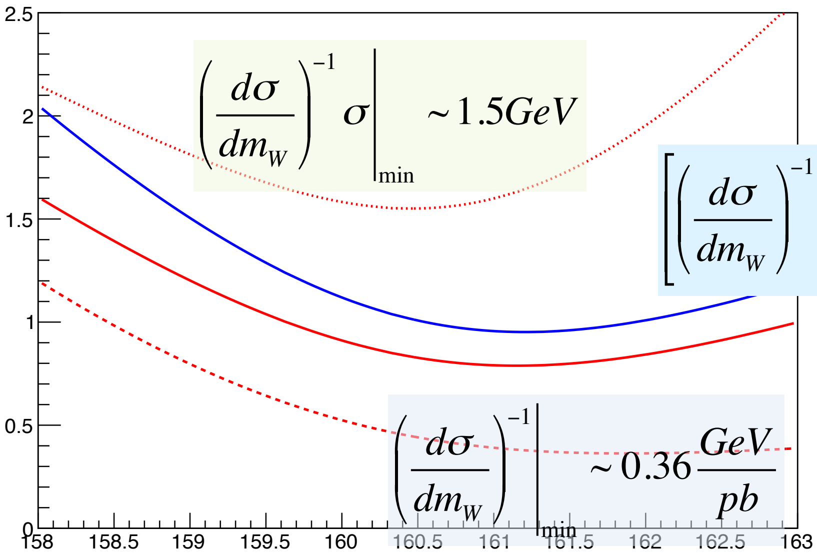
$$m_W = \sigma^{-1}(E)$$

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



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

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



$$\left(\frac{d\sigma}{dm_W}\right)^{-1} \sigma \Bigg|_{min} \sim 1.5 GeV$$

$$\left(\frac{d\sigma}{dm_W}\right)^{-1} \Bigg|_{min} \sim 0.36 \frac{GeV}{pb}$$

ε=0.75 and σ_B=0.3pb

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{min} \approx 0.95 \frac{GeV}{pb^{1/2}}$$

Max stat sensitivity at √s~2m_W+400MeV

FCCee : 4x4/ab ➔ Δm_W(stat)= 0.25 MeV

ILC 0.1-0.4/ab ➔ Δm_W(stat)= 2 MeV
(with polarisation)

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

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \le \frac{1}{2}\Delta E$$

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

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

Δmw≈0.25 MeV would require

ΔE(beam)<0.25 MeV (3x10-6)

Δε/ε, ΔL/L < 10-4

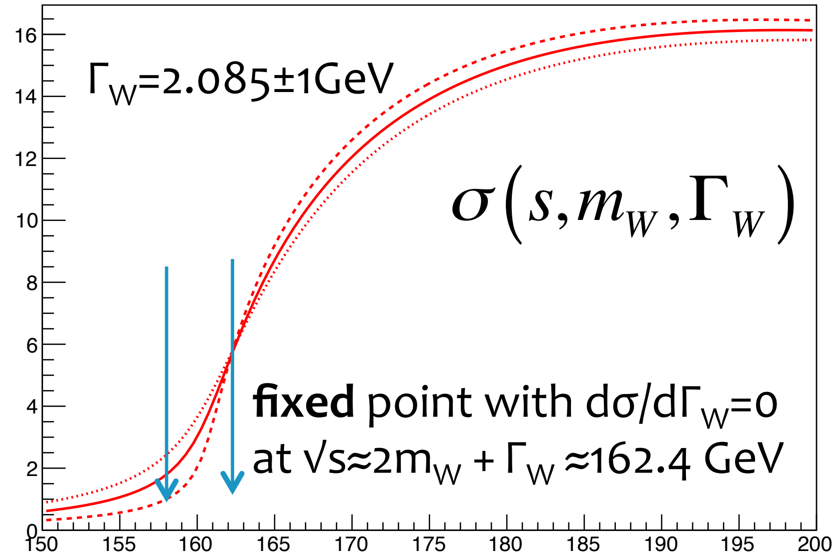
$\Delta\sigma_B$<0.5 fb (10-3)

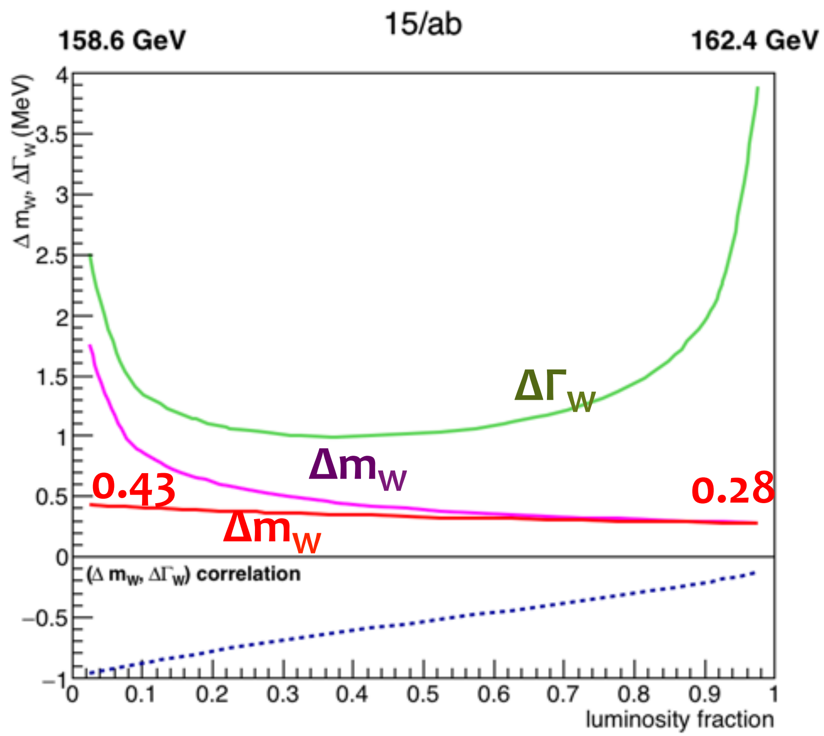
Taking data at different E_{CM} points around $2m_W$ will be necessary to constrain systematic uncertainties

