Measurements of $Z^0 + b$ and $W^{\pm} + c/b$ with 2010 LHC data at ATLAS and CMS

- A Review -

Peter Steinbach

Technical University of Dresden

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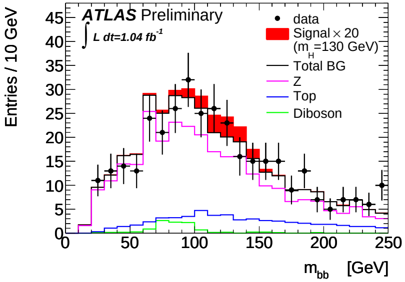
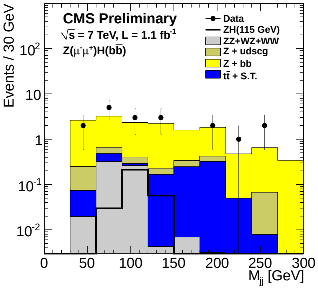
Motivation for di-lepton final states

SM Higgs Searches



Invariant b-tagged jet mass m_{bb} for SM ZH search from [9]

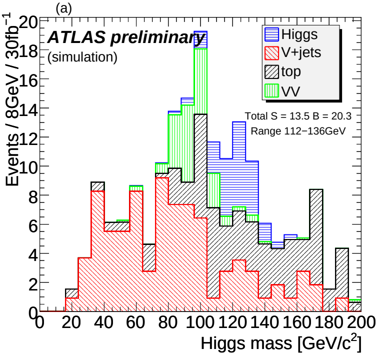
MSSM Higgs Searches



Invariant b-tagged jet mass m_{bb} for SM ZH search from [6]

$Z^0 + b$ poses large contribution to background final states in di-lepton Higgs searches!

Physics motivation for $W^{\pm}$ final states



Invariant b-tagged jet mass m_{bb} for SM WH searches from [8]

$W^{\pm} + b$ poses large contribution to background final states in single-lepton Higgs searches!

Outline

Four measurements on the full 2010 LHC data set of $\mathcal{L}_{int} = 35 - 36\,\mathrm{pb}^{-1}$ were published.

ATLAS $W^{\pm} + b$

cdsweb.cern.ch/record/1380893
accepted by Phys.Lett.B

CMS $W^{\pm} + c$

cdsweb.cern.ch/record/1369558
presented at EPS 2011

ATLAS $Z^{0} + b$

cdsweb.cern.ch/record/1380892
accepted by Phys.Lett.B

CMS $Z^{0} + b$

cdsweb.cern.ch/record/1337739
presented at Moriond QCD 2011

Will try to cover all briefly, trying to emphasize differences or destinctive features between ATLAS and CMS.

A Theory Behind It

Predicting V+HF final states

Monte-Carlo Predictions ...

- ... include heavy flavour in PDF whose fits are not trivial (introduces dependencies on m_c, m_b, see [10])
- ... of $W/Z + c/b$ final states use two approaches

Predicting V+HF final states

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- ... of $W/Z + c/b$ final states use two approaches

4 Flavor Number Scheme (**4FNS**)

- initial states involve u, d, s, c, g partons only
- bottom quarks are produced by gluon splitting only
- gluon splitting to bottom quarks part of matrix element

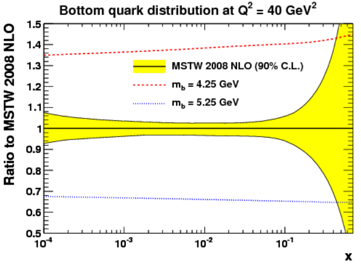
5 Flavor Number Scheme (**5FNS**)

- initial states involve u, d, s, c, g and b partons
- gluon splitting is already integrated into *bPDF*

