ATLAS:
Precision Reach for Masses and Couplings

P. J. Bell
On behalf of the ATLAS Collaboration

XXXIXth Rencontres de Moriond
Electroweak Interactions and Unified Theories
La Thuile, March 2004

Synopsis

- LHC Physics Environment
- ATLAS Design and Performance

Precision Physics

- W mass measurement
- Triple Gauge Couplings
- Top Quark Mass

- Summary

Introduction: ATLAS at the LHC

The LHC: More than a discovery machine…

- proton-proton at $\sqrt{s} = 14$ TeV

- 10^{33}cm^{-2}s^{-1} luminosity during first three years

⇒ 10 fb^{-1} integrated luminosity per year

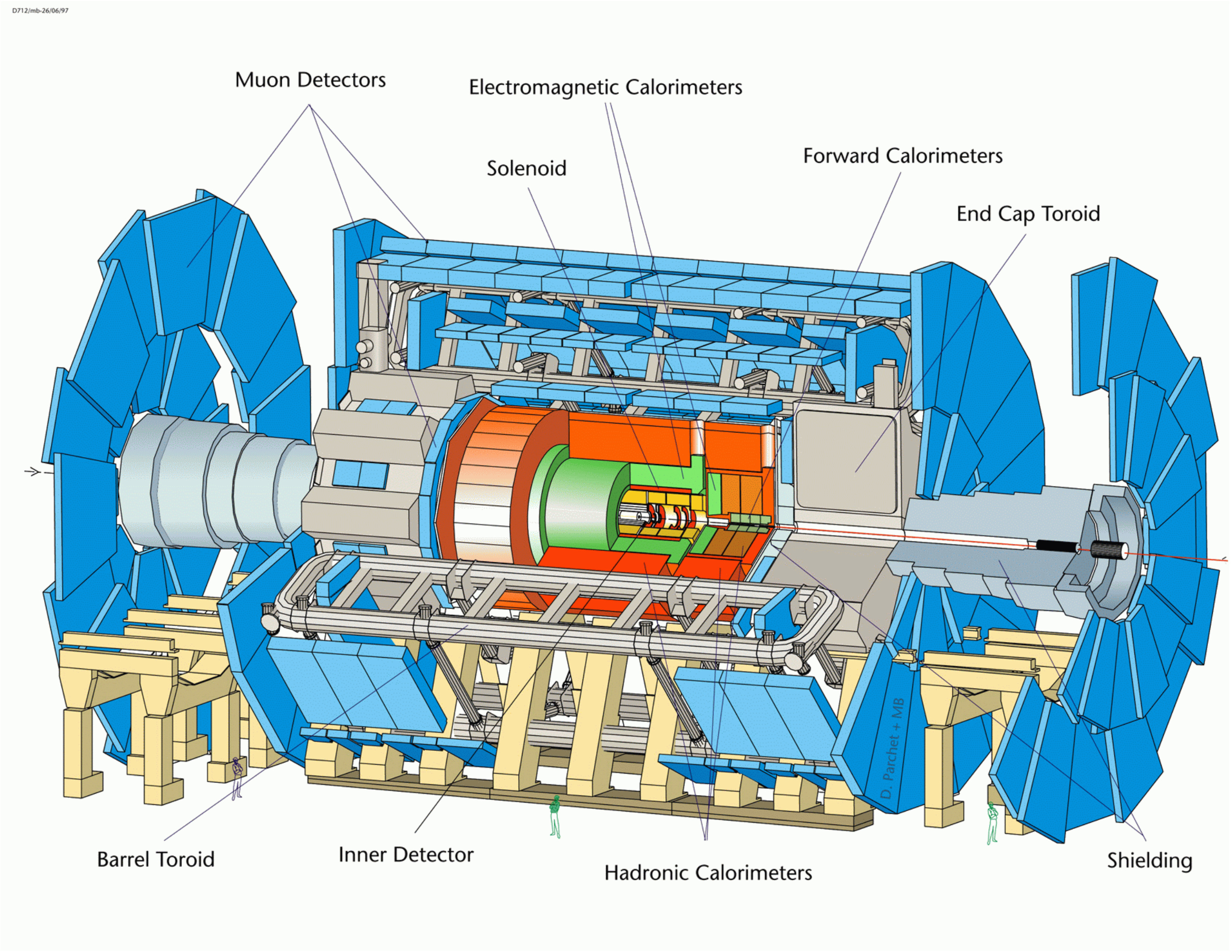
- 10^{34}cm^{-2}s^{-1} design luminosity

