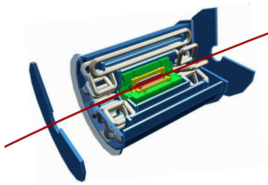
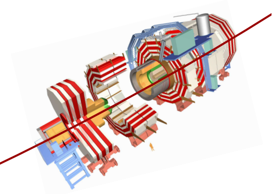
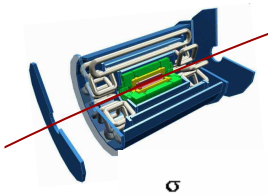


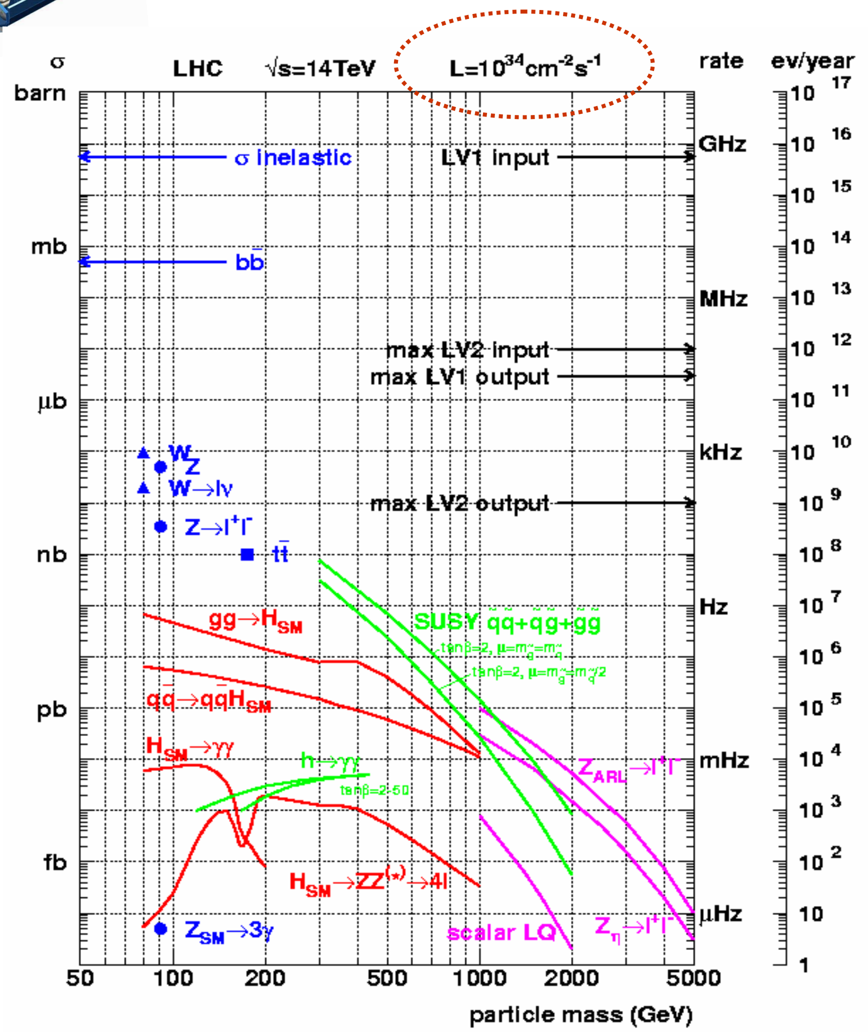
Measurements of W and Z properties at the LHC

Maarten Boonekamp, CEA-Saclay
Epiphany Conference, Cracow, Jan 2007





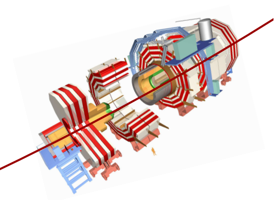
Cross-sections and rates



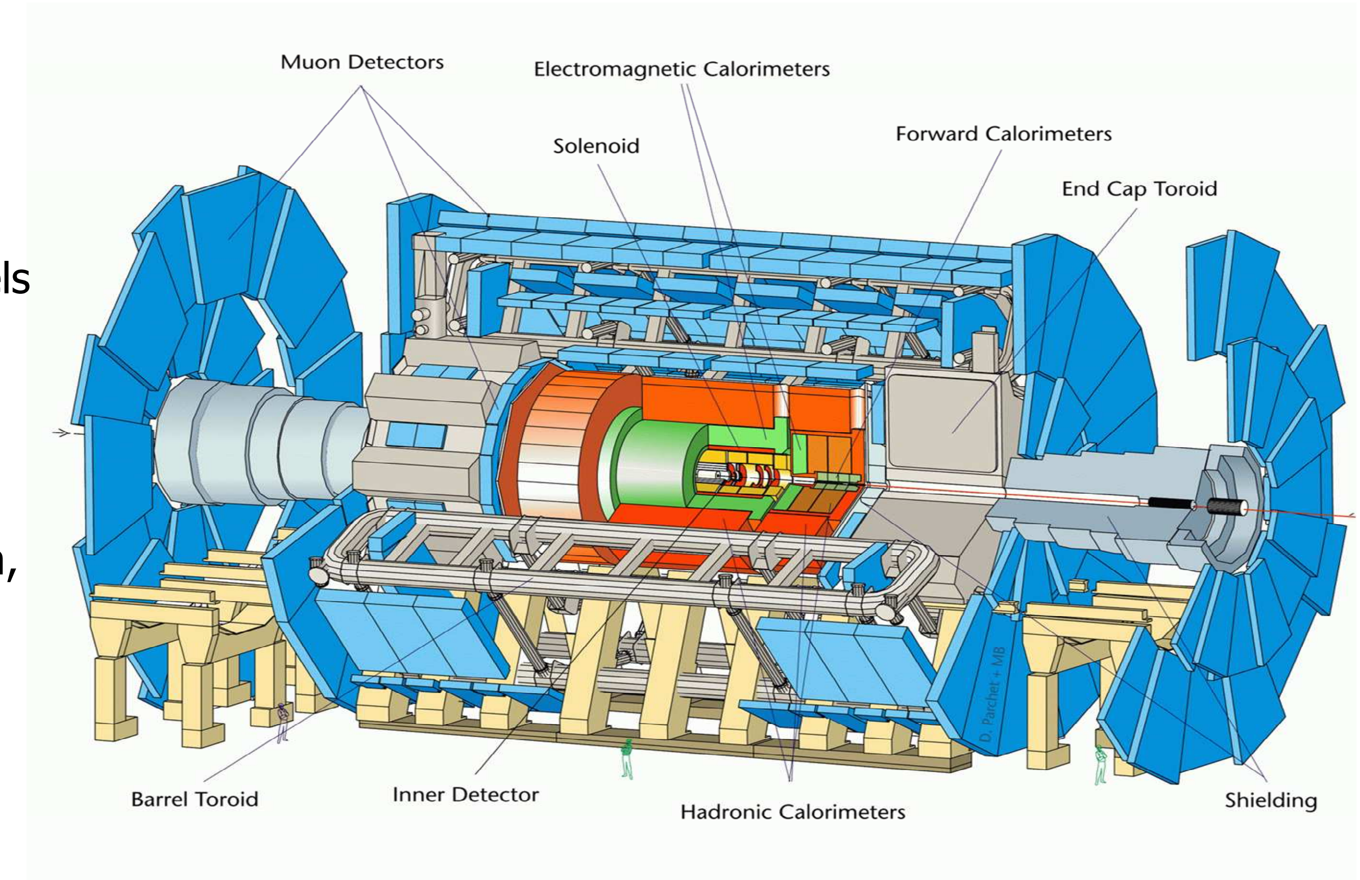
- Cross-sections of interest span >10 orders of magnitude

- $\sigma_W \sim 150$ nb
  BR(W → e+μ) ~ 20%
  10 fb^{-1} ⇔ 300M leptonic events
  Rate(10^{33} cm^{-2} s^{-1}) ~ 30 Hz
  Rate(10^{34} cm^{-2} s^{-1}) ~ 300 Hz

- $\sigma_Z \sim 50$ nb
  BR(Z → ee+μμ) ~ 6.6%
  10 fb^{-1} ⇔ 33M leptonic events
  Rate(10^{33} cm^{-2} s^{-1}) ~ 3.5 Hz
  Rate(10^{34} cm^{-2} s^{-1}) ~ 35 Hz



ATLAS



Trivia : 7000 tons,
L ~ 44 m, ∅ ~ 22 m,
~10^7 electronics channels

Muon Spectrometer :
air-core toroidal system,
$|\eta| < 2.7$

Calorimetry :
LAr EM calorimeter ($|\eta| < 2.5$ / 3.2);
Hadron calorimeter ($|\eta| < 4.9$)

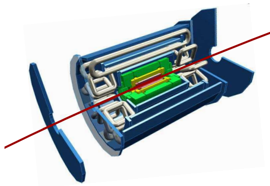
Tracker : Si pixels & strips + TRT; 2 T magnetic field; $|\eta| < 2.5$

Outline

- W,Z physics programme :
  - Motivation : a New Physics oriented example
  - Production properties (differential cross-sections).
  - Decay modes, A_{FB} (skipped).
  - M_W

- Detector performance : what is known about Z events?
  - Leptons come in pairs → efficiency
  - Resonance :
    - M_Z → Energy scale
    - Γ_Z → Resolution
  - Specifications given by the M_W analysis

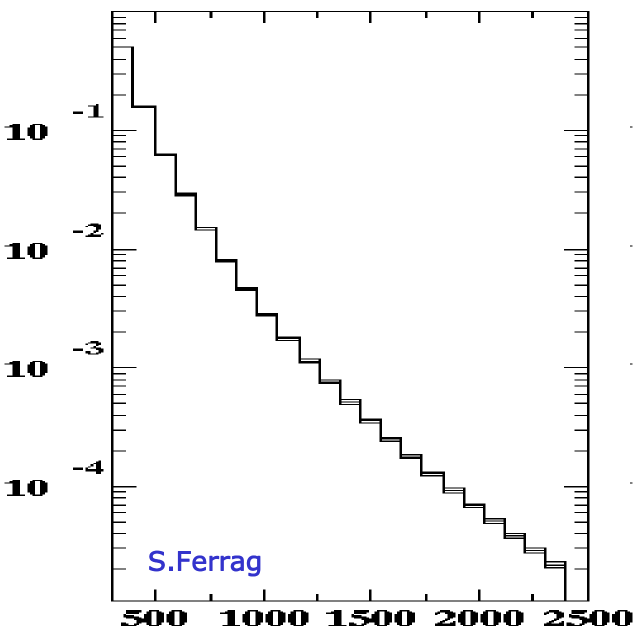
- M_W discussion. How far can we reach?