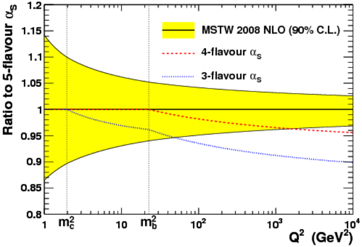
At (N)NLO, both ways of calculating $V + c/b$ should give the same results?!

bottom quark PDFs

MSTW2008nlo Bottom PDF sets from [10]



Comparison of α_s versus Q^2 in 3- to 5-FNS (from [10])

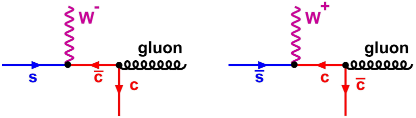


- PDF changes with value m_c, m_b
- heavy flavour scheme used impacts on α_s
- propagated to xsection prediction (PDF) and jet shapes (α_s in hadronisation, parton shower)
- MC predictins should't mix 4/5-flavor number schemes and 4/5-flavor PDF

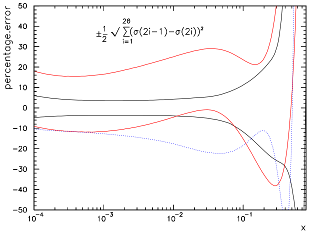
$W^{\pm} + c$ at CMS [7]

Motivation, Characteristics

$W^\pm + c$ sensitive to strange quark PDF



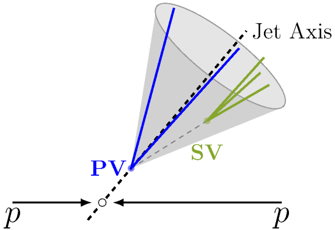
sPDF uncertainties large



Strange quark pdf uncertainties at $Q^2 = 10^4\,\mathrm{GeV}^2$ for fits in **MSTW2008NNLO**, **CT10** and **NNPDF21**

Characteristics

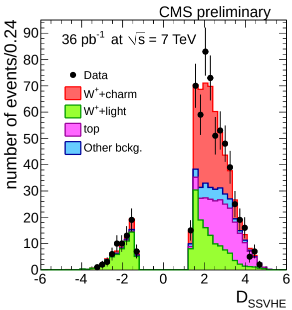
- muon channel only
- standard CMS $W^\pm$ selection ($N_\mu = 1, N_{jets} \leq 2, M_T > 50\,\mathrm{GeV}$)
- c-Tagging using 3D decay length l
  - only events with vertices $\Delta l < 0.15\,\mathrm{cm}$
  - discriminator $D_{SSVHE} = sign(\frac{\Delta l}{l})\log(1 + |\frac{\Delta l}{l}|)$



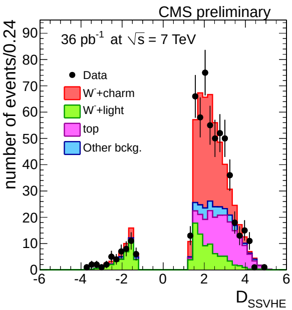
Extracting the Number of Observed Heavy Flavor Jets

Problem

1. c/b-tagging is not enough to select a 100% pure sample of heavy flavor jets
2. use flavor discriminating variable, e.g. $m_{sv}, \sigma(l)/l, D_{SSVHE}$
3. derive template distributions from MC ($W^{\pm} + c$ signal) or side-bands in data ($t\bar{t}$)
4. perform likelihood fit to extract the individual normalisations



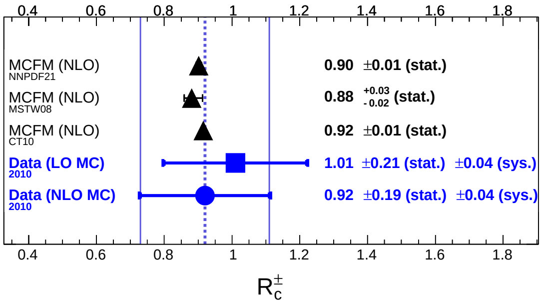
Fitted Event Yields in $W^{+}\bar{c}$ final states