Polarization (ILC) can be used to constrain B at a given E_{CM}
arXiv:1603.06016

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

m_W=80.385 GeV



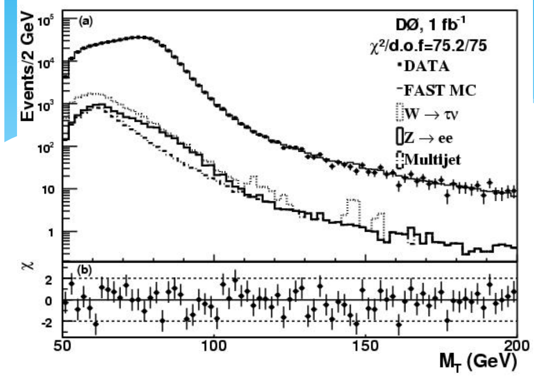


example strategy
take 60% data at $\sqrt{s} \approx 2m_W + \Gamma_W$ (fixed point)
and 40% at lower $\sqrt{s} \approx 2m_W - \Gamma_W$

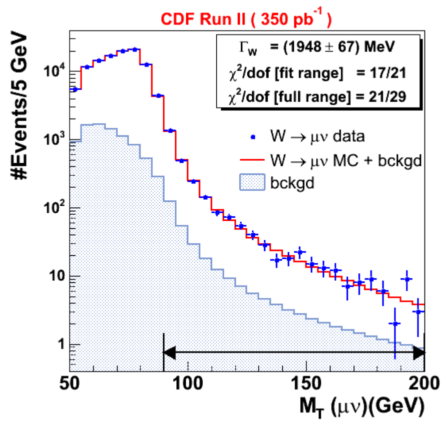
sensitivity to TGC interference ~β^2_W

➔ extract width with **$\Delta\Gamma_W \approx$0.9 MeV** ➔ **$\Delta\alpha_S$**
with limited loss in Δm_W=0.25→0.37 MeV

Width of the W boson : Tevatron



D0: 100<MT<200 GeV



	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	-
Simulation	13	-	-
Recoil	54	49	-
Lepton ID	10	7	-
Backgrounds	32	33	-
$p_T(W)$	7	7	7
PDF	20	20	20
QED	10	6	6
W mass	9	9	9
Total systematic	79	71	27
Statistical	60	67	-
Total	99	98	27

CDF 350/pb: Phys.Rev.Lett.100:071801,2008
Γ_W = 2032 ± 45stat ± 57syst MeV

TABLE I. Systematic uncertainties on the measurement of Γ_W.

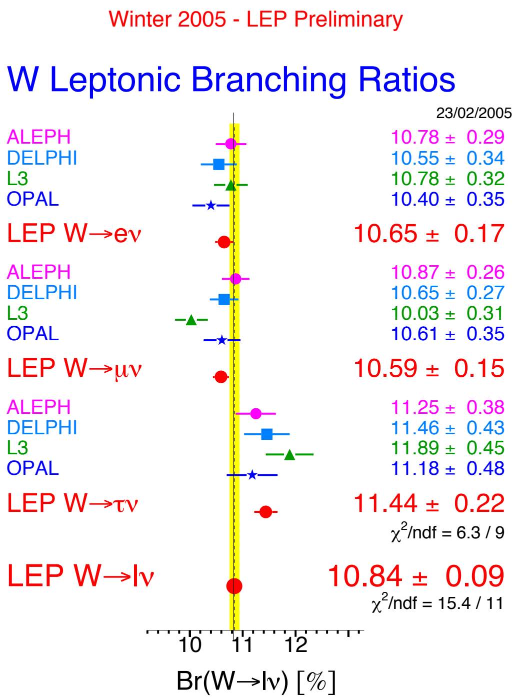
Source	$\Delta\Gamma_W$ (MeV)
Electron response model	33
Electron resolution model	10
Hadronic recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

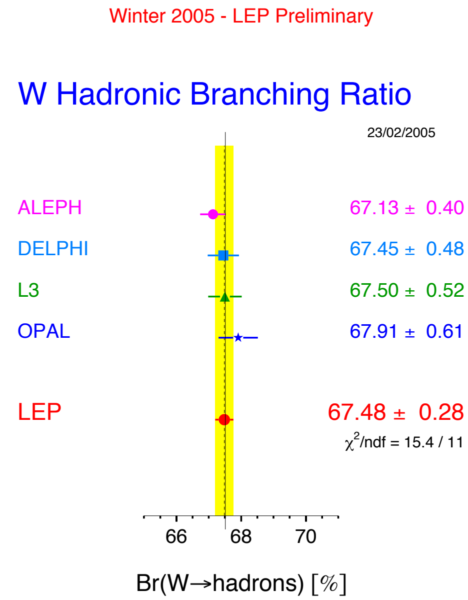
D0 1/fb : PRL 103, 231802 (2009)
Γ_W =2028 ± 39(stat) ± 61(syst) MeV

