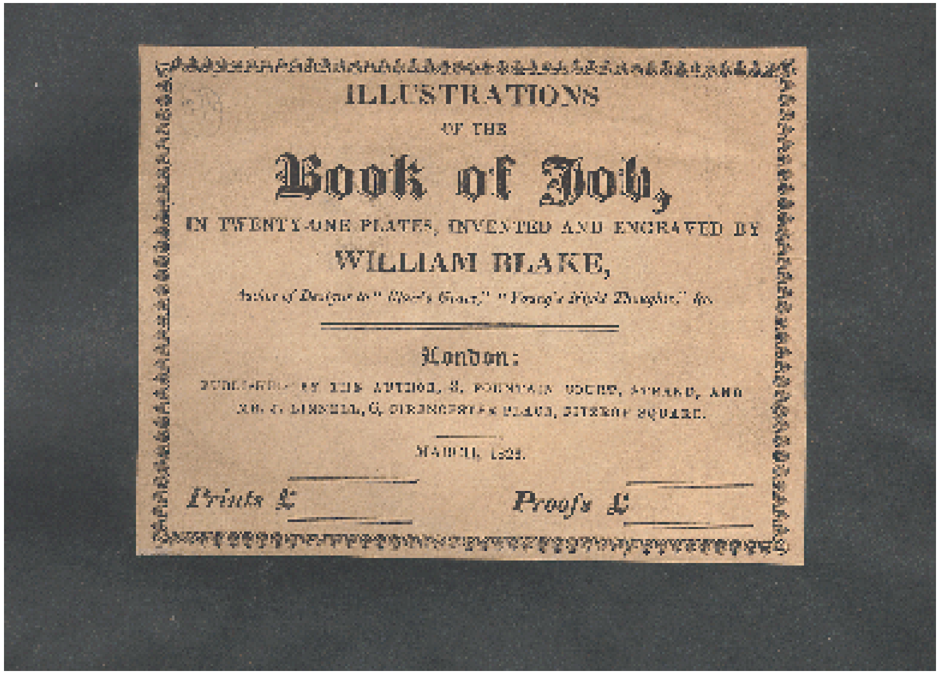
My View of the Standard Model Job List


ILLUSTRATIONS
OF THE
Book of Job,
IN TWENTY-ONE PLATES, INVENTED AND ENGRAVED BY
WILLIAM BLAKE,
London:
PUBLISHED BY THE AUTHOR, 3, FOUNTAIN COURT, STRAND, AND
MR. J. LINNELL, 6, CIRENCESTER PLACE, FITZROY SQUARE.
MARCH, 182[illegible].
Prints £ *Proofs £*

Thomas J. LeCompte

High Energy Physics Division
Argonne National Laboratory

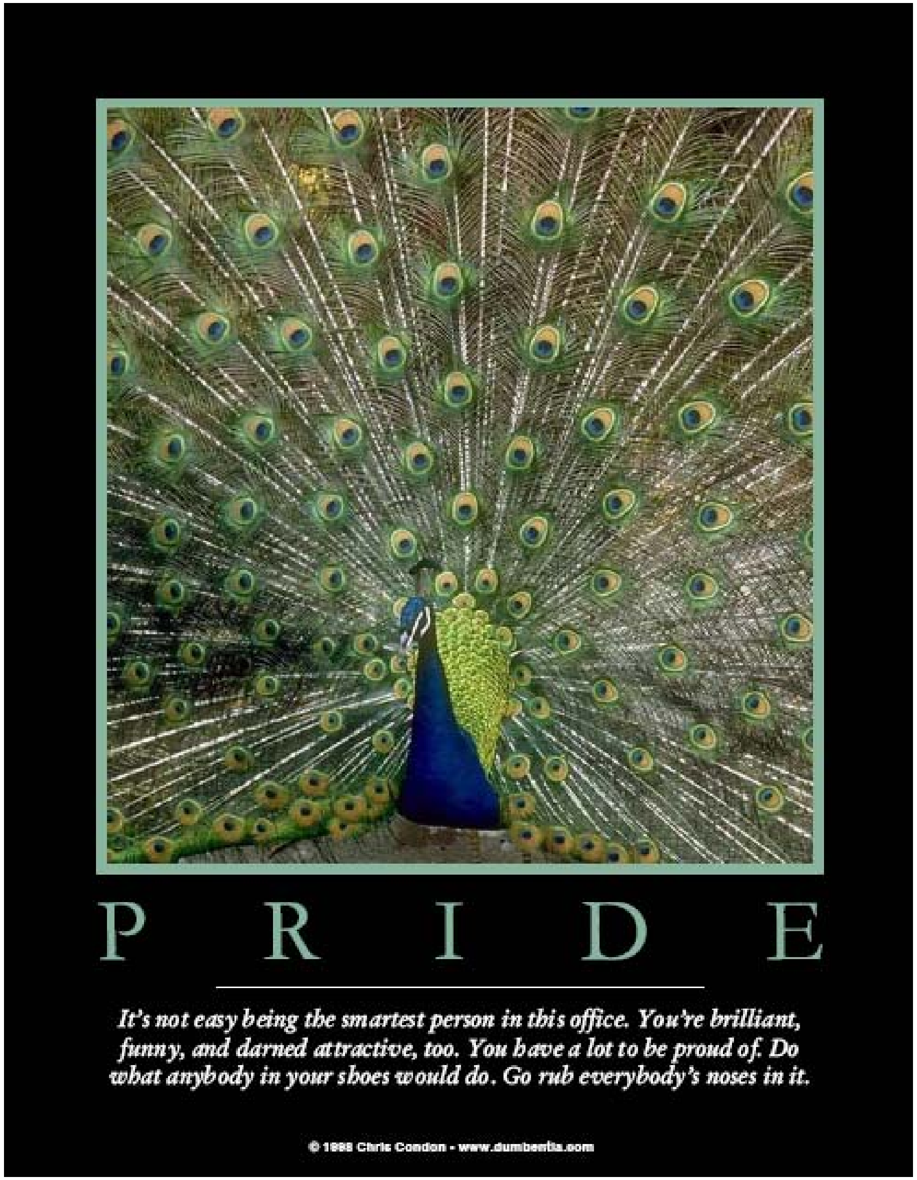
My Goals of This Talk

- I think an informal dialog would be more useful than me prattling on for an hour
  - Interrupt me whenever you want
  - There is no prize for getting to the end of the talk

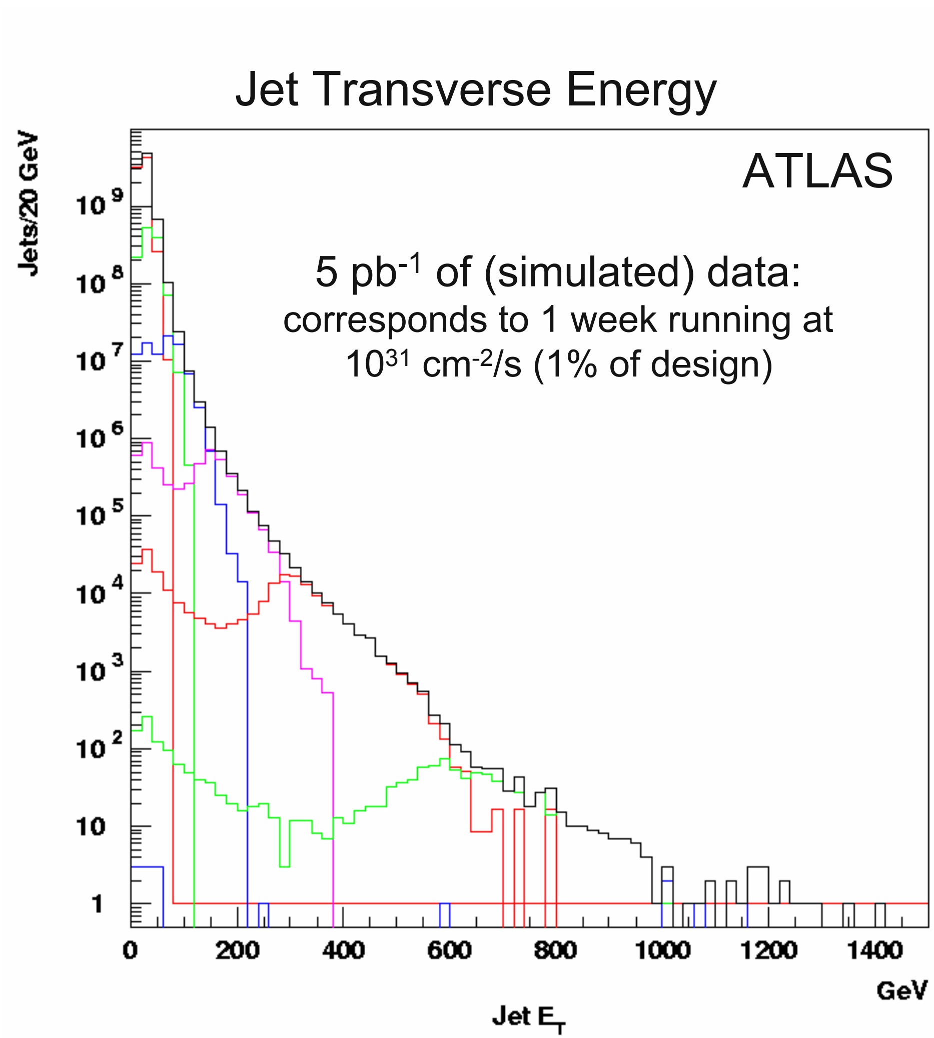
- Some of the jobs listed are entirely experimental
  - Others are not. <hint>

Goal #1

- We (the LHC experiments) need an early measurement that shows we are making progress in understanding the energy frontier
  - We need an early success
    - *For BOTH experiments*



Jets after "One Week"



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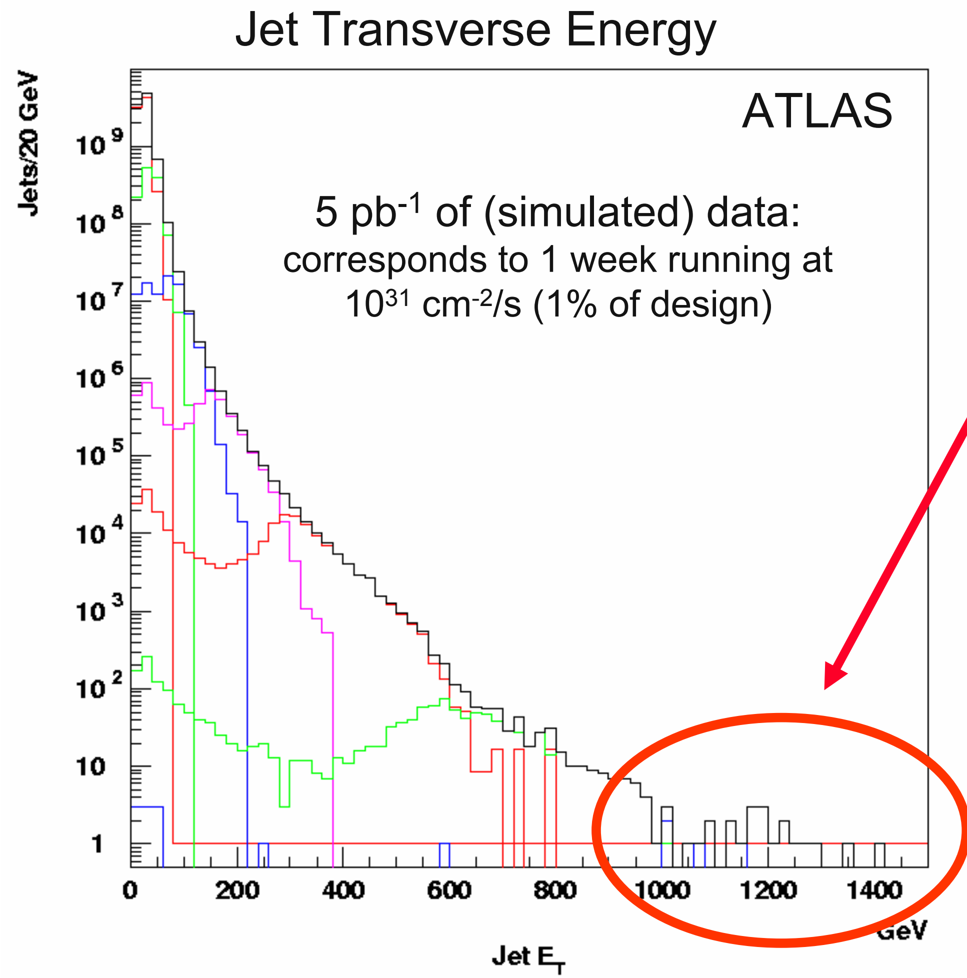
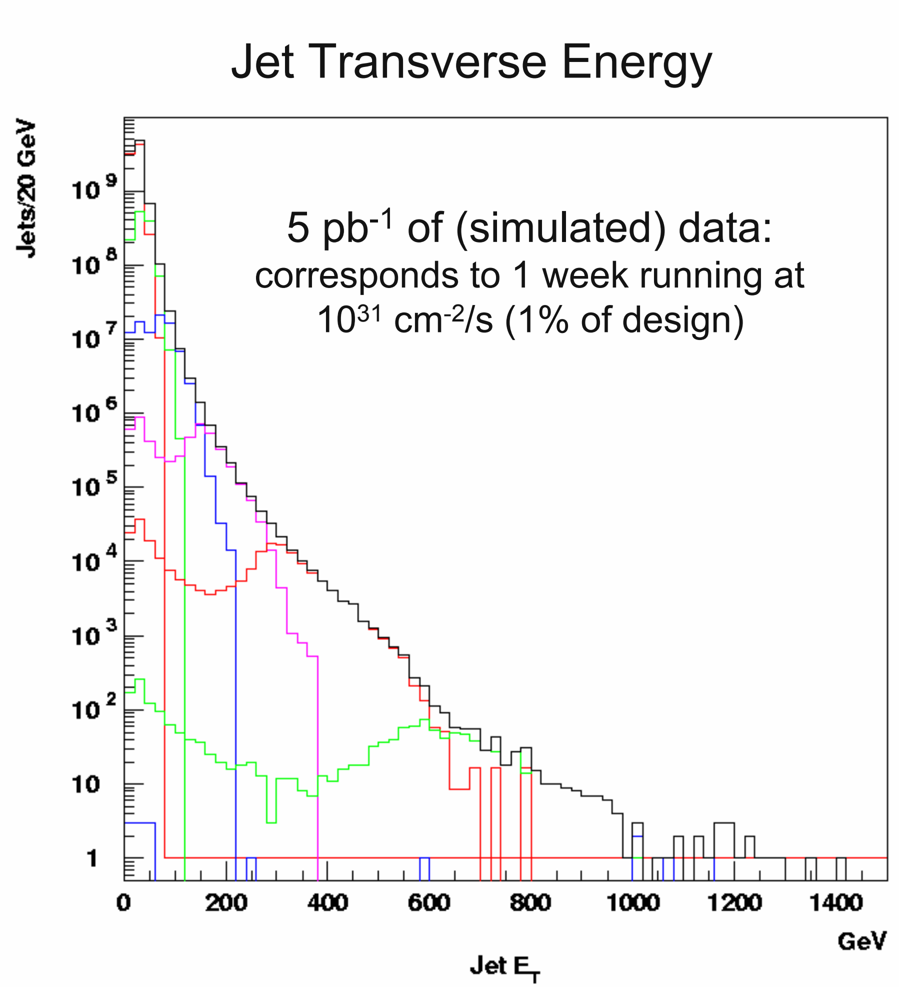


New physics (e.g. quark substructure) shows up here.

