Recent Standard Model Results from ATLAS and CMS

Phenomenology 2014
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Jacob Searcy
On behalf of
ATLAS and CMS Collaborations
Standard Model Physics

- Can mean a variety of things
  - Higgs results have their own talk

- Mission
  - Establish Standard Model Processes
    - First measurements of rare processes
  - Explore physics with high precision
    - Differential cross sections and measurements of SM constants
  - Measure that which can’t be well calculated
    - Non-perturbative physics
Why Study the Standard Model

- Theorists are really creative
  - Large number models
  - Giant parameter spaces
  - Can’t look at every point in every theory
- We know the SM breaks
- Let's find where it does
  - Hope it's at LHC energies
- Also incredibly valuable to tune simulations, PDFs, validate new methods, etc.

Hitoshi Murayama
Jet/PDF/Other
Boson(s)+(jets)
Top Physics

A lot going on!

New SM Results (~6 months)

- Jet multiplicity and differential production cross sections of Z+jets events in proton-proton collisions at 7 TeV: https://cds.cern.ch/record/1667906
- Hadronic event shapes in pp collisions at 7 TeV: https://cds.cern.ch/record/1646367
- PDF constraints and extraction of the strong coupling constant from the inclusive jet cross section at 7 TeV: https://cds.cern.ch/record/1632407
- Measurement of the Differential Cross Section of W-Bosons Produced in Association with Jets in pp collisions at s=7 TeV: https://cds.cern.ch/record/1664744
- Measurement of ZZ production cross section at 7 and 8 TeV and anomalous gauge couplings in Zll2nu decay channel: https://cds.cern.ch/record/163371
- Measurement of the differential isolated diphoton production cross section in pp collisions at sqrt(s) = 7 TeV with the CMS detector: https://cds.cern.ch/record/1597071
- Measurement of WZ and ZZ production in pp collisions at sqrt(s) = 8 TeV in final states with b-tagged jets: http://arxiv.org/abs/1403.3047
- A Search for WWgamma and WZgamma production in pp Collisions at sqrt(s) = 8 TeV: https://cds.cern.ch/record/1563302
- Measurement of the ZZ production cross section and anomalous trilinear gauge couplings in t\bar{t} decays at sqrt(s) = 8 TeV at the LHC: https://cds.cern.ch/record/1563178
- Measurement of WZ production rate: https://cds.cern.ch/record/1564318
- Measurement of the muon charge asymmetry in inclusive pp to WX production at sqrt(s)=7 TeV and an improved determination of light parton distribution functions: http://arxiv.org/abs/1312.6283
- Measurement of inclusive W and Z boson production cross sections in pp collisions at sqrt(s)=8 TeV: http://arxiv.org/abs/1402.0123
- Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at sqrt(s) = 7 TeV: http://arxiv.org/abs/1402.1521
- Measurement of the production cross section for a W boson and two b jets in pp collisions at sqrt(s) = 7 TeV: http://arxiv.org/abs/1310.1138
- Measurement of t\bar{t}-channel spin correlations and top-quark polarization using dilepton final states in pp collisions at 7 TeV: http://arxiv.org/abs/1311.3924
- Search for flavor-changing neutral currents in top-quark decays t\rightarrow Zq in pp collisions at sqrt(s)=8 TeV: http://arxiv.org/abs/1312.4194
- Measurement of the t-bar production cross section in the dilepton channel in pp collisions at sqrt(s)=8 TeV: http://arxiv.org/abs/1402.3803
- Measurement of the t-channel single-top-quark production cross section and of the [ybt] CKM matrix element in pp collisions at sqrt(s)=8 TeV: http://arxiv.org/abs/1403.7366
- Measurement of the top-quark mass in t\bar{t} events measured with lepton+jets and dilepton final states in pp collisions at sqrt(s)=8 TeV: https://cds.cern.ch/record/1690093
- Search for standard model four top quark production at 8 TeV in the lepton + jets channel: https://cds.cern.ch/record/1644574
- Measurement of the inclusive top-quark pair + photon production cross section in the muon + jets channel in pp collisions at 8 TeV: https://cds.cern.ch/record/1644573
- Search for s-channel single-top production in pp collisions at sqrt(s)=8 TeV: https://cds.cern.ch/record/1633190
- Projections for Top FCNC Searches in 3000fb at the LHC: https://cds.cern.ch/record/1605585
- Projected improvement of the accuracy of top-quark mass measurements at the upgraded LHC: https://cds.cern.ch/record/1605627
- Measurement of the chib2chib1 production cross section ratio in pp collisions at sqrt(s)=8 TeV: http://arxiv.org/abs/1402.1367
- Measurement of the ratio of the production cross-section times branching fraction between the Bc to J/psi pi and the B+ to J/psi K and of branching fractions Bc to J/psi pi pi pi over Bc to J/psi pi in CMS at sqrt(s)=7 TeV: https://cds.cern.ch/record/1632149
- Measurement of the Prompt Double J/psi Production Cross Section in pp Collisions at sqrt(s) = 7 TeV: http://cds.cern.ch/record/1633400