Fitted Event Yields in $W^{-}c$ final states

Measurements

Results for $\mathcal{R}_c^{\pm} = \frac{\sigma(W^{+}+\bar{c})}{\sigma(W^{-}+c)}$

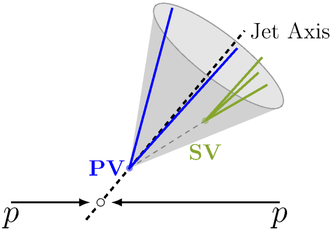


- used LO MC (MADGRAPH) and NLO MC (POWHEG) for signal acceptances/efficiencies
- low systematic uncertainty due to ratio measurement
- strongest systematic uncertainty in: PDF uncertainties, Pile-up Reweighting, Top templates
- also measured $\mathcal{R}_c = \frac{N(W^{+}+\bar{c})+N(W^{-}+c)}{\epsilon_c N(W+jets)}$ (not shown here)

$W^{\pm} + b$ at ATLAS [1]

Characteristics

- measure $\sigma(W + b)$ for $0 < n_{jets} \leq 2$ ($n_{btagjet} = 1$)
- $E_{t,miss} > 25\,\mathrm{GeV}$, $m_T > 40\,\mathrm{GeV}$
- b-tagging with ATLAS SV0 algorithm
  - longitudinal projection of decay length on jet axis L
  - btag weight $w_{SV0} = \frac{\Delta L}{L}$



backgrounds

- QCD normalisation and shape derived from data in each jet multiplicity
  - electron channel: fit to $E_{T,miss}$ distribution
  - muon channel: fit to m_{sv} in events with $E_{t,miss} < 10\,\mathrm{GeV}$
- top normalisation and shape derived from data in side-band of $n_{jets} \geq 4$ and extrapolated down to $n_{jets} = [1 - 2]$

b-tagging

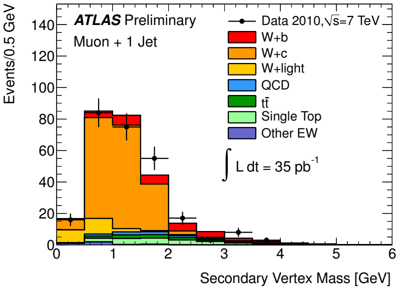
- b-tagging efficiencies and mistag rates calibrated with QCD Multijet and dedicated soft-muon tagger analysis

Extraction of b-tagged jets

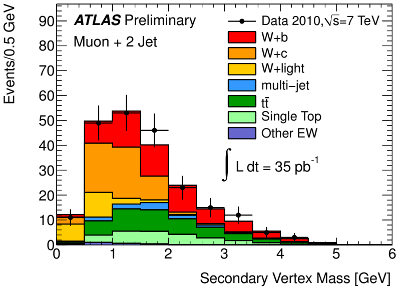
b-tagging

- SV0 tagging algorithm cutting on $\sigma_L/L > 5.85$ ($\epsilon_b = 35\,\%$)
- individual jet multiplicities and lepton flavor are fitted in m_{sv}
- 3 free parameters ($W + b$, $W + c$, $W + u, d, s$)
- background shapes and yields constrained by data-driven methods

Fitted Event Yields for $\mu\nu_\mu + b$ in $n_j = 1$ events

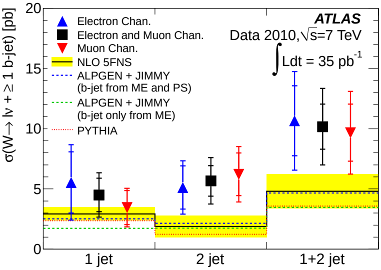


Fitted Event Yields in $\mu\nu_\mu + b$ in $n_j = 2$ events



Results

Results for $W^\pm + n_b \cdot b$ with $(n_b \geq 1)$



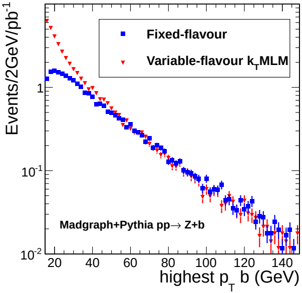
- strongest systematics:
  1. b-tagging efficiency (12%)
  2. $t\bar{t}$ and single t (12%)
  3. template shapes (10%)
  4. model dependence (9%)

