Standard Model physics with the ATLAS early data

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on behalf of
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The Large Hadron Collider (LHC)

Muon Spectrometer ($|\eta| < 2.7$)

- air-core toroids with muon chambers

Tracking ($|\eta| < 2.5$, $B=2T$)

- Si pixels and strips
- TRD (e/π separation)

Calorimetry ($|\eta| < 5$)

- EM : Pb-LAr
- HAD : Fe/scintillator (central), Cu/W-Lar (fwd)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 tons

7 TeV + 7 TeV

Protons

Protons

Luminosity = $10^{34} \text{cm}^{-2} \text{sec}^{-1}$

- pp collision cm : 14 TeV (x7 Tevatron)
- 25 ns bunch spacing
- $1.1 \cdot 10^{11}$ proton/bunch
- Design lumi: $10^{34} \text{cm}^{-2} \text{s}^{-1}$ ($10 \text{ nb}^{-1} \text{s}^{-1}$)
- Physics/year ≈ 100 days
- 100 fb⁻¹ /year; ≈ 20 int./x-ing (≥ 2009)**
- Low lumi: $\approx 10^{33} \text{cm}^{-2} \text{s}^{-1}$ ($1 \text{ nb}^{-1} \text{s}^{-1}$)
- 10 fb⁻¹ /year ; ≈ 2 int./x-ing (2008)**
- Initial lumi: $< 10^{32} \text{cm}^{-2} \text{s}^{-1}$ ($0.1 \text{ nb}^{-1} \text{s}^{-1}$)
- 100-300 pb⁻¹ ??? ; (2007)**

What's on the menu:

- ✓ LHC: a parton accelerator. Understand and constrain PDF's
 - W, Z as standard candles for luminosity monitoring.
 - ✓ LHC as top factory ($t\bar{t}$ x-section nearly a nb!):
 - ✓ m_t - crucial constraint on SM Higgs,
 - ✓ top spin physics (production and decay),
 - ✓ single top,
 - top charge,
 - FCNC in top decays ($t \rightarrow qZ \rightarrow qll, t \rightarrow q\gamma, t \rightarrow qg$),
 - hadronic top decays ($t \rightarrow Wb, W \rightarrow 2\text{jets}$) very useful for in situ JES calibration (W mass!). Also useful for b-tagging calibration!
 - W mass measurement (systematics very challenging)
 - D.Y.: lepton pair spectrum up to high masses. Z resonance - mostly calibration, but also sensitive to new physics.
 - B-physics: prospects depend largely on the actual LHC operation and the length of low lumi period (B_s oscillations and CP violation, B rare decays, b-baryon physics)
 - QCD.
-

and many more...

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LHC parton kinematics

At the TeV scale, uncertainties in cross section predictions for new physics are dominated by **high-x gluon** uncertainty

At the EW scale (ie W and Z masses) theoretical predictions are dominated by **low-x gluon** uncertainty

The Q^2 dependence is determined by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equations

give rise to systematics

The x dependence of $f(x, Q^2)$ is parameterised and fitted to data. Done by various groups: CTEQ, MRST, ZEUS, Alekhin etc.

$$\text{Rate} = \epsilon_{\text{exp}} \times \int dx_1 dx_2 \sigma_{ab \rightarrow X}(x_1 x_2 S = Q^2) f_a(x_1, Q^2) f_b(x_2, Q^2) \times \int L dt$$

just an example ->

single $W^\pm$ Productions

hep-ex/0509002

hep-ex/0511020

hep-ph/0512228

$$u\bar{d} \rightarrow W^+ \rightarrow e^+\nu$$

$$d\bar{u} \rightarrow W^- \rightarrow e^-\bar{\nu}$$

(standard candles at LHC)

The selection :

- Isolated electron $P_T > 25$ GeV, $|\eta| < 2.4$
- $E_T^{\text{miss}} > 25$ GeV
- no jets with $E_T > 30$ GeV, $|\eta| < 2.5$
- $p_t^{\text{recoil}} < 20$ GeV
- BKG < 1% $W/Z \rightarrow \tau$, $Z \rightarrow e^+e^-$, QCD

NNLO corrections small ~ few%
NNLO residual scale dependence < 1%

Uncertainties dominated by PDFs

Error on the low-x gluon shape parameter λ ,
 $xg(x) \sim x^{-\lambda}$ can be significantly reduced (35%)
with just 100 pb⁻¹ of data. (4% exp. systematic
and no Luminosity measurement assumed!)
(Work in progress)

Due to the clean signal and very good control of
theoretical predictions $W^\pm$ and Z production in
their leptonic decays may prove to be one of the
most reliable (parton) luminosity monitors.