⇒ 100 fb^{-1} per year

Process	**Rate [Hz]**	**Events/ Year**	**Events (total)**
$Z \rightarrow e^+e^-$	1.5	$\sim 10^7$	$\sim 10^7$ LEP
$W \rightarrow e\nu$	15	$\sim 10^8$	$\sim 10^4$ LEP
t anti-t	800	$\sim 10^7$	10^4 Tevatron

At low luminosity

ATLAS: Design and Performance



Magnetic Field

2T solenoid plus air core toroid

Inner Detector

$\sigma/p_T \sim 0.05\%\ p_T(\mathrm{GeV})\ (+)\ 0.1\%$

Tracking in range $|\eta| < 2.5$

EM Calorimetry

$\sigma/E \sim 10\% / \sqrt{E(\mathrm{GeV})}\ (+)\ 1\%$

Fine granularity up to $|\eta| < 2.5$

Hadronic Calorimetry

$\sigma/E \sim 50\% / \sqrt{E(\mathrm{GeV})}\ (+)\ 3\%$

Muon Spectrometer

$\sigma/p_T \sim 2\text{-}7\ \%$

Covers $|\eta| < 2.7$

***Precision physics* in $|\eta|<2.5$**

W Mass: Phenomenology

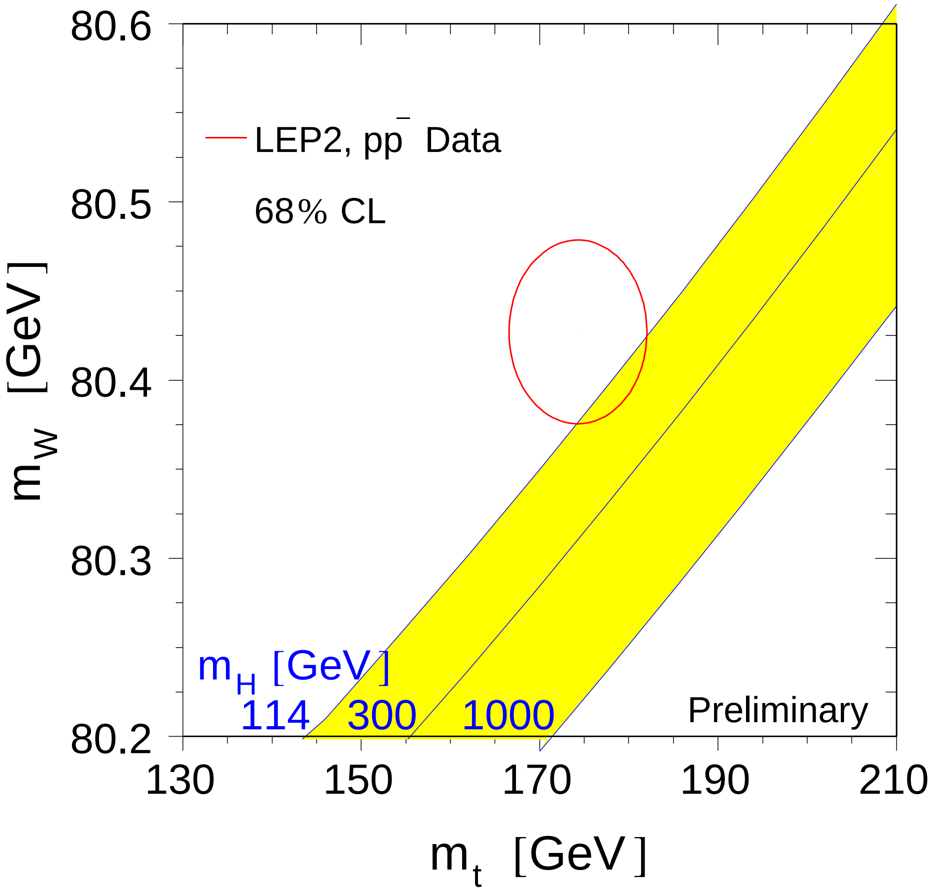
- W mass currently known to about 30MeV from LEP2 and Tevatron

⇒ *Precision can be improved using the large rate at the LHC*

Motivation for improved precision:

- Fundamental parameter of the SM
- Measuring the W and top mass will provide a consistency check on the Higgs mass

⇒ Since top mass will be measured to ~ 2GeV (see later), aim to achieve a precision on the W mass, m_W, of **~15MeV**