ATLAS

- The differential production cross section of the phi(1020) meson in pp collisions measured at 7 TeV with the ATLAS detector: http://arxiv.org/abs/1402.6162
- Measurement of the low-mass Drell-Yan differential cross section at sqrt(s)=7 TeV using the ATLAS detector: http://arxiv.org/abs/1404.1212
- A study of the sensitivity to the proton parton distributions of the inclusive photon production cross section in pp collisions at 7 TeV measured by the ATLAS experiment at the LHC: https://cds.cern.ch/record/1636863
- Measurement of the production of a W boson in association with a charm quark in pp collisions at sqrt(s)=7 TeV with the ATLAS detector: http://arxiv.org/abs/1402.6263
- Measurement of the inclusive isolated prompt photon cross section in pp collisions at sqrt(s)=7 TeV with the ATLAS detector using 4.6 fb-1: http://arxiv.org/abs/1311.1440
- Measurement of the 4l Cross Section at the Z Resonance and Determination of the Branching Fraction of Z->4l in pp Collisions at sqrt(s) = 7 and 8 TeV with ATLAS: http://arxiv.org/abs/1403.5657
- Measurement of the electroweak production of dijets in association with a Z-boson and distributions sensitive to vector boson fusion in proton-proton collisions at sqrt(s)= 8 TeV using the ATLAS detector: http://arxiv.org/abs/1401.7610
- Evidence for electroweak production of WtWj in pp collisions at sqrt(s)=8 TeV with the ATLAS detector: https://cds.cern.ch/record/1690282
- Measurement of the top quark pair production charge asymmetry in proton-proton collisions at 7 TeV using the ATLAS detector: http://arxiv.org/abs/1311.6724
- Measurement of the mass difference between top and anti-top quarks in prompt quark states in pp collisions at sqrt(s)= 7 TeV using the ATLAS detector: http://arxiv.org/abs/1401.2831
- Measurement of the differential cross-section of B+ meson production in pp collisions at sqrt(s)= 7 TeV at ATLAS: http://arxiv.org/abs/1307.0126

- Combined
  - First combination of Tevatron and LHC measurements of the top-quark mass: https://cds.cern.ch/record/1669819
  - Combination of ATLAS and CMS tt\bar{b} charge asymmetry measurements using LHC proton-proton collisions at 7 TeV: https://cds.cern.ch/record/1670517
Observation/Evidence/Search

- A Search for WWGamma and WZGamma production in pp Collisions at sqrt(s) = 8 TeV: https://cds.cern.ch/record/1563302?ln=en
  - Measurement of the 2Z production cross section and anomalous trilinear gauge couplings in 17T events at sqrt(s) = 8 TeV: http://arxiv.org/abs/1401.2942
  - Measurement of the inclusive top-quark pair + photon production cross section in the muon + jets channel in pp collisions at sqrt(s) = 8 TeV: http://arxiv.org/abs/1401.2942
  - Measurement of the inclusive top-quark pair production cross section in pp collisions at sqrt(s) = 8 TeV: https://cds.cern.ch/record/1504199
- Observation of the associated production of a single top quark and a W boson in pp collisions at sqrt(s) = 8 TeV: http://arxiv.org/abs/1401.321
- Search for flavor-changing neutral currents in top-quark decays t to Zq in pp collisions at sqrt(s) = 8 TeV: http://arxiv.org/abs/1401.2942
- Observation of the associated production of a single top quark and a W boson in pp collisions at sqrt(s) = 8 TeV: http://arxiv.org/abs/1401.2942
- Measurement of the ratio of the production cross-section times branching fraction between the Bc to J/psi pi and the B+ to J/psi K and of branching fractions Bc to J/psi pi pi pi over Bc to J/psi pi in CMS at sqrt(s)=7 TeV: https://cds.cern.ch/record/1635097
- Search for s-channel single top-quark production at 8 TeV in the lepton + jets channel: https://cds.cern.ch/record/1644574?ln=en
- Search for standard model four top quark production at 8 TeV in the lepton + jets channel: https://cds.cern.ch/record/1563310?ln=en
- Evidence for electroweak production of W±W±jj in pp collisions at s=8 TeV with the ATLAS detector https://cds.cern.ch/record/1690282
  - Measurement of inclusive W and Z production in pp collisions at s=8 TeV: https://cds.cern.ch/record/1690282
  - Measurement of inclusive W and Z cross sections at sqrt(s)=7 TeV: https://cds.cern.ch/record/1690282
  - Measurement of the inclusive W and Z production cross section in pp collisions at sqrt(s) = 8 TeV: http://arxiv.org/abs/1312.263
- Observation/Evidence/Search
How far have we come?

