Top, Higgs and Electroweak Theory

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Outline

- Fantastic ICHEP for top, Higgs and electroweak physics.
- Theory working hard to match experimental precision.
- Feeds back into new theory constraints.
- Orthogonal development: resonance tagging with machine learning.
Top Physics

- Top quark is pivotal to understanding BSM and EWSB
- Largest coupling with the SM Higgs: hierarchy problem.
  - Top mass: Meta-stability of the SM vacuum.

Degrassi et al, 2012; Buttazzo et al, 2013
Top Physics

- Top is pivotal to understanding BSM and EWSB
- Strongest interacting particle with the SM Higgs: hierarchy problem.
- Missing energy from top decays key backgrounds for many BSM searches.

CMS-SUS-16-051 (single-lepton stops)
Top Physics

- Top physics is high precision physics.
  - $\sigma_{t\bar{t}}$ (pb):

<table>
<thead>
<tr>
<th>13 TeV</th>
<th>Central value</th>
<th>Scale uncert.</th>
<th>PDF+alphaS uncert.</th>
<th>Mass uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Mass (GeV)</td>
<td>172.5</td>
<td>831.76</td>
<td>+19.77 -29.20</td>
<td>+35.06 -35.06</td>
</tr>
<tr>
<td></td>
<td>173.2</td>
<td>815.96</td>
<td>+19.37 -28.61</td>
<td>+34.38 -34.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14 TeV</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Top Mass (GeV)</td>
<td>172.5</td>
<td>984.50</td>
<td>+23.21 -34.69</td>
<td>+41.31 -41.31</td>
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<tr>
<td></td>
<td>173.2</td>
<td>966.01</td>
<td>+22.68 -33.89</td>
<td>+40.52 -40.52</td>
</tr>
</tbody>
</table>

- Tops are everywhere at LHC (inc. LHCb and p-Pb!)
  - In Run 2 so far ~ 180 million $t\bar{t}$ pairs
  - In Run 3, the LHC will become (nearly) GigaTop: need theory precision to match!

Parallels: Burns (p-Pb), Sierra (LHCb)
Top Physics

- Current state-of-the-art: NNLO + $NLO_{EW}$
- $NLO_{EW}$ effects impact tails.
- Boosted tops $\rightarrow$ scale hierarchies $\rightarrow$ resummation
- Currently: NNLO + NNLL’:
- Working towards NNNLL:
- Moving beyond NWA: NLO + $NLO_{EW}$ off-shell

Czakon et al, 1705.04105
Czakon et al, 1803.07623
Wang et al, 1804.05218
Heinrich et al, 1709.08615
Denner et al, 1607.05571

Also:
matching with parton showers...
Example: $\alpha_s$ from $\sigma_{tt}$

- Use NNLO (+NNLL) cross-sections at different energies to extract value of strong coupling.

- Current world average: $\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma_{tt}$ [pb]</th>
<th>Statistical unc. [%]</th>
<th>Systematic unc. [%]</th>
<th>Luminosity unc. [%]</th>
<th>$E_{\text{beam unc.}}$ [%]</th>
<th>Exp. $m_t$ unc. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (7 TeV) [16]</td>
<td>182.5</td>
<td>1.7%</td>
<td>2.3%</td>
<td>2.0%</td>
<td>0.3%</td>
<td>-0.2%</td>
</tr>
<tr>
<td>ATLAS (8 TeV) [16]</td>
<td>242.4</td>
<td>0.7%</td>
<td>2.3%</td>
<td>2.1%</td>
<td>0.3%</td>
<td>+0.2%</td>
</tr>
<tr>
<td>ATLAS (13 TeV) [17]</td>
<td>816.3</td>
<td>1.0%</td>
<td>3.3%</td>
<td>2.3%</td>
<td>0.2%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>CMS (7 TeV) [13]</td>
<td>173.4</td>
<td>1.2%</td>
<td>2.5%</td>
<td>2.2%</td>
<td>0.3%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>CMS (8 TeV) [13]</td>
<td>244.1</td>
<td>0.6%</td>
<td>2.4%</td>
<td>2.6%</td>
<td>0.3%</td>
<td>-0.4%</td>
</tr>
<tr>
<td>CMS (13 TeV) [14]</td>
<td>809.8</td>
<td>1.1%</td>
<td>4.7%</td>
<td>2.3%</td>
<td>0.2%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>TEV (1.96 TeV) [18]</td>
<td>7.52</td>
<td>2.7%</td>
<td>3.9%</td>
<td>2.8%</td>
<td>0.0%</td>
<td>+1.1%</td>
</tr>
</tbody>
</table>