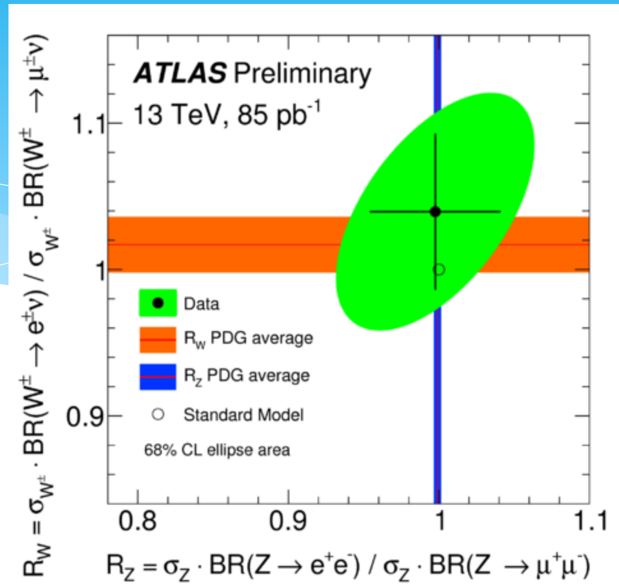
combined : **arXiv:1003.2826**
Γ_W = 2046 ±49 MeV.

W and EWK couplings

W decay couplings







test W universality with LHC data

q/ l universality at 0.6%

difficult for single W→τν

Lept universality test at 1% level

tau BR ~3 σ larger than e/mu

use LHC ditop decays : ATLAS

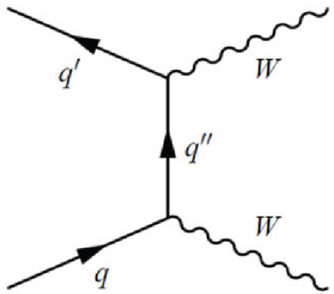
	Measured (top quark)	SM	LEP (W)
$\sigma_{t\bar{t}}$	178 ± 3 (stat.) ± 16 (syst.) ± 3 (lumi.) pb	$177.3 \pm 9.0^{+4.6}_{-6.0}$ pb	
B_j	66.5 ± 0.4 (stat.) ± 1.3 (syst.)	67.51±0.07	67.48±0.28
B_e	13.3 ± 0.4 (stat.) ± 0.5 (syst.)	12.72±0.01	12.70±0.20
B_μ	13.4 ± 0.3 (stat.) ± 0.5 (syst.)	12.72±0.01	12.60±0.18
B_τ	7.0 ± 0.3 (stat.) ± 0.5 (syst.)	7.05±0.01	7.20±0.13

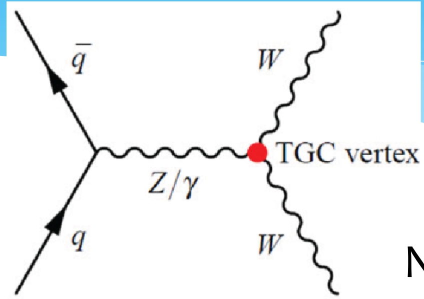
Phys. Rev. D 92, 072005 (2015)

W/Z/γ gauge couplings

diboson rates and kin distributions

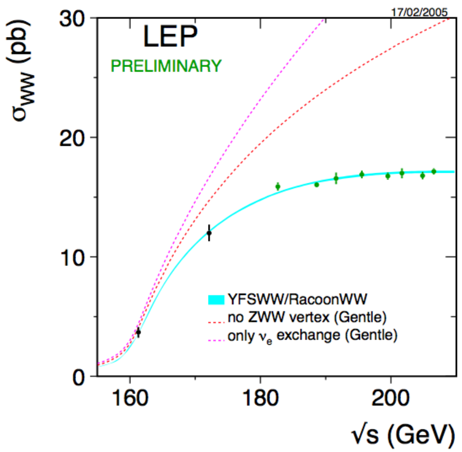
electroweak model signatures



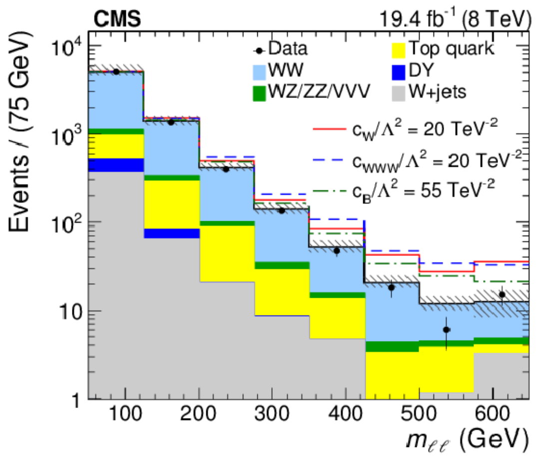


WW, WZ,ZZ,Wγ,Zγ,WWγ,WZγ,jjWW

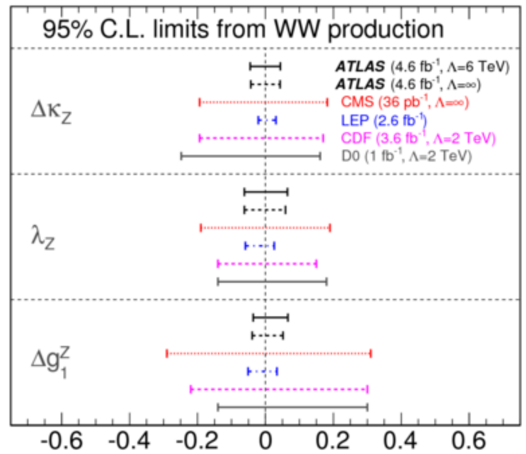
Negative interferences between t-channel and s-channel (TGC) productions [gauge cancellations]