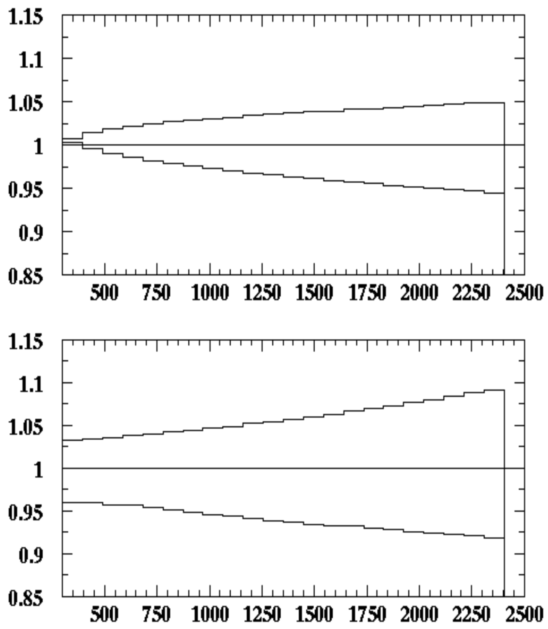


Dileptons at high mass

- High-mass spectrum (where we might look for Z′):

dσ/dM (a.u)



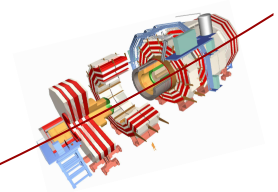


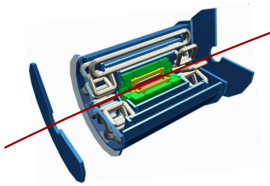
Scale uncertainty (factor 10 variation) : ~ 5% at high mass

Structure function uncertainty : ~ 5-10%

M_{ll} (GeV)

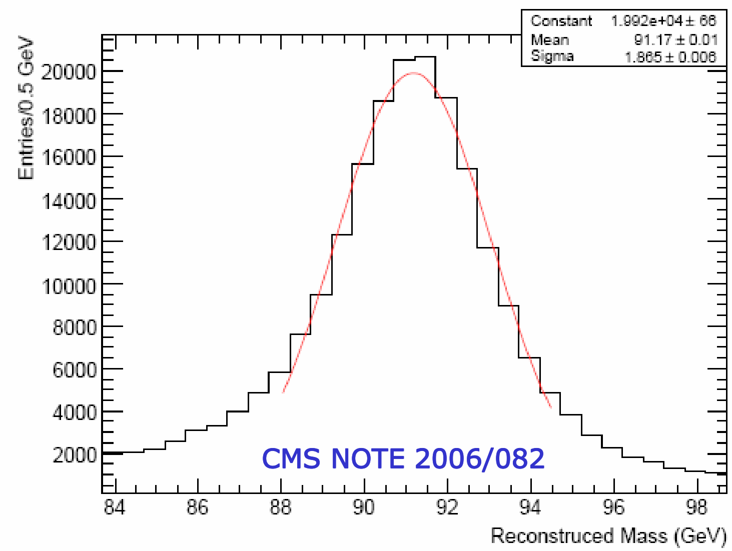
- How to improve without absorbing the effect of possible new physics?

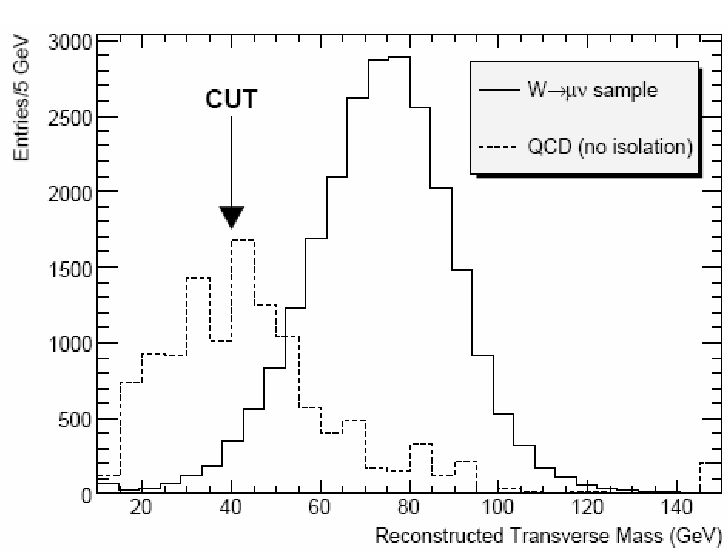


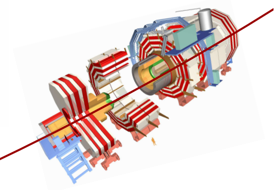


→ Measure W,Z cross-sections

- Measure standard cross-sections sensitive to the same sources of uncertainty, efficiently triggered, and unlikely to hide new physics : W,Z
- Recent analysis (CMS)
  - Z : 2 isolated muons with p_T>20 GeV, $|\eta|$<2, 84<$M_{\mu\mu}$<99 GeV, … $\varepsilon_Z \sim 25\%$
  - W : 1 isolated muon with p_T>25 GeV, $|\eta|$<2, 40<$M_T(\mu, E_T Miss)$<200 GeV, … $\varepsilon_W \sim 20\%$







W,Z total cross-section

- Results, for 1 fb^{-1} (or ~600k $Z \rightarrow \mu\mu$, ~6M $W \rightarrow \mu\nu$ events):
  - Cross-sections :
    - $\sigma(Z \rightarrow \mu\mu + X)$ = 1160 ± 1.5 (stat) ± 27 (syst) pb
    - $\sigma(W \rightarrow \mu\nu + X)$ = 14700 ± 6 (stat) ± 485 (syst) pb

    Already dominated by systematics.

  - Systematics breakdown: theory dominated (acceptance).
    (Frixione, Mangano arrived at the same conclusion).

CMS NOTE 2006/082

Source	Uncertainty (%)
Tracker efficiency	1
Magnetic field knowledge	0.03
Tracker alignment	0.14
Trigger efficiency	0.2
Jet energy scale uncertainties	0.35
Pile-up effects	0.30
Underlying event	0.21
Total exp.	1.1
PDF choice (CTEQ61 sets)	0.7
ISR treatment	0.18
p_T effects (LO to NLO)	1.83
Total PDF/ISR/NLO	2.0
Total	2.3

Source	Uncertainty (%)
Tracker efficiency	0.5
Muon efficiency	1
Magnetic field knowledge	0.05
Tracker alignment	0.84
Trigger efficiency	1.0
Transverse missing energy	1.33
Pile-up effects	0.32
Underlying event	0.24
Total exp.	2.2
PDF choice (CTEQ61 sets)	0.9
ISR treatment	0.24
p_T effects (LO to NLO)	2.29
Total PDF/ISR/NLO	2.5
Total	3.3

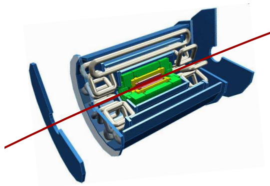
Discussion

- So this is a first step : total cross-sections don't teach us much about how to constrain the theory; the effects that hinder our high-mass predictions are also playing here.

- Specifically, the acceptance uncertainties (not knowing how many events are outside the y, M, $p_T(l)$ windows we select) should be improved.

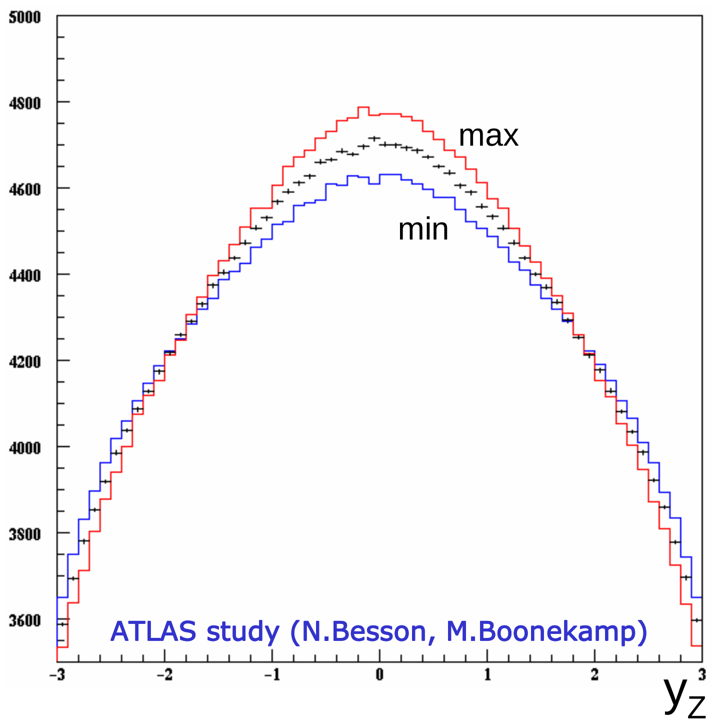
- It is thus important to analyse the shapes : $d\sigma/dy$, $d\sigma/dp_T$, $d\sigma/dM$. Z events are better than W in this respect (fully measured). Since the Z decay is well known, the acceptance uncertainty on differential cross-sections is small.

