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Opportunities in Electroweak Physics at the LHC

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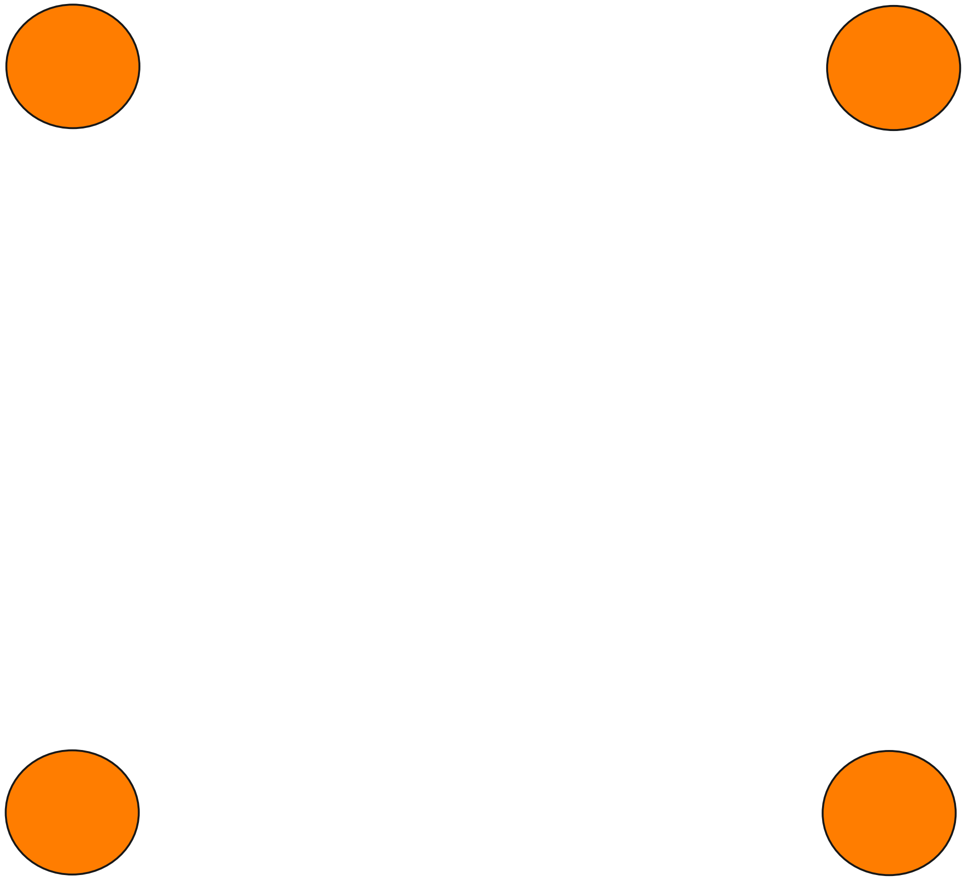
LIP Seminar: 28 January 2008

A Puzzle Before We Start



What is the least amount of railroad track needed to connect these 4 cities?

Wrong Theories

- A Theory can be wrong in two ways:
  - It can be inconsistent with observations
  - It can be inconsistent with itself

- The (Electroweak) Standard Model has no problems with observations
  - g-2 for the electron is 2.0023193043622 +/- 0.0000000000007
    - *Every digit is significant!*

- Unfortunately, it's inconsistent with itself.

Why Study The Standard Model?

- Understanding it is a necessary precondition for discovering anything beyond the Standard Model
  - Whatever physics you intend to do in 2012, you'll be studying SM physics in 2009
    - *Rate is also an issue*

- It's interesting in and of itself
  - It's predictive power remains extraordinary (e.g. g-2 for the electron)

- We know it's incomplete
  - It's a low energy effective theory: can we see what lies beyond it?