pp→WW arXiv.1507.03268



Phys. Rev. D 87, 112001



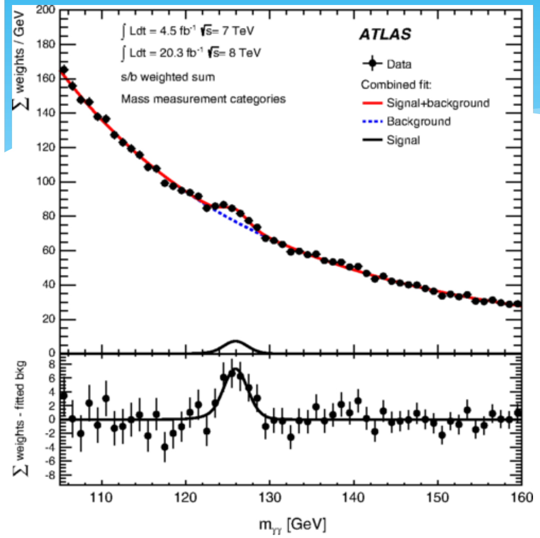
looking forward to 13 TeV results with large lumi !

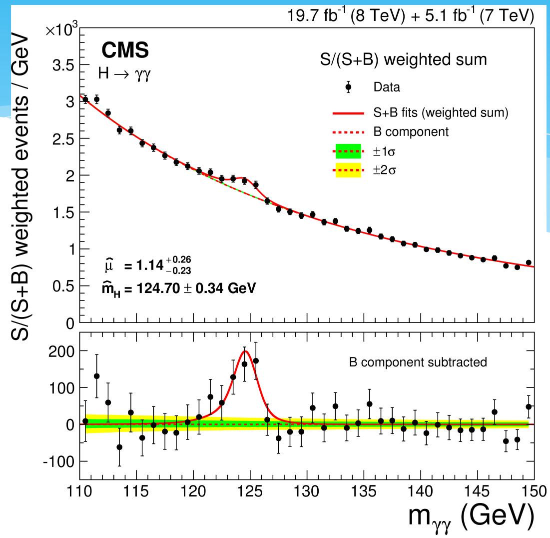
➔ Shu Li Mon 14:30

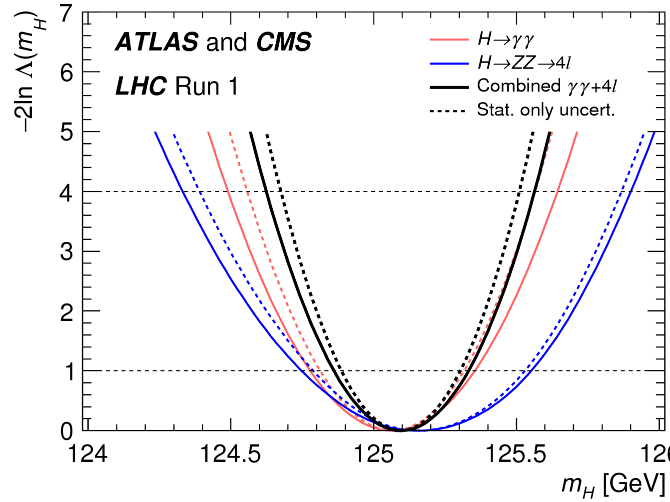
mass of the Higgs boson

➔Remi Lafaye Thu 14:15

mass of the Higgs boson







ATLAS m_H=125.36±0.37(stat)±0.18(syst) GeV

Phys. Rev. D 90 (2014) 052004

CMS m_H= $125.02^{+0.26}_{-0.27}$(stat)$^{+0.14}_{-0.15}$(syst) GeV

Eur.Phys.J.C 75 (2015) 212

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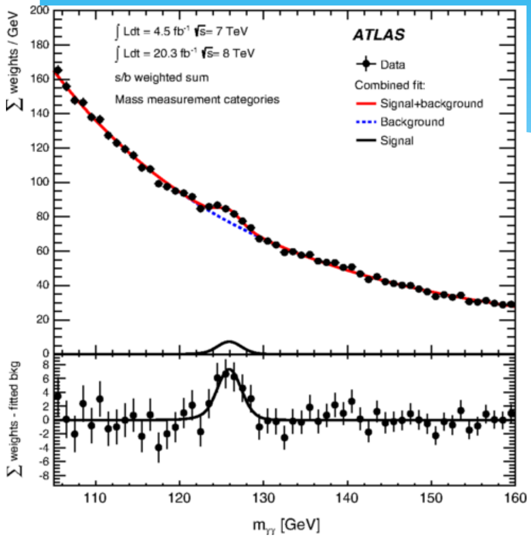
m_H=125.09±0.21(stat.)±0.11(syst.) GeV **0.2% precision**