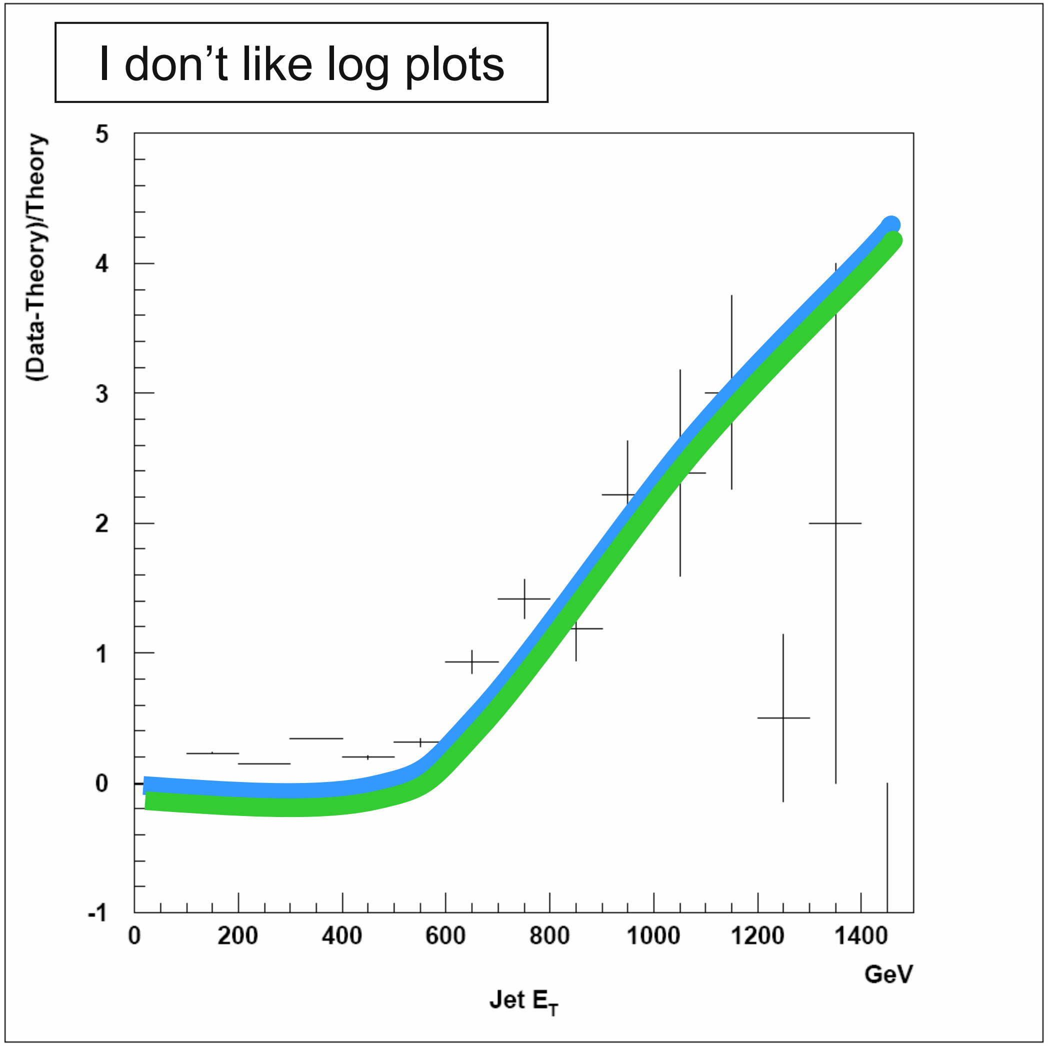
- Number of events we expect to see: **~12**
- If new physics: **~50**
- Number we have seen to date worldwide: **0**

Converting to a 4-Fermion Interaction



- Expected limit on contact interaction: Λ(qqqq) > ~6 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: ~20 TeV
  - The ATLAS measurement is at lower x than the Tevatron: PDF uncertainties are less problematic
- We are investigating the addition of θ* distribution to improve the early limit sensitivity.
  - 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*

Sensitivity to A Contact Interaction



Black: one week's running at 1% of design luminosity.

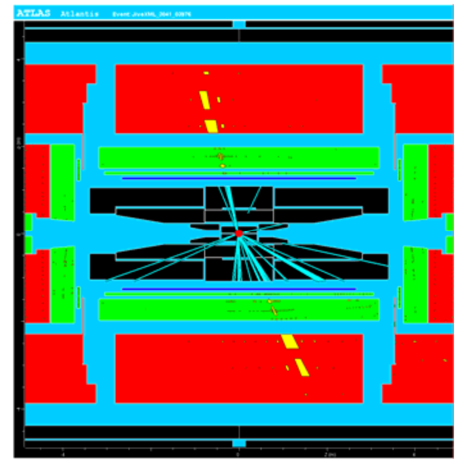
Blue: Expectations for a contact interaction term of ~4 TeV (SM is a line at 0)

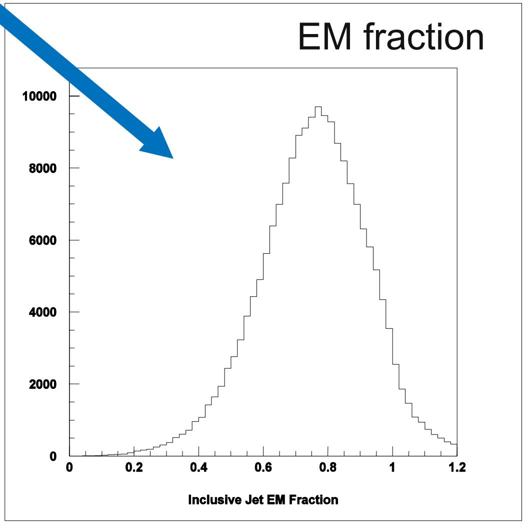
Green: A miscalibration selected to look like a contact interaction

Some care needs to be taken before announcing a major discovery.

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 Energy Scale Job List

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- Use top quark decays as a final check that we have the energy scale right
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The key to the measurement

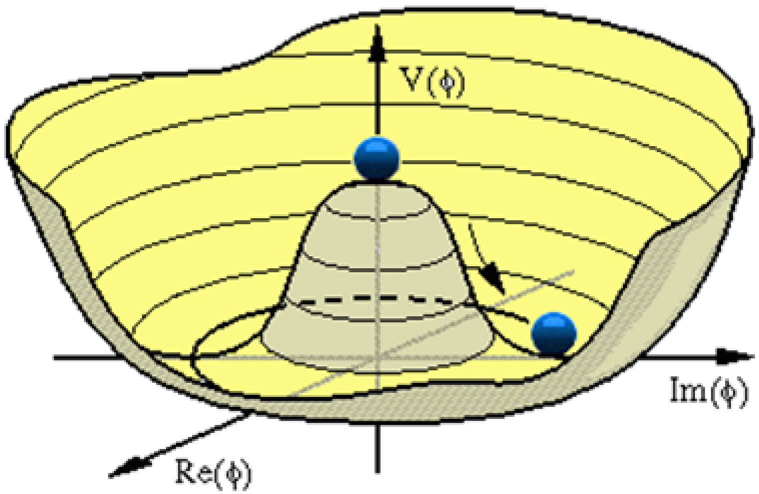
Note that most of the work isn't in getting the jet energy scale right. It's in convincing ourselves that we got the jet energy scale right – and that we have assigned an appropriate and defensible systematic uncertainty to it.

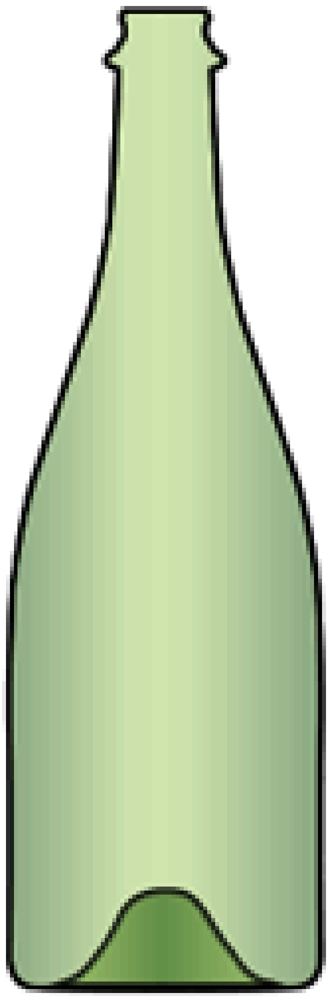
My Ulterior Motive

- When we move onto discovery physics, missing E_T will play a big role
  - SUSY, extra dimensions…
- Understanding jets is a key step in that
  - Mismeasured jets provide the largest source of missing E_T
  - The energy scale for jets is different than for unclustered energy
    - *We cannot get missing E_T right without getting the jets right.*

Goal #2 – Figure Out What's Going On With EWSB

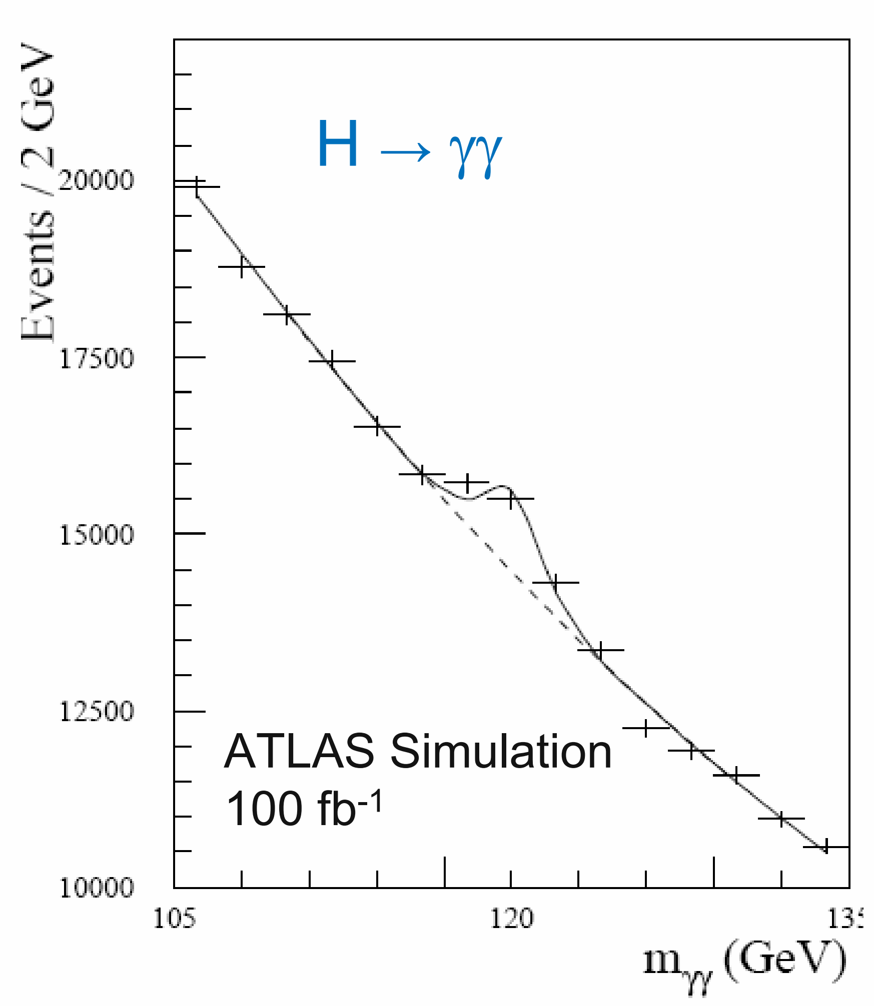
- I find this a much better description than "find the Higgs"