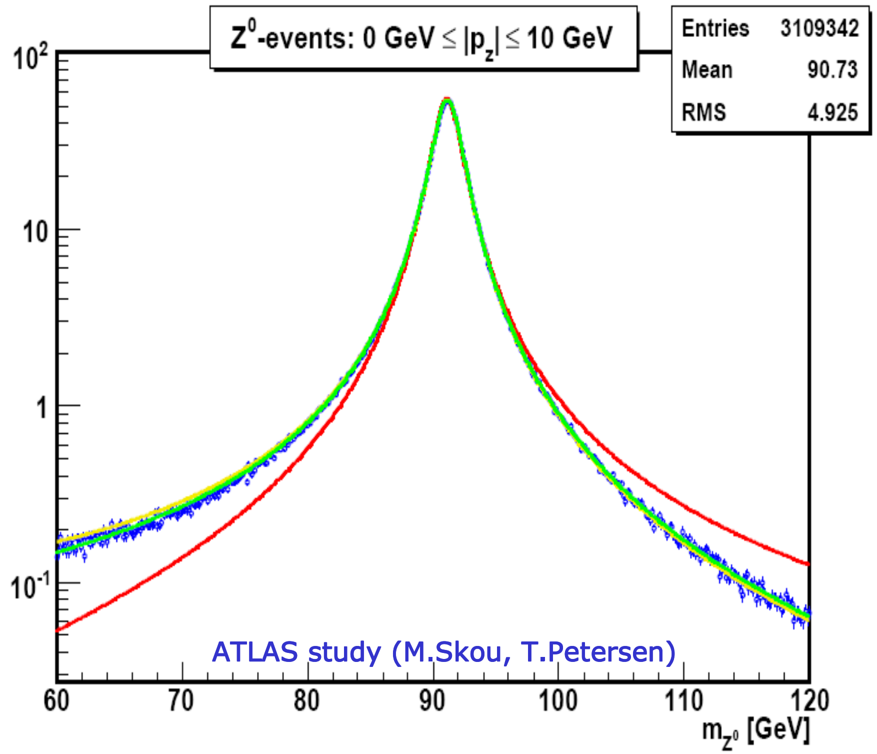
- Improvement on the theoretical description then comes from:
  - Confronting data and theory within the analysed (y,p_T,M) domain
  - Better extrapolation outside the analysed domain



→ Differential cross-sections (1)

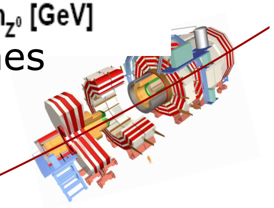
- Two examples on structure functions :





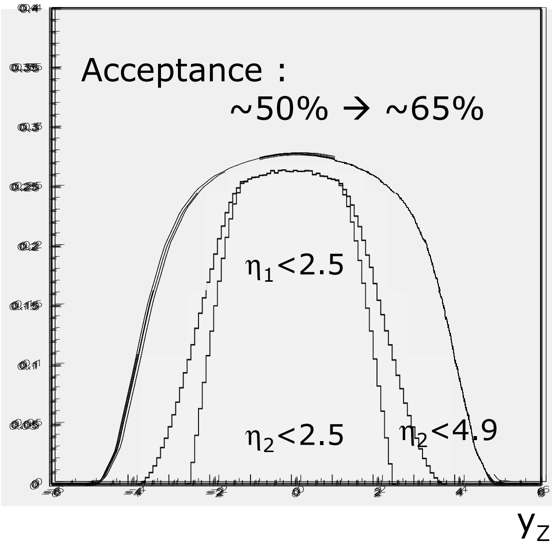
$\delta(d\sigma_Z/dy) \sim 4\%$
→ ~ 0.2% with ~10 fb^{-1}

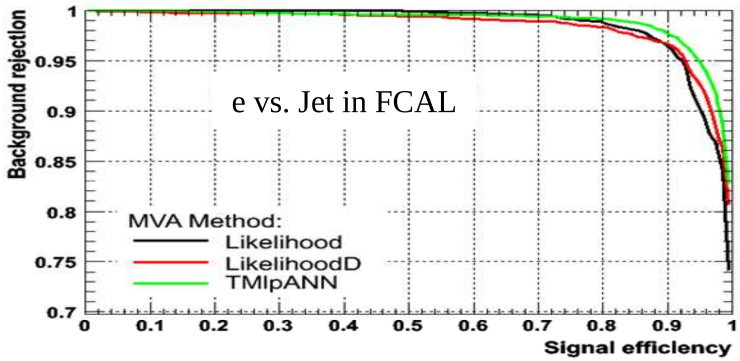
A 1σ pdf variation (today) becomes
a 5σ effect with ~10 fb^{-1}



Differential cross-sections (2)

- It is important to extend the y_Z acceptance if possible, reducing the extrapolation uncertainty. Consider the $Z \rightarrow ee$ channel:





Eff(%)	Rej: 100	Rej: 10
likelihood	77	95
ANN	81	98
likelihoodD	66	97

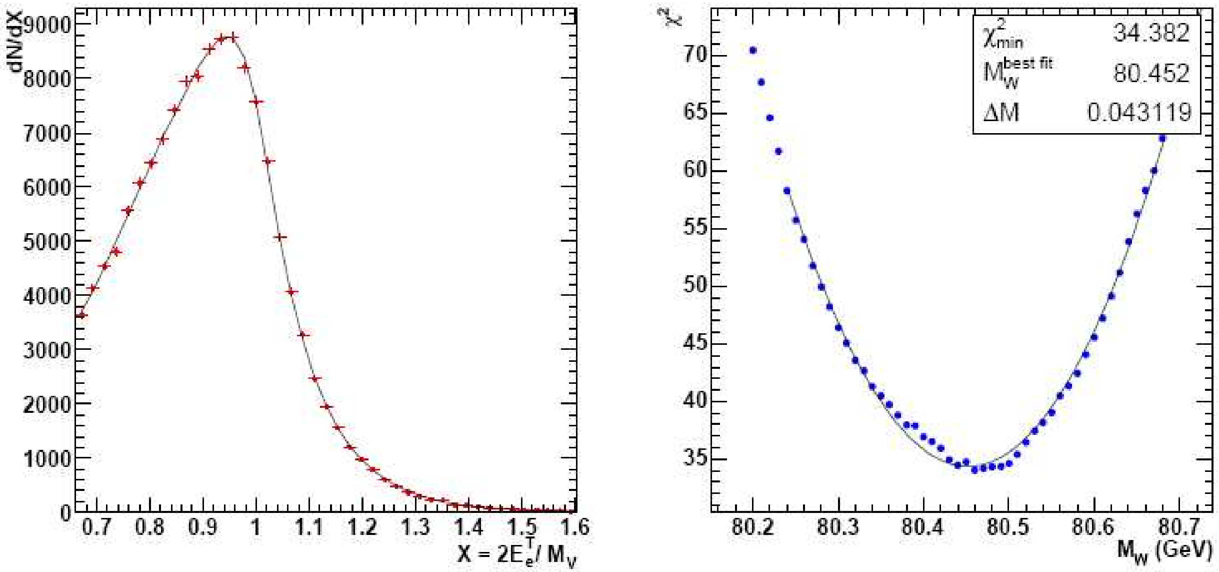
ATLAS studies (M.Aharrouche) in progress

- Link with high mass dileptons :
  - central heavy object (~2.5-3 TeV) has $x \sim M/\sqrt{s} \sim 0.2$
  - Can be controlled by Z events if forward enough : $x_{1,Z} \sim 0.2$ if $y_Z \sim 3.5$
  - Expect ~800k events in $2.5<y_Z<4$ for 10 fb^{-1}

Precision Measurement of M_W

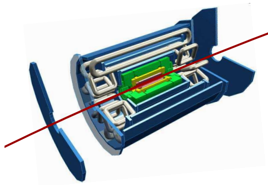
Precision measurements : M_W

- Simple and powerful in principle: consider e.g the $p_T(l)$ spectrum (other sensitive distribution : $M_T(W)$)



Example fit from CMS NOTE 2006/061

- Statistical sensitivity : ~2 MeV (1 channel/experiment, 10 fb^{-1})
- But need to predict the spectrum precisely!



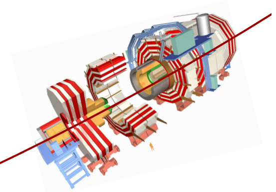
Precision measurements : M_W

- Ingredients
  - Lepton energy scale and resolution. Linearity. Reconstruction efficiency
  - W dynamics : rapidity, transverse momentum, polarization, final state radiation

- Current consensus (hep-ph/0003275…)
  - Lepton energy scale: 15 MeV (limitation : Z → W extrapolation. Linearity)
  - PDF's : 10 MeV (from comparison of existing sets)
  - QED FSR : 10 MeV (calculation up to $O(\alpha^2)$)
  - Lepton resolution : 5 MeV
  - QCD corrections : 5 MeV (limitation : Z → W extrapolation)

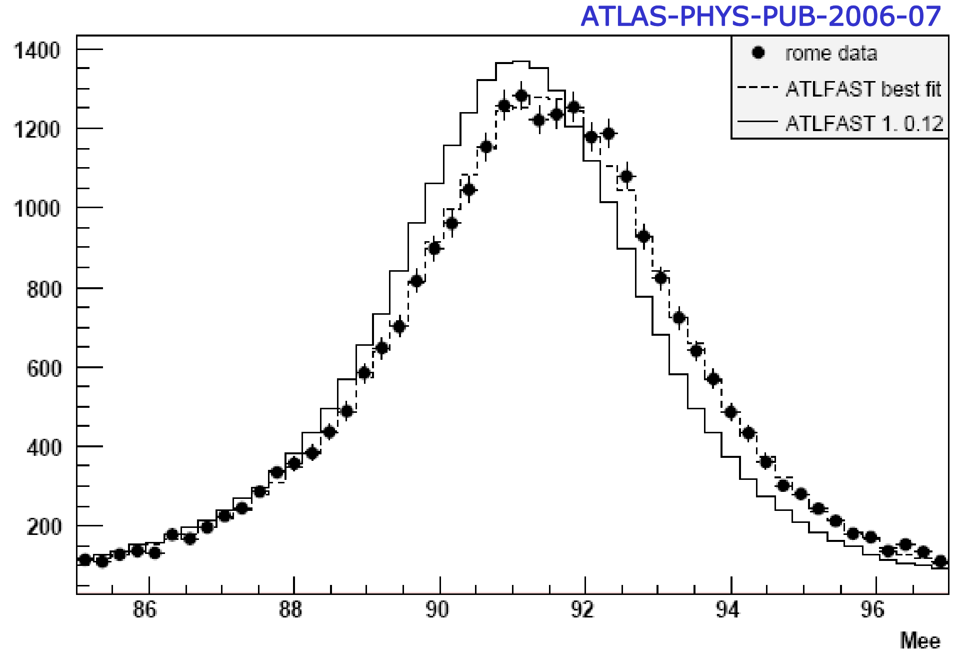
- → The Z calibration sample revisited
  - Improvements on the above. Expected performance

