Prospects on Electroweak Physics from the LHC

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- Sources of uncertainties in EW measurments
- Some studies - Top, W, TGC's and Drell Yan
- For details, please consult:

Proceedings of the Workshop on Standard Model Physics (and more) at the LHC, CERN 2000-004, 9 May 2000
ATLAS Detector and Physics Performance Technical Design Report, Volumes 1-2, CERN/LHCC/99-14, 25 May 1999

Introduction

- Main asset - statistics

- Expected LHC luminosity in first three years ("low luminosity"):

  $\mathcal{L} \sim 10^{33} cm^{-2} s^{-1}$ giving $10 fb^{-1}$/year

- Design luminosity ("high luminosity"):

  $\mathcal{L} \sim 10^{34} cm^{-2} s^{-1}$ giving $100 fb^{-1}$/year

- Some cross sections and expected during the "low luminosity" phase:

Process	σ (pb)	Events/second	Events/year
$W \to e\nu$	1.5×10^4	15	10^8
$Z \to e^+e^-$	1.5×10^3	1.5	10^7
$t\bar{t}$	800	0.8	10^7
$b\bar{b}$	5×10^8	5×10^5	10^{12}
$H(m_H = 700$ GeV$)$	1	10^{-3}	10^4
Inclusive jets ($p_T > 200$ GeV)	10^5	10^2	10^9

$\Rightarrow$ LHC a W and Z boson + t and b quark factory

- Statistical error and systematic errors which scale as $1/\sqrt{N}$ will be negligible
- Uncertainties will be dominated by systematic errors arising from detector and physics knowledge

Main Sources of Uncertainties-I

- Lepton energy and momentum scale:
  - Related to the calibration of tracker, electromagnetic calorimeter and muon spectrometer
  - Dominant source of uncertainty on the m_W measurement at the Tevatron - known to 0.1%
  - At the LHC, need to know to $\sim 0.02\%$ for m_W measurement
  - Use the high statistics $Z \to ll$ sample $\Rightarrow$ Z's close in mass to W and MSSM $h \Rightarrow$ reduced extrapolation error from measurement to calibration region + E/p of isolated electrons
  - Tevatron does not have enough Z's, rely on J/ψ and π^0
  - Preliminary studies from ATLAS with 500000 $Z \to ee$ decays with full simulation:

Source	Requirement	Uncertainty on scale
Material in inner detector	Known to 1%	$< 0.01\%$
Radiative decays	Known to 10%	$< 0.01\%$
Underlying event	Calibrate and subtract	$\ll 0.03\%$
Pile-up at low luminosity	Calibrate and subtract	$\ll 0.01\%$
Pile-up at high luminosity	Calibrate and subtract	$\ll 0.01\%$

  - Difficult but not impossible...

Main Sources of Uncertainties-II

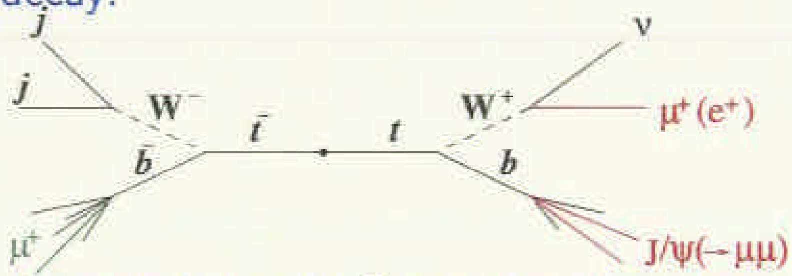
- Jet Energy Scale:
  - Contributes to the uncertainty on m_t measurement
  - Depends not only on the detector but also the knowledge of physics (fragmentation, gluon radiation, etc.)
  - Known to a precision of 3% at the Tevatron using mainly events with a γ or a Z decaying into leptons balanced by one high p_T jet
  - LHC goal - 1% - can use $W \to jj$ from $t \to bW$ for light quark jet calibration, in addition
  - $t\bar{t}$ final states with $t \to bl\nu$ and $t \to bjj$ relatively clean and have a high rate at LHC (~ 0.3 Hz)
- Knowledge of Absolute Luminosity:
  - Contributes to uncertainty in all cross-section measurements
  - Several methods envisaged (very forward two-photon e^+e^- pairs, central two photon production of $\mu^+\mu^-$ pairs)
  - Currently, expected precision $\sim 10\%$ (ATLAS) - will be the dominant systematic error on all cross section measurements
  - Promising : use of W and Z production rate - 1% possible (M.Dittmar, F. Pauss, D. Zurcher, Phys Rev D56, 7284(997))
  - But, need improved theoretical understanding of mechanisms