PDF

$t\bar{t}$ production at the LHC

LHC will be a top factory!

$gg \rightarrow t\bar{t}$

90%

$qq \rightarrow t\bar{t}$

10%

dominates
@ Tevatron

$$\hat{s} = Sx_1x_2$$

$$x_1x_2 \geq \frac{4m_t^2}{S} \cong 6 \times 10^{-4}$$

(Tevatron: $\geq 3 \times 10^{-2}$)

LHC $\sigma_{t\bar{t}} \sim 830 \text{ pb}$ **X100**

Tev: $\sigma_{t\bar{t}} \sim 6,7 \text{ pb}$

LHC Low L $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Tevatron 10^{32} **X10**

Prod Rate **X1000**

S/B way higher!

X-section determination limited by the luminosity and detector systematics.

top mass measurement

$$(\Delta r)_{\text{top}} \approx -\frac{3G_F m_t^2 c_W^2}{8\sqrt{2}\pi^2 s_W^2}$$

+

$$(\Delta r)_{\text{Higgs}} \approx \frac{11G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2} \ln \frac{m_h^2}{m_Z^2}$$

only logarithmic dependence

$$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{s_W^2(1 - \Delta r)}$$

$$s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$$

Status of summer 2005 (hep-ex/0511027):

Top quark mass = $172.7 \pm 2.9 \text{ GeV}$

$m_W = 80.410 \pm 0.032 \text{ GeV}$

$m_H = 91_{-32}^{+45} \text{ GeV}/c^2$

$m_H < 186 \text{ GeV}/c^2$ @ 95% CL (theory incl.)

χ^2 contribution: $\Delta m_W \sim 0.007 \times \Delta m_t$

LHC goal: $\Delta m_t \sim 1 \text{ GeV}/c^2$

Hope to go down to $\delta m_W \sim 0.015 \text{ GeV}$ @LHC

LEP direct: $m_H > 114.4$ @ 95% CL

Single lepton $t\bar{t}$ event selection

Typical selection :

- Isolated lepton $P_T > 20$ GeV
- $E_{T, \text{miss}} > 20$ GeV
- 4 jets with $E_T > 40$ GeV, $|\eta| < 2.5$
- > 1 b-jet ($\epsilon_b \approx 50\%$, $\epsilon_{uds} \approx 10^{-3}$, $\epsilon_c \approx 10^{-2}$)
- BKG $< 2\%$ W/Z+jets, WW/ZZ/WZ

efficiency: $\sim 1-2\%$:

Golden plated channel (BR=30%)

- Clean trigger from isolated lepton
 - Allows for in situ light jet energy scale calibration
 - Reconstruction starts with the W (different ways to pair the right jets)
 - Important to tag the b-jets!
- Largely cleans the sample and helps jet assignment.

top mass reconstruction

1 Hadronic top:

Three jets with highest vector-sum p_T as the decay products of the top

2 W boson:

Two jets in hadronic top with highest momentum in reconstructed jjj C.M. frame.

Hadron side No b-tag
 $L=300 \text{ pb}^{-1}$

W CANDIDATE

TOP CANDIDATE

Mass measurement systematics

Source of uncertainty	Hadronic top $\delta M_{\text{top}} \text{ (GeV/c}^2\text{)}$	Kinematic fit $\delta M_{\text{top}} \text{ (GeV/c}^2\text{)}$
Light jet energy scale (1 %)	0.2	0.2
b-jet energy scale (1 %)	0.7	0.7
b-quark fragmentation	0.1	0.1
ISR	0.1	0.1
FSR	1.	0.5
Combinatorial background	0.1	0.1
Total	1.3	0.9
Statistical error (10 fb⁻¹)	0.05	0.1

In situ calibration possible e.g.:

$$m_t = \langle m_{jjb} - m_{jj} \rangle + M_W(\text{PDG})$$

Statistical error for 10 fb⁻¹ : 0.05 GeV/c²

top mass reconstruction - other channels

□ di-lepton events

- efficiency = 6.5 % $\rightarrow$ 20 000 events @ 10 fb⁻¹
- $\delta m_{\text{stat}} = 0.04 \text{ GeV}/c^2$

Source of uncertainty	$\delta M_{\text{Top}} \text{ (GeV)}$
Statistic & reconstruction method	0.3
b-jet energy scale	0.6
b-quark frag.	0.7
ISR	0.1
FSR	0.6
Parton distribution function	1.2
Total	1.7