- We've lived with the SM for ~25 years
  - Long enough so that features we used to find endearing are starting to become annoying

- Think of the LHC as "marriage counseling" for the SM

Part One:
An Entirely-Too-Fast Review of the Standard Model

Local Gauge Invariance – Part I

- In quantum mechanics, the probability density is the square of the wavefunction: $P(x) = |\Psi|^2$
  - If I change Ψ to $-\Psi$, anything I can observe remains unchanged
- $P(x) = |\Psi|^2$ can be perhaps better written as $P(x) = \Psi\Psi^*$
  - If I change Ψ to $\Psi e^{i\phi}$ anything I can observe still remains unchanged.
  - The above example was a special case ($\phi = \pi$)
- If I can't actually observe ϕ, how do I know that it's the same everywhere?
  - I should allow ϕ to be a function, $\phi(\mathbf{x},t)$.
  - This looks harmless, but is actually an extremely powerful constraint on the kinds of theories one can write down.

Local Gauge Invariance – Part II

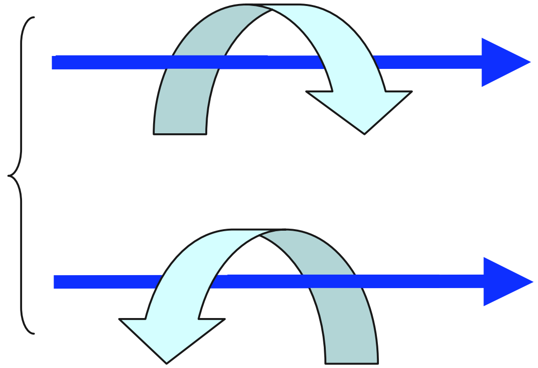
- The trouble comes about because the Schrödinger equation (and its descendents) involves derivatives, and a derivative of a product has extra terms.

- At the end of the day, I can't have any leftover ϕ's – they all have to cancel. (They are, by construction, supposed to be unobservable)

- If I want to write down the Hamiltonian that describes two electrically charged particles, I need to add one new piece to get rid of the ϕ's: a massless photon.

Massless?

- A massive spin-1 particle has three spin states (m = 1,0,-1)
- A massless spin-1 particle has only two.
  - Hand-wavy argument: Massless particles move at the speed of light; you can't boost to a frame where the spin points in another direction.
- To cancel all the ϕ's, I need just the two $m = \pm 1$ states ("degrees of freedom")
  - Adding the third state overdoes it and messes up the cancellations
  - The photon that I add must be massless



$m = \pm 1$ "transverse"

$m = 0$ "longitudinal"

Aside: this has to be just about the most confusing convention adopted since we decided that the current flows opposite to the direction of electron flow.

We're stuck with it now.

A Good Theory is Predictive…or at least Retrodictive

- This is a theoretical tour-de-force: starting with Coulomb's Law, and making it relativistically and quantum mechanically sound, and out pops:
  - Magnetism
  - Classical electromagnetic waves
  - A quantum mechanical photon of zero mass

- Experimentally, the photon is massless ($< 10^{-22} m_e$)
  - 10^{-22} = concentration of ten molecules of ethanol in a glass of water
    - *Roughly the composition of "Lite" Beer*
  - 10^{-22} = ratio of the radius of my head to the radius of the galaxy
  - 10^{-22} = probability Britney Spears won't do anything shameless and stupid in the next 12 months

Let's Do It Again

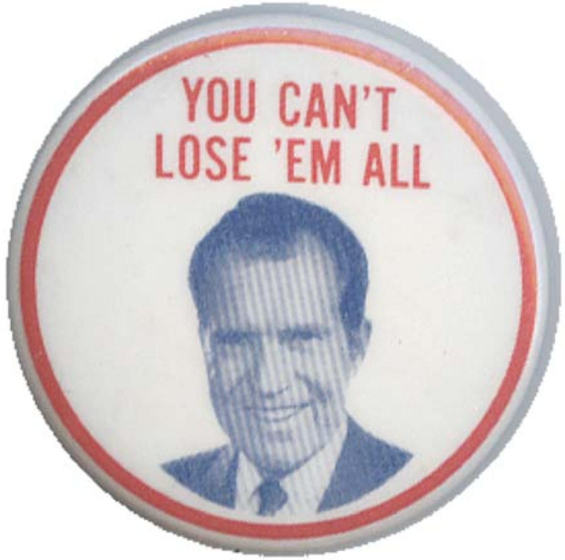
- A Hamiltonian that describe electrically charged particles also gives you:
  - a massless photon ☺

- A Hamiltonian that describes particles with color charge (quarks) also gives you:
  - a massless gluon (actually 8 massless gluons) ☺

- A Hamiltonian that describes particles with weak charge also gives you:
  - massless W^+, W^- and Z^0 bosons
  - Experimentally, they are heavy: 80 and 91 GeV ☹

Why this doesn't work out for the weak force – i.e. why the W's and Z's are massive – is what the LHC is trying to find out.