Phys.Rev.Lett.114 (2015) 191803

mass of the Higgs boson

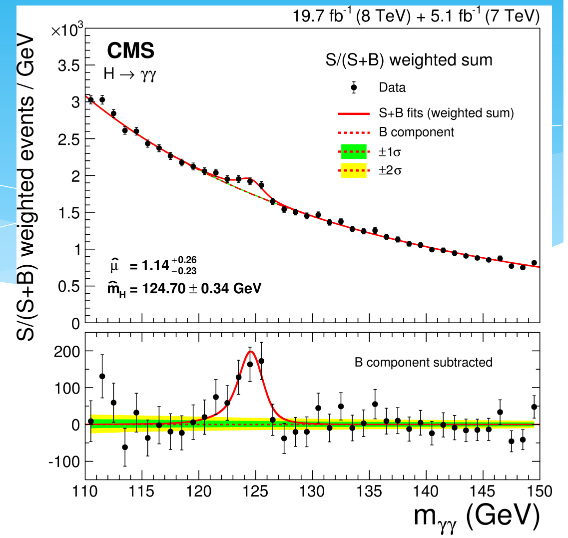


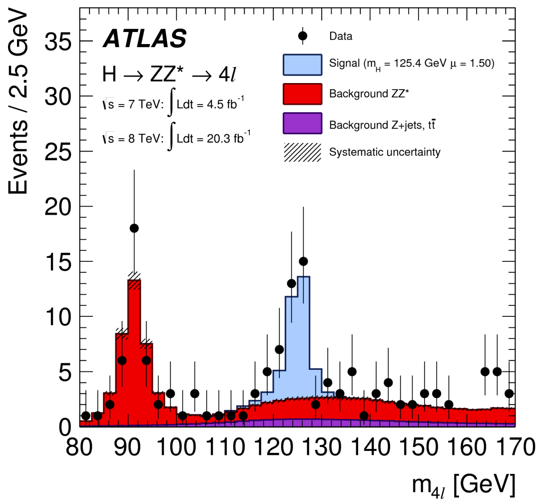
CMS EPJC 74 (2014) 3076

124.70±0.31(stat)±**0.15**(syst) GeV

ATLAS PRD 90, 052004 (2014)

125.98±0.42(stat)±**0.28**(syst) GeV



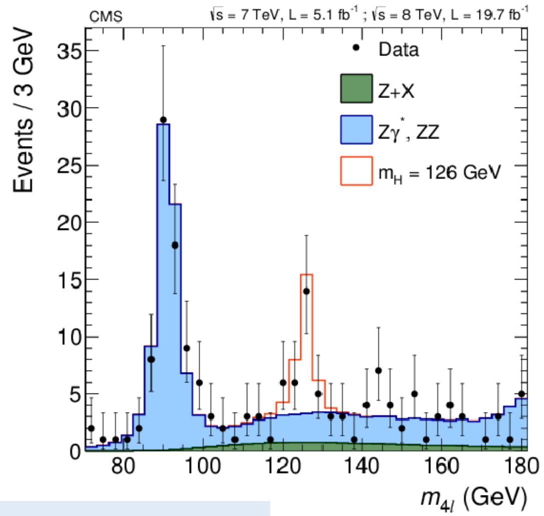


CMS PRD 89, 092007 (2014)

125.59±0.42(stat)±**0.17**(syst) GeV

ATLAS PRD 90, 052004 (2014)

124.51±0.52(stat)±**0.06**(syst) GeV

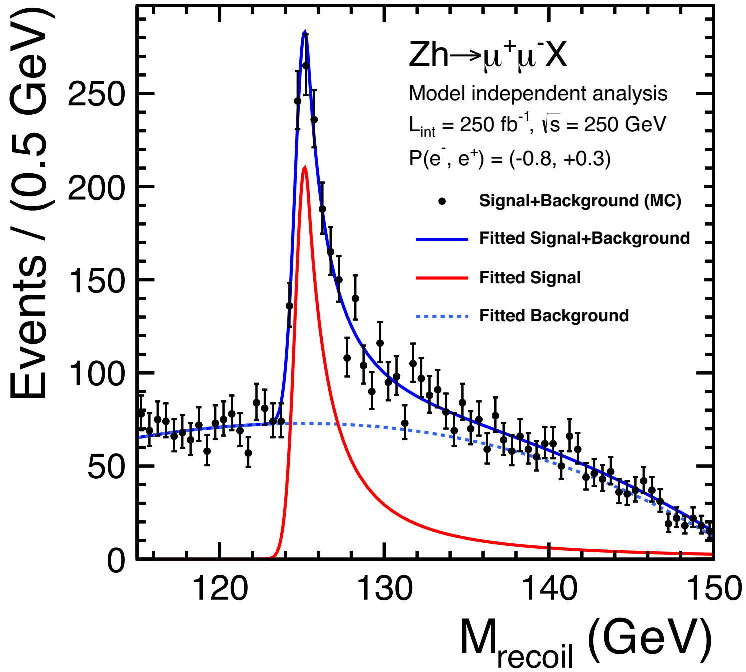


➔Remi Lafaye Thu 14:15

mass of the Higgs boson: future

➔ Thu 15:40-17:00
Adrian Perieanu, Oana Vickey Boeriu
➔ Ioannis Nomidis Fri 10:30