• Lots of work done on the Standard Model
  → The “Standard” Cross Section plot is finished
  → SM does an excellent job over 14 orders of magnitude

Total Cross Section
Jet Physics
Single Boson
Single and top pair channels
Higgs really at 125 GeV
~ 4 Events at LHC right now

Just entering a really exciting time for SM physics. We need a new plot!
  Tri-boson
  Vector Boson Scattering
  Top pairs with vector bosons
t+Z, and others
The Experimentalists’ Plot

CMS Preliminary

Feb 2014

Total cross sections measured down to 100 [fb] - still has some theory in it
The Actual Experimentalists’ Plot

Fiducial Cross sections (cross-section inside experimental acceptance)
Studied processes from 10s of mb - 1 fb
14 orders of magnitude and SM prediction holds up pretty well
Some Highlights

- Several interesting measurements
- Hard to calculate physics
  - Hadronic Event Shapes
  - $\Phi(1020) \rightarrow K^+K^-$
- Precision Physics
  - Top Charge Asymmetry
  - Vector Boson Fusion $Z$
- Establishing Processes
  - Single Top
  - Quartic Interactions
    - $W^\pm Vy$
    - Same Sign $W^\pm W^\pm$
Hadronic Jet Shapes

- New updated with 5 fb$^{-1}$ 7 TeV
- Study a set of “Event” shapes
  - Well defined scalar quantities
    - Transverse thrust, Jet broadening, total/transverse mass and three-jet resolution parameters
- Shapes normalized to scalar sum of pT
  - Reduces Jet Energy Scale uncertainties
- Difficult calculation
  - Measurements are used to tune QCD models in event generators

https://cds.cern.ch/record/1646636?ln=en
Differences seen across different tunes and generators—Important for searches
Example of physics that is hard to calculate

- $\Phi$ produced at energies where pQCD fails

Experimentally challenging

- Tracking at low momentum
  - $p_T > 230$ MeV
  - $p < 800$ MeV
- Particle id with $dE/dx$

Different generators and tunes give very different predictions

Good agreement seen with ALICE measurement

http://arxiv.org/abs/1402.6162
More Exciting Results

- Bosons in Association with Heavy Quarks – Very important for PDFs
  - Measurement of the production cross sections for a $Z$ boson and one or more $b$ jets in pp collisions at $\sqrt{s} = 7$ TeV: http://arxiv.org/abs/1402.1521
  - Measurement of the production cross section for a $W$ boson and two $b$ jets in pp collisions at $\sqrt{s} = 7$ TeV: http://arxiv.org/abs/1312.6608

- Jet Physics – Test pQCD, extract $\alpha_s$
  - PDF constraints and extraction of the strong coupling constant from the inclusive jet cross section at 7 TeV: https://cds.cern.ch/record/1632407?ln=en

- Photon Physics-Constrain PDFs
  - A study of the sensitivity to the proton parton distributions of the inclusive photon production cross section in pp collisions at 7 TeV measured by the ATLAS experiment at the LHC: https://cds.cern.ch/record/1636863
  - Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector using 4.6 fb^{-1}: http://arxiv.org/abs/1311.1440
  - Measurement of the differential isolated diphoton production cross section in pp collisions at $\sqrt{s} = 7$ TeV with the CMS detector: https://cds.cern.ch/record/1597071

Note Recent Studies Only: Several studies have older counterparts from other experiments
Top Quark Charge Asymmetry

