PRECISION PHYSICS WITH THE ATLAS DETECTOR AT THE CERN LHC

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- SM precise measurements (examples) :
  - -- W mass
  - -- Top mass
  - -- Triple Gauge Couplings
- SM Higgs physics :
  - -- Discovery potential
  - -- Measurements of parameters
- B physics:
  - -- CP-violation and aspects of CKM matrix
  - -- Rare B decays

Large Hadron Collider

14 TeV pp Interactions

Most recent machine schedule:
-- 2006: commissioning
-- 2006: Pilot run
-- 2006-7: physics run with ~10 fb^{-1}

$\rightarrow$ 2006 run: understand/calibrate the (complex) LHC detectors, using ~ 10 million W $\rightarrow$ l ν, 2 million Z $\rightarrow$ ll events, 1 million tt events

$\rightarrow$ 2006-7 run: ready for "discovery physics"

Luminosity:
$L_{peak} < 10^{33}\ cm^{-2}\ s^{-1}$ ("low L")
$L_{peak} < 10^{34}\ cm^{-2}\ s^{-1}$ ("high L")
100 fb^{-1} per year
High L: ~ 20 soft interactions per crossing (pile-up)

$\rightarrow$ LHC is a B-factory, top factory, W/Z factory,
Higgs factory, SUSY factory, etc.

$\rightarrow$ Mass reach: up to ≈ 5 TeV
$\rightarrow$ Precision measurements limited by systematics
(mainly performed at low L $\rightarrow$ 'clean' environment)

LHC statistics

Production rates per experiment at 10^{33} cm^{-2} s^{-1}

Process	Events/s	Events/year	Other machines (total statistics)
$W \rightarrow e\nu$	15	10^8	10^4 LEP / 10^7 Tev.
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^5 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
Higgs (m=120 GeV)	0.02	10^5	—
QCD jets $p_T > 200$ GeV	10^2	10^9	10^7

ATLAS Performance and Requirements

MAGNET	Air-core toroids + solenoid in inner cavity Calorimeters outside field, 4 magnets
TRACKER	Si pixel + strips, TRD $\rightarrow$ particle ID, B=2T, $\sigma/p_T \sim 5\times10^{-4}\, p_T + 0.01$
EM CALO	Pb- liquid argon, $\sigma/E \sim 10\%/(E)^{1/2}$, uniform longitudinal segmentation
HAD CALO	Fe-scintillator + Cu-liquid argon (10 λ), $\sigma/E \sim 50\% /(E)^{1/2} + 0.03$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 7\%$ at 1 TeV standalone

- Lepton measurement: $p_T \approx$ GeV $\rightarrow$ 5 TeV
  ($b \rightarrow \ell X$, W'/Z')
- Mass resolution (m ~ 100 GeV) :
  - $\approx$ 1 % ($H \rightarrow \gamma\gamma, 4\ell$)
  - $\approx$ 10 % ($W \rightarrow jj$, $H \rightarrow bb$)
- Calorimeter coverage : $|\eta| < 5$
  (E_T^{miss}, forward jet tag for strongly interacting Higgs)

- Particle identification :

$\varepsilon_b \approx 50\,\%$	$R_j \approx 100$	($H \rightarrow bb$, SUSY)
$\varepsilon_\tau \approx 50\,\%$	$R_j \approx 100$	($A/H \rightarrow \tau\tau$)
$\varepsilon_\gamma \approx 80\,\%$	$R_j > 10^3$	($H \rightarrow \gamma\gamma$)
$\varepsilon_e > 50\,\%$	$R_j > 10^5$	$\leftarrow$ e/jet ~ 10^{-3} $\sqrt{s}$ = 2 TeV e/jet ~ 10^{-5} $\sqrt{s}$ = 14 TeV

Three crucial parameters for precise measurements

Uncertainties on :

- Absolute luminosity : goal < 5%

  Main tools: machine, optical theorem, rate of known processes (W, Z, QED pp $\rightarrow$ pp $\ell\ell$)

- ℓ energy scale : goal 1‰ most cases

  0.2‰ W mass

  Main tool: $Z \rightarrow \ell\ell$ (1 event / ℓ /s at low L)
  close to m_W, m_h

  N.B.: 1‰ achieved by CDF/D0 (despite small Z sample)

- Jet energy scale : goal 1% (m_{top}, SUSY)

  (limited by physics)

  Main tools : Z + 1 jet ($Z \rightarrow \ell\ell$)
  $W \rightarrow jj$ from top decays
  (10^{-1} events/s low L)

  N.B. 4% at Tevatron

Requirements: tracker material to 1%, overall alignment to < 1 μm, overall B-field to < 0.1%, muon E-loss in calorimeters to 0.25%, etc.