W Mass: Measurement

Select: pp → W+X with W→ lν and l = e, μ

- isolated charged lepton with $p_T > 25$ GeV inside $|\eta| < 2.4$
- missing transverse energy $E_T^{miss} > 25$ GeV
- rejection of large p_T W's

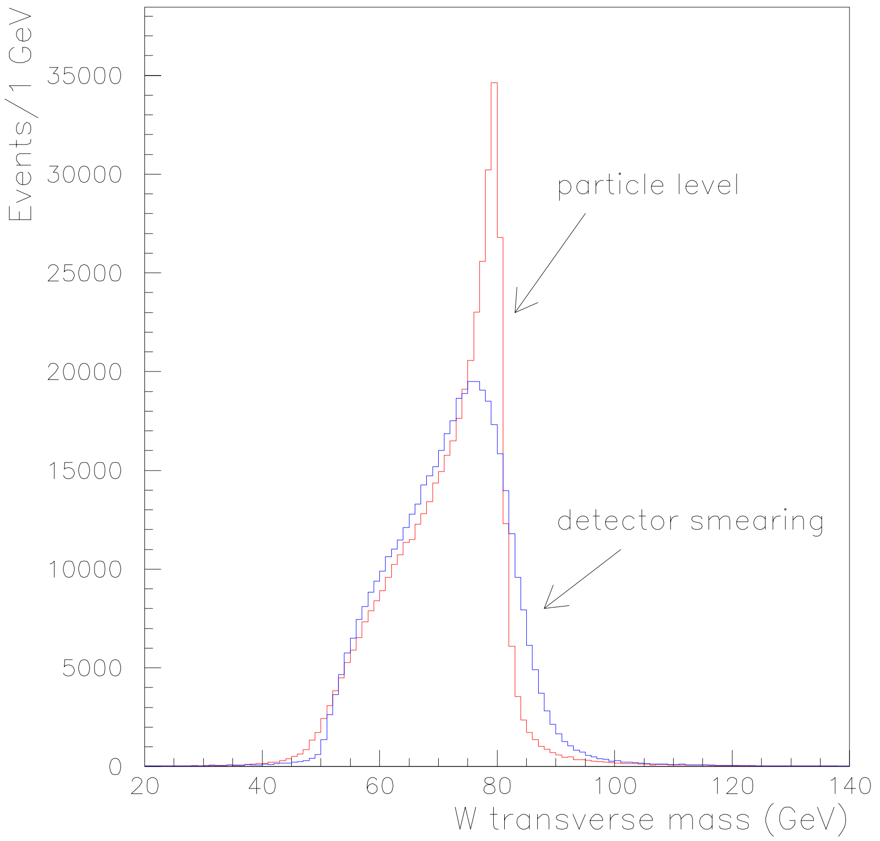
and plot the transverse mass, m_T, given by

$$M_T^W = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

where Δϕ is the azimuthal angle between the l and the recoil X

⇒ Position of falling edge of Jacobian peak sensitive to m_W

- sensitivity is reduced by detector smearing



* LHC cross section is 30nb: after *selection acceptance, reconstruction* and *identification* expect **60M** Ws per low luminosity year => *precision on m_W is systematics limited…*

W Mass: Precision

Source	**Assumptions**	**Δm_W (per channel)**
Statistics	60M Ws/year	<2 MeV
W width		7 MeV
Parton distribution functions		<10 MeV
Recoil modelling		5 MeV
Radiative decays		<10 MeV
p_T^W spectrum		5 MeV
Backgrounds	Known to 30(7)% for e(μ)	5 MeV
Lepton identification		5 MeV
Lepton *E-p* scale	Known to 0.02%	<15 MeV
Lepton *E-p* resolution	Known to 1.5%	5 MeV
Total		**<25 MeV**

Total uncertainty on m_W is **~25MeV** per channel

⇒ Combining channels this reduces to 20MeV (15MeV combined with CMS)

Gauge Couplings: Phenomenology

The self -couplings between the electroweak gauge bosons are specified by the $SU(2)_L \times U(1)_Y$ gauge symmetry of the Standard Model

Measurements of the gauge couplings therefore:

- Provide a test of this non-Abelian structure

⇒ the SM TGCs WWγ and WWZ have been beautifully confirmed at LEP.

But also, probe for possible new physics

⇒ *Anomalous* triple (or quartic) gauge couplings

- The most general Lorentz invariant parametrisation of WWV with V=Z,γ is governed by *14 couplings*, 7 for each vertex.