- Recent studies by CMS (note 2006/061) and ATLAS (t.b.p)



M_W : energy scale and resolution (1)

- The mass scale (β) and mass resolution (σ) from the Z peak :
  - $M_{data} \equiv (1+\beta)\, M_{MC}$; $\sigma_{data} \equiv \sigma_{MC}$



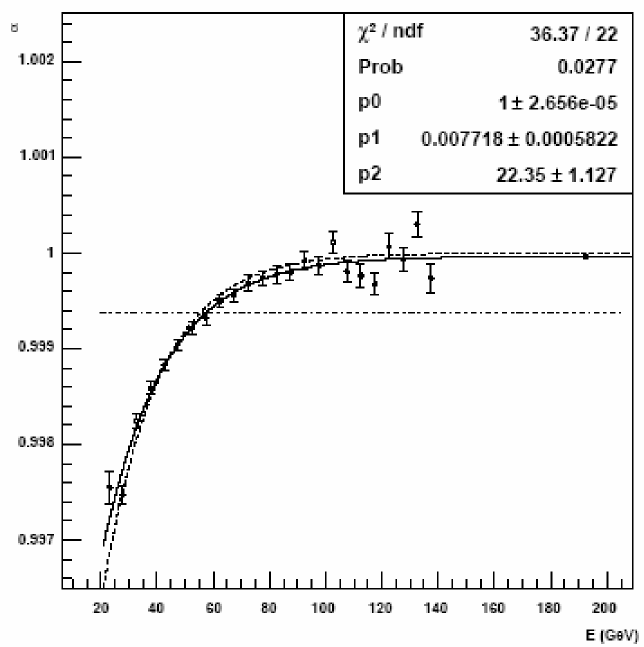
  - Achievable precision : $\delta\beta \sim 10^{-5}$, $\delta\sigma \sim 10^{-4}$

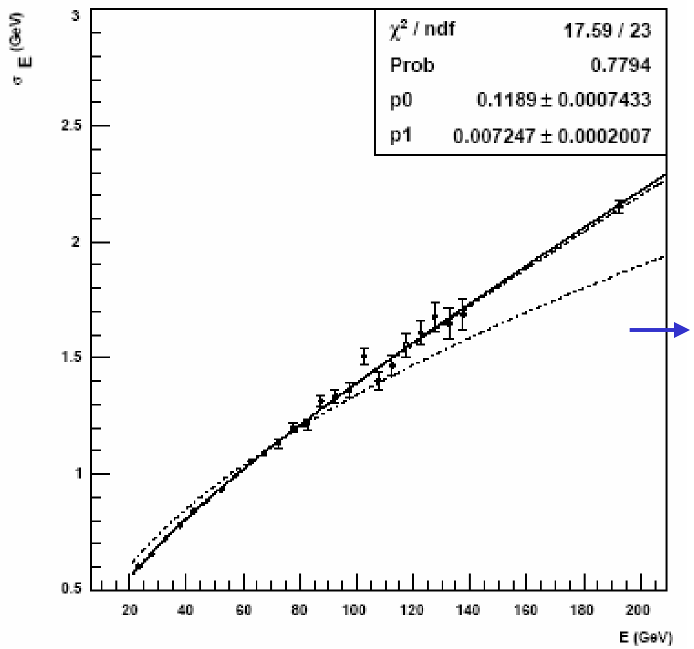
- But indeed, how does this translate to a W-mass measurement?

M_W : energy scale and resolution (2)

- Now differentiate in energy (i.e consider lepton energy bins i, j). Repeat previous fit for every pair configuration (i,j):
  - $M_{ij}^2 = E_i E_j (1-\cos\theta)$; $(1+\beta_{ij})^2 M_{ij}^2 = (1+\alpha_i)E_i(1+\alpha_j)E_j(1-\cos\theta)$
  - $\Rightarrow \beta_{ij} \sim (\alpha_i+\alpha_j)/2$; $\sigma_{ij}^2/M^2 = \sigma_i^2/E_i^2 + \sigma_j^2/E_j^2$; write this for all (i,j)
  - and solve the linear system (least squares) to get the α_i and σ_i^2

ATLAS-PHYS-PUB-2006-07

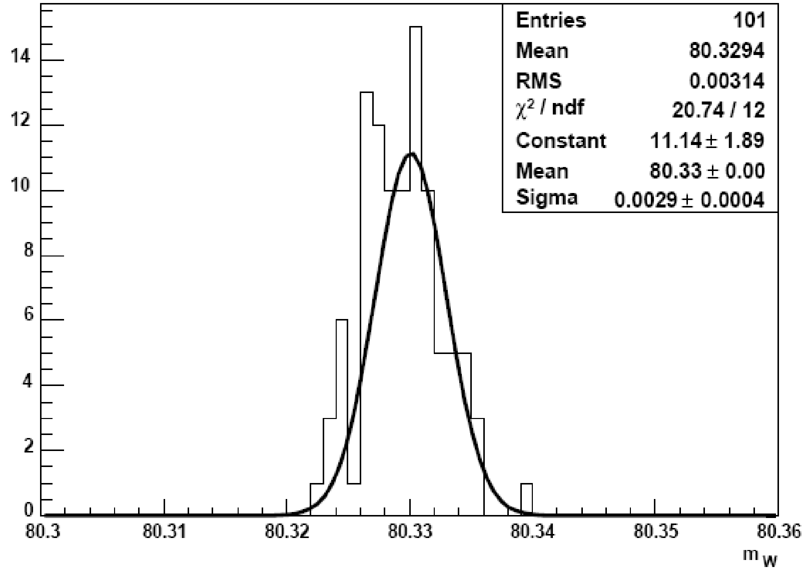




→ Can be fed to $p_T(l)$ spectrum

M_W : energy scale and resolution (3)

- Propagation to M_W : vary the linearity and resolution functions within their uncertainties (at random), distribute M_W(fit) :

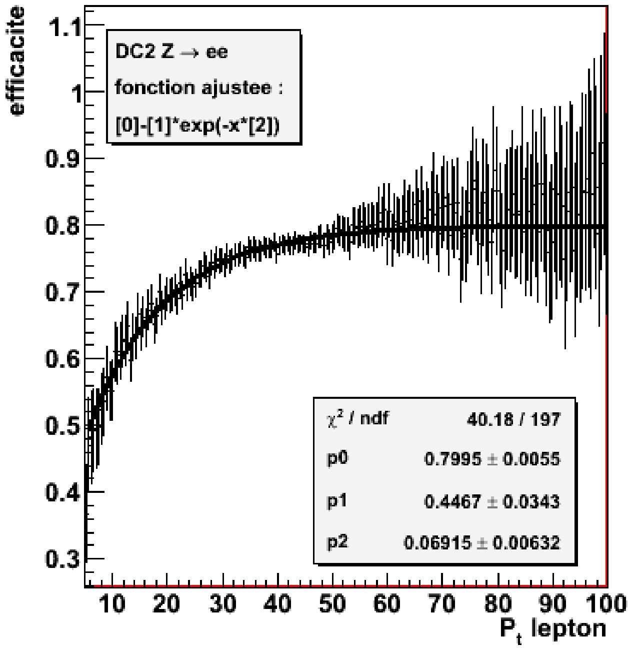


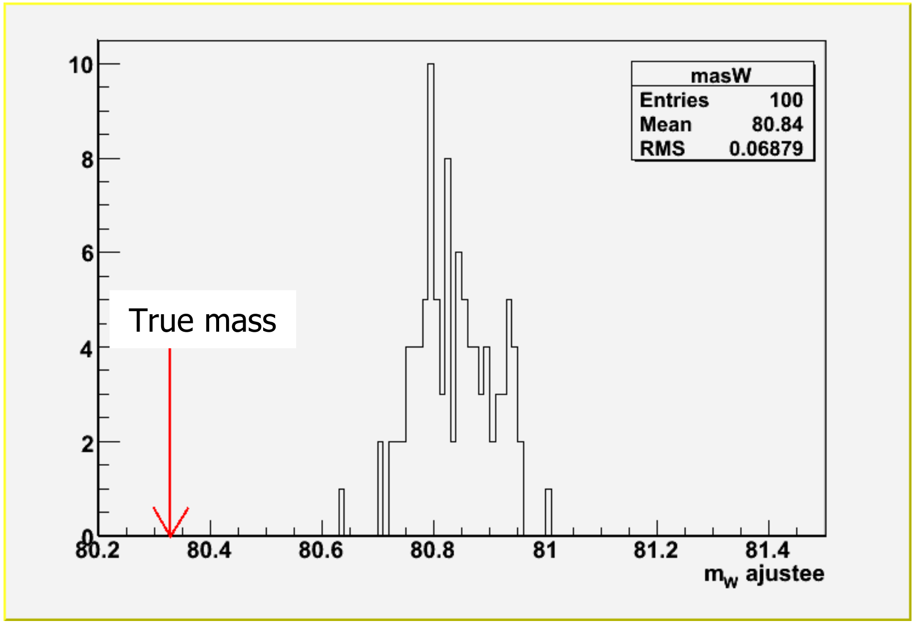
- → δM_W(scale) = 3 MeV (one channel/experiment, 10 fb^{-1})
  After combinations, get ~1 MeV → strong correlation with δM_Z!