Measurements in the top-quark sector

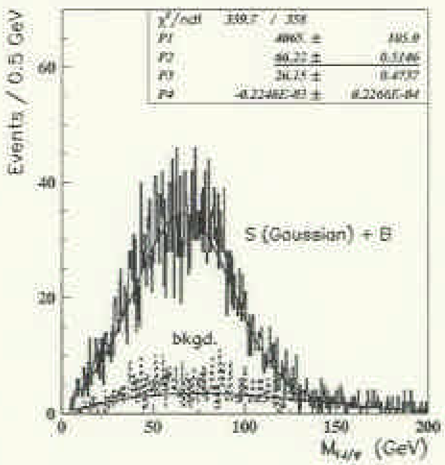
- Precision measurements in this sector necessary to get more clues on the origin of the fermion mass hierarchy
- Exploration of top properties only just begun at the Tevatron...
- At the LHC, the large statistics will allow measurements of mass, production cross section, branching ratios, couplings and exotic decays
- $t\bar{t}$ production main background to new physics processes + top events will be used to calibrate the jet energy scale.
- $t\bar{t}$ production cross section: Tevatron $\sim$ 7pb, LHC ~ 800pb + higher LHC luminosity $\Rightarrow$ LHC statistics $\sim 1000\times$ Tevatron
- In 2005: $\Delta m_t \sim 3$ GeV (Tevatron)
- At the LHC, statistical error < 100 MeV - precision limited by systematics:
  - 1% uncertainty on jet scale $\Rightarrow \sim 2$ GeV on m_t
  - Further improvements by using high p_t $t\bar{t}$ pairs (decay products well separated and less sensitive to jet recontruction
- Total uncertainty of 1% may be achieved

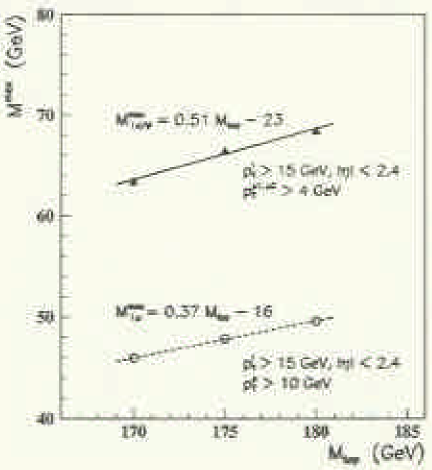
Measurement of the top Mass

- New idea from CMS - exploit correlation between m_t and the invariant mass distribution of J/ψ (from the decay of a b-hadron) and the lepton from the associated W decay:



- Overall branching ratio 5.3×10^{-5} but very clean and can be used at the highest luminosity - expect 1000 events/year at high luminosity





- Correlation between $M_{J/\psi}l$ and m_t stronger than $l\mu$
- Systematic uncertainty, $\Delta m_t \leq 1$ GeV achievable

W Mass Measurement

- At LHC startup, precision on W mass, $\Delta m_W \sim 30$ MeV (LEP2 and Tevatron)

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

- Radiative corrections, $\Delta r \propto m_t^2$ and $\log m_H \Rightarrow m_t$ and m_W contrain the mass of SM Higgs and MSSM h
- To be able to compare measurements with SM predictions, necessary to have similar weights for m_W and m_t in a χ^2 test

$$\Delta M_W \approx 0.7 \times 10^{-2} \Delta m_t$$

- $m_t \sim 2$ GeV at the LHC $\Rightarrow \Delta m_W \sim 15$ MeV - beyond Tevatron and LEP2
- Constrain on $m_H \sim 30\%$ - if/when the Higgs is found, will provide an important consistency check of the theory
- Expect 300 million events/year/experiment at low luminosity - factor 10 larger than Tevatron