- as indicated by earlier CDF measurement [4], data exceeds MC predictions at NLO and LO

Interlude: Model dependent systematics

Problem

- b-tagging performance is correlated with true jet kinematics
- accurate predictions of jet spectra vital (ME vs PS, 4FNS vs 5FNS, UE tunes)
- different models can have impact on fitted number of heavy flavor jet



Leading b-parton p_t in MADGRAPH $Z + b$ fixed-flavour MC sample (blue squares) and MADGRAPH $Z + j$ variable-flavour MC sample (red triangles) from [5]

Summary $W^\pm + c/b$

- $W^\pm + c/b$ final state analyses conducted on 2010 data suffer from large statistical uncertainties
- important experiences with data-driven methods for background extraction and data/MC reweighting gained

- $W^\pm + c$ has reproduced the theoretical expectations
- $W^\pm + c$ with 2011 will certainly impact on sPDF fits

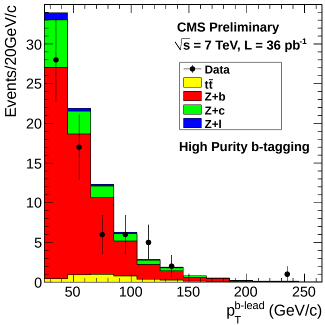
- $W^\pm + b$ exceeded expectation by $\mathcal{O}(1.5\sigma)$ as did previous measurement by CDF
- despite the irreducible top backgrounds, $W^\pm + b$ will help constrain bPDF fits

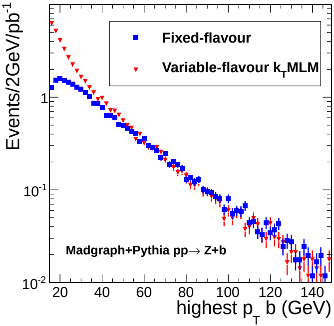
Z^0 Sector

$Z^0 + b$ at CMS [5]

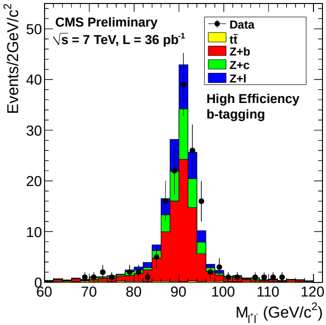
Motivation, Characteristics

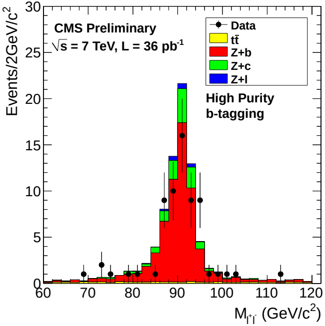
- analysis in muon and electron channel
- observe $\mathcal{R} = \frac{\sigma(pp \to Z+b+X)}{\sigma(pp \to Z+j+X)}$
- fitted flavor fractions instead of normalisations
- tried shape comparisons 4FNS vs 5FNS