W mass

Year 2006 : $\Delta m_W < 30$ MeV LEP2+Tevatron

Motivation to improve:

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

↑ $f\,(m_{top}^2, \log m_H)$

$\Delta m_W \approx 0.7 \times 10^{-2}\, \Delta m_{top}$ to get similar errors

$\Delta m_{top} \sim 1.5$ GeV (LHC) requires

$\Delta m_W \approx 15$ MeV

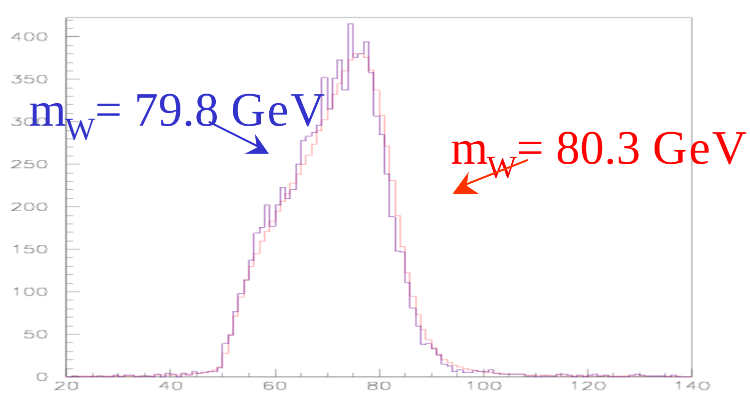
-- constrains m_H to 25%

-- if/when Higgs found: check consistency of theory

- Main asset at LHC: large statistics of $Z \to \ell\ell$ (6 million for 10 fb^{-1})
- Most serious challenge: lepton scale must be known to ~ 0.02%. Should be possible because Z-mass very close

→ hope to measure m_W to ± 15 MeV at LHC

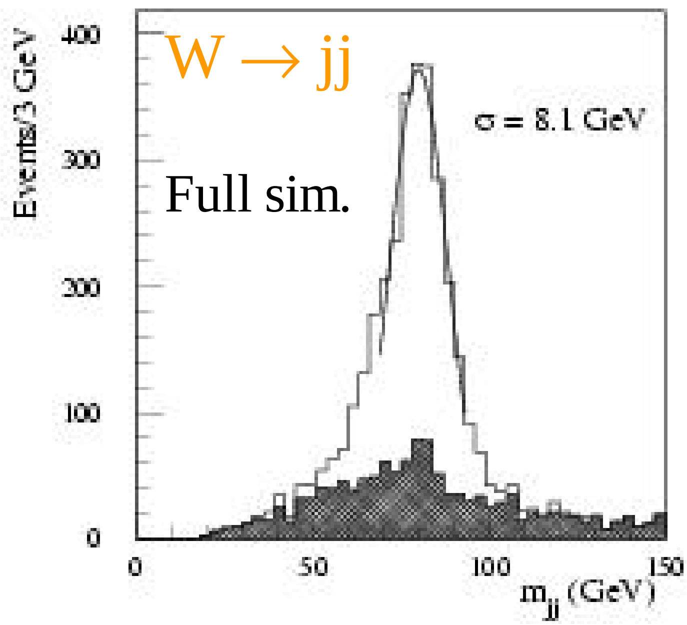
Expect ~ 60 million well measured $W \to \ell\nu$ (ℓ = e, μ) for 10 fb^{-1} (~ 10 times larger cross-section than at Tevatron)