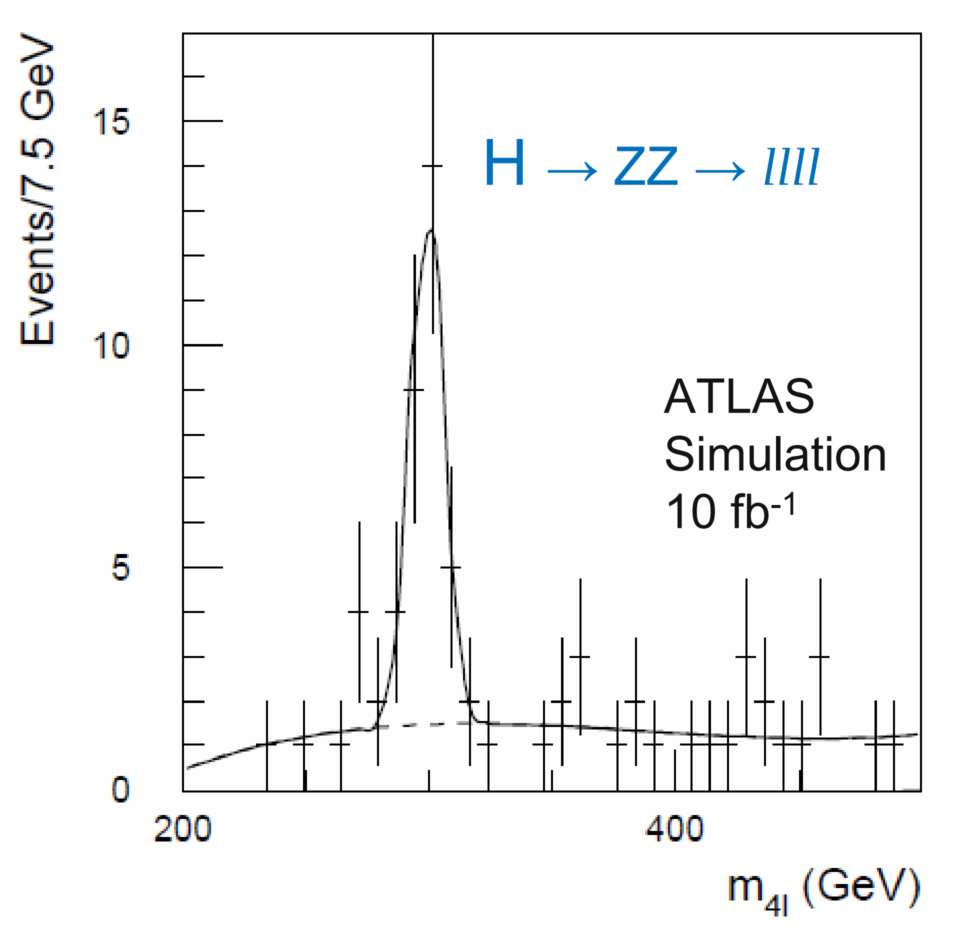




Part of the Answer

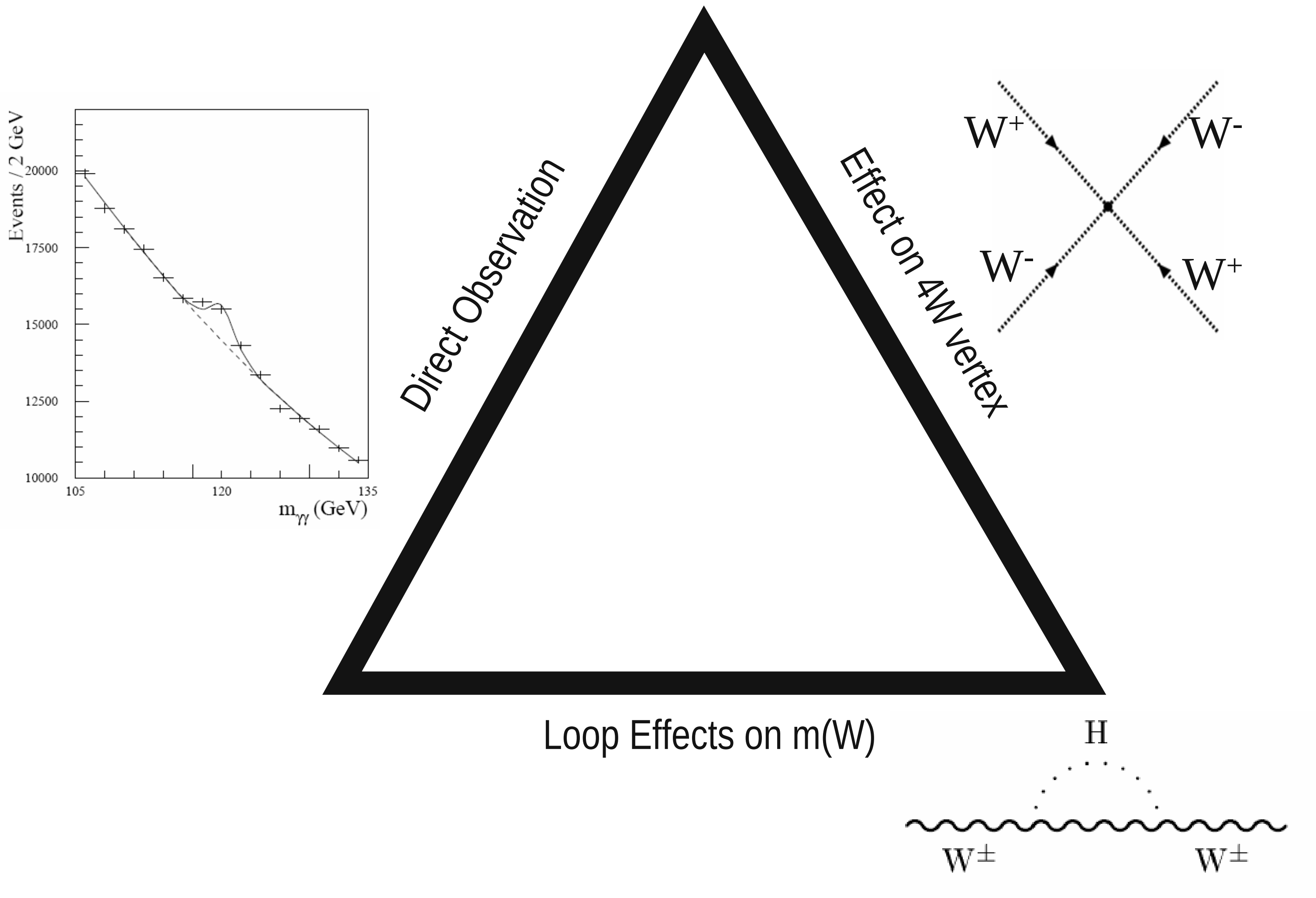
This is part of the program-
but only part of the program



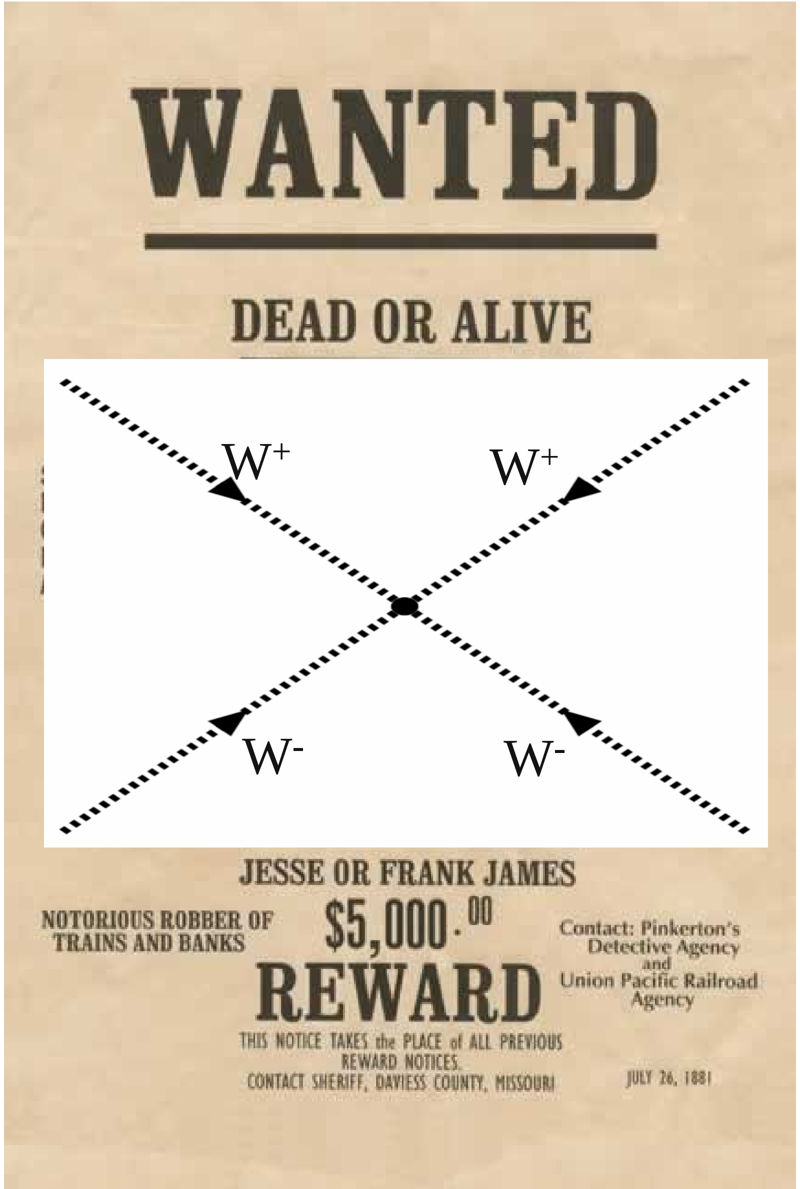


The Higgs Triangle

Two of the three necessary measurements are SM measurements.

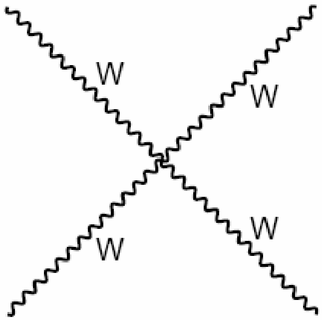


Portrait of a Troublemaker



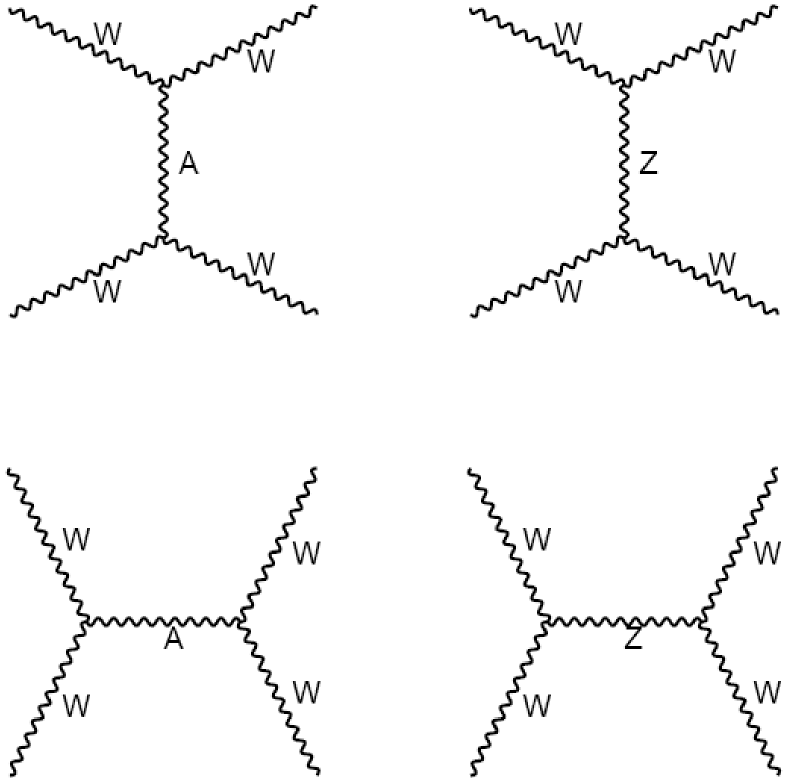
- This diagram is where the SM gets into trouble.
- It's vital that we measure this coupling, whether or not we see a Higgs.
- Unfortunately, we don't measure couplings – we measure rates.

A Complication



If we want to understand the quartic coupling…

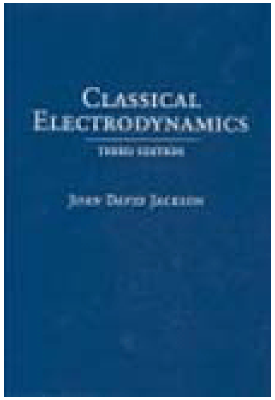
…first we need to measure the trilinear couplings



We need a TGC program that looks at all final states: WW, WZ, Wγ (present in SM) + ZZ, Zγ (absent in SM)

The Semiclassical W

- Semiclassically, the interaction between the W and the electromagnetic field can be completely determined by three numbers:
  - The W's electric charge
    - *Effect on the E-field goes like $1/r^2$*
  - The W's magnetic dipole moment
    - *Effect on the H-field goes like $1/r^3$*
  - The W's electric quadrupole moment
    - *Effect on the E-field goes like $1/r^4$*



- Measuring the Triple Gauge Couplings is equivalent to measuring the 2nd and 3rd numbers
  - Because of the higher powers of 1/r, these effects are largest at small distances
  - Small distance = short wavelength = high energy

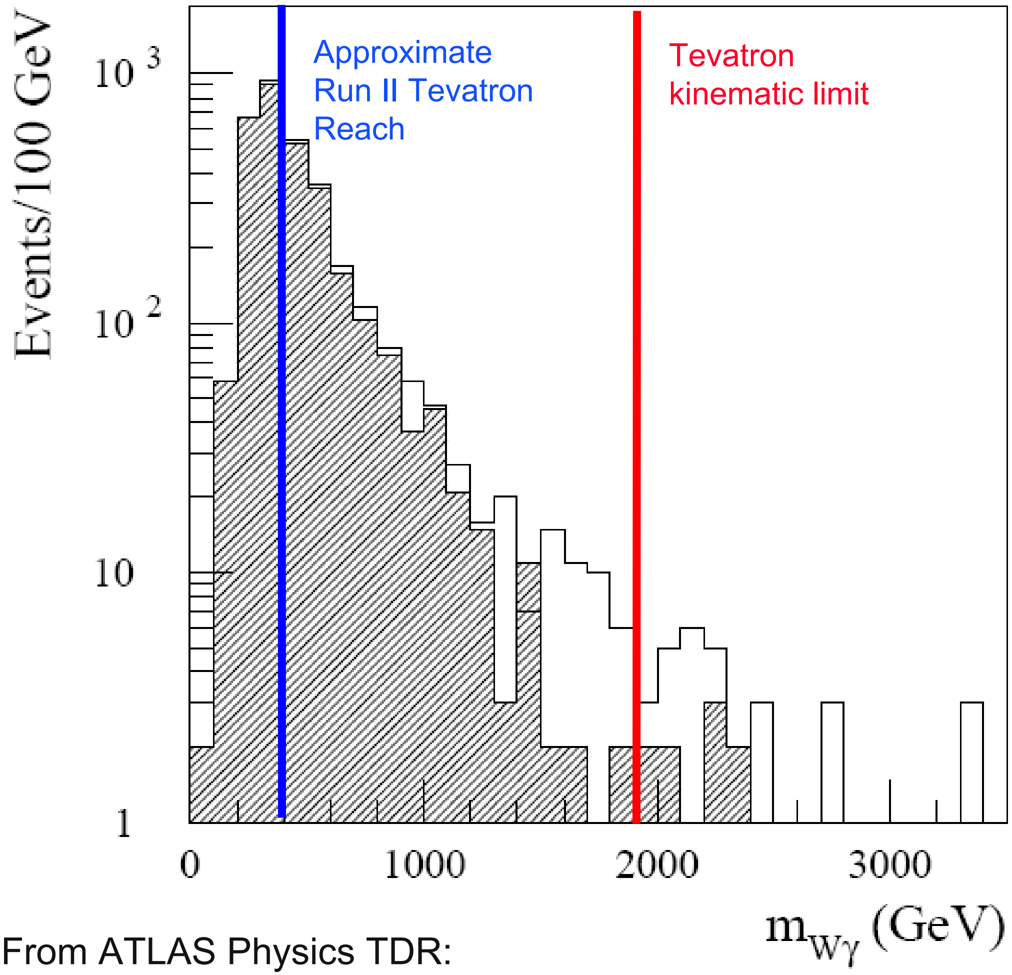
Triple Gauge Couplings

- There are 14 possible $WW\gamma$ and WWZ couplings

- To simplify, one usually talks about 5 independent, CP conserving, EM gauge invariance preserving couplings: g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z
  – In the SM, $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$
    - Often useful to talk about Δg, $\Delta\kappa$ and $\Delta\lambda$ instead.
    - Convention on quoting sensitivity is to hold the other 4 couplings at their SM values.
  – Magnetic dipole moment of the W = $e(1 + \kappa_\gamma + \lambda_\gamma)/2M_W$
  – Electric quadrupole moment = $-e(\kappa_\gamma - \lambda_\gamma)/2M_W^2$
  – Dimension 4 operators alter Δg_1^Z,$\Delta\kappa_\gamma$ and $\Delta\kappa_Z$: grow as $s^{½}$
  – Dimension 6 operators alter λ_γ and λ_Z and grow as s