⇒ EM gauge invariance, C, P and CP conservation: **g_1^Z, κ_Z, λ_Z and κ_γ, λ_γ**

* In the SM, $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$

⇒ usually quote the *deviations* from the SM: **Δg_1^Z, $\Delta\kappa_Z$, λ_Z and $\Delta\kappa_\gamma$, λ_γ (=0 in SM)**

* At LHC, greater sensitivity due to higher luminosity and higher centre-of-mass energy

TGCs: Measurement

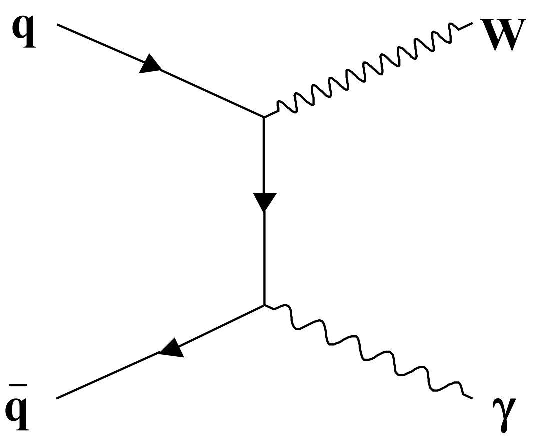
- Any ATGC contribution to some process gives a quadratic increase in the cross-section with the anomalous parameter

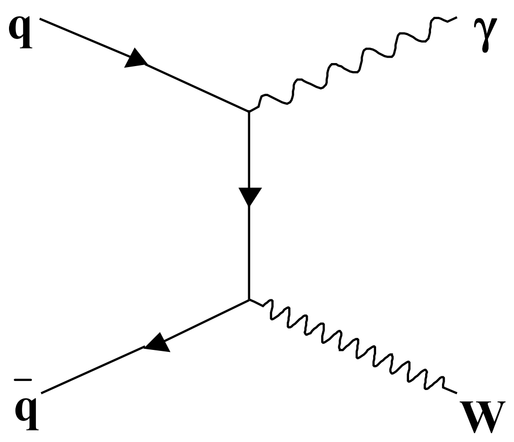
⇒ can set limits on ATGC parameters by comparing observed and expected event rates

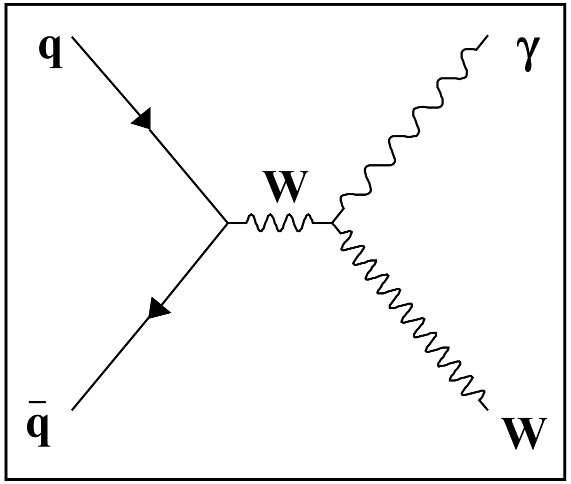
- Method is sensitive to overall normalisation hence systematic errors in, e.g. luminosity, and gives no information about where any AQGC contribution originates

⇒ Better to use a fit to the spectrum of some observable using a MC prediction

Example 1: Measure possible anomalous contribution to **WWγ** in Wγ production







TGCs Example 1: $WW\gamma$

- Consider $pp \rightarrow W\gamma$ with $W \rightarrow l\nu$, $l = e,\mu$

⇒ Maximum likelihood method applied to the p_T spectrum of γ offers good sensitivity to possible anomalous couplings $\Delta\kappa_\gamma$ and λ_γ

Selection:

$P_{T\gamma} > 100\text{GeV}$
$P_{Tl} > 25$ GeV
$P_T^{miss} > 25$ GeV
$\Delta R_{l\gamma} > 1$

⇒ Expect ~3000 events in 30fb^{-1}
(as plotted)

- sensitivity is in high p_T tail
(where backgrounds are small)

TGCs Example 2: WWZ

- Can also measure ATGC contribution to WWZ through pp→WZ

⇒ Maximum likelihood method applied to p_T spectrum of the Z offers good sensitivity to couplings Δg_1^Z, $\Delta\kappa_Z$ and λ_Z

Selection:

3 leptons with $p_T > 25$GeV

(One pair should be of same flavour, opposite sign and satisfy $|m_{ll}-m_Z| < 10$ GeV)