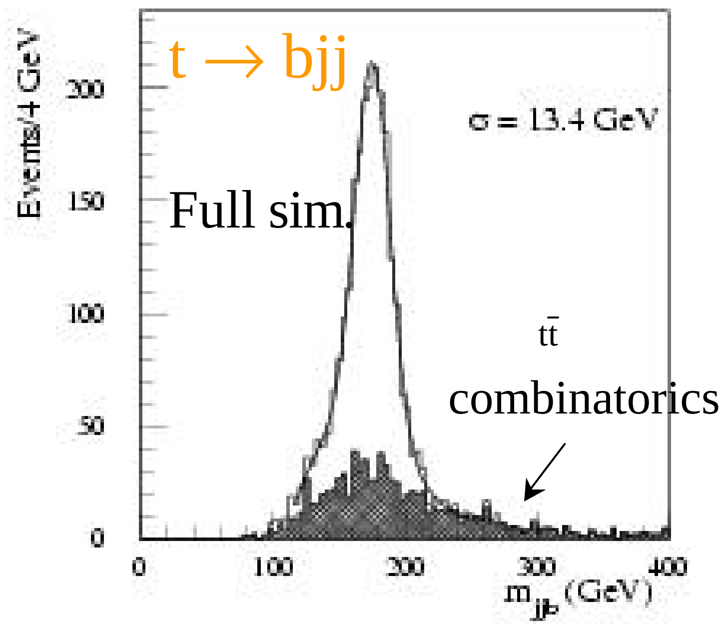


m_T^W (GeV)

Top mass

- Year 2006 : $\Delta m_{top} \approx$ 2-3 GeV (Tevatron)
- Best channel: $t \to Wb \to \ell\nu b$ $t \to Wb \to jjb$
- After all cuts : 130 000 $t\bar{t}$ events 10 fb^{-1}, S/B ~ 65





Contribution	Δm_{top} (GeV)
statistics	< 0.07
light-jet scale	0.3
b-jet scale	0.7
b-fragmentation	0.3
ISR	0.3
FSR	1.2
background	0.2
Total	≈1.5 GeV

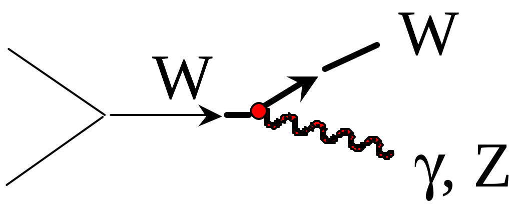
10 fb^{-1}
1 experiment

} jet scale known to 1%

limited by knowledge of physics

Other methods (high-p_T top, 2ℓ and 3ℓ channels): similar error but different systematics

Triple Gauge couplings



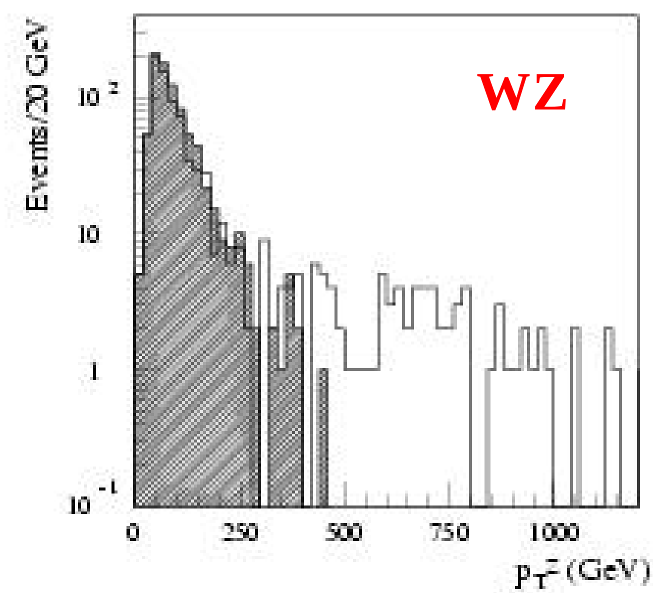
$W\gamma \rightarrow \ell\nu\,\gamma$
$WZ \rightarrow \ell\nu\,\ell\ell$

- Probe non-Abelian structure of SU(2) x U(1) and sensitive to New Physics
- Year 2006 : g^1_Z, λ_γ, k_γ, λ_Z, k_Z known to $\leq 10^{-2}$ from LEP2+Tevatron
- Some anomalous contributions (λ-type) increase with s
  $\rightarrow$ high sensitivity at LHC
- Sensitivity from :
  -- cross-section (mainly λ-type) and p_T measurements
  -- angular distributions (mainly k-type)