LHC :
Δm_H precision 0.2% ➔ 5 10^{-4}
(250→100→50 MeV) with
300-3000/fb



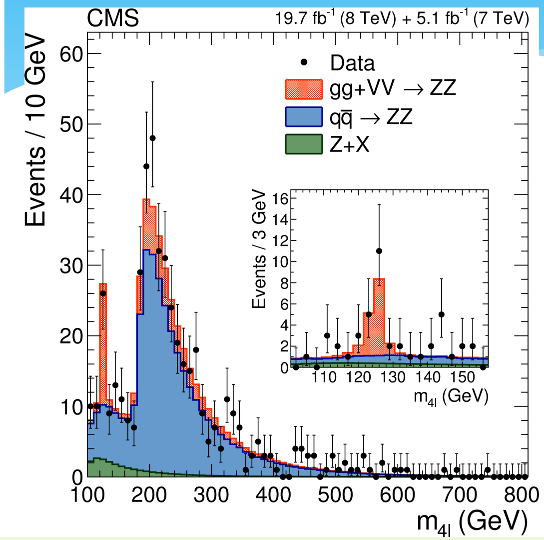
e+e- ILC TDR Vol2
fit of recoil mass distribution
in ZH→μμX

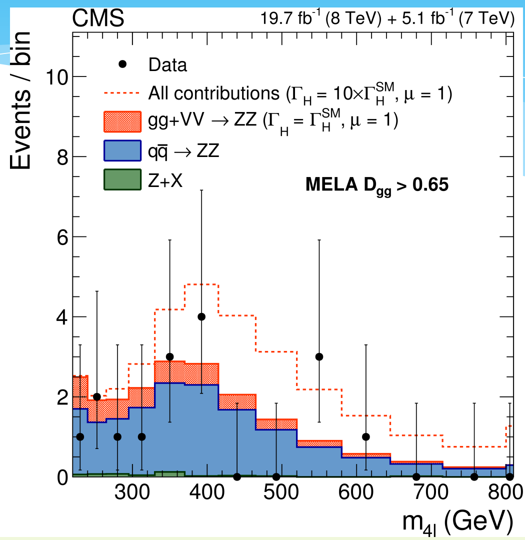
Δm_H precision 30 MeV
with 250/fb @240 GeV (ILC)

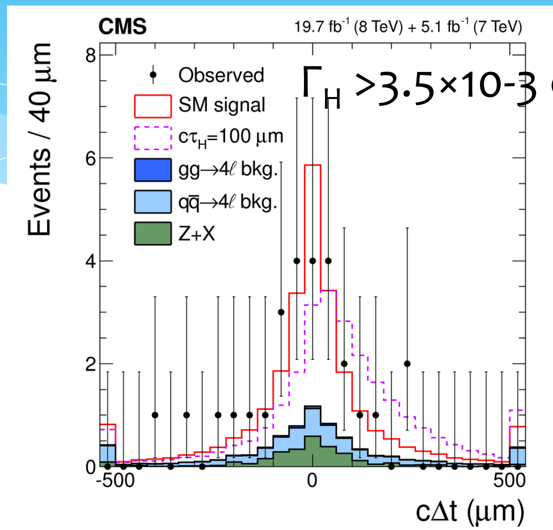
Δm_H precision 5 MeV [**arXiv:1411.5606**]
with 5/ab @240 GeV (FCCee/CEPC)

width of the Higgs boson

SM prediction at m_H=125 GeV is Γ_H=4.1 MeV







$\Gamma_H > 3.5\times 10^{-3}$ eV

Run1 LHC Higgs boson width from off-shell production in the ZZ decay mode
Γ_H<20 MeV @95%CL (interpretation with some model dependence)
precision could scale ~statistically to $\Delta\Gamma_H$=2 MeV (300/fb)

→Raoul Rontsch
Thu 16:55

<u>In e+e- :</u>
Total inclusive ee→ZH cross section and BR(H→ZZ) can be combined to establish Γ_H with precisions of 6%(ILC)-3%(FCCee)

$\Gamma_H=\Gamma(H\to ZZ)/BR(H\to ZZ)$
$\Gamma(H\to ZZ)$ from σ_{HZ}

mass of the top quark

Mon 13:30-16:00
Young Do Oh, Cecile Deterre, Markus Seidel
Reinhild Peters, Jie Yu, Hiroshi Yokoya