- NB : a priori knowledge of absolute scale ~1% (from detector simulation)

M_W : reconstruction efficiency (1)

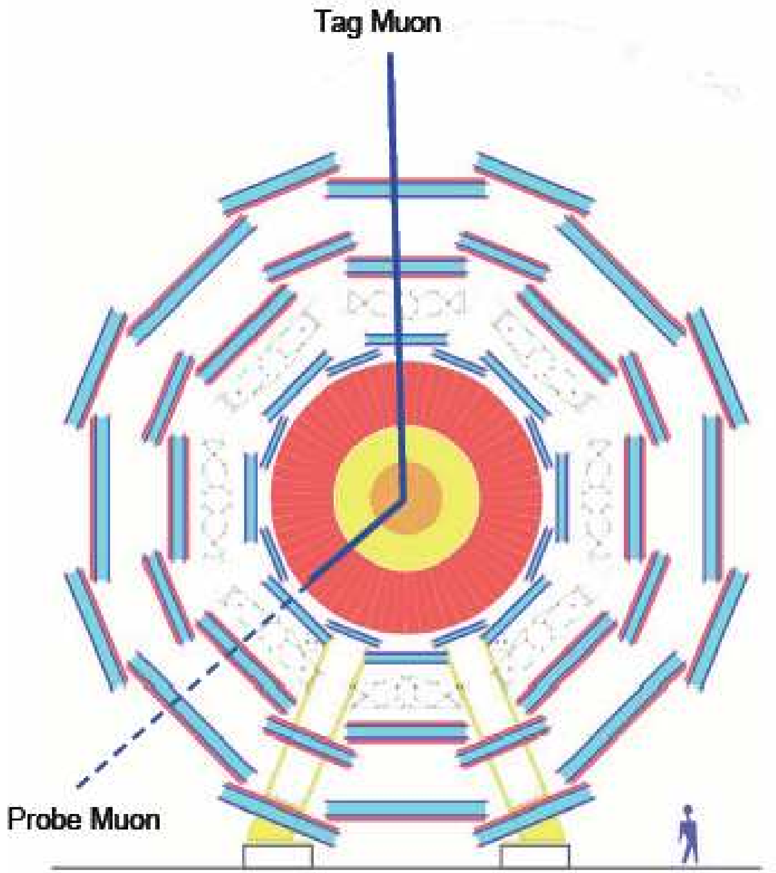
- p_T dependence of efficiency distorts the $p_T(l)$ spectrum. Ignoring it causes a surprisingly large bias (especially in the electron channel):





M_W : reconstruction efficiency (2)

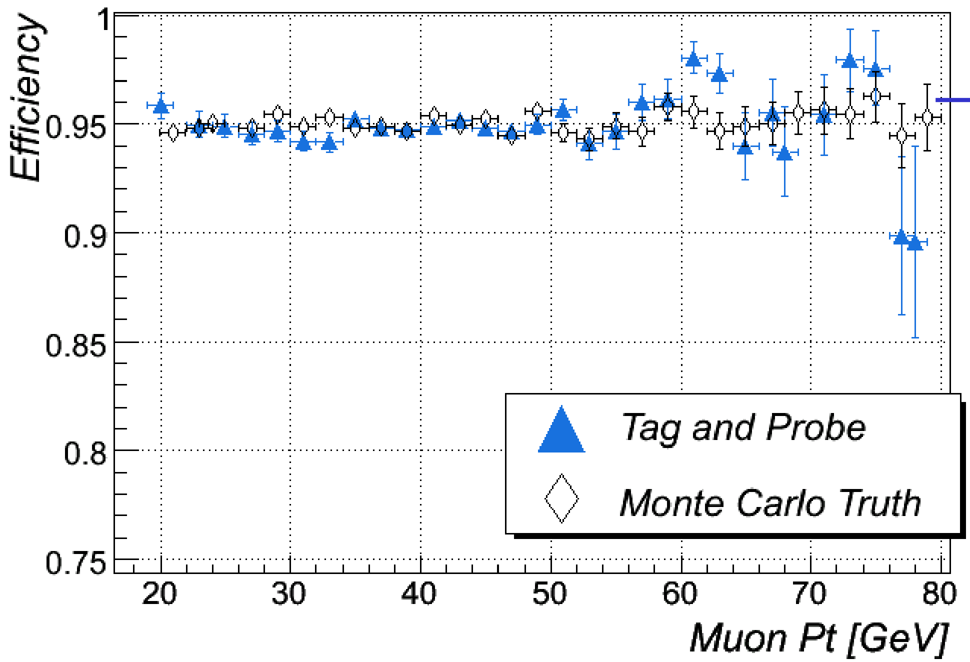
- But again, efficiency can be measured in Z events (muon example):



- Tag Muon: Track in Inner Detector AND Muon Spectrometer (+Isolation and pT-Cuts)
- Probe Muon: Track in Inner Detector (+Isolation and pT-Cuts)
- If this di-muon mass is near 91GeV and $\Delta\varphi>2$, then the probe muon is assumed to be a real muon
- muon efficiency is given by the fraction of probe muons with tracks in the Muon Spectrometer

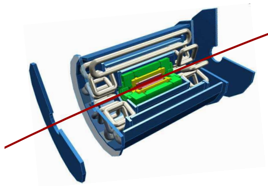
M_W : reconstruction efficiency (3)

- Results : works well, even in the presence of background.



To be fed to $p_T(l)$ spectrum

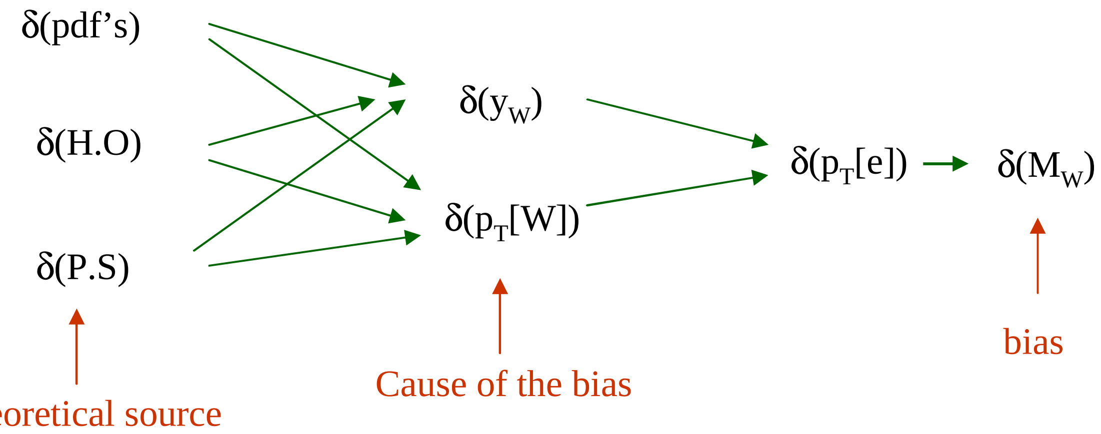
- After correction, the remaining M_W systematic is ~2 MeV (muon channel), and ~10 MeV (electron channel, stronger p_T dependency).



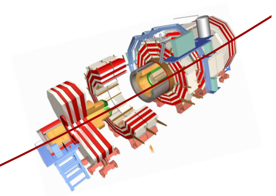
M_W : W dynamics

- The observed lepton distributions result from
  - W → l angular distribution
  - W distributions

- What happens:

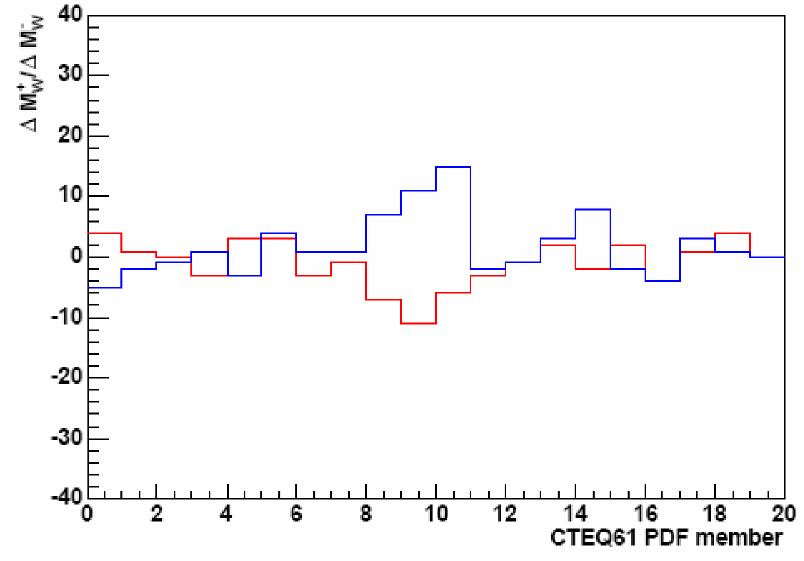


- What can we say?



M_W : structure functions (1)

- Directly affect y_W (…and indirectly p_{TW})
- Using CTEQ6 pdf “uncertainty sets”, one can evaluate the current uncertainty :

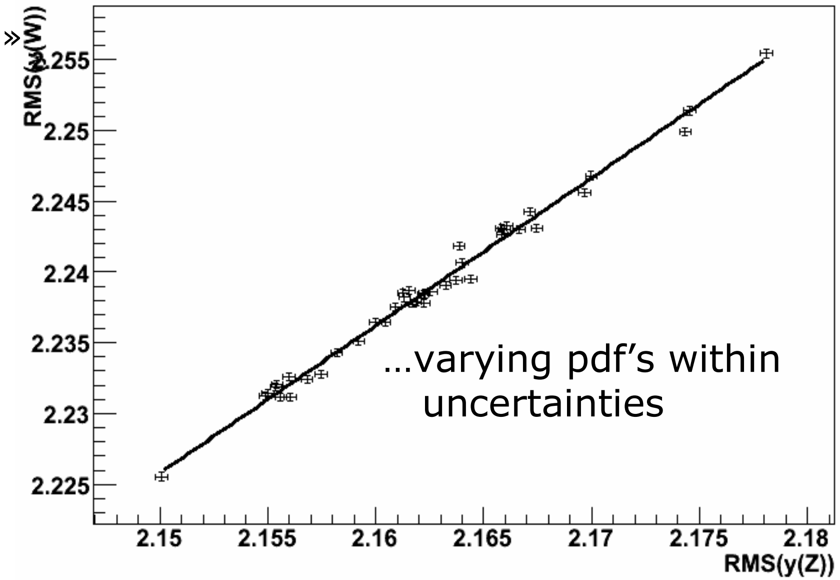


- $\delta M_W \sim 25$ MeV : worse than expected!

M_W : structure functions (2)

- But how do W and Z production relate?