30 fb^{-1}
1 experiment

SM

Δg^1_Z=0.05

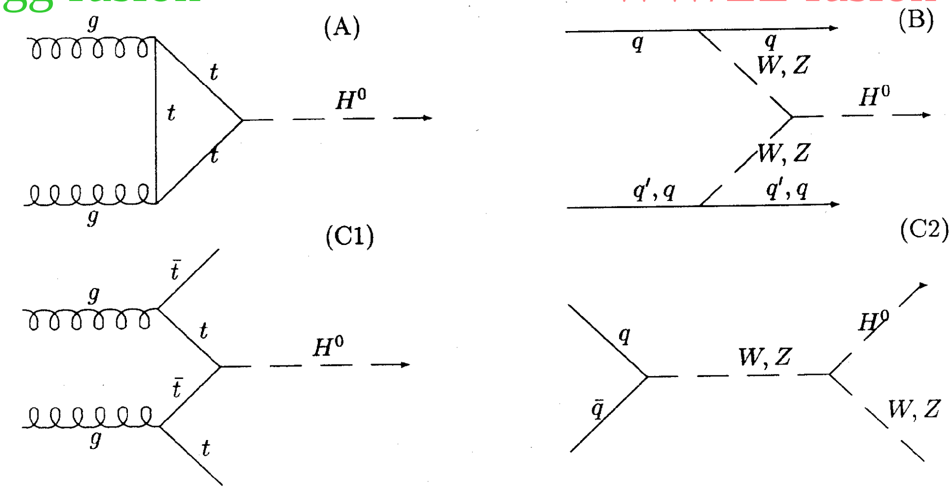


Higgs Physics

SM Higgs production

gg fusion

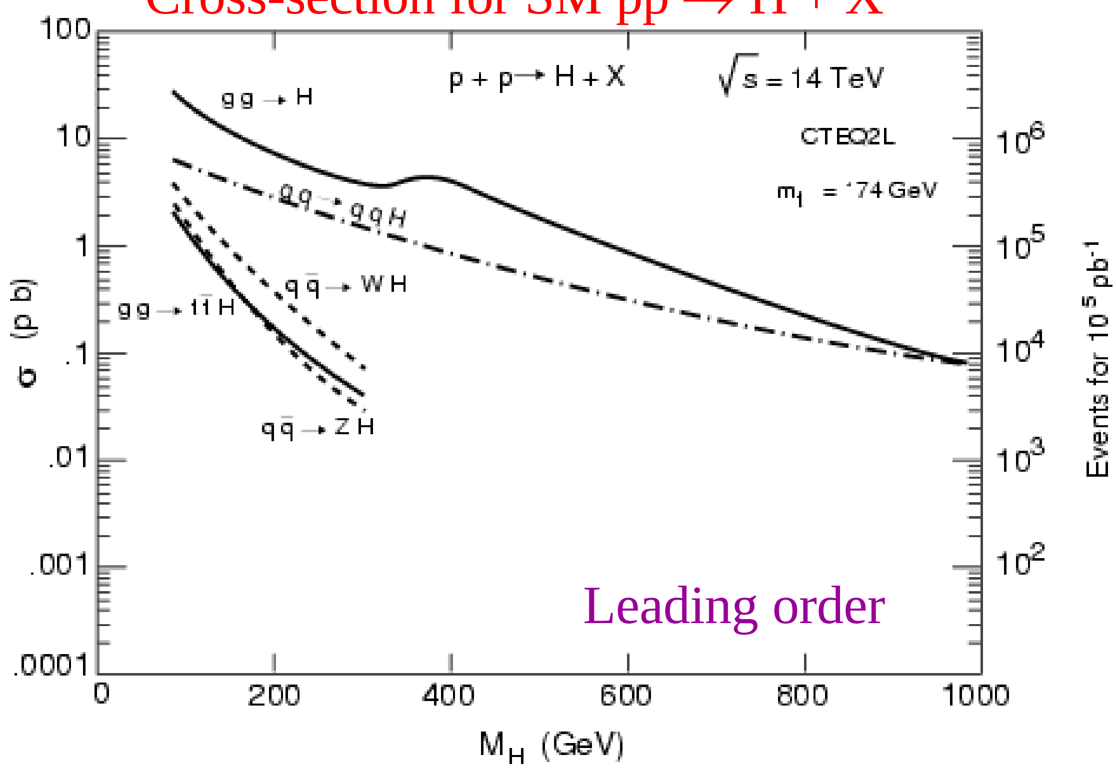
WW/ZZ fusion



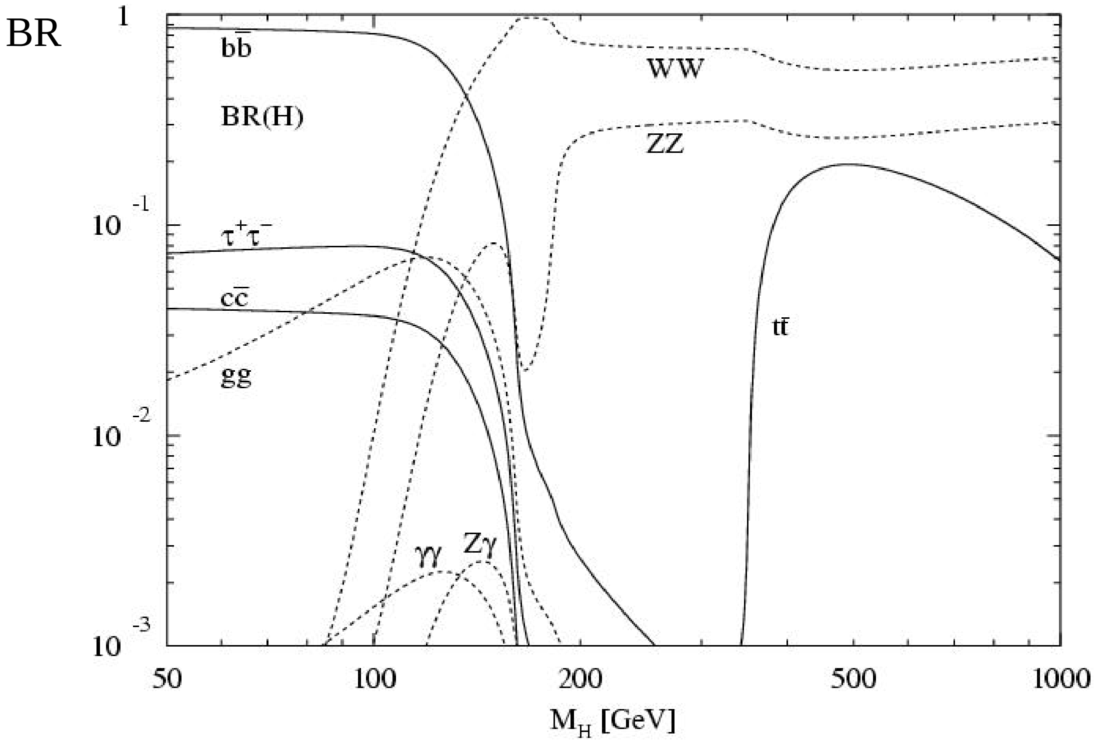
associated $t\bar{t}H$

associated WH, ZH

Cross-section for SM pp → H + X



Main search channels at LHC



Fully hadronic final states dominate but cannot be extracted from large QCD backgrounds:

e.g. σ (H $\rightarrow b\bar{b}$) ≈ 20 pb direct production, m_H =120 GeV

σ ($b\bar{b}$) ≈ 500 μb

$\rightarrow$ no hope to trigger / observe H $\rightarrow$ bb, ττ, cc, gg

$\rightarrow$ look for final states with ℓ, γ (ℓ = e,μ)