- These can change either because of loop effects (think e or μ magnetic moment) or because the couplings themselves are non-SM

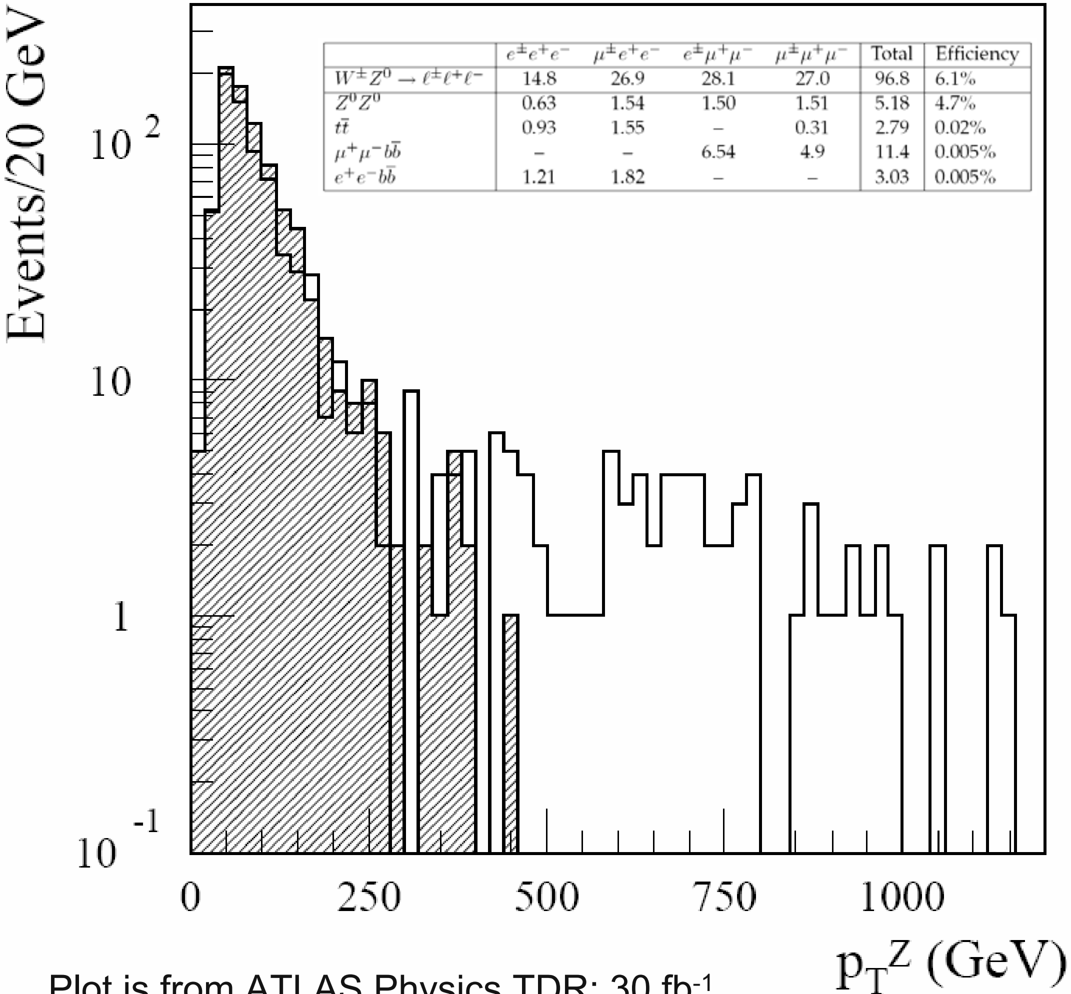
Why Center-Of-Mass Energy Is Good For You



From ATLAS Physics TDR:
30 fb^{-1}

- The open histogram is the expectation for $\lambda_\gamma = 0.01$
  - This is ½ a standard deviation away from today's world average fit
- If one does just a counting experiment above the Tevatron kinematic limit (red line), one sees a significance of 5.5σ
  - Of course, a full fit is more sensitive; it's clear that the events above 1.5 TeV have the most distinguishing power

Not An Isolated Incident

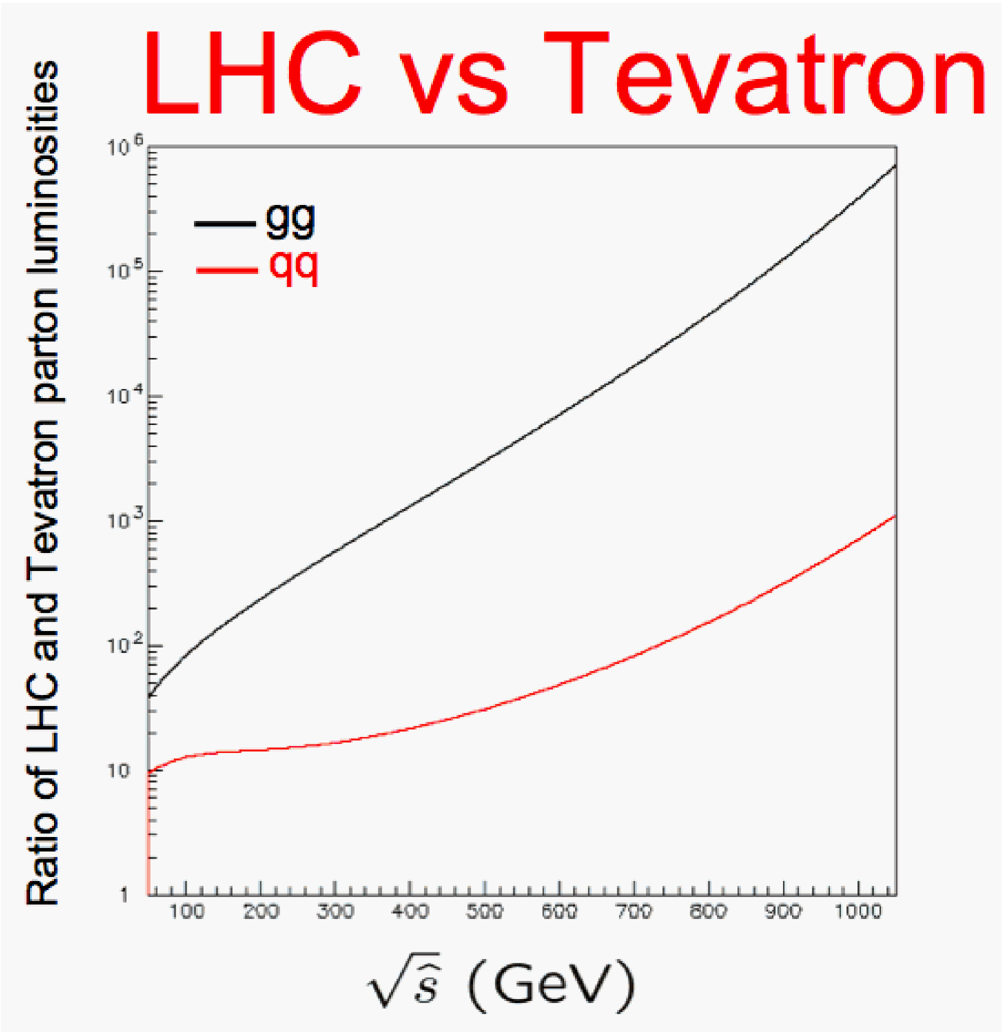


	$e^{\pm}e^{+}e^{-}$	$\mu^{\pm}e^{+}e^{-}$	$e^{\pm}\mu^{+}\mu^{-}$	$\mu^{\pm}\mu^{+}\mu^{-}$	Total	Efficiency
$W^{\pm}Z^{0} \to \ell^{\pm}\ell^{+}\ell^{-}$	14.8	26.9	28.1	27.0	96.8	6.1%
$Z^{0}Z^{0}$	0.63	1.54	1.50	1.51	5.18	4.7%
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02%
$\mu^{+}\mu^{-}b\bar{b}$	–	–	6.54	4.9	11.4	0.005%
$e^{+}e^{-}b\bar{b}$	1.21	1.82	–	–	3.03	0.005%

Plot is from ATLAS Physics TDR: 30 fb^{-1}
Insert is from CMS Physics TDR: 1 fb^{-1}

- Qualitatively, the same thing happens with other couplings and processes
- These are from WZ events with $\Delta g_1^Z = 0.05$
  - While not excluded by data today, this is not nearly as conservative as the prior plot
    - *A disadvantage of having an old TDR*

