Getting to 1 fb$^{-1}$ at the LHC

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**The Main Message**

- The most important thing we can do in the early year’s running is to get ready for later, high luminosity running
  - I hope to present an overview of the path from $10^{31}$ to $10^{33+}$
- In any measurement, there are two components:
  - 1. Making the measurement correctly
  - 2. Convincing yourself that you’ve made the measurement correctly
  - Usually #2 is harder than #1
Prediction #1: 
Early LHC Luminosity Will be Lower Than We Think/Hope
Why not \(10^{34}\) on Day One?

Luminosity Equation:

\[
L = \frac{fE n_b N_p^2}{\epsilon_n \beta^*}
\]

Quantities we cannot easily change:
- \(f\): revolution frequency of the LHC
  - set by radius and \(c\)
- \(E\): beam energy
  - set by physics goals
- \(\epsilon_n\): beam emittance at injection
  - set by getting the beam into the LHC

Quantities we can change
- \(n_b\): number of bunches
  - Factor of 3 lower initially
- \(\beta^*\): strength of final focus
  - Factor of ~2 possible
- \(N_p\): protons per bunch
  - Can be as small as we want
  - Initially, can be within a factor of ~2 of design

This works out to \(4 \times 10^{32}\) on Day One
LHC Stored Energy in Perspective

- LHC stored energy at design ~700 MJ
  - Power if that energy is deposited in a single orbit: ~10 TW (world energy production is ~13 TW)
- Battleship gun kinetic energy ~300 MJ

USS New Jersey (BB-62)
16”/50 guns firing
Prudence and Luminosity Profile

- There is a HUGE amount of stored energy in the LHC at design
- Safety/sanity requires that we operate with less stored energy until we have plenty of experience with beam aborts
  - This means less intense proton beams
  - This means substantially lower luminosity
    - *luminosity goes as the square of stored energy*
    - We will probably insist on many successful unintentional store terminations before putting more beam in the machine
- Expect that the luminosity will grow slowly
  - Perhaps $10^{31}$ in 2007
  - Perhaps growing by an order of magnitude a year.
    - *If we are not absolutely confident in our ability to tolerate an unintentional store termination, this will grow more slowly*
What is 1 fb⁻¹?

- 1 fb⁻¹ = 10¹⁴ collisions
  - 2 nanograms of matter produced in collisions (about the same mass as a cell)
- 1 fb⁻¹ = 10⁷ seconds of running at 10³²
  - More likely 5 x 10⁶ seconds at 2 x 10³²
    - The LHC running schedule is not very aggressive
    - 2 x 10³² is an accepted guess for pre-10³⁴ luminosity
- My best guess: this will happen some time in Year 3

- Note that the Tevatron has just hit the 1 fb⁻¹ milestone, 20 years after the first collisions
  - Probably 75% of the collisions it will ever produce will be in the last few years of operation
Prediction #2:

The Staging of the ATLAS Detector will be Largely Unnoticed outside of ATLAS.
Descoping and Staging

- Not all of ATLAS will be ready to be installed on time
  - See next slide

- “You have to go with the detector you have, not the detector you wish you had”

Early descoping: Bent Pyramid of Sneferu c. 2600 BCE
What Will Be Staged? (My Best Guess)

- Some of the central muon planes –
  - Degrades momentum resolution
- Some (more) of the forward muon system
  - Reduces muon acceptance
- Innermost silicon layer
  - Reduces B-tagging efficiency
- Trigger and DAQ
  - Lowers maximum luminosity

Staging details depend on who finishes first – the detector or the accelerator
How much does poorer B-tagging hurt us?

Top reconstruction at ATLAS without B tagging: just pick the three highest $E_T$ jets in a lepton+4 jets event, and plot.