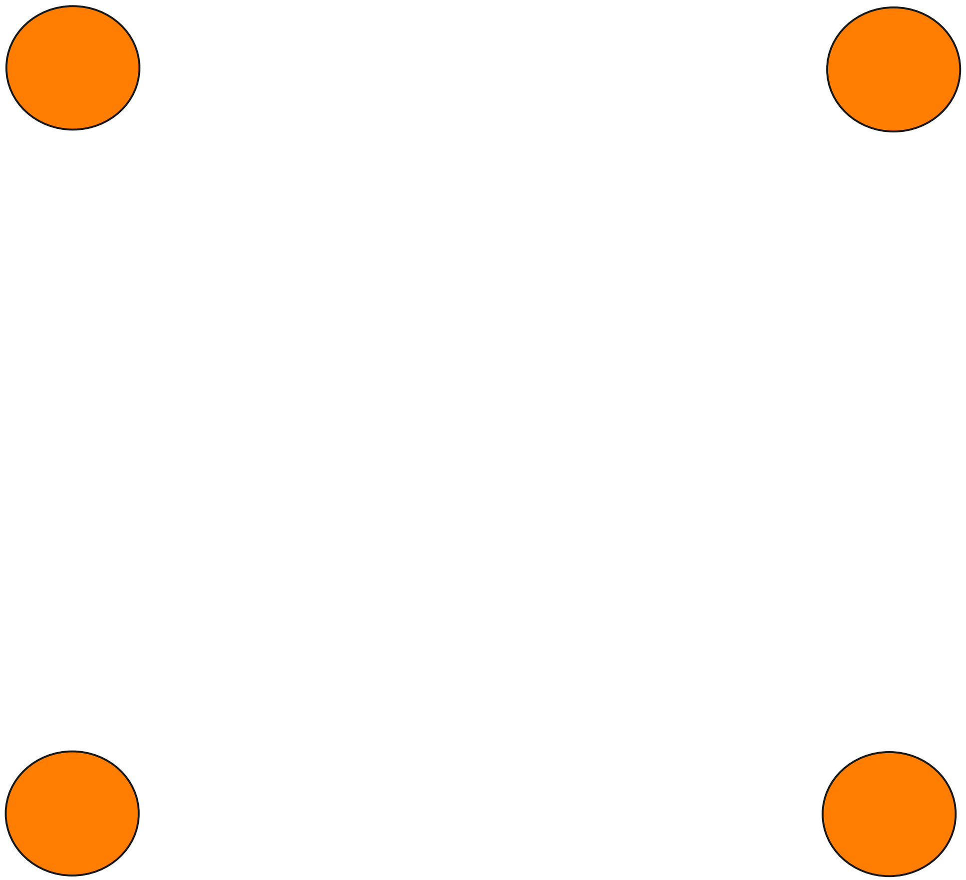
The "No Lose Theorem"



- Imagine you could elastically scatter beams of W bosons:
  WW → WW
- We can calculate this, and at high enough energies the cross-section violates unitarity
  - The probability of a scatter exceeds 1 - nonsense
  - The troublesome piece is (once again) the longitudinal spin state
- "High enough" means about 1 TeV
  - A 14 TeV proton-proton accelerator is just energetic enough to give you enough 1 TeV parton-parton collisions to study this