□ fully hadronic events

- efficiency = 0.08 % $\rightarrow$ 3300 events @ 10 fb⁻¹
- $\delta m_{\text{stat}} = 0.18 \text{ GeV}/c^2$

Source of uncertainty	$\delta m_{\text{top}} \text{ (GeV}/c^2)$
Light jet energy scale	0.8
b-jet energy scale	0.7
b-quark fragmentation	0.3
ISR	0.4
FSR	2.8
TOTAL	3

W polarization in top decay

- Top decay : predominantly source of longitudinal W's
 - Polarization depends only on M_t and M_W (LO)

	Longitudinal W^+ (F_0)	Left-handed W^+ (F_L)	Right-handed W^+ (F_R)
Standard Model ($M_{\text{top}}=175$ GeV) NLO	0.703 $\left(= \frac{M_t^2}{M_t^2 + 2M_W^2} \right)$ 0.695	0.297 $\left(= \frac{2M_W^2}{M_t^2 + 2M_W^2} \right)$ 0.304	0.000 0.001

Sensitive to EWSB

Test of V-A structure

- All 3 components in angular distribution of lepton in W rest frame :

$$\frac{1}{N} \frac{dN}{d\cos\Psi} = \frac{3}{2} \left[F_0 \cdot \left(\frac{\sin\Psi}{\sqrt{2}} \right)^2 + F_L \cdot \left(\frac{1-\cos\Psi}{2} \right)^2 + F_R \cdot \left(\frac{1+\cos\Psi}{2} \right)^2 \right]$$

Angle between:

- lepton in W rest frame and
- W in top rest frame

W helicity results

ref : hep-ex/0508061

□ Results for 10 fb⁻¹, fast simulation :

SM values		F_0	F_R
		0.703	0.000
$\pm$ Stat	semi + dilep	± 0.004	± 0.003
$\pm$ Syst	semi + dilep	± 0.016	± 0.012

□ From W polarization, deduce **sensitivity to tWb anomalous couplings** → model independent approach, i.e. effective Lagrangian

Tevatron @ 2 fb⁻¹

Stat only:

$F_0 \approx 0.09$

$F_R \approx 0.03$

$t\bar{t}$ spin correlation

$gg \rightarrow t\bar{t}$ (1S_0) 90%
 $qq \rightarrow t\bar{t}$ (3S_1) 10%

- Tops not polarized in pairs, but **correlations** between spins
 - Like-helicity pairs more abundant in LHC

$$A = \frac{\sigma(t_L \bar{t}_L) + \sigma(t_R \bar{t}_R) - \sigma(t_L \bar{t}_R) - \sigma(t_R \bar{t}_L)}{\sigma(t_L \bar{t}_L) + \sigma(t_R \bar{t}_R) + \sigma(t_L \bar{t}_R) + \sigma(t_R \bar{t}_L)} \neq 0$$

$$A_D = A_X + A_Y + A_Z$$

≈equivalent;
 Sensitive to BSM production mechanisms

- Measure angular distributions of daughter lepton in top rest frames

$$\frac{1}{N} \frac{d^2 N}{d(\cos \theta_1) d(\cos \theta_2)} = \frac{1}{4} (1 - A \alpha_1 \alpha_2 \cos \theta_1 \cos \theta_2)$$

Angle between $t(\bar{t})$ and spin analysers

$$\frac{1}{N} \frac{dN}{d \cos \Phi} = \frac{1}{2} (1 - A_D \alpha_1 \alpha_2 \cos \Phi)$$

Angle between spin analysers

$M_{t\bar{t}} < 550 \text{ GeV}$

ref : hep-ex/0303092

$\alpha=1$ for charged lepton from t ($d\sigma/d\cos\theta \sim (\mathbf{t}-m_t\mathbf{s}) \cdot \mathbf{l} \mathbf{b.v}$)

Spin correlation results

ref : hep-ex/0508061

□ Results with fast simulation of detector (10 fb^{-1}):

SM values	A	A_D	A^1	A_D^1	$^1(M_{t\bar{t}} < 550 \text{ GeV})$ enhance correlation
	0.33	-0.24	0.42	-0.29	
relative errors					$\Delta A/A$ $\Delta A_D/A_D$
Statistical	semi + dileptonic				3% 3%
Systematic	semi + dileptonic				5% 3%

A, A_D precision driven by dileptonic

➔ Precision dominated by systematics

Sensitivity to new physics:

Any deviation from SM prediction might sign the presence of $t\bar{t}$ production through a new mechanism.

a heavy spin-0 (Higgs ?), new vector particle or spin-2 (KK graviton ?)