$m_{\text{top}} = 162.7 \pm 0.8 \text{ GeV}$

$m_{\text{top had}} = 78.1 \pm 0.8 \text{ GeV}$

Jet energy scale calibration possible from shift in $m(W)$

Credit: Stan Bentvelsen
Early Top Details

Why is B-tagging less important at the LHC?
- Top cross-section is growing: $\sigma(t)/\sigma(W)$ (and by extension, $W+jets$) is an order of magnitude larger (exact value is still uncertain)
- The top and anti-top are more separated
  - kinematic advantage to higher center of mass energy
  - Reduces combinatoric confusion (big problem at the TeVatron)

Even without the innermost silicon layer, some B-tagging will be possible (comparable to the TeVatron)
- These predictions are on the pessimistic side

Signal only: 100 pb$^{-1}$, electrons only. 50 pb$^{-1}$ of e+$\mu$ data would be similar

Includes background estimate
Top Mass at a Femtobarn

- Today’s TeVatron top mass uncertainty is 2.3 MeV (hep-ex/0603039)
  - 40% of the uncertainty is statistical, 60% is systematic
  - Based on up to 750 pb⁻¹ (CDF) and 390 pb⁻¹ (D0)
- (My own) scaling to 4 fb⁻¹ suggests an uncertainty near 1.8 MeV
  - Dominated by systematics (1.7 MeV)
- To improve on this, the LHC has to get the systematics under control at the 1% level
  - Typically, this takes years
  - Luminosity helps, but what this level of systematic understanding really needs is time
- This may be difficult to do and to demonstrate early on.
  - Can we “cherry pick” events? We will have ~10000 of them.
Rare Top Decays

- After 1 fb$^{-1}$, the LHC will have ~an order of magnitude more top quarks than than Tevatron
- Most rare decay signatures do not require the same level of systematic control as m(t). Consider $t \to c\gamma$
  - Signature 1: $\gamma + 4$jets, $m(\gamma j_1) = m(t)$, $m(j_2j_3) = m(W)$, $m(j_2j_3b_4) = m(t)$
  - Signature 2: $W + \gamma + 2$jets: $m(\gamma j_1) = m(t)$, $m(Wb_2) = m(t)$
    - Technical Note: two values for $m(Wb_2)$: only one has to be near $m(t)$
    - Essentially, the measurement is “cut and count”. Jet energy scale uncertainty is a few percent uncertainty on the background; cuts are tuned so that the expected background is $\sim 1/2$ an event
    - B-tagging helps somewhat: there is a tradeoff between kinematic and B-tagging cuts
- 1 fb$^{-1}$ would give limits like $10^{-3} - 10^{-4}$ for FCNC decays

Wish list: it would be very nice if we had a Monte Carlo that could give a boson + N hard jets, with the details of the jet kinematics being predicted well enough to predict the effect of mass cuts like these.
Are Rare Top Decays Even Interesting?

- Even Standard Model top FCNC decays have partial widths millions of times larger than the bottom counterparts.
- The problem is that they compete with
  - 2 GeV of $t \to b$ decays, instead of
  - 400 µeV of $b \to c$ decays.
- For a theory to be interesting to experimenters, we need partial widths in the MeV ballpark.

Wish list: If you want experimenters to set limits on a process that you don’t expect to be there, it helps to have a model that predicts that something will appear.

This model doesn’t have to be any good.
Muon Identification

- The ATLAS muon system is designed for a resolution of 10% for 1 TeV muons
  - This requires knowledge of the detector position to ~10’s of microns over 10’s of meters
    - *To remind you, the coefficient of thermal expansion is ~10^{-5}/K*
  - For early running, there won’t be any 1 TeV muons
  - Even if the muon spectrometer has initially poorer resolution, the effect on most muons is minimal

Worsening the outer muon spectrometer resolution has virtually no impact below ~100 GeV, and only minimal impact between 100 & 200 GeV.