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Measurement of W Mass - ATLAS

- Use leptonic decays of the W:

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

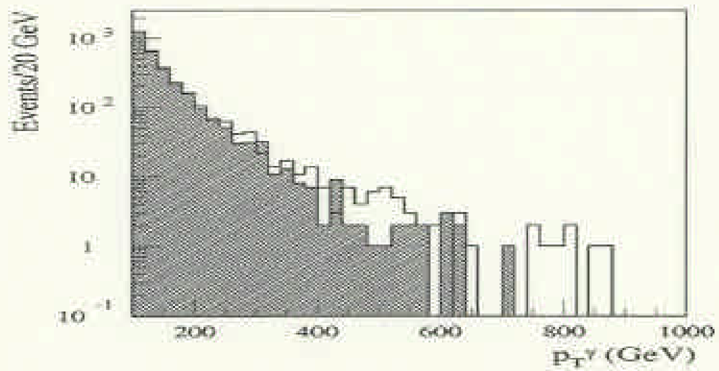
- p_T^ν obtained from p_T^l and recoil

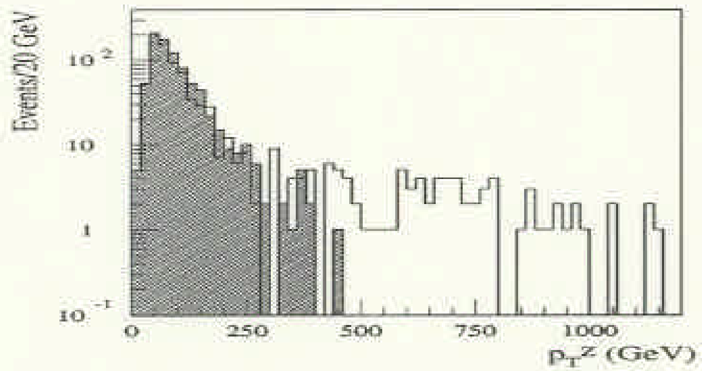
Source	ΔM_W (CDF I) (MeV)	ΔM_W (CDF IB) (MeV)	ΔM_W (ATLAS) (MeV)
Statistics	145	65	< 2
$E - p$ scale	120	75	15
Energy resolution	80	25	5
Recoil model	60	33	5
Lepton identification	25	–	5
p_T^W	45	20	5
Parton distribution functions	50	15	10
W width	20	10	7
Radiative decays	20	20	< 10
Background	10	5	5
TOTAL	230	113	< 25

Combination of both lepton channels+ATLAS and CMS, LHC uncertainty reduceable to ~ 15 MeV

Determination of TGC's

- Study of Triple-Gauge Couplings ($WW\gamma$ or WWZ) provide direct test of non-abelian structure of the SM gauge group
- May yield hints of New Physics - many new processes expected to give anamolous contributions to triple-gauge vertices
- SM : five parameters g_1^Z (0), λ_γ, λ_Z (0) and κ_γ, κ_Z (1)
- In 2005: $\sim 10\%$ precision from LEP2 and Tevatron
- LHC will benefit from large statistics and high centre-of-mass energy
- With $30\ fb^{-1}$, shaded histogram: SM, white histogram: $\lambda_\gamma = 0.01$ (left) and $g_1^Z = 0.05$ (right):





- Enhancement at high $p_T^{\gamma,Z}$ clearly visible
- Expect: $\sim 2500(W\gamma)$ and $1200(WZ)$ events with background (ATLAS)

Determination of TGC's

- Different extraction techniques depending on the statistics and dimensionality of experimental distributions
- Use binned maximum likelihood fit to distributions of the observables, combined with total cross section information
- Expected sensitivity limits (95% CL) at LHC with 30 fb^{-1}(ATLAS) and 100 fb^{-1}(CMS):