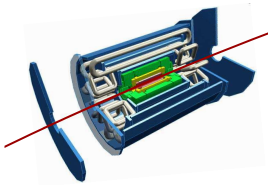
W rapidity « shape »



Z rapidity « shape »

- The Z rapidity uncertainty will be divided by ~20 (10 fb^{-1})
  - (see also earlier comments on $d\sigma_Z/dy$)

- And so will the W rapidity uncertainty : as a result, dM_W(pdf's)~1 MeV

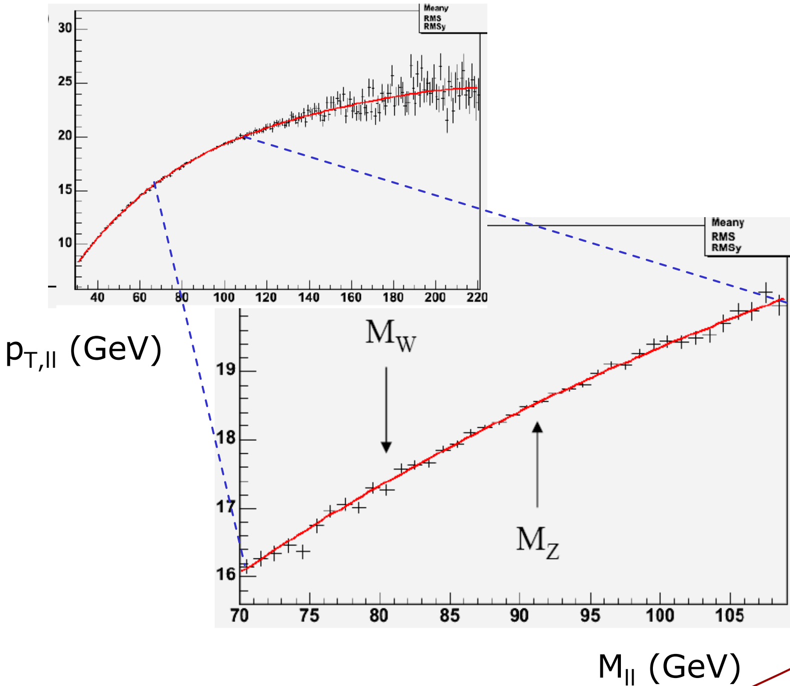


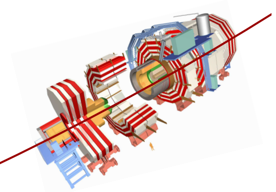
M_W : p_T spectrum (1)

- W,Z p_T predictions is currently a busy subject. Large uncertainties remain
- However, QCD tells that the mechanisms at work in W and Z production are identical. Differences come from phase space ($M_W \neq M_Z$) and different couplings of W and Z to the partons in the proton.
- Consider $p_{T,ll}$ as a function of M_{ll} :

Thanks to high precision at the peak and the large lever arm provided by the continuum:

- $\delta p_T(M_{ll}=M_Z) \sim 5$ MeV
- $\delta p_T(M_{ll}=M_W) \sim 7$ MeV





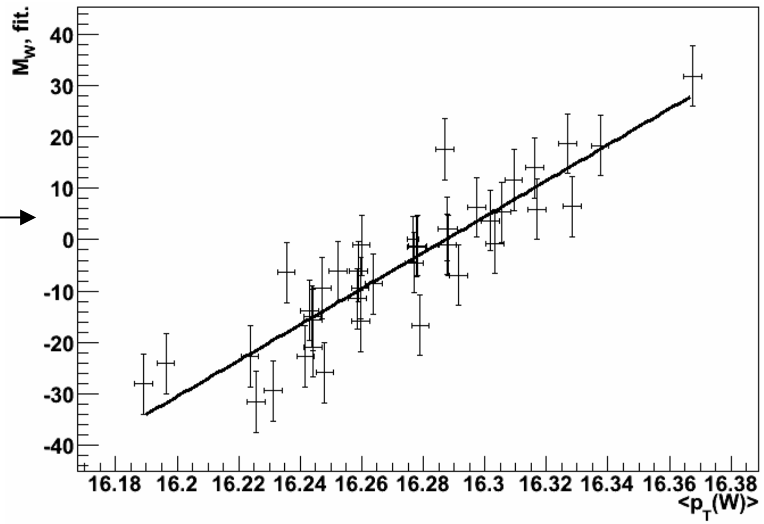
M_W : p_T spectrum (2)

- Not to say that $p_{T,W}=p_{T,ll}(M_{ll}=M_W)$! Non-universalities (EW) need to corrected for.
  Can be precisely computed (need precision MC!)
  Measuring the off-peak $p_{T,ll}$ allows to get rid of the phase space difference and control the non-perturbative effects.

- This improves over the "ratio method", where all W distributions are defined from Z distributions rescaled by M_W/M_Z – this is a crude approximation, not suited to LHC statistics.

- To finish : $\delta M_W = 0.3\ \delta p_T$ →

  So $\delta p_T(M_{ll}=M_W)\sim 7$ MeV
  gives $\delta M_W \sim 2$ MeV

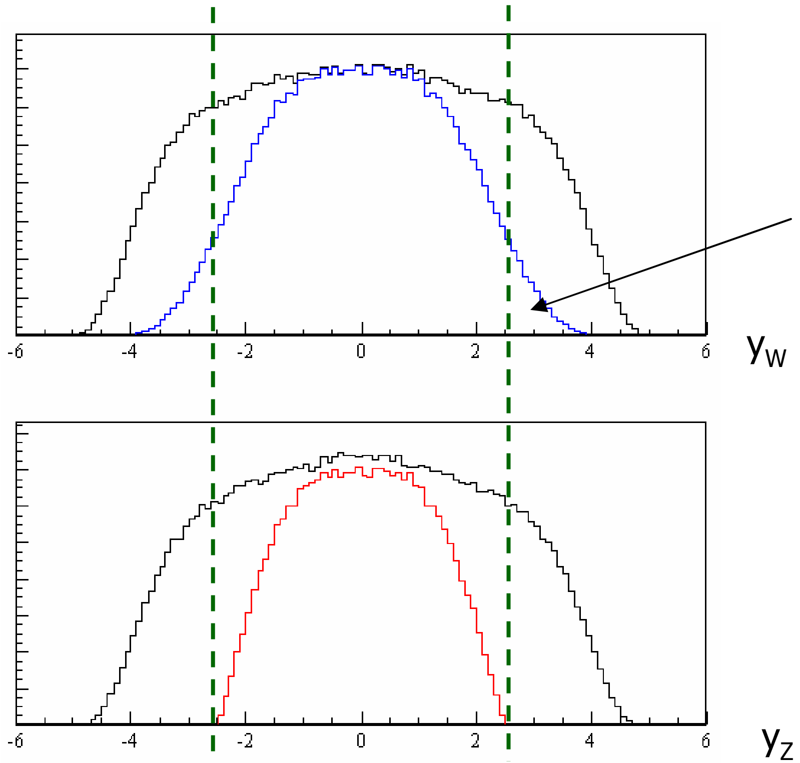


The W acceptance objection (1)

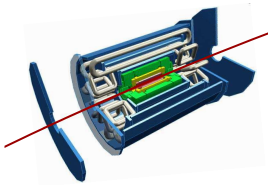
- Often read : in Z events, require two leptons; in W events, only one (neutrino unconstrained). Hence there is a y_W region out of our control. This will be a limiting systematic!

W : 1 lepton with $|\eta|<2.5$

Z : 2 leptons with $|\eta|<2.5$



Uncovered region : 21% (fraction of selected W population)

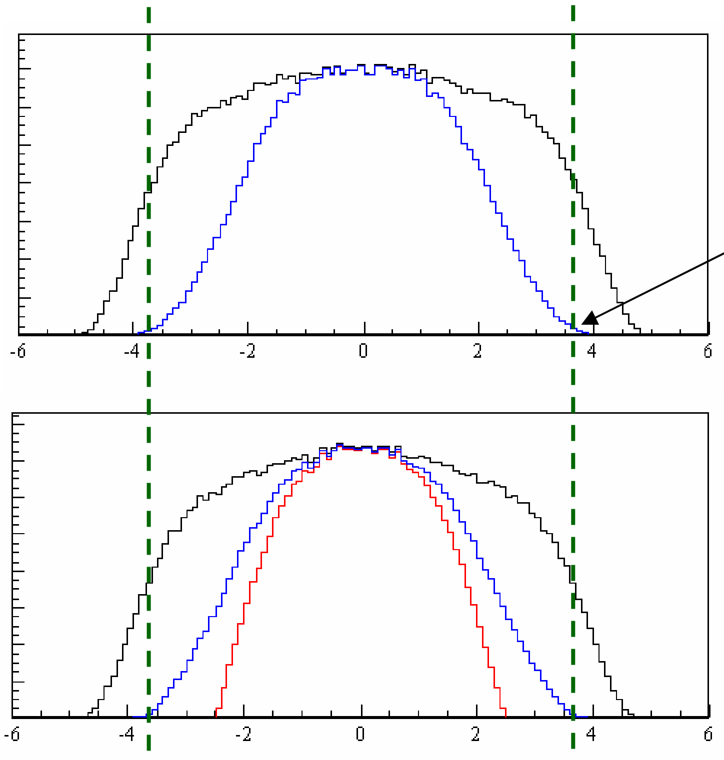


The W acceptance objection (2)

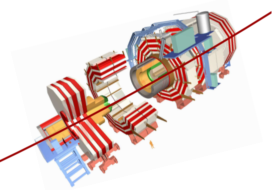
- But we saw before that we can increase the acceptance, by selecting electrons in the forward calorimeters (only 1; the other must have $|\eta|<2.5$, to trigger)