Credit: Bing Zhou
More on Lepton Identification

- We can use the Z decays to
  - Insure that the electromagnetic calorimeter energy scale is correct
  - Improve the alignment – and thus the resolution – of the muon spectrometer
- A 10 pb$^{-1}$ early run should give ~10,000 Z events in each channel
  - Later runs will improve our statistical uncertainty

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An example from the Tevatron: tracking misalignments introduce a “false curvature”. A particle of known mass (for them the J/ψ, for us the Z) can be used to identify and remove this problem.

Since trackers measure $1/\rho$, not $\rho$, going to higher momentum is an interpolation, not an extrapolation.
Tevatron $B \rightarrow \mu\mu$ Searches

CDF and D0 limits have been leapfrogging each other since Run II began.

Generic comment about Tevatron discovery: With 1 fb$^{-1}$ on tape, if we were going to make a 5$\sigma$ discovery, we would already be starting to see limits fail to improve.
**B → μμ at the LHC**

**Good news for the LHC**
- Cross-section goes up by ~6
- Acceptance goes up by ~3
- Thicker detectors beat down $B → hh$ background

**Bad news for the LHC**
- Triggering forces the $p_T$ threshold up
- Lose factor of ~5 (?)

**Maybe a reach of 6-8 x 10^{-8} is realistic in the 1^{st} $\text{femtobarn}$**

**At higher luminosities, the triggering problem becomes worse and worse**

**A promising strategy is to trigger on 3 muons**
- Requiring the other $B$ to decay via $b → μX$ or $b → c → μX$
- This reduces signal by 5-10
- This should be devastating to our largest background, intertwined $b$ pairs

**Ultimately, we want sensitivity beyond the SM prediction**
- We will reach this
- Exactly when depends on background rates and triggerability.
Prediction #3: Missing $E_T$ will be hard
Why Are We Doing This Anyway?

- Find the Higgs
  - This will take years, unless both the following are true:
    - We are lucky
    - Nature is kind
  - A single scalar Higgs and nothing else would be a disaster
    - Progress is made by having disagreements between expectations and measurements
    - Verifying that there is a single scalar Higgs and nothing else will take more than a decade and maybe even an ILC

- Search for SUSY
  - No SUSY would seriously irritate my colleague Carlos Wagner, which would have certain positive “quality of life” issues for me.
  - The party line is “Just look at the inclusive missing $E_T$ distribution; you can’t miss it” and occasionally, “The background to SUSY is SUSY”

- Some other surprise
This plot compares the measurement of inclusive missing $E_T$ with a known source (invisible width of the Z):

- We’re starting with a background ~2 orders of magnitude larger at reasonable $E_T$.

This is all Monte Carlo, of course, and the usual disclaimers apply.
Where is All this Missing $E_T$ Coming From?

- It ain’t SUSY.
- ~98-99% is from mismeasured jets
  - Jet mismeasurement is rare, but there are a heckuva lot of them
  - About $\frac{1}{2}$ of 1% of jets have significant energy loss to neutrinos
    - *From light flavor, not heavy flavor!*
  - Identification of this process is often – but not always - easy
- Much of the remainder is from missing ("crack seeking") leptons

Personal Conclusion: We can’t do a credible Missing-$E_T$ based SUSY search until we understand jets.

Question for the Audience: Would you believe a Missing-$E_T$ based SUSY search that didn’t show a credible $Z \to \nu\nu$ signal?
Prediction #4

Prediction #4: Jets Will Be Among Our Most Interesting Early Measurements
Expected limit on contact interaction: \( \Lambda(qqqq) > \sim 6 \text{ TeV} \)
- Rule of thumb: 4x the \( E_T \) of the most energetic jet you see
- Present PDG limit is 2.4-2.7 TeV
- Ultimate limit: \( \sim 20 \text{ TeV} \)
- The ATLAS measurement is at lower \( x \) than the Tevatron: PDF uncertainties are less problematic