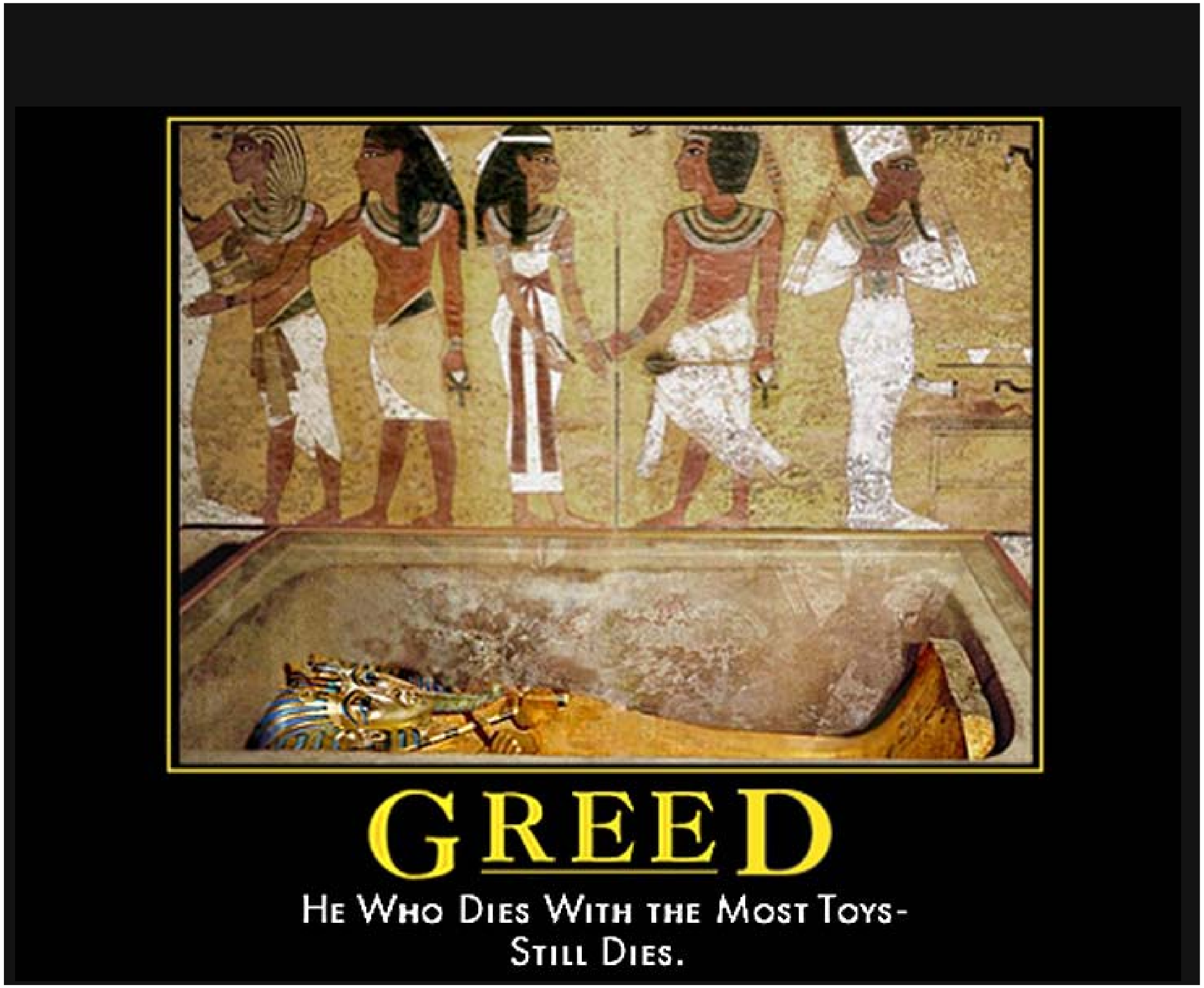
Not All W's Are Created Equal



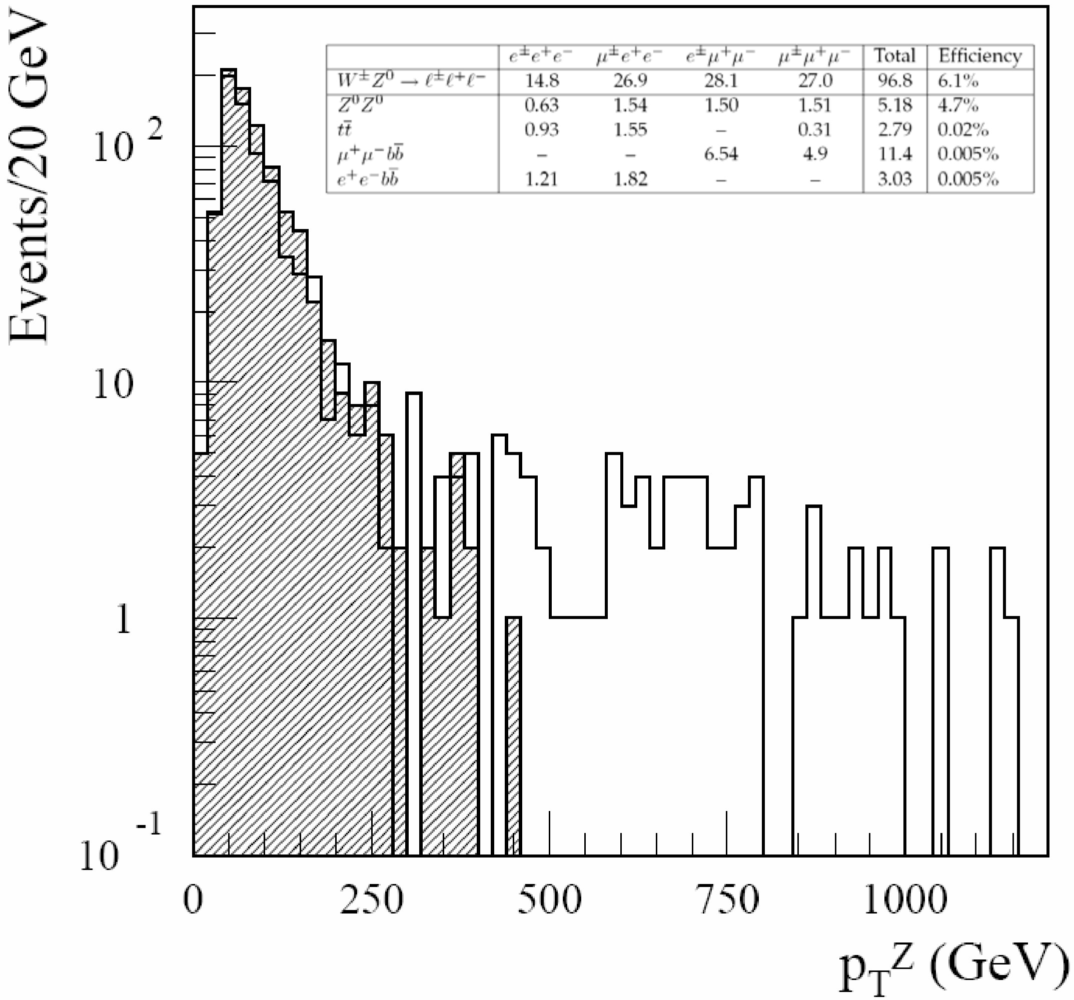
From Claudio Campagnari/CMS

- The reason the inclusive W and Z cross-sections are 10x higher at the LHC is that the corresponding partonic luminosities are 10x higher
  - No surprise there
- Where you want sensitivity to anomalous couplings, the partonic luminosities can be hundreds of times larger.
- The strength of the LHC is not just that it makes millions of W's. It's that it makes them in the right kinematic region to explore the boson sector couplings.

How To Motivate an Experimenter



What I See In This Plot



	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency
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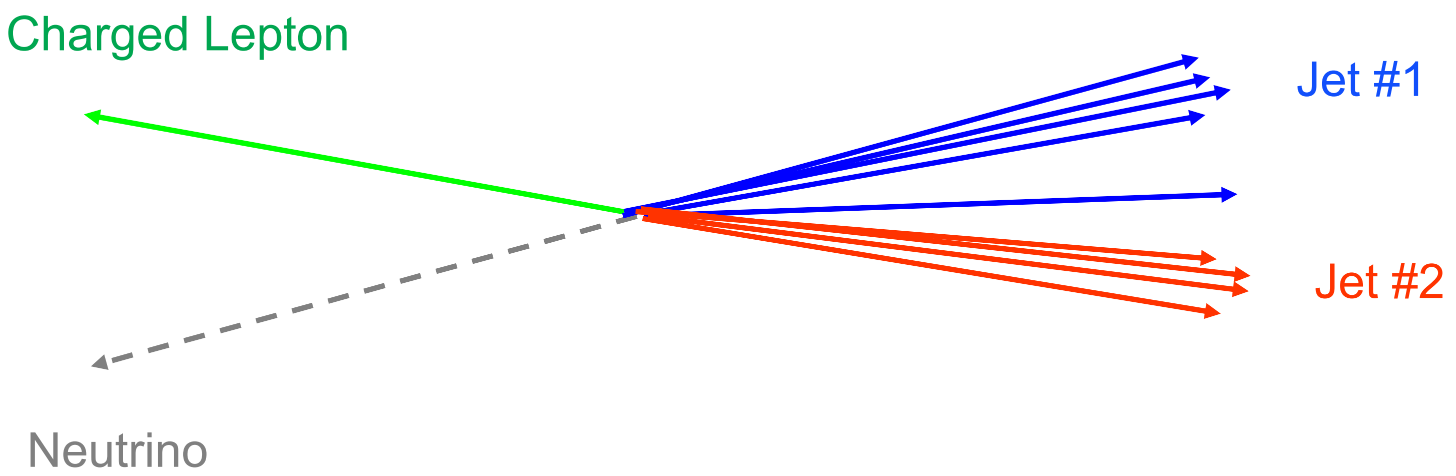
$e^+ e^- b\bar{b}$	1.21	1.82	–	–	3.03	0.005%

- If I could replace $Z \to ee$ and $\mu\mu$ with $Z \to jj$, I would get an order of magnitude more sensitivity.

What One of these Events would look like



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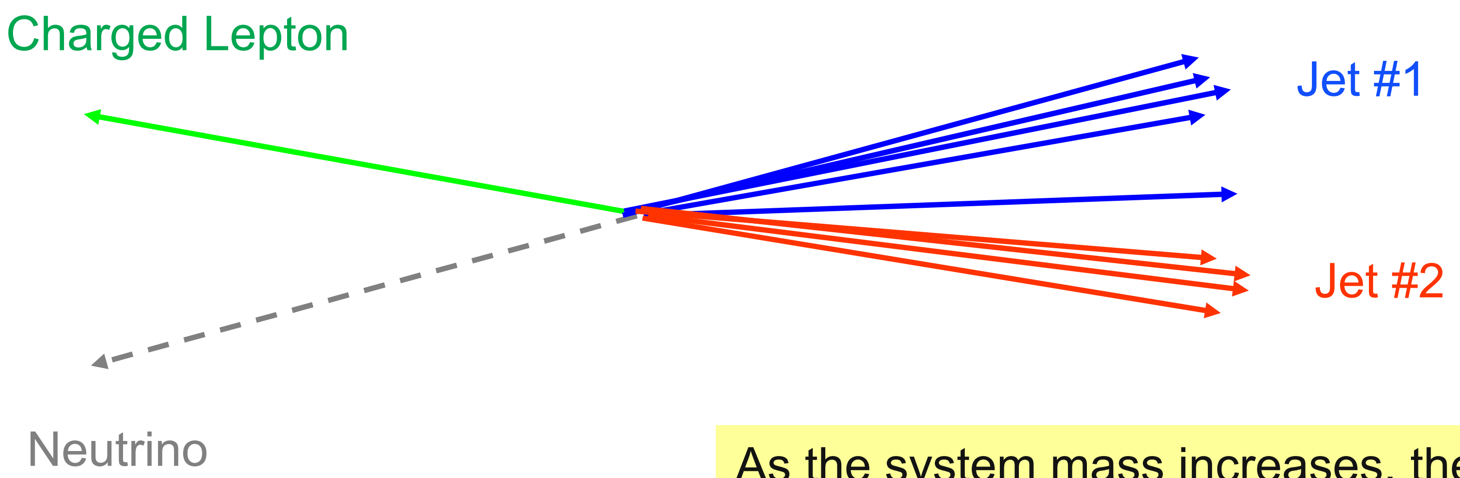
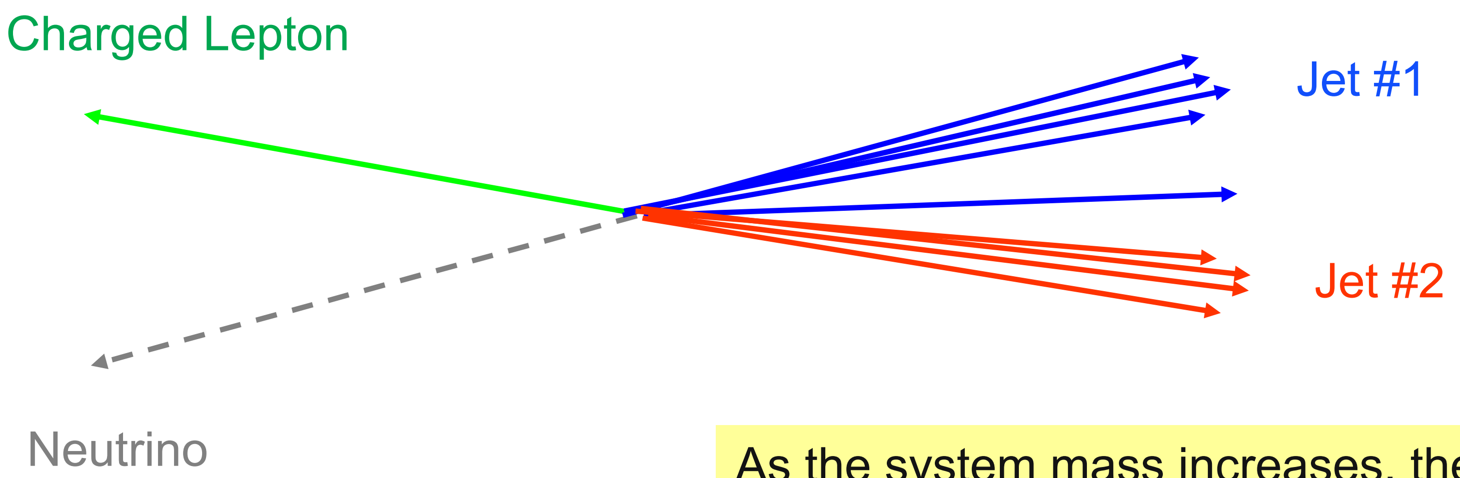


As the system mass increases, the jets tend to merge – we need to be able to identify when we have one jet and when we have two.

What One of these Events would look like



As the system mass increases, the jets tend to merge – we need to be able to identify when we have one jet and when we have two.

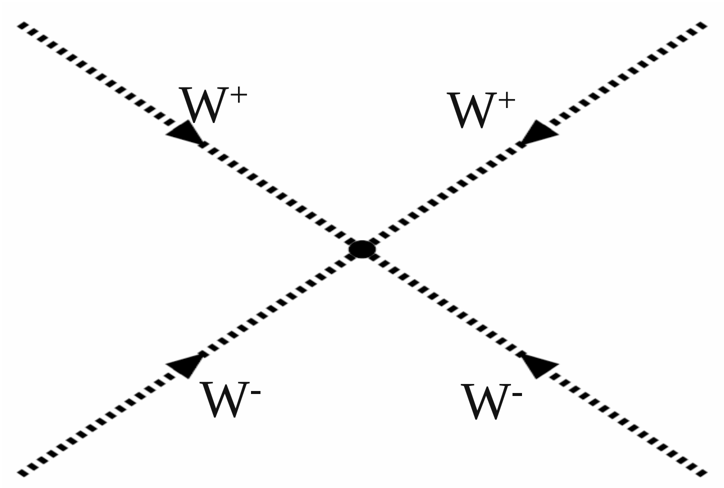
We need to work on (and are working on) the more general problem of how to treat "jets" that are really W's, Z's and tops.

Job #3: Improving W+N jets Monte Carlos

- The present W/Z + N Jets Monte Carlos can have large disagreements
  - Especially in certain kinematic ranges
  - The previous signature carves out a really tiny part of phase space
  - As N gets large, things get worse.
    - *Parton – jet matching adds additional complications*

- We're going to have to straighten this out
  - I think this means a coordinated effort between theorists and experimenters

Back to the Quartic Couplings



M_{Higgs} (GeV)	200	400	600	800
$W^+W^-W^-$	68	28	25	25
$W^+W^+W^-$	112	49	44	44
W^+W^-Z	32	17	15	15
W^-ZZ	1.0	0.51	0.46	0.45
W^+ZZ	1.7	0.88	0.79	0.79
ZZZ	0.62	0.18	0.13	0.12

From Azuelos et al. hep-ph/0003275

100 fb-1, all leptonic modes inside detector acceptance

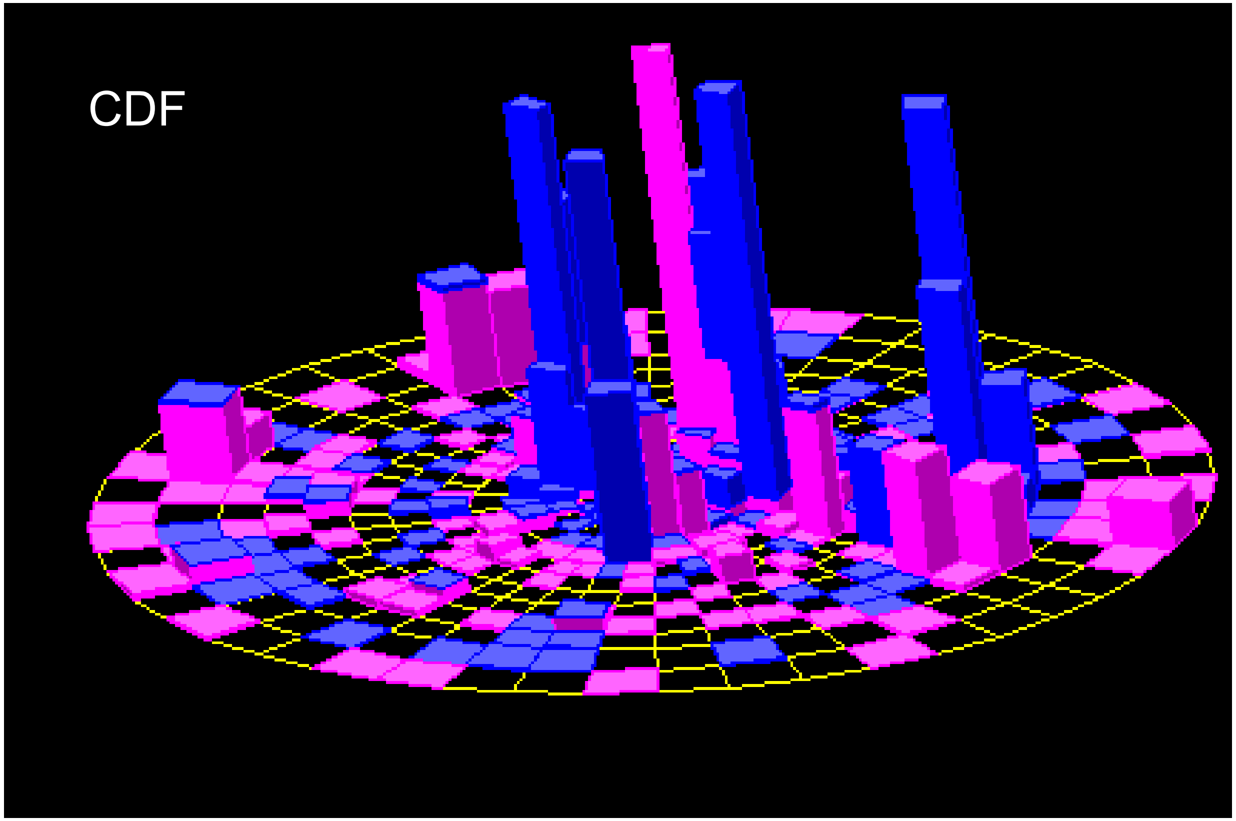
- These are visible in the channel pp → WWW.
- Yields are not great

Aside: the first QGC we will see is WW$\gamma\gamma$, from the $w_1w_1w_3w_3$ piece.