Signal Extraction

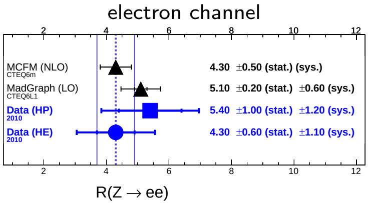


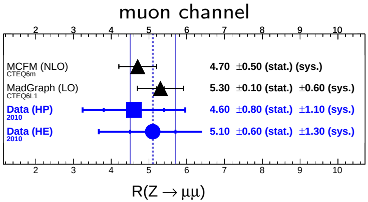


approaches and cross checks

- compared fit yields from two b-tagged data samples for cross checks
  - High Efficiency Tagger ($\epsilon_{b,MC} = 0.43 \pm 0.01(stat.) \pm 0.09(syst.)$)
  - High Purity Tagger ($\epsilon_{b,MC} = 0.3 \pm 0.01(stat.) \pm 0.06(syst.)$)
- different tagging setups yield different flavor compositions

Results





$$\mathcal{R} = \frac{\sigma(pp \to Z^0 + b + X)}{\sigma(pp \to Z^0 + j + X)}$$

- no unfolding conducted (comparison to theory unfair)
- strongest systematic impact:
  1. mistagging rate (13 – 16%)
  2. b-tagging efficiency (15%)
- comparison between 4FNS and 5FNS inconclusive due to statistical uncertainties

$Z^0 + b$ at ATLAS [2]

Ansatz, Characteristics

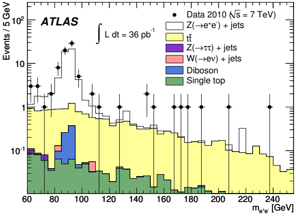
Ansatz

- jet based cross section in electron and muon channel
- aim for $\sigma^b(Z)$ and $\mathcal{R} = \sigma^b(Z)/\sigma(Z)$
- unfold to particle level for comparison to LO (SHERPA, ALPGEN) and NLO (MCFM) pQCD predictions

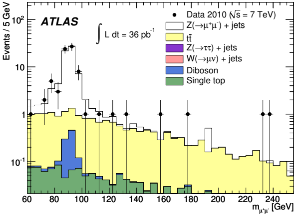
Characteristics

- equivalent lepton and jet selection to ATLAS' $W^{\pm} + b$ measurement
- no $E_{T,miss}$ or m_T cuts
- QCD Multijet background extracted from Data
- found negligible impact of Underlying Event/MPI on Z+b selection

electron channel

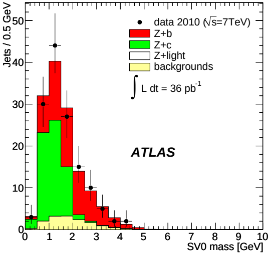


muon channel



A Case for Statistics

Fitted N_b for muon and electron channel



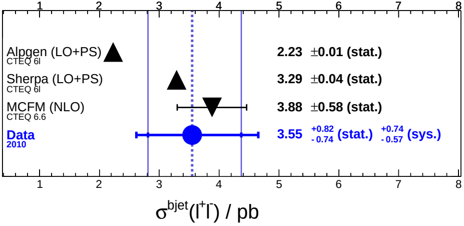
b-jets	$63.6^{+14.7}_{-13.2}$
c-jets	$59.9^{+13.4}_{-14.0}$
u, d, s, g jets	$0.0^{+5.1}$
Other backgrounds	14.5

Observations

- fit on bottom, charm and light flavor templates with fixed background template
- pseudo-experiments: fit stable
- light flavor yield at 0 (statistics at play)
- High Purity sample fit in CMS $Z^0 + b$ note also $f_{light} = 0$.