Vertex	Coupling	$(m_{W\gamma}, \lvert\eta^*\rvert)$	(p_T^γ, θ^*)	p_T^γ
$WW\gamma$	$\Delta\kappa_\gamma$	0.035	0.046	0.043
$\Lambda_{FF} = 10$ TeV	λ_γ	0.0025	0.0027	0.0020
WWZ	Δg_1^Z	0.0078	0.0089	—
	$\Delta\kappa_Z$	0.069	0.100	—
$\Lambda_{FF} = 10$ TeV	λ_Z	0.0058	0.0071	—
$ZZ\gamma$	h_{30}^Z	—	—	6.4×10^{-4}
$\Lambda_{FF} = 6$ TeV	h_{40}^Z	—	—	1.8×10^{-6}

Expect an improvement in sensitivity by up to two(four) orders of magnitude for anamolous $WW\gamma/WWZ(ZZ\gamma)$ couplings wrt current Tevatron limits

Drell-Yan Production of Lepton Pairs

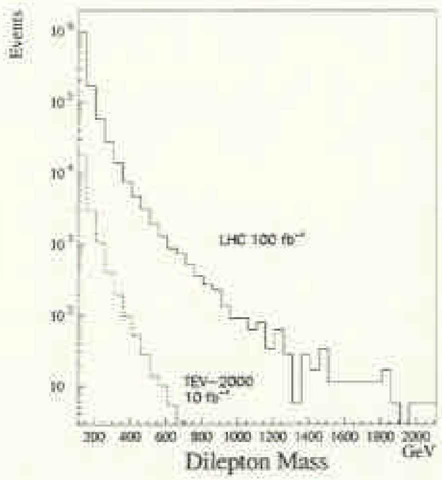
- In the SM, production of lepton pairs in hadron-hadron collisions described by s-channel exchange of γ or Z bosons

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{\alpha^2}{4s}[A_0(1+\cos^2\theta) + A_1\cos\theta]; \hat{\sigma} = \frac{4\pi\alpha^2}{3s}A_0, A_{FB} = \frac{3}{8}\frac{A_1}{A_0}$$

- At the Z-peak, Z dominates the exchange, at higher energies both γ and Z contribute

$$\frac{d\hat{\sigma}}{d\Omega} \sim |\gamma_s + Z_s + \text{New Physics ?!}|^2$$

Events near the Z-pole: $\sin^2\theta_{eff}^{lept}$ and pdf's
High mass pairs (110-400 GeV): precision studies at the LHC
Very high mass pairs (400-4000 GeV): sizeable sample at LHC for tests of SM, searches of new phenomena at the TeV scale



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Drell-Yan Production of Lepton Pairs

- Comparison of event yields:

Pair Mass	LEP2 600 pb^{-1} SM / Data	CDF 110 pb^{-1} Data	TEV2 10 fb^{-1} PYTHIA	LHC 100 fb^{-1} PYTHIA
Z pole	-	-	$\sim 1.5 \times 10^6$	$\sim 134 \times 10^6$
> 110 GeV	12500	148 ($>$ 150 GeV)	46000	2.6×10^6
> 400 GeV	-	1	250	33000

- Measurement of $\sin^2 \theta_{eff}^{lept}$ - difficult to compete with LEP/SLC and Tevatron (central acceptance, PDF control) $\Rightarrow$ can improve PDF
- Possible to measure $\frac{\sigma_{DY}^{high\,Q^2}}{\sigma_Z}$ with $< 1\%$ systematic error
- A_{FB} can be measured upto 2 TeV with $> 3\sigma$
- Probe EW radiative corrections as a function of Q^2 up to 1.5 TeV at 2σ level
- Rich search field - low scale gravity, contact interactions, sneutrinos, Z'

Conclusions

- In addition to its huge potential for the discovery of New Physics, LHC will allow precision measurements if the EW sector
- Significant improvements on Tevatron and LEP results obtainable with only one-two years of operation
- Some illustrative studies presented - non exhaustive
- Statistical error will be negligible for most measurements - systematic effects will limit precision
- Precision of many measurements will be limited by the knowlegde of physics
- Need improved theoretical calculations to match experimental accuracy