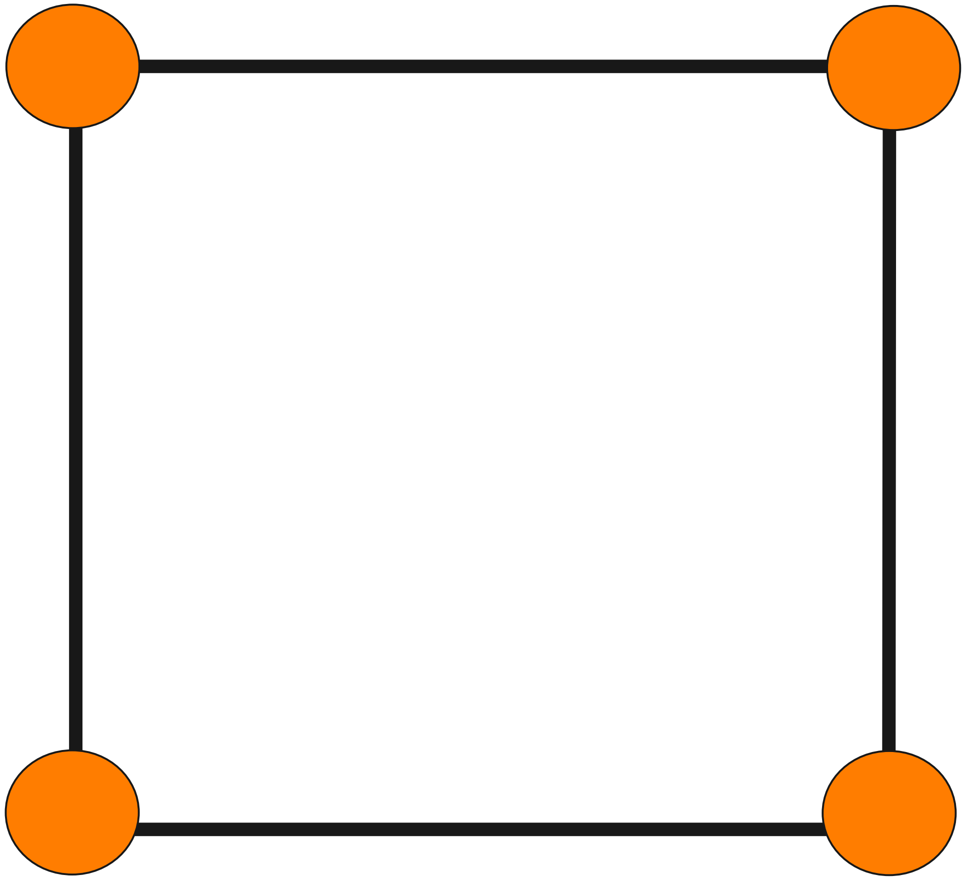
The Standard Model is a low-energy effective theory. The LHC gives us the opportunity to probe it where it breaks down. Something new must happen.

Spontaneous Symmetry Breaking



What is the least amount of railroad track needed to connect these 4 cities?