Also: high precision $\sin \theta_W$ in DY from ATLAS (Vincter).
Example: $\alpha_s$ from $\sigma_{t\bar{t}}$

- Top quark pole mass $m_t = 173.2 \pm 0.87$ GeV
- Bayesian stats: Theory prediction=prior, experimental result=likelihood function.
- Marginalise posterior to get pdf for strong coupling constant.

\[
f^{\text{pred}}(\sigma_{t\bar{t}} | \alpha_s) = f^{\text{PDF}}(\sigma_{t\bar{t}} | \alpha_s) \otimes f^{m_{t}}(\sigma_{t\bar{t}} | \alpha_s) \otimes f^{\text{Scale}}(\sigma_{t\bar{t}} | \alpha_s),
\]

\[
L(\alpha_s) = \int f^{\text{pred}}(\sigma_{t\bar{t}} | \alpha_s) \cdot f^{\exp}(\sigma_{t\bar{t}} | \alpha_s) \, d\sigma_{t\bar{t}}.
\]

$\alpha_s(M_Z^2) = 0.1177^{+0.0034}_{-0.0036}$

<table>
<thead>
<tr>
<th>Center</th>
<th>Stat.</th>
<th>Syst.</th>
<th>$E_{\text{beam}}$</th>
<th>Lumi.</th>
<th>$m_t$</th>
<th>PDF</th>
<th>Scale</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.1177</td>
<td>+0.0003</td>
<td>+0.0007</td>
<td>+0.0001</td>
<td>+0.0006</td>
<td>+0.0012</td>
<td>+0.0020</td>
<td>+0.0022</td>
</tr>
</tbody>
</table>
Example: Large-\(x\) gluon PDF from differential \(\sigma_{t\bar{t}}\)

- NNLO fully differential distributions (stable tops)
- Enables NNLO PDF fits with top-quark pair distributions.
- Decreases uncertainty in PDFs at large-x.

Czakon et al, 1611.08609

Czakon, Heymes, Mitov, 1511.00549

NNPDF Collaboration, 1706.00428

CMS, 1711.03143

NNPDF Collaboration, 1706.00428
NNPDF with NNLO distributions

- Include NNLO differential top pairs, NNLO Z transverse momentum, NNLO inclusive jet production.
- Allows extraction of strong coupling constant
- Current world average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$
- Result from NNPDF: $\alpha_s^{\text{NNLO}}(m_Z) = 0.1185 \pm 0.0005^{\text{exp}} \pm 0.0001^{\text{meth}} \pm 0.0011^{\text{th}} = 0.1185 \pm 0.0012 \ (1\%)$.

Future possible improvements from:
- Use of boosted tops: (NLO EW, resummation)
- Particle-level distributions: towards NNLO with decays.
EFT for BSM

• Precision measurements and calculations applicable to BSM interpretations too.
  • Particularly true for differential information!

Image Credit: F Riva
EFT for BSM

- Precision measurements and calculations applicable to BSM interpretations too.
- Particularly true for differential information!
EFT for BSM

- Precision measurements and calculations applicable to BSM interpretations too.
- Particularly true for differential information!
EFT for BSM

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_i c_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_i c_i^{(8)} \frac{\mathcal{O}_i^{(8)}}{\Lambda^4} + \ldots \]

- D5: Weinberg operator
- D6: 59 operators.
- Study effects of these, or a subset
- E.g. those which affect the top physics: 16 operators

\[
\begin{align*}
O^{(1)}_{qq} &= (\bar{q} \gamma_\mu q)(\bar{q} \gamma_\mu q) \\
O^{(3)}_{qq} &= (\bar{q} \gamma_\mu \tau^I q)(\bar{q} \gamma_\mu \tau^I q) \\
O_{uu} &= (\bar{u} \gamma_\mu u)(\bar{u} \gamma_\mu u) \\
O^{(8)}_{qq} &= (\bar{q} \gamma_\mu T^A q)(\bar{q} \gamma_\mu T^A q) \\
O^{(8)}_{qd} &= (\bar{q} \gamma_\mu T^A q)(\bar{d} \gamma_\mu T^A d) \\
O^{(8)}_{ud} &= (\bar{u} \gamma_\mu T^A u)(\bar{d} \gamma_\mu T^A d).
\end{align*}
\]