- Exploring physics with high statistics
- Huge number of top quarks
  - Can perform complicated measurements
- Asymmetry in q-\overline{q} interaction
  - Interesting results from the Tevatron
  - Challenging at the LHC g-g cross section large
    - Need a valence quark colliding against a sea quark
      - System boosted into the forward region
- Variable of interest

\[ A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \]
\[ \Delta|y| \equiv |y_t| - |y_\overline{t}| \]
Ac Results

- New Combination
- ATLAS-CONF-2014-012
- aka. CMS PAS TOP-14-006
- Combination becoming well measured
- Interesting physics in the tails of distributions

https://cds.cern.ch/record/1670517?ln=en
Vector Boson Fusion production of Z

- Physics with high statistics
- Large background
- Smaller signal
  - Just becoming established
- Signature
  - Two leptons
    - $M(l,l) \sim Z$ mass
  - Two jets
    - High $M(j,j)$
    - Large $dY(j,j)$

Lets you directly study this WWZ Vertex

Have to isolate from this!
- New 8 TeV measurements
  - CMS-PAS-FSQ-12-035
- EWK Z+2 jets established @ >5σ
- First unfolded-differential measurements
More Recent Results

• More Top Quark Properties
  – Measurement of the top-quark mass in t t-bar events with lepton+jets final states in pp collisions at sqrt(s)=8 TeV: https://cds.cern.ch/record/1690093?ln=en
  – Measurement of the inclusive top-quark pair + photon production cross section in the muon + jets channel in pp collisions at 8 TeV: https://cds.cern.ch/record/1644573?ln=en
  – Measurement of the mass difference between top and anti-top quarks in pp collisions at sqrt(s) = 7 TeV using the ATLAS detector: http://arxiv.org/abs/1310.6527
  – First combination of Tevatron and LHC measurements of the top-quark mass: https://cds.cern.ch/record/1669819?ln=en

• Lots of Diboson Physics
  – Measurement of ZZ production cross section at 7 and 8 TeV and anomalous gauge couplings limits in 2ell2nu decay channel: https://cds.cern.ch/record/1633371?ln=en
  – Measurement of WZ and ZZ production in pp collisions at sqrt(s) = 8 TeV in final states with b-tagged jets: http://arxiv.org/abs/1403.3047
  – Measurement of the ZZ production cross section and anomalous trilinear gauge couplings in III'l' decays at sqrt(s) = 8 TeV at the LHC: https://cds.cern.ch/record/1563178?ln=en
  – Measurement of WZ production rate: https://cds.cern.ch/record/1564318?ln=en

• Drell Yan Studies - Tests of High Precision Calculations
  – Measurement of the low-mass Drell-Yan differential cross section at sqrt(s)=7 TeV using the ATLAS detector: http://arxiv.org/abs/1404.1212

• Rare Z Decay to 4l
  – Measurement of the 4l Cross Section at the Z Resonance and Determination of the Branching Fraction of Z->4l in pp Collisions at sqrt(s) = 7 and 8 TeV with ATLAS: http://arxiv.org/abs/1403.5657
Rare Processes
Single Top

- Processes still being established

Just observed at the Tevatron (FERMILAB-PUB-14-031-E)
Searches from LHC

Well established measurements from ATLAS, CMS, D0, CDF

First observation $> 5\sigma$ CMS
Updated from $3.6\sigma$ CMS, $4.2\sigma$ Atlas
Single Top

- Need all three to constrain new physics
- Distinguishes different new physics models


- Distinguishes different new physics models
Standard Model doing a pretty good job

New from ATLAS
- 8 TeV t-channel

New from CMS
- 8 TeV t-channel
- 8 TeV tW - First > 5σ
- 8 TeV s-channel
Vector Boson Scattering (VBS) and Quartic Interactions

- Process definitely not established
  - Major area of future research

Very few experimental constraints

- $\gamma\gamma \rightarrow W^\pm W^\mp$ CMS (arxiv:1305.5596)
  - Recent Results

- $W^\pm V\gamma$ - CMS
- $W^\pm W^\pm jj$ - ATLAS

- Challenging
  - Small cross sections
  - Complicated backgrounds
$W^\pm V\gamma \to lvjjy$

- SM process that has never been measured

- Sensitive to new physics

$W^\pm V\gamma \rightarrow lvjj\gamma$

- Measured in Events with
  - 1 lepton + 1 photon + MEt
  - Two Jets $70 \text{ GeV} < M(j,j) < 100 \text{ GeV}$
- Standard Model still out of reach
  - Limit at $3.4 \times \text{SM cross section}$
  - Good sensitivity to aQGC couplings
- Watch for this in the next runs!