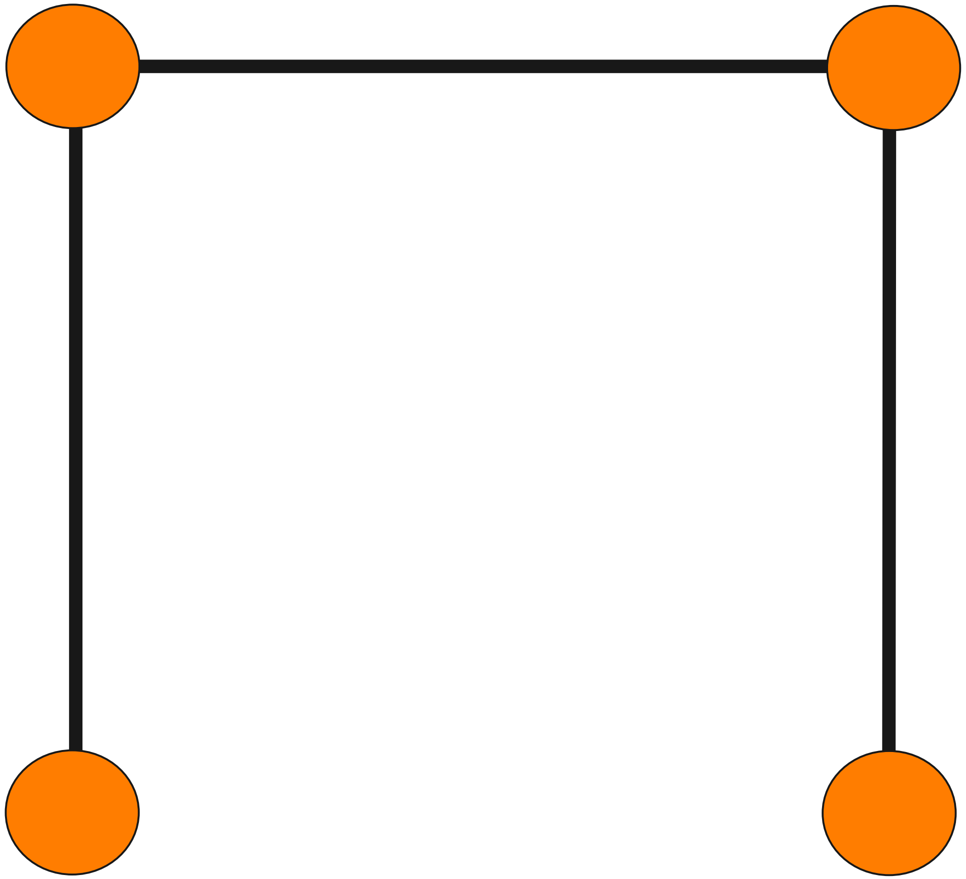
One Option



I can connect them this way at a cost of 4 units.

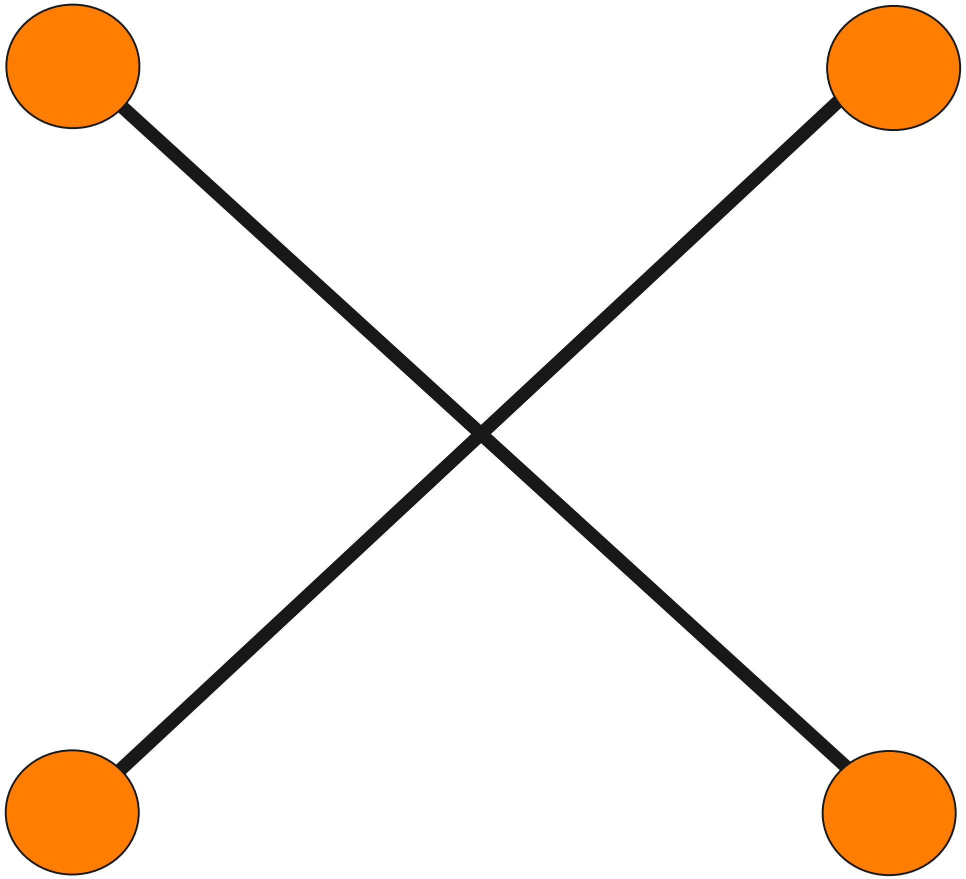
(length of side = 1 unit)