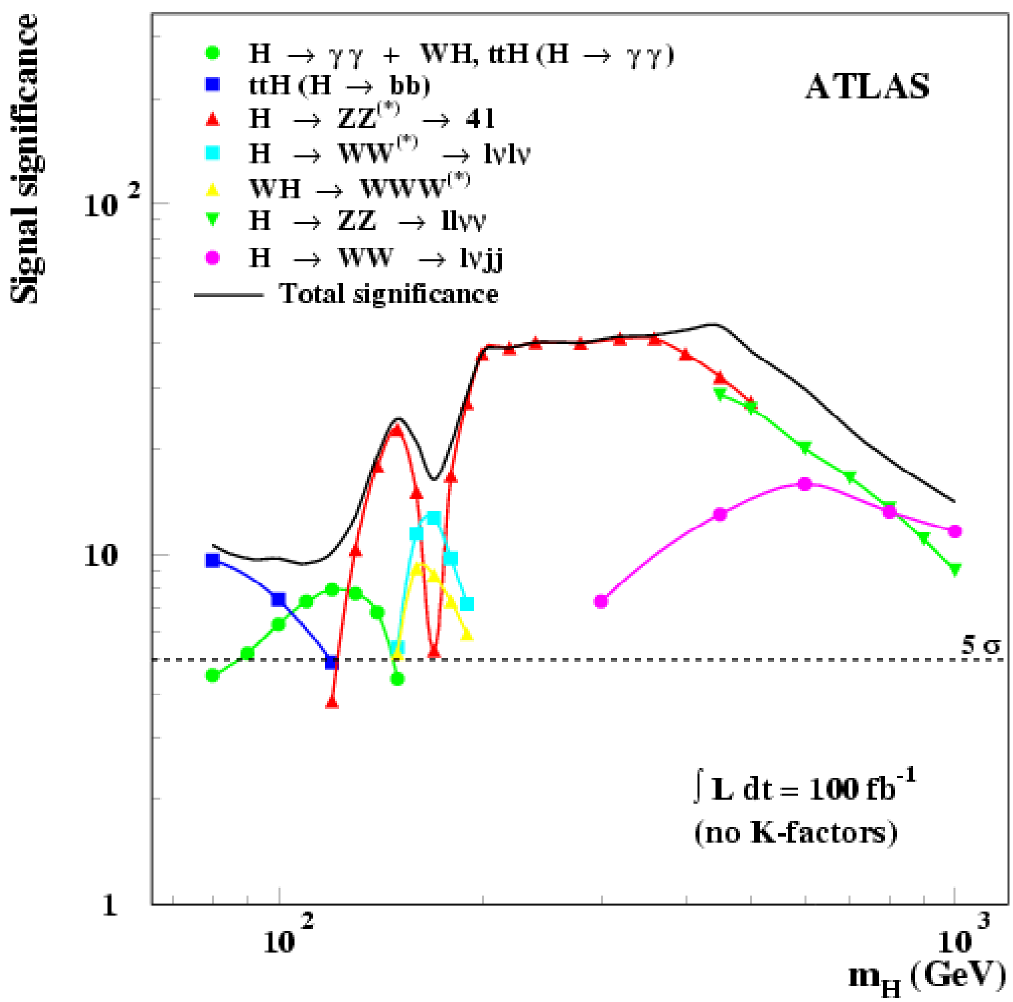
m_H < 130 GeV : $t\bar{t}H \rightarrow \ell b\bar{b} + X$, $H \rightarrow gg$

m_H > 130 GeV : Main channel is $H \rightarrow ZZ \rightarrow 4\ell$ (gold-plated)

Detector performance is crucial: b-tag, ℓ/γ E-resolution, γ /j separation, E_T^{miss} resolution, etc.
Higgs sector used as benchmark for detector optimisation

Overall discovery potential for SM Higgs

$$\frac{S}{\sqrt{B}}$$



- m_H > 130 GeV : discovery is straightforward with gold-plated $H \rightarrow ZZ \rightarrow 4\ell$ channel ($S/B \geq 3$).

- m_H < 130 GeV : mainly $H \rightarrow \gamma\gamma$, $ttH \rightarrow ttbb$
  - -- LEP "hints" at ~115 GeV
  - -- relevant to MSSM

100 fb^{-1} : ~ 4 years of LHC operation

Measurement of the Higgs mass

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No theoretical error
e.g. mass shift for large Γ_H (interference resonant/non-resonant production)

Precision 0.1% - 1%

ATLAS 300 fb^{-1}

$$\frac{\Delta L}{L} = 5\%$$

Dominant systematic uncertainty: γ/ℓ E scale.

Assumed 1‰
Goal 0.2‰

Measurements of couplings (few preliminary examples)

- measure ratios of rates for different channels
  $\rightarrow$ cross-section, L, Γ cancel $\rightarrow$ get ratios of couplings
  $\rightarrow$ many constraints of theory

- Errors: statistics (dominant), systematics on background subtraction in some channels

ATLAS
300 fb $^{-1}$

From gg-fusion :

$$\frac{R\ (H \rightarrow gg)}{R\ (H \rightarrow ZZ \rightarrow 4\ell)} \Rightarrow \frac{g_{Hgg}}{g_{HZZ}}$$

$120 \leq m_H \leq 150$ GeV
precision ~15%

$$\frac{R\ (H \rightarrow WW \rightarrow \ell n \ell n)}{R\ (H \rightarrow ZZ \rightarrow 4\ell)} \Rightarrow \frac{g_{HWW}}{g_{HZZ}}$$

$150 \leq m_H \leq 180$ GeV
precision ~15%

From associated ttH, WH :

$$\frac{R\ (ttH + WH \rightarrow gg)}{R\ (ttH + WH \rightarrow bb)} \Rightarrow \frac{g_{Hgg}}{g_{Hbb}}$$