What about the addition of \( \theta^* \) distribution to improve the early limit sensitivity? Theoretical guidance would be appreciated here.
- A nice feature is that this depends on the position of the jets instead of the energy.
  - It’s harder to mismeasure the position than the energy
Outrunning the Bear

- Present limits on 4-fermion contact interactions from the Tevatron are 2-4-2.7 TeV
- This may hit 3 TeV by LHC turn-on
  - Depends on how many people work on this
- If we shoot for 6 TeV at the LHC and only reach 5 TeV, we’ve already made substantial progress
- Note that there are ~a dozen jets that are above the Tevatron’s kinematic limit: a day at the LHC will set a limit that the Tevatron can never reach.
Getting the X-axis ($E_T$) Right

- **Starting point:**
  - The EM calorimeter is calibrated with the known Z mass using Z decays to electrons.
  - Despite being hadrons, most (80%) of the jet energy at ATLAS ends up in the EM calorimeter, not the hadronic calorimeter.
  - The hadronic calorimeter is calibrated from test beam.
  - This is probably good to 10% or better.

- **Improvements:**
  - Look at balancing: a jet recoils against a Z, a photon, or another jet. Their $p_T$'s should balance (within higher order effects like $k_T$).
Jet Energy Scale Job List

- See that the Z decay to electrons ends up in the right spot
  - Demonstrates that the EM calorimeter is calibrated
- Balance jets with high and low EM fractions
  - Demonstrates that the EM and hadronic calorimeters have the same calibration
- Balance one jet against two jets
  - Demonstrates that the calorimeter is linear
- Balance jets against Z’s and photons
  - Verifies that the above processes work in an independent sample
  - Demonstrates that we have the same scale for quark and gluon jets
- Use top quark decays as a final check that we have the energy scale right
  - Is m(t) = 175 and m(W) = 80? If not, fix it!

Note that most of the work isn’t in getting the jet energy scale right. It’s in convincing ourselves that we got the jet energy scale right – and that we have assigned an appropriate and defensible systematic uncertainty to it.
Jet Balancing & EM Fraction

Jet balance should not depend on the jets’ EM fractions. It does, at the few % level. The effect is smaller for high $E_T$ jets, central jets, and jets that are very close to back-to-back.

Look at events with exactly two back-to-back jets:

Two back-to-back jets should balance in $E_T$ irrespective of whether the energy is mostly electromagnetic or mostly hadronic.
Z-Jet Balancing

Goal – set jet energy scale by balancing jets against a (well-measured) Z

All $Z^0$ candidates

The $Z \rightarrow \gamma\gamma$ peak is from electrons where we miss the track.

The jet energy is low with respect to the Z. Wrong jet scale? Overcorrected leptons? Missing jets?

Credit: Heujin Lim
**Two Jets Are Better Than One!**

- **Z+2 jets** are better balanced than **Z+1 jet events**.
- Investigating why – perhaps related to low efficiency for finding soft jets?

*Credit: Jimmy Proudfoot*
A Short Shopping List for Theorists

- At the TeVatron, there is often one dominant signal process and one dominant background process. This is not often the case at the LHC.
  - It appears that the root cause is the lack of antiquarks in the initial state. Getting them off gluons complicates things.
  - In the experimental world, this is known, but not yet felt in our guts
    • Repetition will help here
  - It would be good to have an idea of how uncertain predictions are because of this.

- Many LHC processes (signal or background) produce multiple hard jets
  - Does there exist a Monte Carlo that not only gets the number and spectrum right, but also the detailed kinematics? (e.g. dijet masses, angular separation, etc.)
Conclusions and Prediction #5

- “It is difficult to predict, especially the future”
- I hope I convinced you that
  - We have a lot of work to do to get believable physics out of the LHC
  - We have a vision of the path we need to take to get there, and we’ve already started down the path (e.g. hunting down 5% effects in the jets)
  - Real life will be harder than our predictions
  - But real life will likely be more exciting than our predictions
May All of Your Predictions Be Pleasant Ones