Option Two



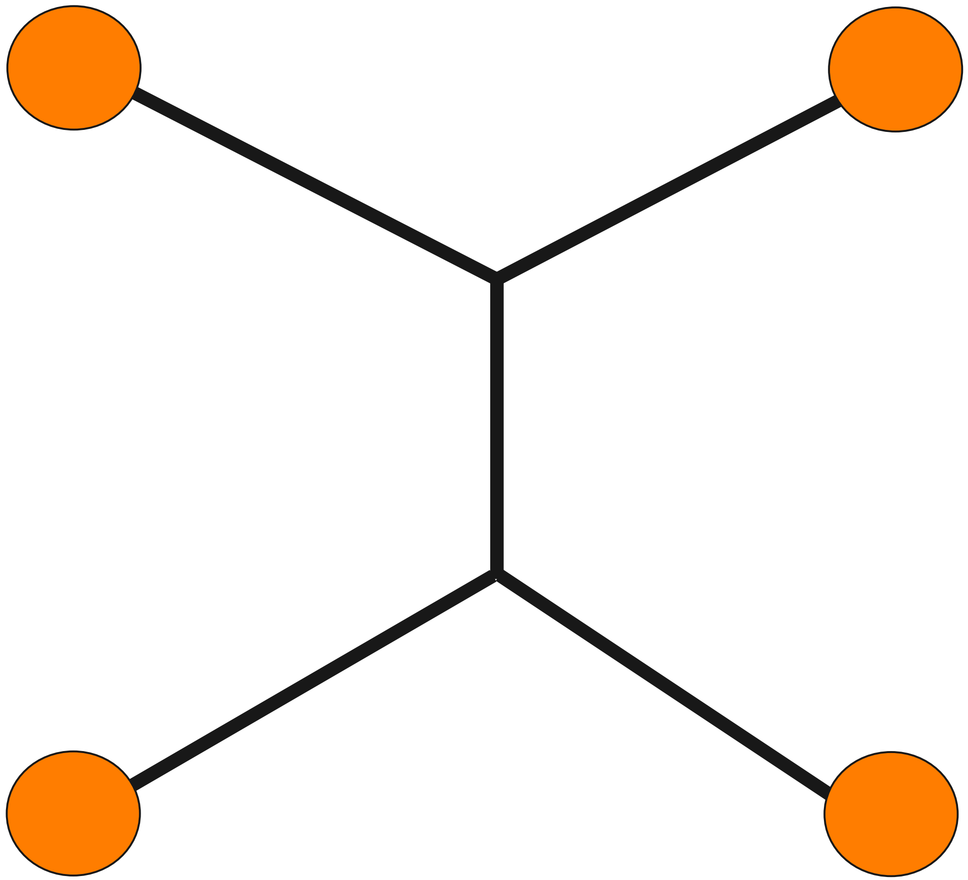
I can connect them this way at a cost of only 3 units.

The Solution that Looks Optimal, But Really Isn't



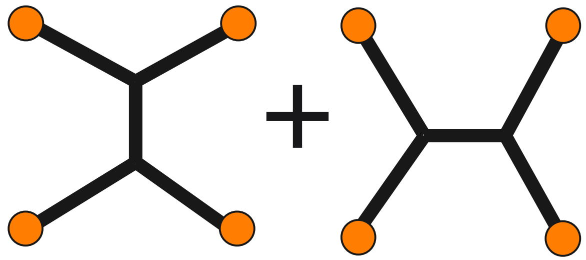
This requires only $2\sqrt{2}$

The Real Optimal Solution



This requires $1+\sqrt{3}$

Note that the symmetry of the solution is lower than the symmetry of the problem: this is the definition of *Spontaneous Symmetry Breaking*.



n.b. The sum of the solutions has the same symmetry as the problem.

A Pointless Aside

One might have guessed at the answer by looking at soap bubbles, which try to minimize their surface area.

But that's not important right now…

Another Example of Spontaneous Symmetry Breaking

Ferromagnetism: the Hamiltonian is fully spatially symmetric, but the ground state has a non-zero magnetization pointing in some direction.