Results

$\sigma^{bjet}(Z^0 \to \ell^+\ell^-)$



- statistical uncertainty of measurement dominant
- LO and NLO predictions within 2σ of measurement
- excess of ALPGEN coincides with CDF findings, [3]
- strongest systematic impact:
  1. model dependence (10%)
  2. b-tagging efficiency (9%)

Summary $Z^0 + b$

- compared to $W^{\pm} + c/b$, Z^0 final states are harder (order of magnitude lower cross section)
- however, $Z^0 + b$ offers a clean environment to constrain theory
- all results agree with predictions at LO and NLO
- 2011 data will allow a high precision extraction of $\sigma(Z + b)$ and measurements of $\sigma(Z + bb)$
- with 2010 data, measurements targeting 4FNS vs 5FNS were conducted but inconclusive

Summary

- vector boson plus heavy flavor final states are an interesting field to test pQCD
- it provides a unique handle to constrain fits to heavy flavor PDFs
- many methods applied in the measurements mentioned can be directly adapted to Higgs/SUSY searches involving leptons, b-jets (and missing energy)
- accurate modelling of jet spectra crucial for heavy flavor analyses
- 2010 LHC data accumulated was insufficient to settle for competing theoretical descriptions

Looking forward to 2011 results (with $200x$ **more data)!**

CMS $W^{\pm} + c$: Experimental cuts

object cuts

- muon channel only
  - $p_{t,\mu} > 25\,\mathrm{GeV}$
  - $|\eta_{\mu}| < 2.1$
  - isolation, $I^{rel}_{comb} = \Sigma(E_T(ECAL) + E_T(HCAL) + p_t(tracks))|_{\Delta R<0.3} < 0.1$
  - $\Delta R(\mu, jet) > .3$
- Anti-Kt jets, $d = 0.5$
  - $p_{t,jet} > 20\,\mathrm{GeV}$
  - $|\eta_{jet}| < 2.1$
- c-Tagging
  - use only vertices with 3D decay length uncertainty $\Delta l < 0.15\,\mathrm{cm}$
- veto events with $N_{\mu} > 1$
- veto events with $N_{jets} > 2$

event cuts

- single muon trigger, $p_{t,trigger} > 15\,\mathrm{GeV}$
- transverse mass $M_T > 50\,\mathrm{GeV}$

ATLAS $W^{\pm} + b$: Experimental cuts

object cuts

- muon channel
  - $p_{t,\mu} > 20\,\mathrm{GeV}$
  - $|\eta_\mu| < 2.4$
  - isolation: $\Sigma(E_{T,clusters})|_{\Delta R<.3} < 4\,\mathrm{GeV}$ and $\Sigma(p_{t,tracks})|_{\Delta R<.3} < 4\,\mathrm{GeV}$
  - $\Delta R(\mu, jet) > .4$
- electron channel
  - $E_t > 20\,\mathrm{GeV}$
  - $|\eta_e| < 2.47$ and not $1.32 < |\eta_e| < 1.52$
  - constant efficiency isolation requirement
- Anti-Kt jets, $d = 0.5$
  - $p_{t,jet} > 20\,\mathrm{GeV}$
  - $|\eta_{jet}| < 2.1$
  - veto jets with $\Delta R(e, jet) < .5$
- b-tag: $w_{SV0} > 5.85$ ($\epsilon_{b,MC} = 0.35$)

event cuts

- single muon or electron trigger
- $N_{PV} > 0$ with 3 tracks at $p_t > 150\,\mathrm{MeV}$
- veto events with $N_\mu \neq 1$ or $N_e \neq 1$
- $E_{t,miss} > 25\,\mathrm{GeV}$
- $m_T > 40\,\mathrm{GeV}$

ATLAS $W^{\pm}+b$: Phase Space

leptons

- measurement in electron and muon channel
- lepton momentum $p_{t,\ell} > 20\,\mathrm{GeV}$
- lepton pseudo rapidity $|\eta_\ell| < 2.5$
- lepton-jet separation $\Delta R(\ell, jet) > .5$
- neutrino momentum $p_{t,\nu_\ell} > 25\,\mathrm{GeV}$
- transverse mass $m_t > 40\,\mathrm{GeV}$

jets

- Anti-kt jets, $d = 0.4$
- jet momentum $p_t^j > 25\,\mathrm{GeV}$
- jet rapidity $|y^j| < 2.1$
- jet multiplicity $n_j \leq 2$
- b-jet multiplicity $n_j = 1$ or $n_j = 2$