$80 \leq m_H \leq 120$ GeV
precision ~30%

$$\frac{R\,(ttH \rightarrow gg, bb)}{R\,(WH \rightarrow gg, bb)} \Rightarrow \frac{g_{Htt}}{g_{HW}}$$

$80 \leq m_H \leq 120$ GeV
precision ~25%

Measurement of SM Higgs width

Direct measurement : from width of reconstructed mass peak for m_H > 200 GeV ($\Gamma_H > \Gamma_{detector}$ in SM)

Systematics: luminosity (~5%),
cross-section (~5%),
background subtraction (< 5%),
radiative $Z \rightarrow \ell\ell\gamma$ (1.5%)

Precision 6%
300 GeV < mH < 700 GeV

Statistics and systematic errors included

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ATLAS
300 fb^{-1}

Measurement of the Higgs production rates ($\sigma \cdot BR$)

Typical precision: 7%(12%)
120 GeV < mH < 600 GeV

Dominant errors: statistics, luminosity, background systematics

$$\frac{\Delta L}{L} = 5\% \ (10\%)$$

ATLAS 300 fb^{-1}

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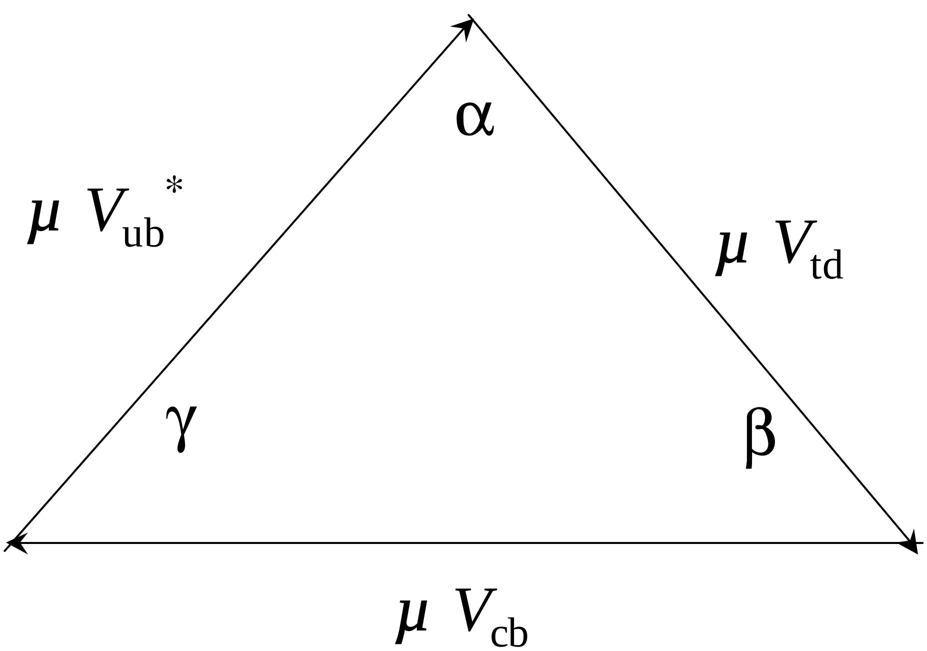
ATLAS B physics potential

Why B physics around CKM?

- Check CKM matrix description of CPV
- Measurement of fundamental SM parameters (⇒are theoretical « predictions » of CKM angles and magnitudes correct? Hints of underlying theory)
- Overconstrained system (triangle closure and # measurements of same quantity):
  - Check of assumptions in calculations in B systems
  - Look for deviations from new physics

CKM Unitarity Triangle

$$V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} = 0$$



arg V_{cb} = 0, arg V_{ub} = – γ, arg V_{td} = – β

$B^0 \rightarrow J/\psi\ K^0_s$:sin(2β)

- Gold-plated mode: clean both experimentally and theoretically
- Asymmetry:

$$A(t)= \frac{N(B^0 \rightarrow J/\psi\ K^0_s)-N(B^0 \rightarrow J/\psi\ K^0_s)}{N(B^0 \rightarrow J/\psi\ K^0_s)+N(B^0 \rightarrow J/\psi\ K^0_s)}$$

- $A(t)=A_{dir}\cos(\Delta mt)+A_{mix}\sin(\Delta mt)$
- $A_{dir}\sim 0$, $A_{mix}=-\sin(2\beta)$