<table>
<thead>
<tr>
<th>Process</th>
<th>muon channel number of events</th>
<th>electron channel number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W\gamma$+jets</td>
<td>$136.9 \pm 3.5 \pm 9.2 \pm 0.0$</td>
<td>$101.6 \pm 2.9 \pm 8.0 \pm 0.0$</td>
</tr>
<tr>
<td>$WV$+jet, jet→$\gamma$</td>
<td>$33.1 \pm 1.3 \pm 4.6 \pm 0.0$</td>
<td>$21.3 \pm 1.0 \pm 3.1 \pm 0.0$</td>
</tr>
<tr>
<td>MC $t\bar{t}$+$\gamma$</td>
<td>$12.5 \pm 0.8 \pm 2.9 \pm 0.5$</td>
<td>$9.1 \pm 0.7 \pm 2.1 \pm 0.4$</td>
</tr>
<tr>
<td>MC single top</td>
<td>$2.8 \pm 0.5 \pm 0.2 \pm 0.1$</td>
<td>$1.7 \pm 0.6 \pm 0.1 \pm 0.1$</td>
</tr>
<tr>
<td>MC $Z\gamma$+jets</td>
<td>$1.7 \pm 0.1 \pm 0.1 \pm 0.1$</td>
<td>$1.5 \pm 0.1 \pm 0.1 \pm 0.1$</td>
</tr>
<tr>
<td>multijets</td>
<td>$&lt;0.2 \pm 0.0 \pm 0.1 \pm 0.0$</td>
<td>$7.2 \pm 3.6 \pm 3.6 \pm 0.0$</td>
</tr>
<tr>
<td>SM $WW\gamma$</td>
<td>$6.3 \pm 0.1 \pm 1.5 \pm 0.3$</td>
<td>$4.7 \pm 0.1 \pm 1.1 \pm 0.2$</td>
</tr>
<tr>
<td>SM $WZ\gamma$</td>
<td>$0.6 \pm 0.0 \pm 0.1 \pm 0.0$</td>
<td>$0.5 \pm 0.0 \pm 0.1 \pm 0.0$</td>
</tr>
<tr>
<td>Total predicted</td>
<td>$193.9 \pm 3.9 \pm 10.8 \pm 1.0$</td>
<td>$147.6 \pm 4.8 \pm 9.6 \pm 0.7$</td>
</tr>
</tbody>
</table>

Data | 183 | 139

https://cds.cern.ch/record/1563302?ln=en
Massive VBS (v=W,Z)

- $V_L V_L \rightarrow V_L V_L$ ($V = W, Z$)
  - Violates unitary without cancellations with the Higgs
  - Heavy Higgs bosons can ruin this balance

Same Sign WWjj

- Di-boson VBS processes have final states with two jets

  - Production can be separated into strong production and purely electroweak

  - Strong production is much larger than electroweak production
  - Except in same sign WW
    - Great place to start
Experimental Signature – Same Sign WWjj

- Two same sign leptons
- Missing Traverse Energy
- Two jets with large $M(j,j)$ and $dY(j,j)$

https://cds.cern.ch/record/1690282
Large $M(j,j)$ Ewk and Strong production

- Significance over background for electroweak production = 3.6
  First evidence in an exciting new set of processes
Conclusions

• Great time to be studying the standard model
  – Lots of data for the hard measurements
  – Access to new kinematic regions
  – Precision takes time, so keep looking for more to come from these runs

• New processes being established
  – First observation of Wt single top channel and VBF Z
  – First evidence of electroweak WWjj
  – These are the precision tools of the future

• Our understanding of the SM continues to improve in difficult regions
Backup Material
PDF constraints and extraction of the strong coupling constant from the inclusive jet cross section at 7 TeV

- LHC probes high energies
- Jet production can be used to constrain PDFs
- Jet data allows $\alpha_s$ to be fit as a free parameter

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019^{\text{exp.}} \pm 0.0028^{\text{PDF}} \pm 0.0004^{\text{NP}} + 0.0055 - 0.0022^{\text{scale}}$$

https://cds.cern.ch/record/1632407?ln=en