W : 1 lepton with $|\eta|<2.5$

Z : 1 lepton with $|\eta|<2.5$
1 lepton with $|\eta|<4.9$

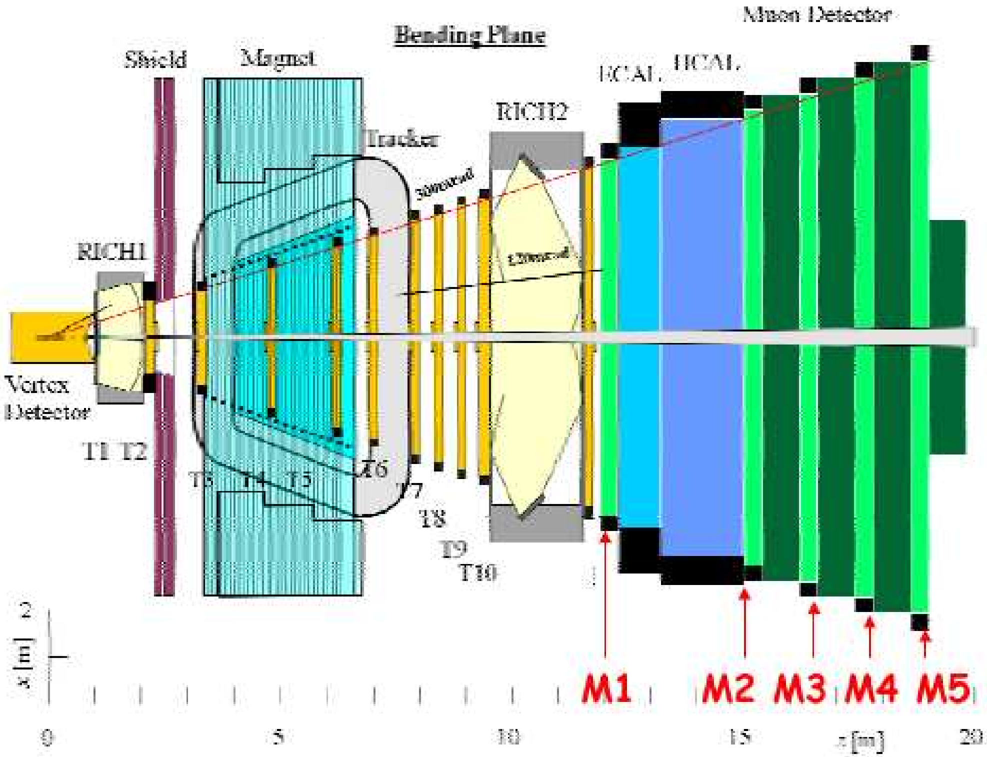


Uncovered region : 0.6%
(fraction of selected W population)



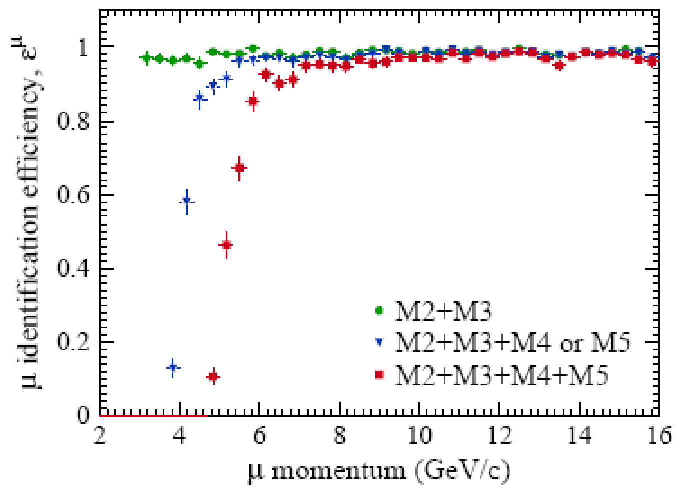
The W acceptance objection (3)

- Even better : Z production at LHCb



Muon acceptance :
$2.1 < |\eta| < 4.8$

Good reconstruction efficiency:

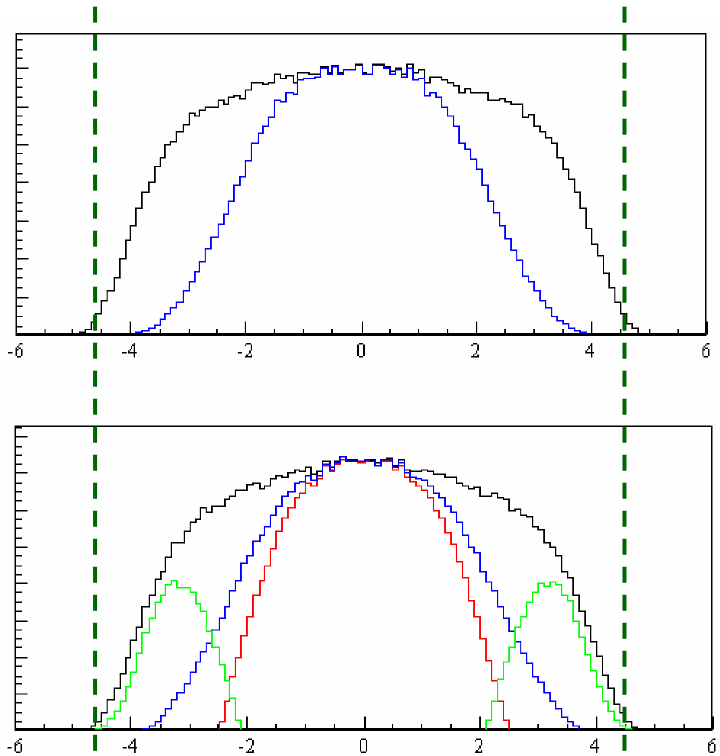


The W acceptance objection (4)

- Including LHCb :

W : 1 lepton with |η|<2.5

Z : 2 leptons with 2.1<|η|<4.8



Uncovered region : 0%!

- Our Z acceptance is now larger than the W acceptance, and there is large overlap between ATLAS/CMS and LHCb (allows cross-checks)

- In terms of x1,x2 : the W range is now covered, even without leaving the Z peak

A few comments

- A popular M_W measurement method at the Tevatron is the « ratio method », that deduces W distributions (those used for the mass determination : $p_T(l)$, $M_T(W)$) from Z ones, modulo a rescaling factor M_W/M_Z.
  This acknowledges universality of QCD effects

- There is a tendency to apply this at the LHC (cf. CMS NOTE 2006/061)

- But this will fail badly. Approximations of the ratio method:
  - Integration over the W and Z phase space, assuming the M_W/M_Z factor maps the Z phase space into the W one

  will induce prohibitive systematics when aiming at high precision

- The previous slides all show that improvement comes, on the contrary, from analyzing the Z phase space in detail, and apply phase space dependent corrections to the W distributions

- More involved, but mandatory

Simplified picture of the analysis

- Analyse the Z sample.

Z distribution :		Constrains (mainly):
Resonance	→	Energy scale, resolution == $f(E_T,\eta)$
Rapidity	→	Parton luminosities == f(x1,x2)
p_T (vs. M_{ll})	→	non-perturbativie QCD parameters == $f(p_T,M_V)$

- Correct for EW effects. For example :

  Photon radiation affects the resonance shape → Energy scale
  EW corrections affect Z pT spectrum (through lepton acceptance effects)

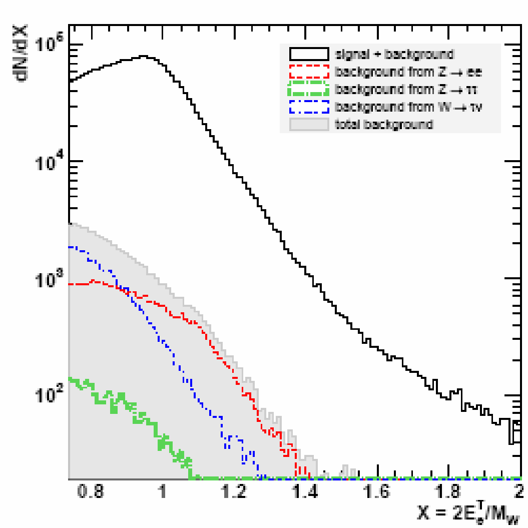
- Obtain correct W distributions, now depending only on M_W, Γ_W

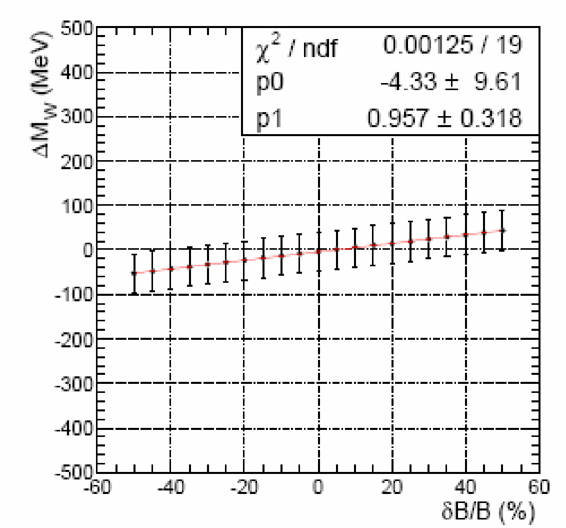
- Fit those to the data

M_W : backgrounds

- Backgrounds distort the $p_T(l)$ spectrum
  - Main expected sources : Z → ll (1-2%), W → τν (1-2%), Z → ττ (0.2%)
  - QCD expected small (0.1%) after tight lepton selections

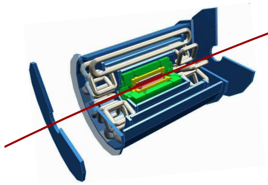
- CMS studied the impact of imperfectly known background rates:





CMS NOTE 2006/061

concluding δM_W (MeV)= $\delta B/B$ (%) ; $\delta B/B$ = 5% giving δM_W=5 MeV.



M_W : summary

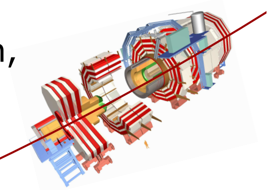
- So far, per channel/experiment for 10 fb^{-1}:

(source)	(old est.)	(updated estimate)	(tool)
Energy scale, linearity:	15 MeV	~3 MeV	Z lepton spectra
Lepton resolution :	5 MeV	<1 MeV	"
PDF's :	10 MeV	~1 MeV	$d\sigma_Z/dy$, $d\sigma_Z/dM$
QCD corrections :	5 MeV	~2 MeV	$d\sigma_Z/dp_T$
Backgrounds :	5 MeV	~5 MeV	known to ~5% (conservative)

- NB : this discussion relies on $p_T(l)$. $M_T(W)$ is more stable against theory, but poses another problem (E_TMiss calibration)

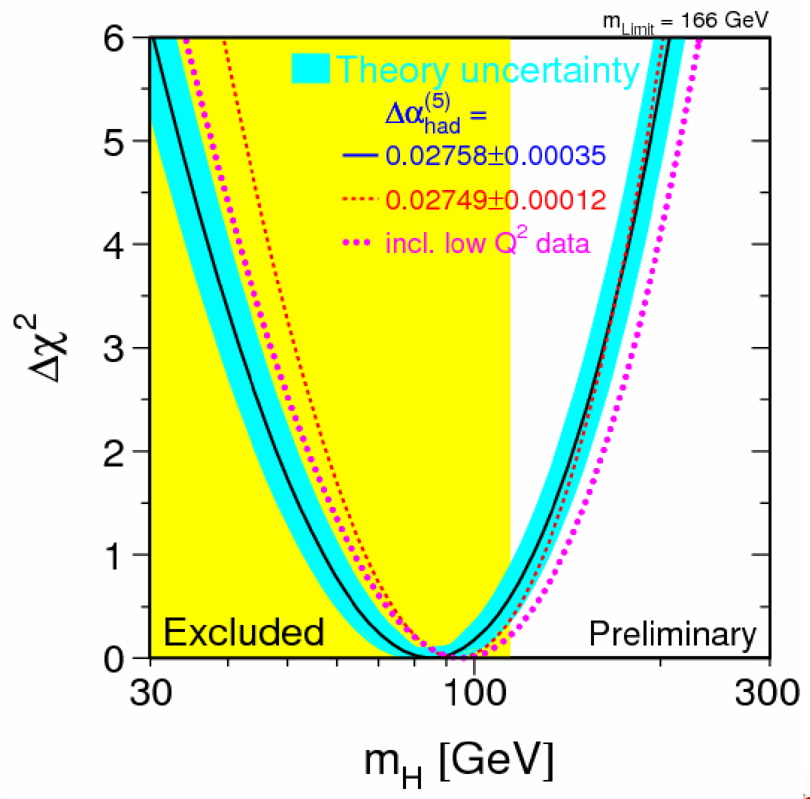
- **$\delta M_W \leq 5$ MeV** looks achievable when combining, or with higher luminosity.