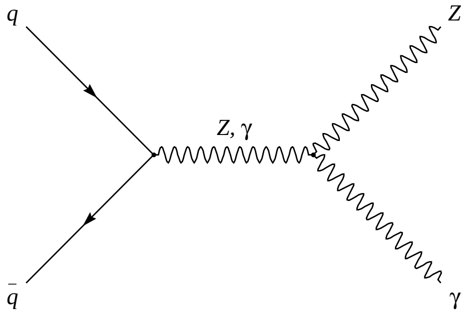
$P_T^{miss} > 25$GeV

⇒ Expect ~1200 events in 30fb^{-1}

Neutral Triple Gauge Couplings

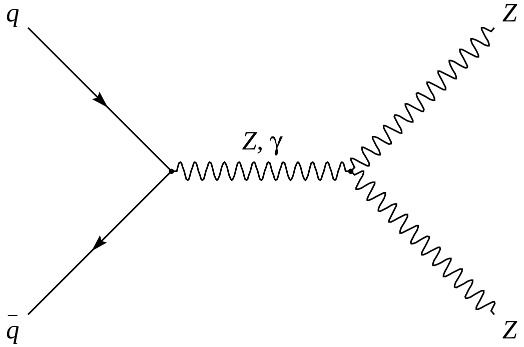
Not Present in the Standard Model

- Possible anomalous $Z\gamma\gamma/ZZ\gamma$ contribution to $pp \to Z\gamma$



Couplings specified by 8 parameters:
h_i^V with i=1…4 and V=Z,γ

- Possible anomalous $ZZ\gamma/ZZZ$ contribution to $pp \to ZZ$:



Couplings specified by 4 parameters:
f_i^V with i=4,5 and V=Z,γ

Example: Fit to the p_T spectrum of the γ
=> Again, the sensitivity is in the tail of the distribution

Triple Gauge Couplings: Precision

- Table shows expected 95% CLs on individual couplings in 30fb^{-1} (*three years* of low luminosity running)
- Both systematics and statistics limited since the sensitivity in the tails of the distributions.
- ~Order of magnitude improvement over LEP limits.

Charged TGC parameter	**95% CL LEP2 (2003)**	**95% CL 30fb^{-1} ATLAS**
$\Delta\kappa_\gamma$	-0.13, +0.13	-0.075, +0.076
λ_γ	-0.089, +0.020	-0.0035, +0.0035
Δg_1^Z	-0.074, +0.028	-0.0086, +0.011
$\Delta\kappa_Z$	-	-0.11, +0.12
λ_Z	-	-0.0072, +0.0072

Top Quark Mass

- m_t is a fundamental parameter of the SM (currently 174.3±5.1GeV, Tevatron Run I)
  - Together with m_W provides consistency check on SM Higgs mass m_H.
  - t quark events are principal background to many other processes
- At low luminosity, expect 8M t anti-t pairs per year (NLO estimate)

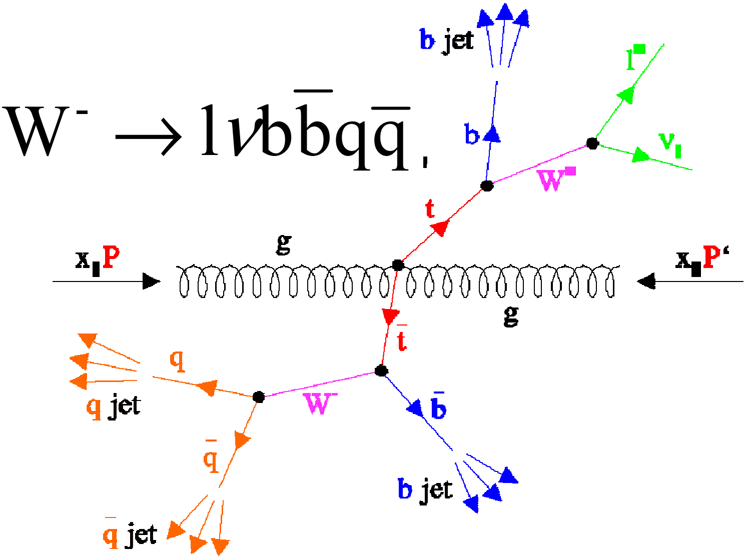
tt decays (99.9% t→Wb)		**BR**	**Events in 10fb^{-1}**
Multi-jet	W→jj and W→jj	44.4%	3.7M
Semileptonic (l=e,μ)	W→jj and W→lν	29.6%	2.5M
Dilepton (l=e,μ)	W→lν and W→lν	4.9%	400,000