…$J/\psi\ K^0_s$: results

- After one year

	J / y ® m$^+$m$^-$	**J / y ® e$^+$e$^-$**
$N(B^0 \rightarrow J/\psi K^0_s)$	160 000	4 800
δ(sin2β)	0.022	0.031

- All combined δ(sin2β)=0.017
- All combined three years: δ(sin2β)=0.01

B^0_s ® J/y f

- Yet another golden decay-mode:
  - Trigger and reconstruction similar to $J/\psi\ K^0_s$
  - Fast B^0_S oscillation to be resolved
- Theoretically clean but complex:
  - Final state is a mixture of CP eigenstates which can be resolved with angular analysis:

CP Violation weak phase in $B_s^0 \rightarrow J/\psi\phi$

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The x_s-ϕ_s region allowed by Standard Model (SM), Left-right symmetric models (NP-LR), Iso-singlet down quark mixing Model (NP-DQ) and the region of experimental sensitivity of ATLAS.

Rare decays potential

FCNC decays b$\rightarrow$ s, b$\rightarrow$ d occur only at loop level in SM $\rightarrow$
Br < O(10^{-5}). Sensitive to new physics.

- $B \rightarrow \mu\mu$ can be seen before LHC only if drastically enhanced comparing to SM.

Leptonic:

- $B^0_s \rightarrow \mu^+\mu^-$ (Br SM~4.10^{-9}), $B^0_d \rightarrow \mu^+\mu^-$ (Br SM~1.10-^{10}) (Tevatron experimental limit <$10^{-6)}$
- Tiny branching ratios: ideal place to search for new physics at LHC
- Self triggering : can be looked for at high luminosity as well
- Reconstruction uses vertexing and isolation
- 4.7 sigma B^0_s observation after 3 years at low luminosity and one at high luminosity
- Some B^0_d events but difficult since mass resolution is 70 MeV

  $\Rightarrow$On going work especially at high luminosity

Rare decays, conclusions

•Improve and increase statistics seen at e^+e^- factories or Tevatron.
•Simulations showed that ATLAS is capable to measure at high luminosity 10^{34} cm^{2}s^{-1} and substantially improve results.
•Measure branching ratio of $B^0_s \rightarrow \mu^+\mu^-$ which is of order B_r < O (10^{-9}).
•Perform a high sensitivity search for $B^0_d \rightarrow \mu^+\mu^-$

Conclusions

- Great ATLAS-LHC potential for precise measurements (keywords: huge statistics, excellent detector), e.g.:
  - -- m_W to ≈ 15 MeV
  - -- TGC to 10^{-3} -10^{-2}
  - -- many measurements in top sector (precision few %)
  - -- B-physics, Higgs, SUSY, Exotics, etc.

  → in many cases improve on precision from previous machines

Higgs physics

- SM Higgs:
  - -- can be discovered ($\geq 5\sigma$) over full mass range with 10 fb^{-1} (~7 months at $2x10^{33}$) provided detector is well understood
  - -- with present machine schedule this observation will be possible end 2006/ beg 2007

- Precise measurements of Higgs parameters possible:
  - -- masses to 0.1% – 1%
  - -- width to 10-20%
  - -- coupling ratios to ~10-20%

  → <u>many constraints on theory and first systematic investigation of Higgs boson properties</u>

•Detector performance is crucial

Higgs sector has been challenging benchmark for LHC detector design and performance optimisation : γ / e / μ / τ energy resolution and identification, E_T^{miss} resolution, b-tagging, multi-jet mass spectroscopy, forward jet tag, etc.

Large number of accessible channels demonstrates sensitivity of ATLAS to large variety of signatures and therefore their potential also for other scenarios and for new / unexpected physics

B physics

•General purpose LHC central detector ATLAS is well equipped for rigorous B-physics program

•In CP violation the main emphasis will be on the underlying mechanisms and evidence of new physics. ATLAS is especially precise in measurement of β. Appart from e^+e^- B factory 'benchmark modes' the LHC 'gold-plated' mode $B_s^0 \rightarrow J/\Psi\ \phi$ has been studied

•Rare decays with 2 muons have the most favourable experimental signature allowing to measure also at 10^{34} cm^2s^{-1}. $B_s^0 \rightarrow \mu^+\mu^-$ with a SM ratio 10^{-9} will be seen already after one year.