\[
\begin{align*}
O_{uW} &= (\bar{q} \sigma^{\mu\nu} \gamma^I u)\bar{\varphi}W^I_{\mu\nu} \\
O^{(3)}_{uq} &= i(\varphi^\dagger D^I_{\mu\nu}\varphi)(\bar{q} \gamma_\mu \tau^I q) \\
O^{(1)}_{uG} &= i(\varphi^\dagger \tilde{D}^I_{\mu\nu}\varphi)(\bar{q} \gamma_\mu q) \\
O^{(1)}_{\varphi u} &= (\varphi^\dagger i \tilde{D}^I_{\mu\nu} \varphi)(\bar{u} \gamma_\mu u) \\
O_{G} &= f_{ABC}G^{A\nu}_{\mu}G^{B\lambda}_{\nu}G^{C\mu}_{\lambda} \\
O^{(1)}_{\varphi G} &= (\varphi^\dagger \varphi)G^{A\nu}_{\mu}G^{A\mu}_{\nu} \\
O_{\varphi G} &= (\varphi^\dagger \varphi)\tilde{G}^{A\nu}_{\mu}G^{A\mu}_{\nu} \\
O^{(1)}_{\varphi B} &= i(\varphi^\dagger \tilde{D}^I_{\mu\nu}\varphi)(\bar{q} \gamma_\mu q) \\
O_{\varphi B} &= (\varphi^\dagger i \tilde{D}^I_{\mu\nu} \varphi)(\bar{u} \gamma_\mu u).
\end{align*}
\]
EFT for BSM

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}^{SM} + \sum_i c_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_i c_i^{(8)} \frac{\mathcal{O}_i^{(8)}}{\Lambda^4} + \cdots \]

Sensitivity in top-pair production distributions.
Moving from parton → particle level distributions

Hot off the press:
Top-EFT at ILC/CLIC. Improve HL-LHC constraints by \( \mathcal{O}(10^2) \)
Durieux et al, 1807.02121

Buckley et al, 1512.03360
Miller Parallel
EFT for BSM

- Neutral Diboson Processes: pp → ZZ, WW
- Probe anomalous triple gauge couplings
- NNLO differential for all relevant final states, off-shell

Grazzini et al, 1507.02565
Kallweit, Wiesemann, 1806.05941
Belusca-Maito et al, 1710.05563
Corbett, MJD, Englert, Nordstrom, 1710.07530
Degrande, 1308.6323

- Only enter at dimension at 8 in the effective Lagrangian
- 4 of these operators, 3 which violate CP.

\[ \mathcal{O}_{WW} = i H^\dagger W_{\mu\nu} W^{\rho\mu} \{ D_\rho, D^\nu \} H, \]
\[ \mathcal{O}_{BW} = i H^\dagger B_{\mu\nu} W^{\rho\mu} \{ D_\rho, D^\nu \} H, \]
\[ \mathcal{O}_{BB} = i H^\dagger B_{\mu\nu} B^{\rho\mu} \{ D_\rho, D^\nu \} H. \]

\[ \Gamma^{\alpha\beta\mu}(q_1, q_2, P) = \frac{i(P^2 - m_Z^2)}{m_Z^2} \left[ f_4^Z (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^Z \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho \right]. \quad (1) \]

\[ f_4^Z = \frac{M_Z^2 v^2}{2 c_W s_W} \frac{(c_W^2 c_{WW} + 2 c_W s_W c_{BW} + 4 s_W^2 c_{BB})}{\Lambda^4}, \]
EFT for BSM

- What models are we probing?
- Spin-0: Complex 2HDM
- Cross-sections are $\mathcal{O}(10^{-3})$ fb

Matching shows C2HDM operators are dimension 12!

- Spin $\frac{1}{2}$: Vectorlike fermions
- Small cross-sections at LHC.
  - Need to take STU constraints into account

\[ -\mathcal{L}_{\text{mass}} \supset m_\ell \tilde{l}_L^\ell \tilde{l}_R^\ell + m_e \tilde{e}_L^e \tilde{e}_R^e + m_\nu \tilde{\nu}_L^\nu \tilde{\nu}_R^\nu + \text{h.c.} \]
\[ + Y'_e (\tilde{l}_L^e H) e_R^e + Y''_e (\tilde{l}_R^e H) e_L^e + \text{h.c.} \]
\[ + Y'_\nu (\tilde{l}_L^\nu H) \nu_R^\nu + Y''_\nu (\tilde{l}_R^\nu H) \nu_L^\nu + \text{h.c.} \]
EFT for BSM

- Spin ½: Vectorlike fermions
- Small cross-sections again at LHC. Need to take STU constraints into account