➔ Thu 8:30
Andre Hoang

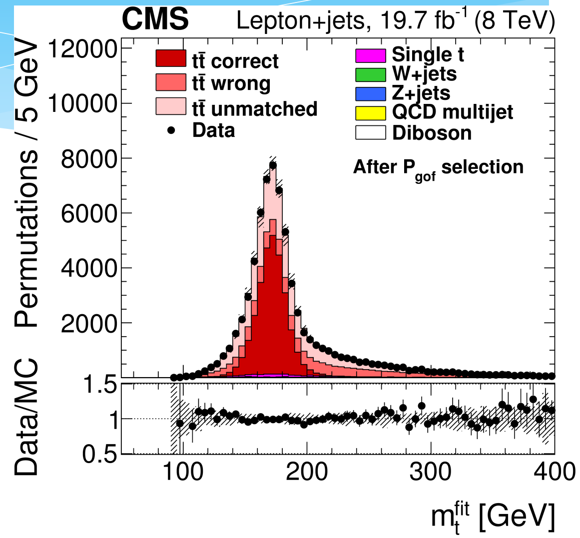
Top quark mass : LHC

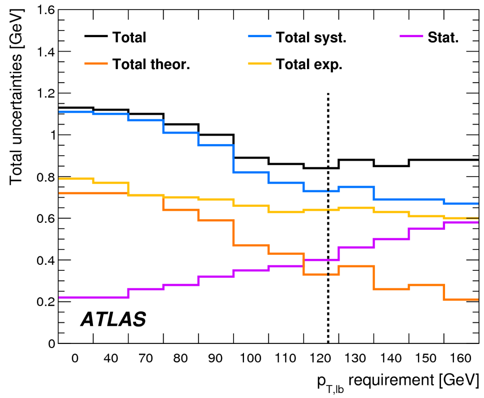
CMS l+jets systs

Combined m_t result	δm_t(GeV)
Experimental uncertainties	
Method calibration	0.03
Jet energy corrections	
– JEC: Intercalibration	0.01
– JEC: In situ calibration	0.12
– JEC: Uncorrelated non-pileup	0.10
Lepton energy scale	0.01
E_T^{miss} scale	0.03
Jet energy resolution	0.03
b tagging	0.05
Pileup	0.06
Backgrounds	0.04
Trigger	<0.01
Modeling of hadronization	
JEC: Flavor	0.33
b jet modeling	0.14
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	0.10
ME-PS matching threshold	0.08
ME generator	0.11
Top quark p_T	0.02
Modeling of soft QCD	
Underlying event	0.11
Color reconnection modeling	0.10
Total systematic	0.47
Statistical	0.13
Total Uncertainty	0.48

theo definition depends on renormalisation scheme
need to relate it to the experimental (MC)

CMS Run1 : **PRD 93(2016)2004**
172.44±0.13(stat)±0.47 (syst) GeV



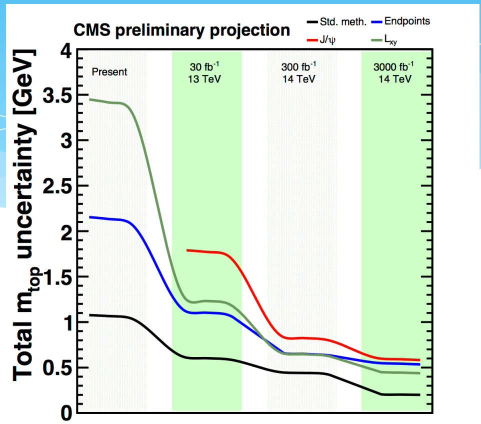


ATLASRun1: **Phys. Lett. B761 (2016) 350**
m_t=172.84±0.34(stat)±0.61(syst) GeV
(missing l+jets with 8TeV data)

Top quark mass: LHC future

CMS-PAS-FTR-13-017

	Current	Future			Comment
Center-of-mass energy	7 TeV l+jets	13 TeV	14 TeV	14 TeV	
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
Fit calibration	0.06	0.03	0.03	0.03	MC statistics
b-JES	0.61	0.27	0.09	0.03	3D fit
Residual JES	0.28	0.28	*0.2*	*0.06*	*differential*
Lepton energy scale	0.02	0.02	0.02	0.02	unchanged
Missing transverse momentum	0.06	0.06	0.06	0.06	unchanged
Jet energy resolution	0.23	0.23	*0.2*	*0.06*	*differential*
b tagging	0.12	0.06	0.06	0.06	factor 2 (data)
Pileup	0.07	0.07	0.07	0.07	unchanged
Non-$t\bar{t}$ background	0.13	0.06	0.06	0.06	factor 2 (S/B)
Parton distribution functions	0.07	0.04	0.04	0.04	factor 2 (PDF fits)
Renormalization and factorization scales	0.24	0.12	0.12	*0.06*	full NLO + *differential*
ME-PS matching threshold	0.18	0.09	0.09	*0.06*	full NLO + *differential*
Underlying event	0.15	0.15	0.15	*0.06*	*differential*
Color reconnection effects	0.54	0.27	*0.2*	*0.06*	factor 2 + *differential*
Systematic	0.98	0.60	0.44	0.20	
Statistical	0.43	0.15	0.05	0.01	
Total	1.07	0.62	0.44	0.20	