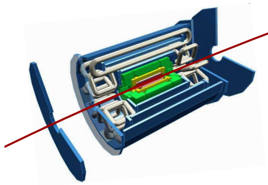
- No results yet, but encouraging situation :
  - QED FSR : recently much improved PHOTOS program (Golonka, Was), now includes radiation up to $O(\alpha^4)$ and exponentiation.
  - W polarisation : affects the lepton distributions, to be studied using WINHAC (Jadach, Placzek), in development



Consequences : M_H determination

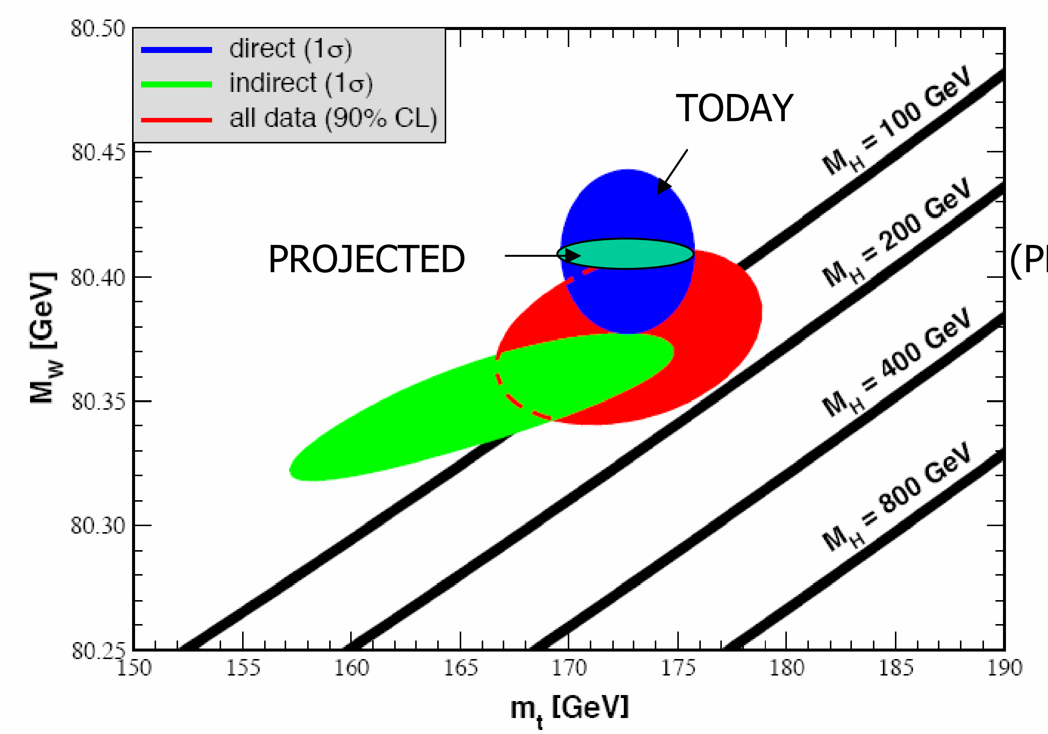
- Just a few comments….
- Today :
  δM_W ~ 30 MeV ; δMt ~ 2 GeV
  → δM_H ~ 45%
  (M_H = 85 +39 -28 GeV)
- Projected :
  δM_W ~ 5 MeV ; δMt ~ 0.5 GeV
  (need to assume M_t improvement!)
  → δM_H ~ 10-15%





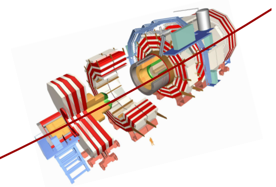
Consequences : SM consistency

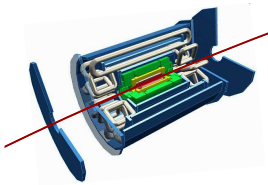
- More interestingly, confront direct / indirect M_W measurements :



(PDG 2006)

→ Question the SM independently of Higgs observation





Conclusions

- At the LHC, W and Z are expected in very large statistics. This promises good control of detector performance (efficiencies, energy scale, resolution)

- Will be improved by orders of magnitude : lepton universality (W,Z BR's), FCNC

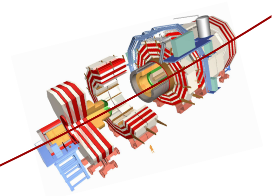
- Cross-sections : the shapes (which play the key role) will be determined $>20 \times$ more precisely than current predictions

- M_W : exploiting all experiments, we can arrange the analysis such that the W phase space is entirely included in the Z one. Hence no extrapolation.

  Acknowledging EW corrections play an important role, but assuming they carry small intrinsic uncertainty, the Z provides enough distributions to disentangle all QCD effects.

  As a result, the case for $\delta M_W \sim \delta M_Z$ is very strong, and critically relies on the theoretical efforts presented at this workshop.

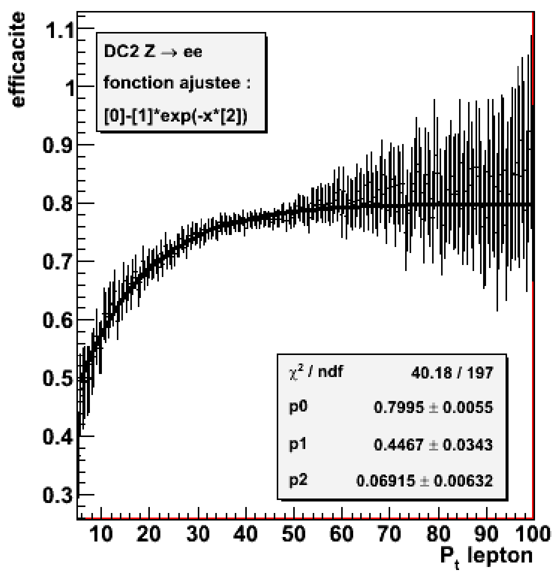
Exciting challenges ahead!

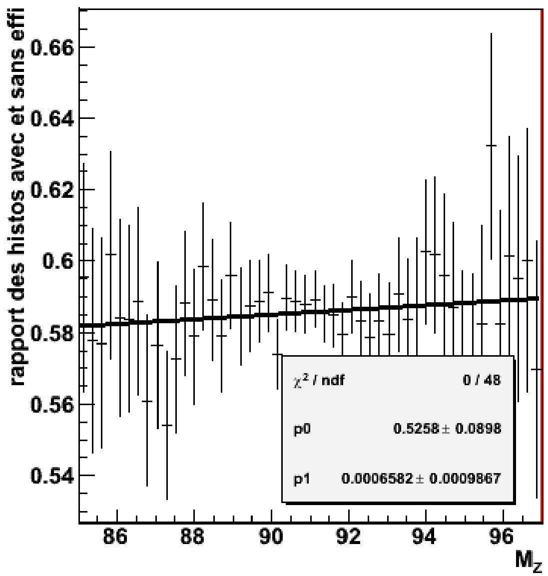


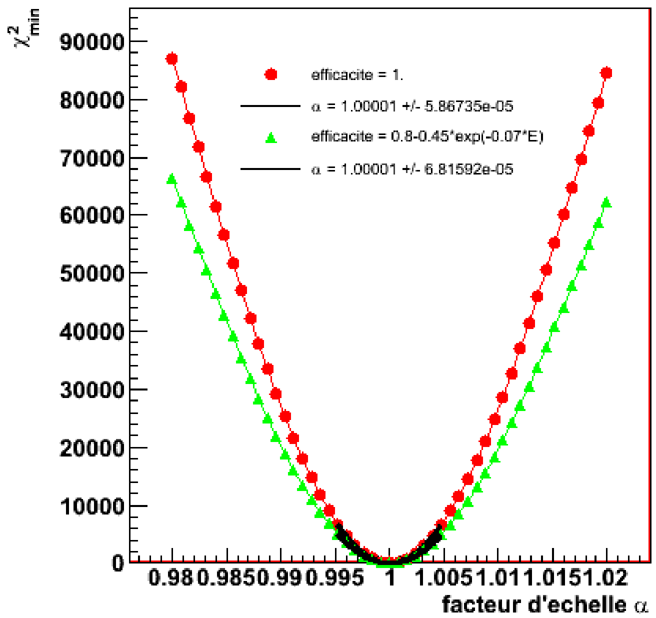
SPARES

Echelle d'énergie et efficacités

- Efficacité ou échelle d'énergie d'abord?
- Rapport entre $d\sigma/dM_Z$ avec et sans efficacité : pas de pente significative.
- L'échelle de masse est constante, avec ou sans fonction d'efficacité dans les « données »







Echelle d'énergie et fonctions de structure

Impact des fonctions de structure sur l'échelle d'énergie:

- La somme quadratique des biais donne **$\delta\alpha \sim 2.5$ MeV** (précision actuelle)
  → **non limitant!**