Similar ideas for Higgs:
- Craig et al, 1305.5251
- Englert, McCullough 1330.1526

D8 operators can be generated by
- Bellazzini, Riva, 1806.09640

Spin 2 resonances (e.g. KK gravitons)

Pseudo-Goldstini (non-linearly realised supersymmetry)
To be resolved

lepton+jets

Parallels: Burns, Berta, Peters, Zenaiev
Theory frontier continues to move

- Differential distributions
- Finite-mass effects in diboson production
- NNLO QCD + NLO EW
- Decays and matching to showers

2017 LH Proceedings, 1803.07977

Image credit: Salam
<table>
<thead>
<tr>
<th>process</th>
<th>known</th>
<th>desired</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow t\bar{t}$</td>
<td>$N^2\text{LO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$</td>
<td>$N^2\text{LO}_{\text{QCD}}$ (w/ decays)</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{\text{QCD}}$ (w/ decays, off-shell effects)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{\text{EW}}$ (w/ decays, off-shell effects)</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + j$</td>
<td>$\text{NLO}_{\text{QCD}}$ (w/ decays)</td>
<td>$N^2\text{LO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$ (w/ decays)</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{\text{EW}}$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + 2j$</td>
<td>$\text{NLO}_{\text{QCD}}$ (w/ decays)</td>
<td>$\text{NLO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$ (w/ decays)</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + Z$</td>
<td>$\text{NLO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$ (w/ decays)</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + W$</td>
<td>$\text{NLO}_{\text{QCD}}$</td>
<td>$\text{NLO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$ (w/ decays)</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{\text{EW}}$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow t/\bar{t}$</td>
<td>$N^2\text{LO}_{\text{QCD}}^*$(w/ decays)</td>
<td>$N^2\text{LO}<em>{\text{QCD}} + \text{NLO}</em>{\text{EW}}$ (w/ decays)</td>
</tr>
</tbody>
</table>

Table I.4: Precision wish list: top quark final states. $N^2\text{LO}_{\text{QCD}}^*$ means a calculation using the structure function approximation.
<table>
<thead>
<tr>
<th>process</th>
<th>known</th>
<th>desired</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to V$</td>
<td>$N^3\text{LO}_{QCD}^{(z\to 0)}$ (incl.)</td>
<td>$N^3\text{LO}<em>{QCD}+N^2\text{LO}</em>{EW}+N^{(1,1)}\text{LO}_{QCD\otimes EW}$</td>
</tr>
<tr>
<td></td>
<td>$N^2\text{LO}_{QCD}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{EW}$</td>
<td></td>
</tr>
<tr>
<td>$pp \to VV'$</td>
<td>$N^2\text{LO}_{QCD}$</td>
<td>$N^2\text{LO}<em>{QCD}+\text{NLO}</em>{EW}$</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{EW}$</td>
<td>$\text{NLO}_{QCD}$ (gg channel, w/ massive loops)</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{QCD}$ (gg channel)</td>
<td></td>
</tr>
<tr>
<td>$pp \to V + j$</td>
<td>$N^2\text{LO}<em>{QCD}+\text{NLO}</em>{EW}$</td>
<td>hadronic decays</td>
</tr>
<tr>
<td>$pp \to V + 2j$</td>
<td>$\text{NLO}<em>{QCD}+\text{NLO}</em>{EW}$</td>
<td>$N^2\text{LO}_{QCD}$</td>
</tr>
<tr>
<td>$pp \to V + b\bar{b}$</td>
<td>$\text{NLO}_{QCD}$</td>
<td>$N^2\text{LO}<em>{QCD} + \text{NLO}</em>{EW}$</td>
</tr>
<tr>
<td>$pp \to VV' + 1j$</td>
<td>$\text{NLO}_{QCD}$</td>
<td>$\text{NLO}<em>{QCD}+\text{NLO}</em>{EW}$</td>
</tr>
<tr>
<td></td>
<td>$\text{NLO}_{EW}$ (w/o decays)</td>
<td></td>
</tr>
<tr>
<td>$pp \to VV' + 2j$</td>
<td>$\text{NLO}_{QCD}$</td>
<td>$\text{NLO}<em>{QCD}+\text{NLO}</em>{EW}$</td>
</tr>
</tbody>
</table>

+jets, Higgs (not shown)...
Machine learning for phenomenology

- Many problems in collider phenomenology are now being attacked with machine learning (ML) methods.
- In particular: deep learning.
- (Boosted) Jet/Resonance Tagging
- Fast detector simulations (showers in calorimeters, etc)
- Pileup mitigation
- Jet clustering
- Bump-hunting
- More...