Tevatron:
Expect $\approx 40\%$ @ 2 fb^{-1}

Single top production (1)

Three production mechanisms:

Wg fusion: 245 ± 27 pb

S.Willenbrock et al., Phys.Rev.D56, 5919

Wt: $62.2^{+16.6}_{-3.7}$ pb

A.Belyaev, E.Boos, Phys.Rev.D63, 034012

W* 10.2 ± 0.7 pb

M.Smith et al., Phys.Rev.D54, 6696

NLO already available for Wg fusion (± 9 pb) and Wt.

- Main Background [$\sigma \times \text{BR}(W \rightarrow \ell \nu)$, $\ell = e, \mu$]:

- tt	$\sigma = 833$ pb	[246 pb]
- Wbb	$\sigma = 300$ pb	[66.7 pb]
- Wjj	$\sigma = 18 \cdot 10^3$ pb	[$4 \cdot 10^3$ pb]

Wg	[54.2 pb]
Wt	[17.8 pb]
W*	[2.2 pb]

Main uncertainty due to:

- **choice of b,g PDF's, (dominates by far!)**
- the renormalisation scale μ ,
- m_t .

Tevatron:

Wg fusion:	$2.1 \text{ pb} \pm 5\%$
Wt:	$0.1 \text{ pb} \pm 10\%$
W*:	$0.9 \text{ pb} \pm 5\%$

Two orders of magnitude smaller!

Single top production (2)

Physics motivation:

- Tevatron will have hard time to establish the 5σ -evidence with the 2 fb^{-1} of data
- LHC will see it immediately
➤ Allows direct determination of $ V_{tb} ^2 - O(\%)$	} <-PDF limited	
➤ Test of V-A nature of the Wtb vertex $P \approx 100\%$		Wg and Wt channels
➤ Anomalous couplings, FCNC ($gu \rightarrow t$)		
- Charged Higgs bosons (2HDM), extra gauge bosons W' , (extra dim KK, etc.) - increase of the total x-section
- Possibility of seeing heavy resonances in the s -channel tb final system (starting from $\approx 30 \text{ fb}^{-1}$)
- Interest in measuring x-sections of the three channels separately!
Experimentally challenging!
High backgrounds. Strongly dependent on detector performance.

Summary

- I hope I've convinced you there is lots of interesting and relevant physics within the SM @ LHC, often giving possibility of insight into BSM phenomena.
- Many can be explored to full extent in the first years of the LHC operation. Systematics dominate in most cases.
- Theoretical predictions very often are limited by the PDF uncertainties. The latter can be substantially reduced using very first LHC data.
- There is much more I haven't covered!
- Lots of excitement ahead of us even before we start seeing directly Higgs or "new physics".

BACKUP SLIDES

PDF constraining potential of ATLAS

Effect of including the ATLAS W Rapidity “pseudo-data” in global PDF Fits:
how much can we reduce the PDF errors when LHC is up and running?

Simulate real experimental conditions:

Generate 1M “data” ($\approx 100 \text{ pb}^{-1}$) sample with CTEQ6.1 PDF through ATLFAST detector simulation and then include this *pseudo-data* (with imposed 4% error) in the global ZEUS PDF fit (with Det.->Gen. level correction). **Central value of ZEUS-PDF prediction shifts and uncertainty is reduced:**

low-x gluon shape parameter λ , $xg(x) \sim x^{-\lambda}$:

BEFORE $\lambda = -0.199 \pm 0.046$

AFTER $\lambda = -0.181 \pm 0.030$

} 35% error reduction

In ZEUS-PDF fit the $e^\pm$ Normalisation left free $\Rightarrow$ no assumption on Luminosity measurement!

(G.Mahlon, S.Parke hep-ph/9512264)

FIG. 4. Differential cross section for $t\bar{t}$ production as a function of the $t\bar{t}$ invariant mass for the LHC with center of mass energy 14 TeV, decomposed into LR+RL and LL+RR helicities in the zero momentum frame of the $t\bar{t}$ pair for both $q\bar{q}$ and gg components.

FIG. 6. The solid curve is the fraction of those $t\bar{t}$ pairs at the LHC (14 TeV) with an invariant mass below $M_{t\bar{t}}$ which have helicities LL+RR. The dashed curve is the fraction of the total cross section with an invariant mass below $M_{t\bar{t}}$.