Improving the Quartics

- More channels
  - The rate estimates assume all three W's have to decay leptonically, to avoid backgrounds from top pairs
  - There are plenty of ttbar events. Not so many tt events.
    - *Only the two same sign W's need to go leptonically*
    - *Buys you an order of magnitude in rate*
- Vector Boson Fusion
  - Harder than in the Higgs case (no resonance)
  - Experimentally challenging because of the forward jets

The "Ring of Fire"

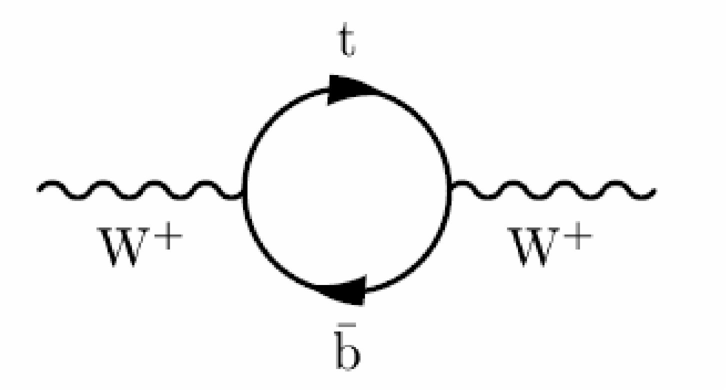


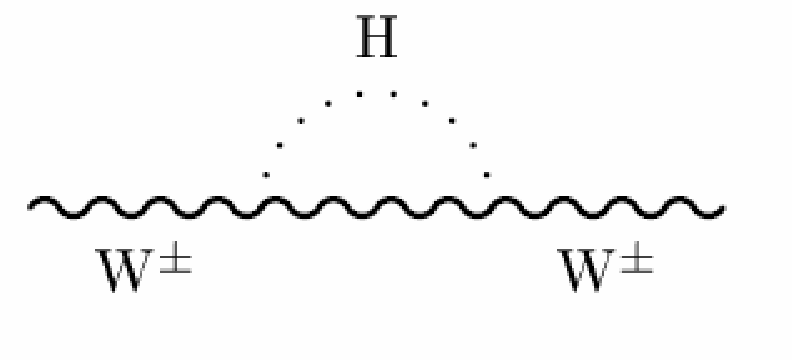
Proximity to the beamline can put a lot of extra energy in the forward region.

This complicates measurements of jets in this area.

We need to work at this (job #4) but it's not easy.

Job #5: The W Mass





I am not going to try and sell you on the idea that the LHC will reach a precision of 5 or 10 MeV.

Instead, I want to outline some of the issues involved.

One Way Of Thinking About It

If we shoot for 5 MeV, how close might we come?

What needs to happen to get down to 5 (or 15, or 25) MeV?

(If you shoot for 5, you might hit 10. If you shoot for 10, you probably won't hit 5)

8 MeV is 100 parts per million.

The State of the Art: CDF Results

CDF II preliminary **$L = 200\ pb^{-1}$**

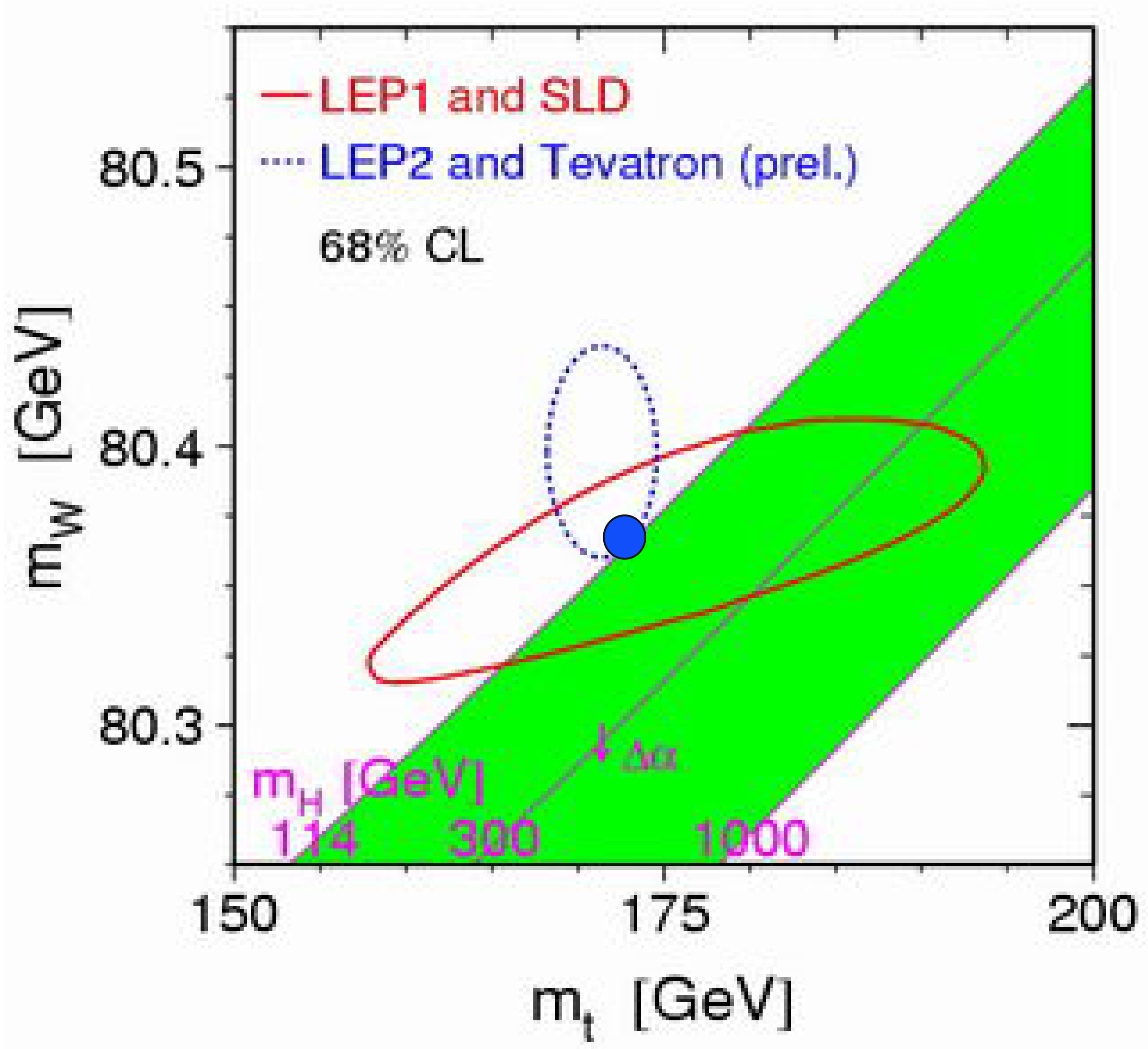
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

These systematics are statistically limited.

These systematics are not.

The “Best Possible Future”

The blue circle represents an uncertainty of 6 MeV on the W mass and 1 GeV on the top mass.

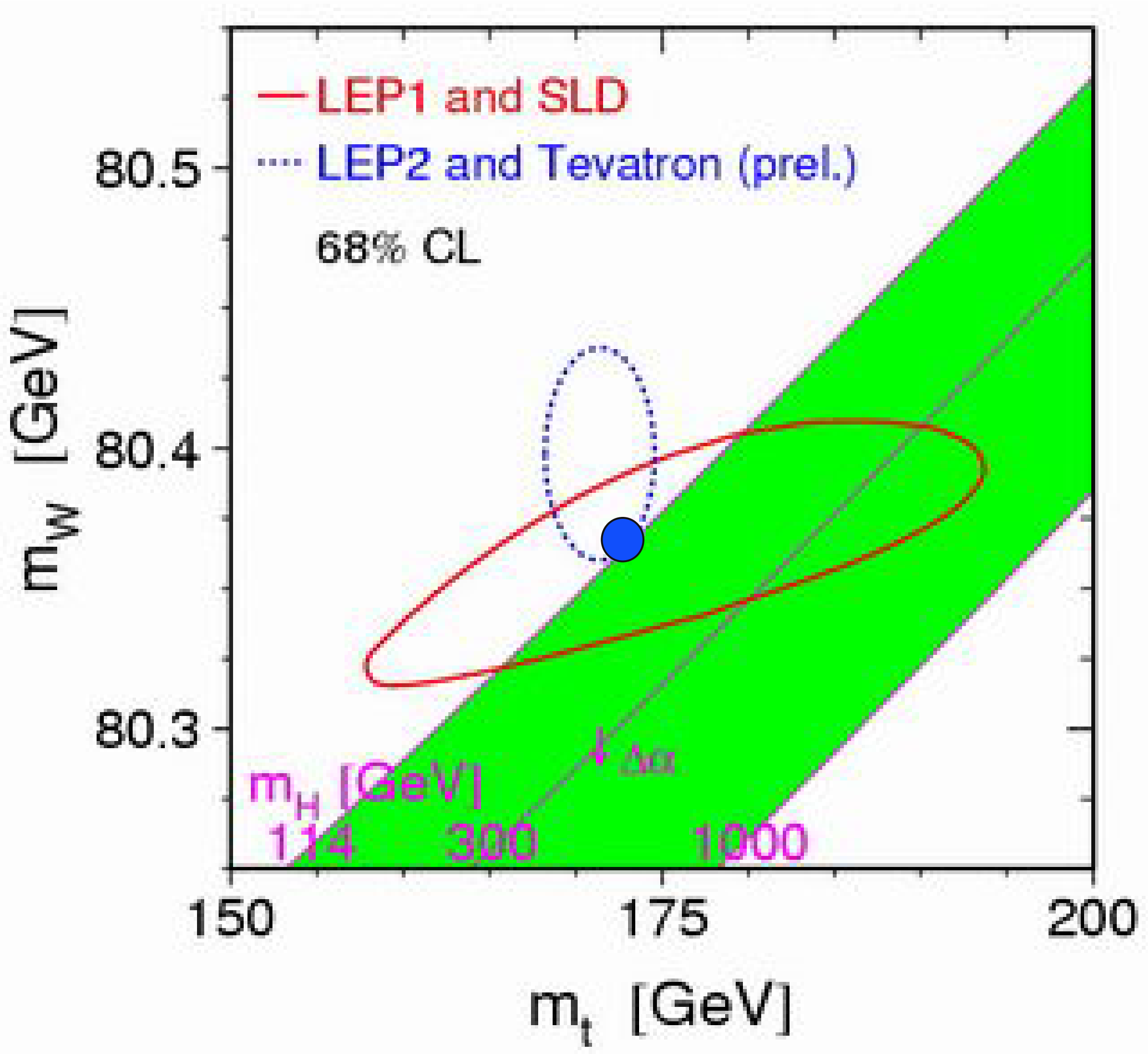


The "Best Possible Future"

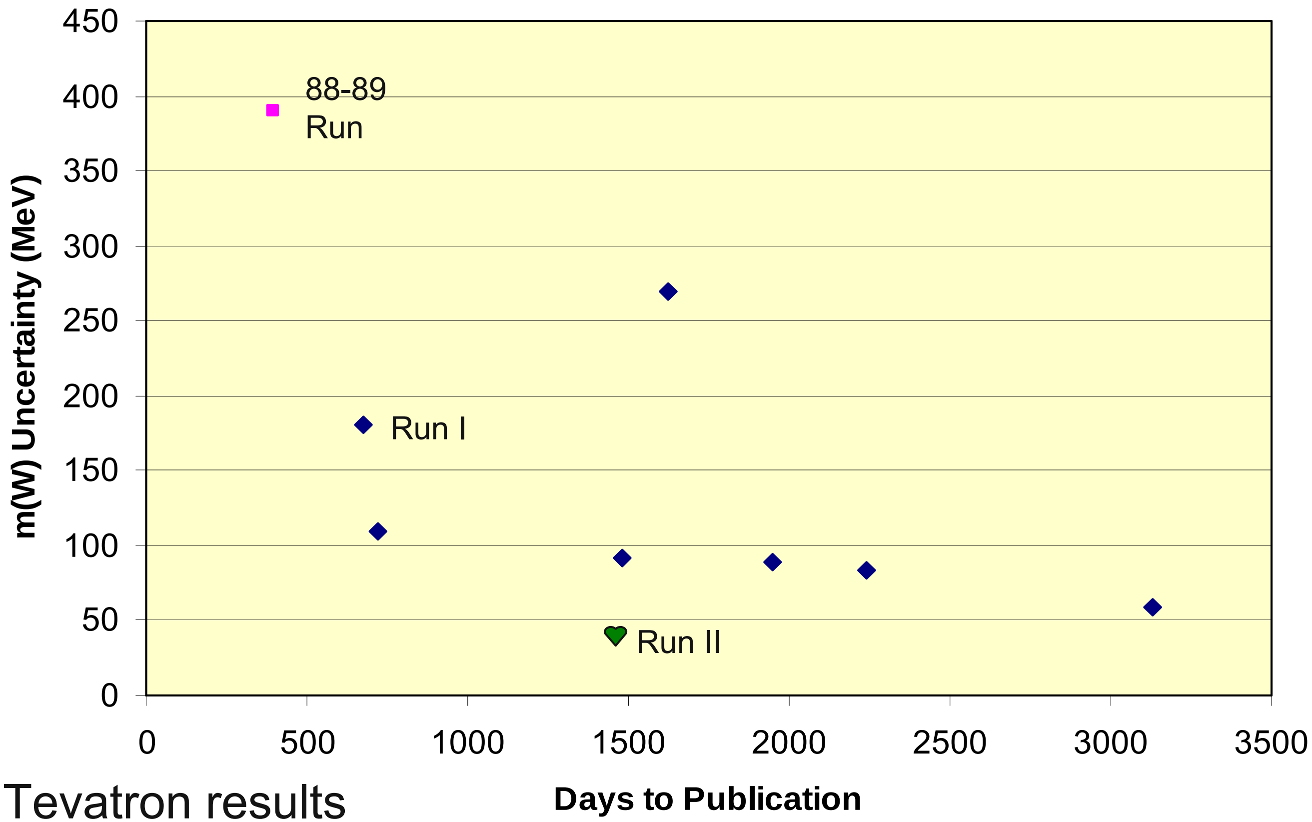
The blue circle represents an uncertainty of 6 MeV on the W mass and 1 GeV on the top mass.