CMS $Z^0 + b$: Cuts on reconstructed objects

leptons

- muon and electron channel
- $p_{t,e} > 25\,\mathrm{GeV}$, $p_{t,\mu} > 20\,\mathrm{GeV}$
- $|\eta_e| < 2.5$, $|\eta_\mu| < 2.1$
- required isolated leptons
- lepton-jet separation $\Delta R(\ell, jet) > 0.5$

jets

- anti-kt, $d = 0.5$
- $p_{t,j} > 25\,\mathrm{GeV}$
- $|\eta_j| < 2.1$
- $\not{E}_t < 40\,\mathrm{GeV}$

ATLAS $Z^0 + b$: Phase Space

leptons

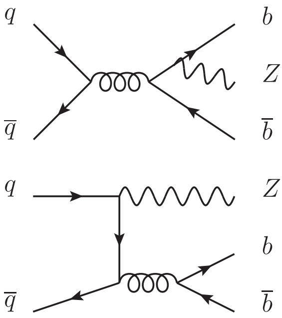
- use dressed leptons (with photons within $\Delta R < 0.1$)
- electrons and muons: $p_{t,\ell} > 20.\,\mathrm{GeV}$, $|\eta_\ell| < 2.5$
- $15\,\mathrm{GeV}$ mass window: $76 < m_{\ell\ell} < 106\,\mathrm{GeV}$

jets

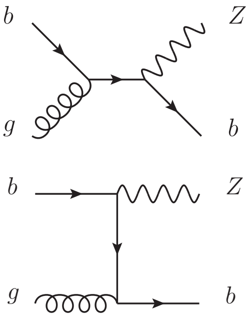
- `Anti-Kt`, $d = 0.4$
- $p_{t,jet} > 25.\,\mathrm{GeV}$, $|y_{jet}| < 2.1$
- remove any jet with $\Delta R(Z^0\text{lepton}, jet) < 0.5$

V+HF Feynman Rules

4 (Fixed) Flavor Number Scheme



5 (Variable) Flavor Number Scheme



[1] G. Aad et al.
Measurement of the cross section for the production of a w boson in association with b-jets in pp collisions at $\sqrt{s} = 7$ tev with the atlas detector. oai:cds.cern.ch:1380799.
Technical Report arXiv:1109.1470. CERN-PH-EP-2011-132, CERN, Geneva, Sep 2011.
Comments: 10 pages plus author list (24 pages total), 8 figures, 4 tables, submitted to Physics Letters B.

[2] Georges Aad et al.
Measurement of the cross-section for b-jets produced in association with a Z boson at sqrt(s)=7 TeV with the ATLAS detector.
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* Temporary entry *.

[3] T. Aaltonen et al.
Measurement of cross sections for *b* jet production in events with a *z* boson in $p\overline{p}$ collisions at $\sqrt{s} = 1.96\ \mathrm{TeV}$.
Phys. Rev. D, 79:052008, Mar 2009.

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First Measurement of the b-jet Cross Section in Events with a W Boson in p anti-p Collisions at s**(1/2) = 1.96-TeV.
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[5] S. Chatrchyan et al.
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Technical Report CMS-PAS-EWK-10-015, CERN, 2011.
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[6] S. Chatrchyan et al.
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Technical Report CMS-PAS-HIG-11-012, CERN, 2011.

[7] S. Chatrchyan et al.
Study of associated charm production in w final states at sqrt s = 7 tev.
Technical Report CMS-PAS-EWK-11-013, 2011.
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Atlas sensitivity to the standard model higgs in the hw and hz channels at high transverse momenta.
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Search for the standard model higgs boson produced in association with a vector boson and decaying to a b-quark pair with the atlas detector at the lhc.
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[10] A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt.
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