For mass measurement most sensitive channel is semileptonic (single lepton plus jets):

- high p_T lepton gives trigger efficiency
- low QCD background compared to multi-jet channel
- favourable branching ratio compared to dilepton channel (and only one missing ν)

Top Mass: Measurement

$t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow l\nu b\bar{b}q\bar{q}$



Selection

Single lepton plus jets channel

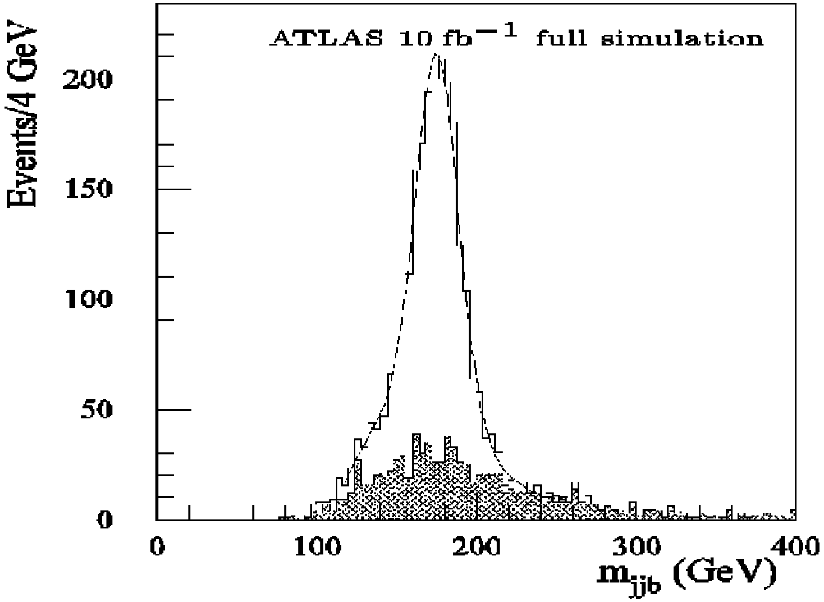
- isolated lepton p_T>20GeV
- E_T^{miss} > 20GeV
- four jets with p_T > 40GeV (including two b-tagged jets)

⇒3.5% efficiency; 87,000 events/year

Mass Measurement

- reconstruct W→ jj from jets *not* b-tagged
- combine the W with a b tagged jet to reconstruct possible jjb combination

⇒Fit the peak in the m_{jjb} spectrum



Top Mass: Precision

- Reconstruction of $t \rightarrow jjb$ demands precise knowledge of energy calibration for the jets (light and b)

⇒ Hope to achieve 1% precision

(W→ jj from t anti-t events will be used as an *in situ* tool for this calibration)

⇒ Limit then comes from uncertainty of FSR

- Could reconstruct the leptonically decaying W channel and fit $m_{jjb}=m_{l\nu b}$ – halves FSR uncertainty

Source	Δm_t
Statistics	0.1GeV
b fragmentation	0.1GeV
ISR	0.1GeV
FSR	1.0GeV
Background	0.1GeV
Light q jet energy calibration	0.2GeV
b quark jet energy calibration	0.7GeV
Total	**~1.3GeV**

Alternative

Use semi-leptonic decays in which one b jet contains a muon and the other a J/Ψ which decays to two muons

⇒ Select 1 isolated lepton and 3 non-isolated muons, 2 of which reconstruct a J/Ψ

- Insensitive to jet energy scale so systematic error on m_t less than 0.9GeV

But, small branching ratio: ~400 events/year at *high luminosity* after selection

Summary

- LHC: high energy and high luminosity

⇒ a discovery machine but also a precision physics tool

⇒ a W factory, a Z factory, a top factory…

- High rates mean precision measurements often limited by systematic effects

but, large samples will allow precise *in situ* calibrations to reduce these

e.g. For W mass measurement

- a challenge to know lepton energy momentum scale to 0.02%, yet have 10^7 $Z \rightarrow ll$ events/year to use for calibration

- Measurement of W mass, gauge couplings and top mass all provide important tests of the electroweak sector. In the first three years should be able to
  - Improve Δm_W from ~30MeV to ~20MeV (at ATLAS)
  - Improve Δm_t from ~5GeV to <2GeV
  - Improve sensitivity on TGCs compared to LEP2 by an order of magnitude