Going beyond 1 GeV on the top mass requires some theoretical guidance on exactly what we measure: PMASS(6,1)

Job #6



Rapidity – of getting m(W) results published



Tevatron results

The trend is for later runs to be on a curve which begins lower and to the right of earlier runs.

No hadron collider experiment has published an uncertainty of 100 MeV in less than 1400 days.

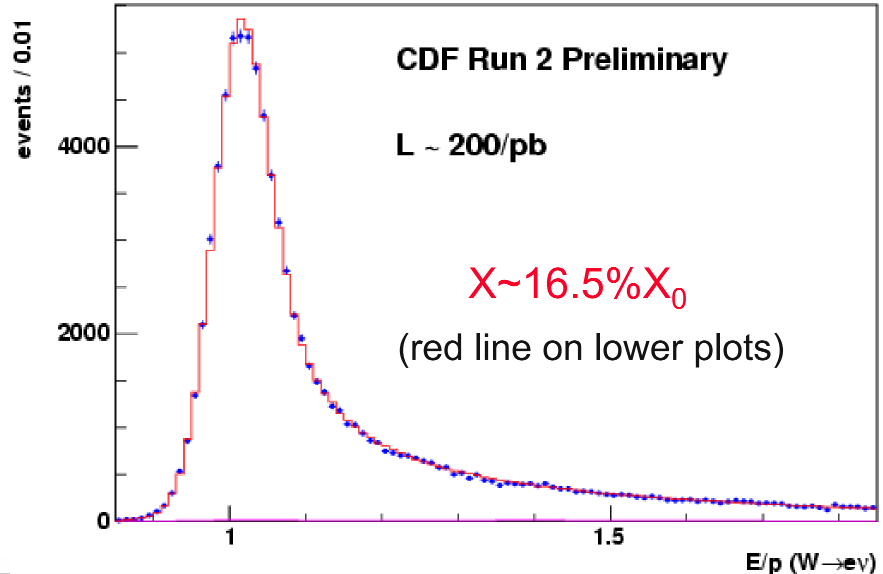
Measuring m(W) – Why It Takes so Long

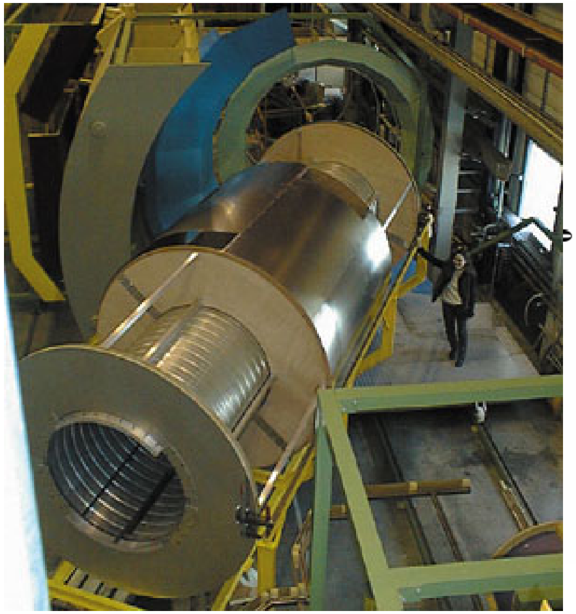
- Set Momentum Scale
  - Use known states like Z^0, J/ψ, and Υ family
  - As this is done, removing tracking systematic problems:
    - *Misalignments, miscalibrations, twists, distortions, false curvatures, energy loss…*
- Set Energy Scale
  - Use electrons and "known" material and momentum scales
- Recoil & Underlying Event Characterization
- Modeling, Modeling, Modeling
  - Transverse mass vs. lepton p_T vs. missing energy, QCD radiation, QED radiation, production models, underlying event, residual nonlinearities…

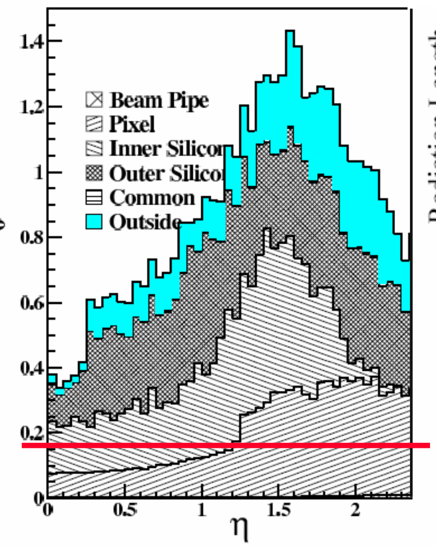
It's not unusual for >1000 plots to appear in the (complete) set of internal notes for this analysis

Difficulty 1: The LHC Detectors are Thicker

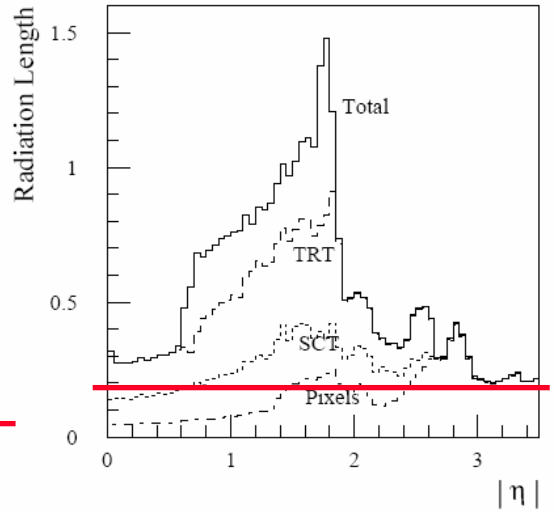
- Detector material interferes with the measurement.
  - You want to know the kinematics of the W decay products at the decay point, not meters later
  - Material modeling is tested/tuned based on electron E/p
- Thicker detector = larger correction = better relative knowledge of correction needed



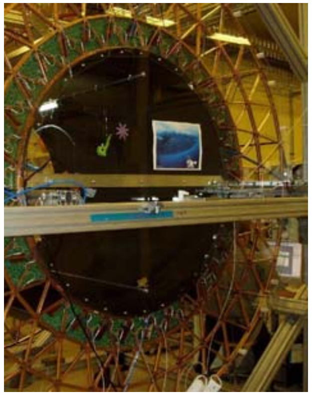




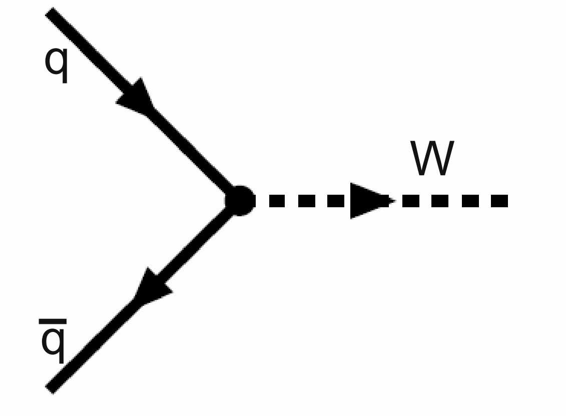
CMS material budget

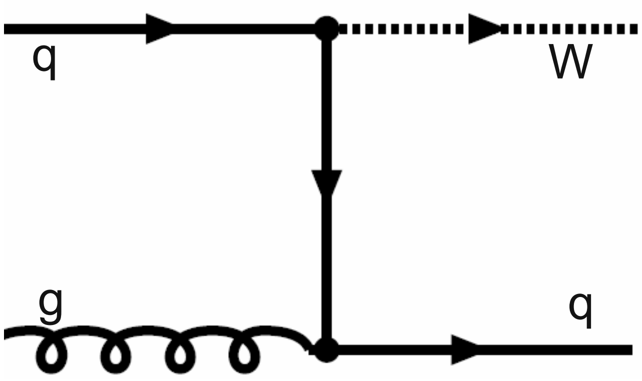


ATLAS material budget



Difficulty 2 – QCD corrections are more important





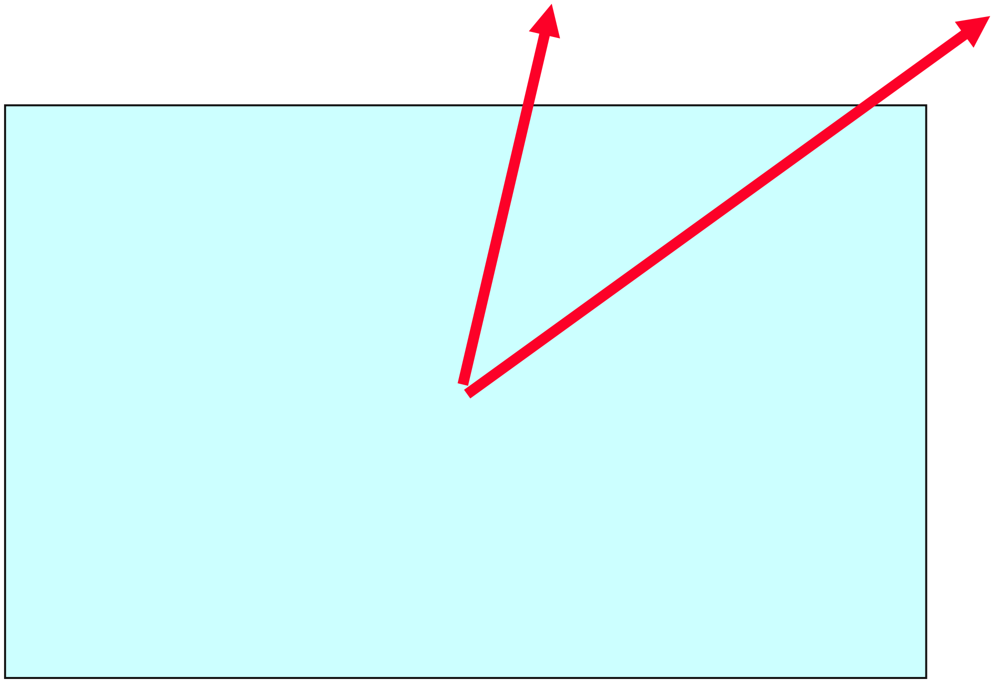
- No valence antiquarks at the LHC
  - Need sea antiquarks and/or higher order processes
- NLO contributions are larger at the LHC
- More energy is available for additional jet radiation

- At the Tevatron, QCD effects are already ¼ of the systematic uncertainty
  - Reminder: statistical and systematic uncertainties are comparable.
- To get to where the LHC wants to be on total m(W) uncertainty is going to require **continuous** effort on this front.

Real-life Experimental Complications

- We say “lepton scale”. At the 60 ppm level, we don’t know that we have a single scale.
  - Leptons of different rapidity traverse a (slightly) different field
  - The W^+ and W^- have different y(lepton) distributions: (parity violation)
  - The Z^0 doesn’t quite sample the same scale as the W’s
- QCD Corrections
  - In most cases, measuring the Z p_T constrains the W p_T spectrum
  - The high x gluon eignevector causes problems
  - Heavy flavor is something the W is sensitive to, but not the Z
    - *Leads us to Job #6*

The Kind of Thing Experimenters Worry About

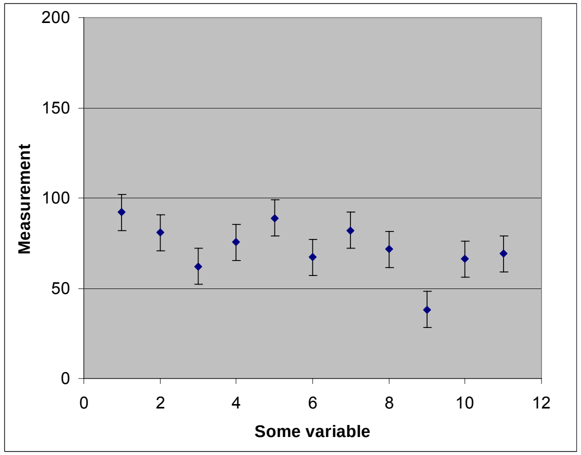


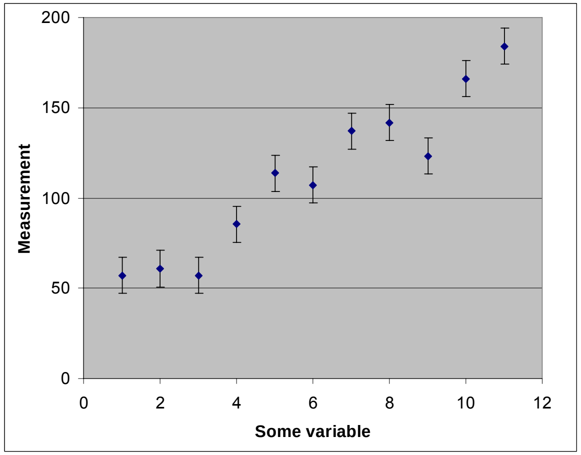
Two leptons – do they see the same field? To 100 ppm?

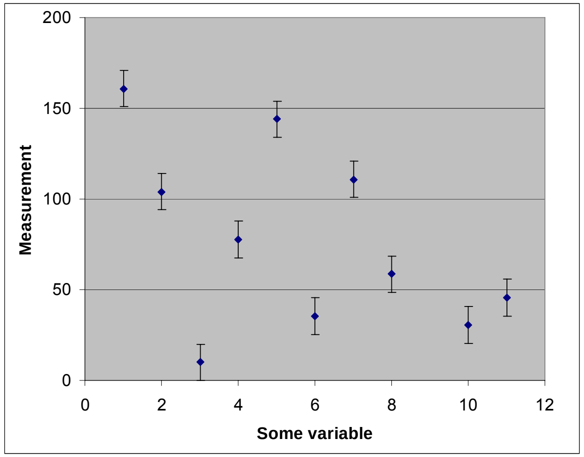
Major Advantage – the W & Z Rates are Enormous

- The W/Z cross-sections at the LHC are an order of magnitude greater than the at the Tevatron
- The design luminosity of the LHC is ~an order of magnitude greater than at the Tevatron
  - I don't want to quibble now about the exact numbers and turn-on profile for the machine, nor things like experimental up/live time
- Implications:
  - The W-to-final-plot rate at ATLAS and CMS will be ~½ Hz
    - Millions of W's will be available for study – statistical uncertainties will be negligible
    - Allows for a new way of understanding systematics – dividing the W sample into N bins (see next slide)
  - The Z cross-section at the LHC is ~ the W cross-section at the Tevatron
    - Allows one to test understanding of systematics by measuring m(Z) in the same manner as m(W)
    - The Tevatron will be in the same situation with their femtobarn measurements: we can see if this can be made to work or not
  - One can consider "cherry picking" events – is there a subsample of W's where the systematics are better?