Larkoski et al, 1709.04464
Guest et al, 1806.11484

Plenary: Yokohama, Sexton-Kennedy
Parallel Sessions: Stoye, Schramm
Machine Learning Jet Substructure

“Jet Images”: Use deep neural networks used in computer vision to discriminate between jets.

“Flattening the calorimeter into a 2D image...”

de Oliveira et al, 2015
Machine Learning Jet Substructure

- Sum transverse energy in calo tower in 0.1x0.1 grid in eta-phi space.
- Perform translations, rotations, reflections in eta-phi space
  - (Zoom to minimise pt dependence)
  - Crop and normalise

PYTHIA 8
Machine Learning Jet Substructure

- Sum transverse energy in calo tower in 0.1x0.1 grid in eta-phi space.
  - Perform translations, rotations, reflections in eta-phi space
    - (Zoom to minimise pt dependence)
    - Crop and normalise
  - Average Jet-Images for W jets and QCD jets

Barnard, Dawe, MJD, Rajcic, 1609.00607

de Oliveira et al, 2015
Taggers for Everything: MC

- Quark vs gluon, W/Z, Higgs, top, anti-QCD and BSM...
Machine Learning Jet Substructure

- Supervised learning: need a known training sample

Sensitive to differences between parton showers

Train on data from regions of high signal purity?
  e.g. semileptonic top.

Barnard, Dawe, MJD, Rajcic, 1609.00607
Machine Learning Jet Substructure

- Classification without Labels (CWoLa): train on mixtures of classes (QCD jets, W jets)
  - Two samples of events M1 and M2, with different proportions of signal and background.
  - Train a supervised neural network to discriminate between M1 and M2.

Dery et al, 1702.00414
Metodiev et al, 1708.02949
Cohen et al, 1706.09451
Komiske et al, 1801.10158
Machine Learning Jet Substructure

- This results in an optimal classifier for distinguishing S and B!
- To convert M1-M2 classifier to S-B classifier need benchmark point.
- Usually just depends on hard-scattering, not parton shower etc.

Metodiev et al, 1708.02949
What is the machine learning?

- Concern: these are fancy black boxes.
- “The more you know, the less black the boxes will be” (Ben Nachman)
  - Pixel-by-pixel convolution of DNN output with pixel-intensity
  - Subleading subjet location strongly correlated with DNN output
- Improvements over tagging variables from exploiting colour-flow and radiation patterns
What is the machine learning?

- Are these methods accessing information outside the jet mass?
- Or subjet location (as in n-subjettiness)?

Train in a restricted phase-space:

\[ 80 < m_J < 81 \text{ GeV} \]
\[ 0.19 < \tau_{21} < 0.21 \]

\[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k} \}. \]
What is the machine learning?

- Correlation coefficients in restricted phase space.
- Exploiting information in radiation patterns
- W-jets: more radiation between subjets
- QCD-jets: radiation more widely spread

More W-like

\[ W' \to WZ, \ \sqrt{s} = 13 \text{ TeV}, \ \text{Pythia 8} \]
\[ 250 < p_T < 260 \text{ GeV}, 0.19 < \tau_{21} < 0.21, 79 < \text{mass} < 81 \]

More QCD-like

\[ W' \to WZ, \ \sqrt{s} = 13 \text{ TeV}, \ \text{Pythia 8} \]
\[ 250 < p_T < 260 \text{ GeV}, 0.39 < \tau_{21} < 0.59, 79 < \text{mass} < 81 \]

\[ 0.19 < \tau_{21} < 0.21 \]
\[ 0.39 < \tau_{21} < 0.41 \]
\[ 0.59 < \tau_{21} < 0.61 \]
What is the machine learning?

- How does this feed back into theory?

Datta, Larkoski, 1704.08249
Construct basis of functions for probing phase space with products of $n$-subjettiness observables based on ML considerations.

Datta, Larkoski, 1710.01305

Louppe et al, 1702.00748
Four-momenta as words, clustering history as sentences

Henrion et al
Re-imagining jet clustering: jets as graphs vs jets as trees. Learn clustering metric directly from data!
Outlook

- All I want for Christmas is a chargino.
- And an extensive precision measurements program.

- Precision hadron collider physics for Top/Higgs/EW
  - Requires precision predictions
- Fundamental measurements of Standard Model parameters
  - Searches for New Physics
- The Age of the Differential Distribution!