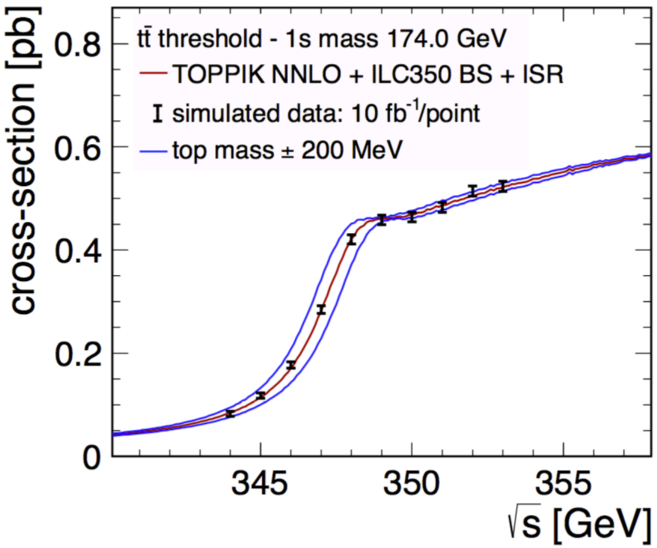


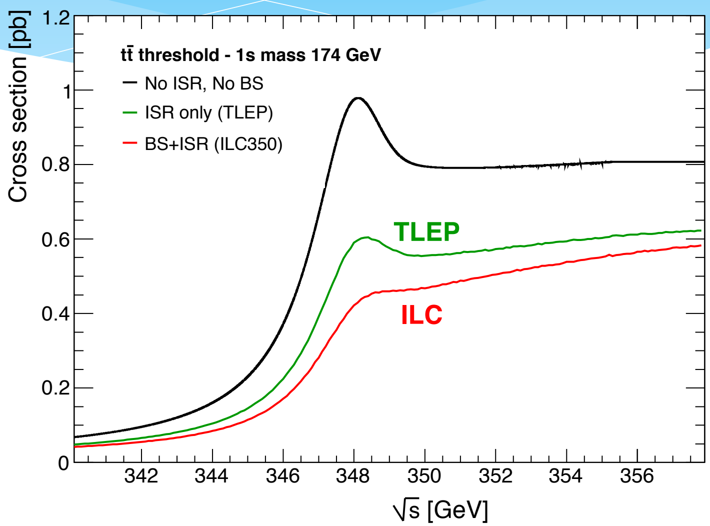
$\Delta m_t \approx$500 MeV
→400 → 200 MeV

with →300/fb → 3/ab

Top quark mass: e+e- future

The tt pair production at $\sqrt{s} \approx 2m_t$, allows for precise measurements of m_t , Γ_t α_s.



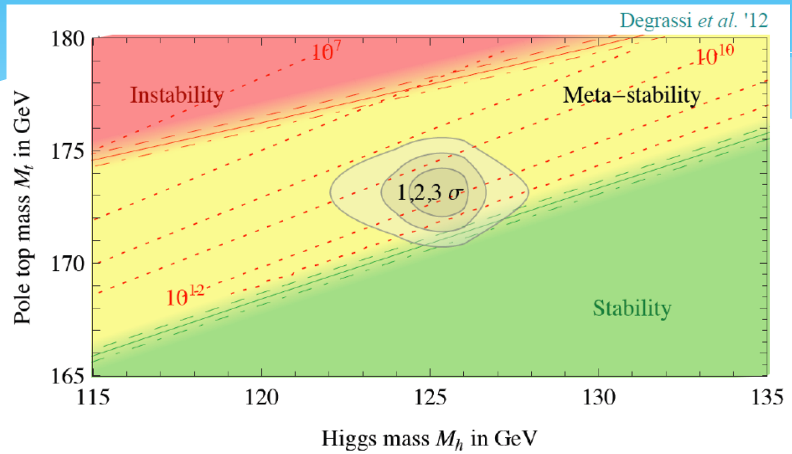


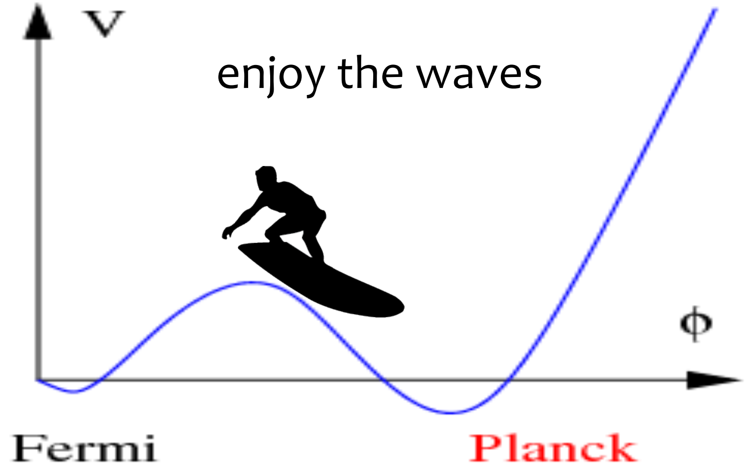
ILC TDR 300/fb over 10 energy points in 10 GeV around the threshold ➔
Δm_t = 34 MeV, $\Delta\alpha_s(m_Z)$ = 0.0023 and $\Delta\Gamma_t$ = 42MeV

➔Roman Poeschl Tue 11:00

FCCee//CEPC : 800/fb Δm_t = 10 MeV $\Delta\Gamma_t$ = 10 MeV (**arXiv:1308.6176**)

m_W, m_H & m_t


Degrassi et al. '12
Instability
Meta−stability
Stability
1,2,3 σ
10^7
10^10
10^12
Pole top mass M_t in GeV
Higgs mass M_h in GeV
180
175
170
165
115
120
125
130
135


V
enjoy the waves
φ
Fermi
Planck

summary

* The current status of EW precision measurements still standing in large measure on the shoulders of SLD/ LEP1/2 precision measurements for Z /W (Δm_Z 0.002%) & on Tevatron legacy (Δm_W 0.02%)
* LHC Run1 legacy : Higgs boson Δm_H 0.2% and Δm_t 0.3%
* LHC future 13/14 TeV data promising to advance in the
  * exploration of gauge couplings: multi-bosons, VBF, VV scattering
  * Higgs couplings measurements (and m_H, Γ_H)
  * improvements in m_t, m_W , $\sin^2\theta_W$ also possible
* Next e+e- collider will bring game-changing EW precisions