Systematics – The Good, The Bad, and the Ugly







Good

- Masses divided into several bins in some variable
- Masses are consistent within statistical uncertainties.

Bad

- Clearly there is a systematic dependence on this variable
- Provides a guide as to what needs to be checked.

Ugly

- Point to point the results are inconsistent
- There is no evidence of a trend
- Something is wrong – ***but what?***

W Mass Summary

- ATLAS and CMS have set themselves some very ambitious goals even with a 20 MeV mass uncertainty – much less 5
  - This will not be easy
  - This will not be quick
  - It might not even be possible

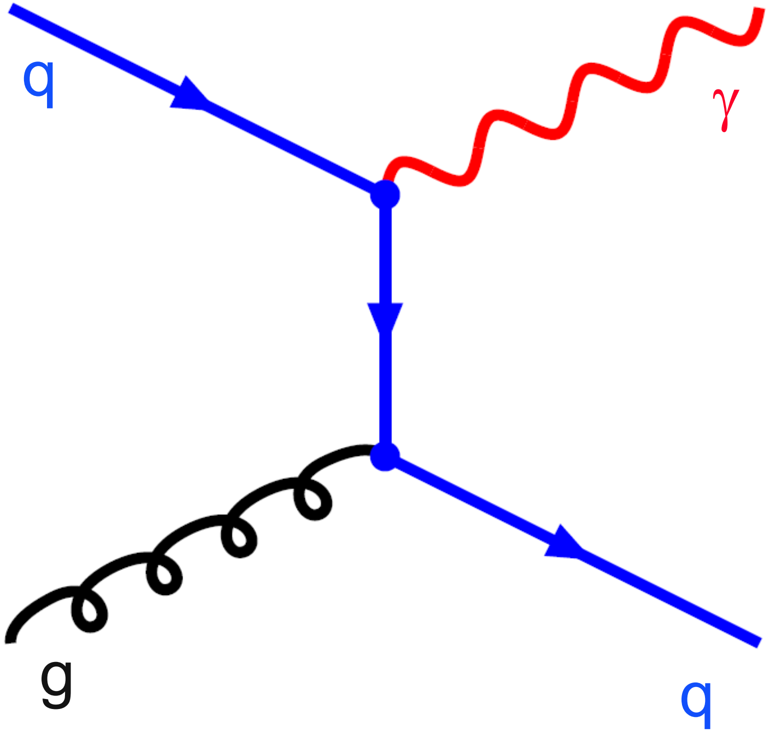
- Having a large sample of Z's gives us hope we can control systematics to the level we need.
  - Hope is not a guarantee

- We will probably need to measure the average of m(W+) and m(W-) as opposed to "the W mass".

- Even after the Higgs is discovered, this measurement is important
  - Finding one Higgs is not necessarily the same as finding all of them.
  - Indirect constraints will be important in interpreting the discovery

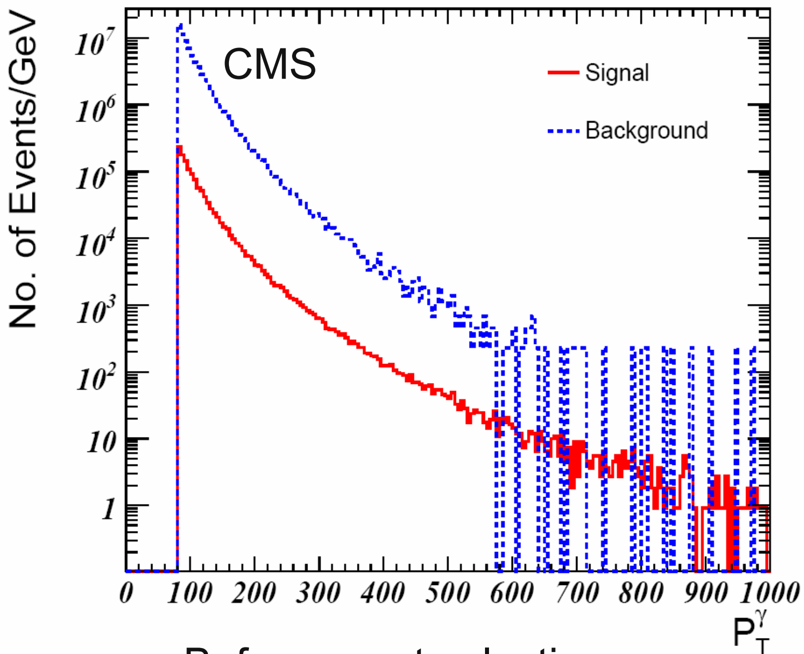
Job #7: Improving the Gluon: Direct Photons

- DIS and Drell-Yan are sensitive to the quark PDFs.
- Gluon sensitivity is indirect
  - The fraction of momentum not carried by the quarks must be carried by the gluon.
  - Antiquarks in the proton must be from gluons splitting
- It would be useful to have a direct measurement of the gluon PDFs
  - This process depends on the (known) quark distributions and the (unknown) gluon distribution

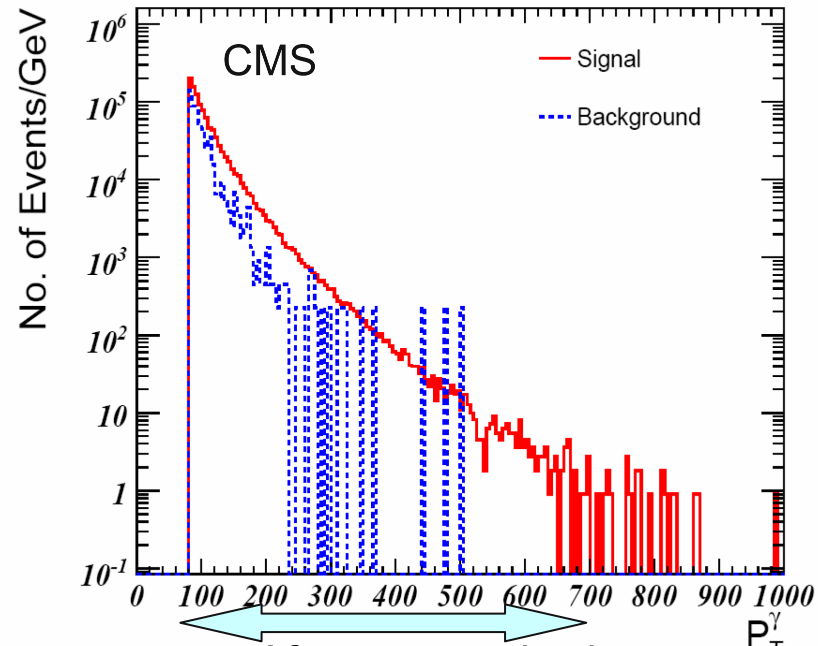


Direct photon "Compton" process.

Direct Photons & Backgrounds



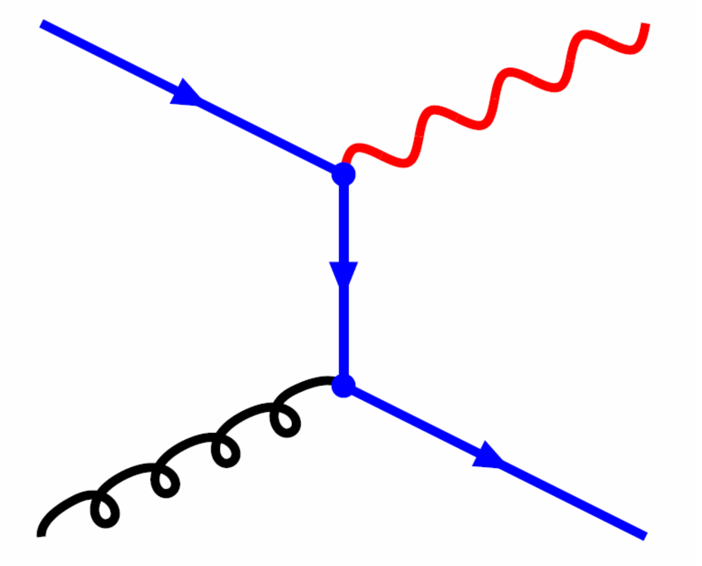
Before event selection



After event selection

- There are two "knobs we can turn"
  - Shower shape – does this look like a photon (last slide)
  - Isolation – if it's a fake, it's likely to be from a jet, and there is likely to be some nearby energy
- Different experiments (and analyses in the same experiment) can rely more on one method than the other.

Job #8-10: Heavy Flavor in the Proton



- One can scatter a gluon off of a heavy quark in the proton as well as a light quark
  - This quark can be identified as a bottom or charmed quark by “tagging” the jet
  - This measures how much b (or c) is in the proton

- Replace the γ with a Z, and measure the same thing with different kinematics

- Replace the Z with a W and instead of measuring how much charm is in the proton, you measure how much strangeness there is

…and so on…

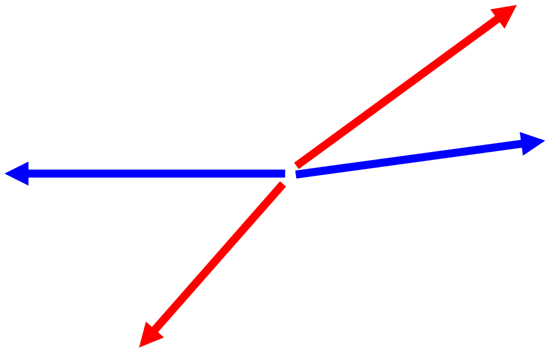
Job #11: Understand Double Parton Scattering

- Two independent partons in the proton scatter:

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{Effective}}$$ might be better characterized by $$\sigma_{AB} = A(\hat{s}) \frac{\sigma_A \sigma_B}{\sigma_{Inelastic}}$$

- Searches for complex signatures in the presence of QCD background often rely on the fact that decays of heavy particles are "spherical", but QCD background is "correlated"
  - This breaks down in the case where part of the signature comes from a second scattering.
  - A source of Forward jets in "VBF"?

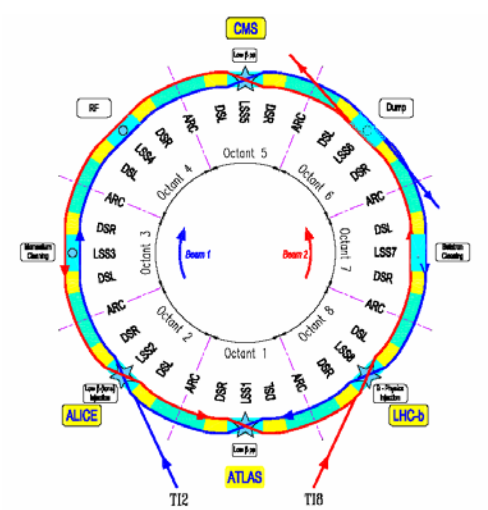
- We're thinking about bbjj as a good signature
  - Large rate/large kinematic range
  - Relatively unambiguous which jets go with which other jets.



So, When Is This Going To Happen?

The latest schedule shows the LHC ready for beam around May 26th.

Beam will be injected into sectors as soon as they are cold.



	Pressure test	Cool-down		Powering tests	
Sector 12	wk. 49 (2007)	wk. 07 (2008)	wk. 12 (2008)	wk. 13 (2008)	wk. 25 (2008)
Sector 23	*Done*	wk. 06 (2008)	wk. 11 (2008)	wk. 12 (2008)	wk. 23 (2008)
Sector 34	*Done*	wk. 10 (2008)	wk. 15 (2008)	wk. 16 (2008)	wk. 24 (2008)
Sector 45 1	*Done*	*Started*	wk. 48 (2007)	wk. 49 (2007)	wk. 03 (2008)
Sector 45 2		wk. 14 (2008)	wk. 17 (2008)	wk. 18 (2008)	wk. 25 (2008)
Sector 56	*Done*	wk. 49 (2007)	wk. 07 (2008)	wk. 09 (2008)	wk. 19 (2008)
Sector 67	*Done*	wk. 05 (2008)	wk. 11 (2008)	wk. 12(2008)	wk. 20 (2008)
Sector 78 1	*Done*	*Done*	*Done*	*Done*	*Done*
Sector 78 2	*Done*	wk. 04 (2008)	wk. 10 (2008)	wk. 11 (2008)	wk. 22 (2008)
Sector 81	*Done*	wk. 51 (2007)	wk. 09 (2008)	wk. 10 (2008)	wk. 22 (2008)

As of last week, they were ~4 weeks behind this schedule.

LHC Beam Stored Energy in Perspective

Luminosity Equation:

$$L = \frac{fE}{\varepsilon_n} \frac{n_b N_p^2}{\beta^*}$$

- Luminosity goes as the *square* of the stored energy.
- 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
- It’s best to increase the luminosity with care

My Take on The Schedule

- If we only have the same old problems (i.e. no new ones) there will beam in late summer
  - Each surprise adds two months to that date
- We will turn on with very low luminosity and this will grow slowly as we learn to handle the stored energy
  - Luminosity grows as the square of stored energy
- After maybe a year, the luminosity will shoot up like a rocket
  - Luminosity grows as the square of stored energy

Summary – the SM Job List

- 1. Make an early measurement – like a limit on the (qqqq) coupling
- 2. Find the Higgs
- 3. Improve the modeling of W/Z + N jets (with N as large as possible)
- 4. Work on forward jet reconstruction
- 5. Measure m(W)
- 6. Understand what the top quark mass is (and should be)
- 7. Constrain the gluon density
- 8-10. Measure the flavor content and asymmetries in the proton
  - 8. Strange (W+charm)
  - 9. Charm (Z/γ+charm)
  - 10. Bottom (Z/γ + bottom)
- 11. Understand double parton scattering

The “BSM shopping List”

- Come by 1506 and place your orders for what you would most like the LHC to discover.