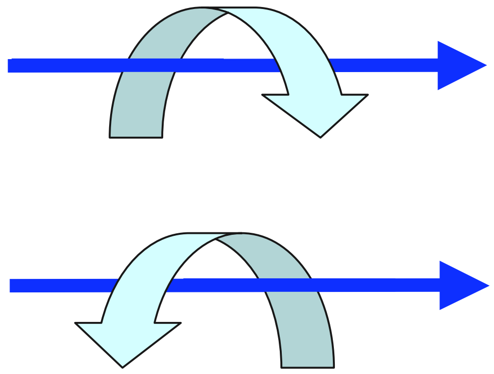
The Higgs Mechanism

- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \begin{pmatrix} \varphi^- \\ \varphi^{*0} \end{pmatrix}$$

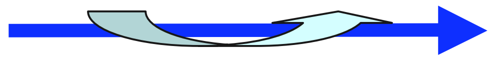
- Write down the interactions between the new doublet and itself, and the new doublet and the weak bosons in just the right way to
  - Spontaneously break the symmetry: i.e. the Higgs field develops a non-zero vacuum expectation value
    - *Like the magnetization in a ferromagnet*
  - Allow something really cute to happen

The Really Cute Thing



$m = \pm 1$ "transverse"

- The massless w^+ and ϕ^+ mix.
  - You get one particle with *three* spin states
    - *Massive particles have three spin states*
  - The W has acquired a mass
- The same thing happens for the w^- and ϕ^-



$m = 0$ "longitudinal"

- In the neutral case, the same thing happens for one neutral combination, and it becomes the massive Z^0.
- The other neutral combination doesn't couple to the Higgs, and it gives the massless photon.
- That leaves one degree of freedom left, and because of the non zero v.e.v. of the Higgs field, produces a massive Higgs.

How Cute Is It?

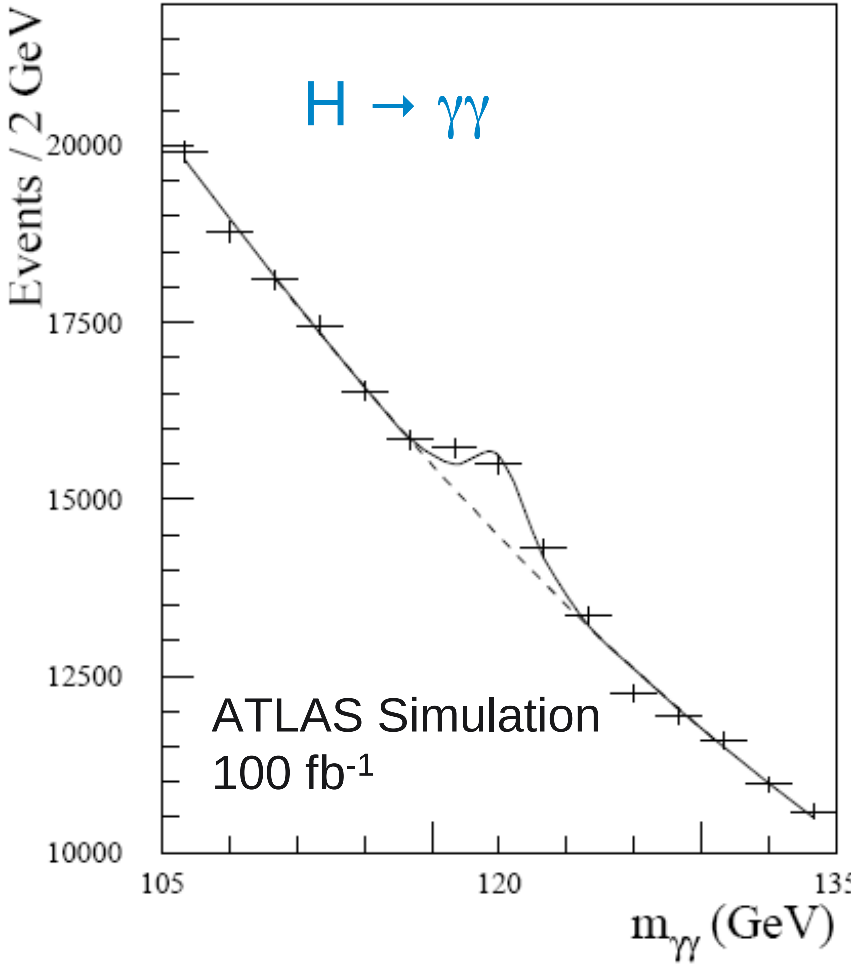
- There's very little choice involved in how you write down this theory.
  - There's one free parameter which determines the Higgs boson mass
  - There's one sign which determines if the symmetry breaks or not.

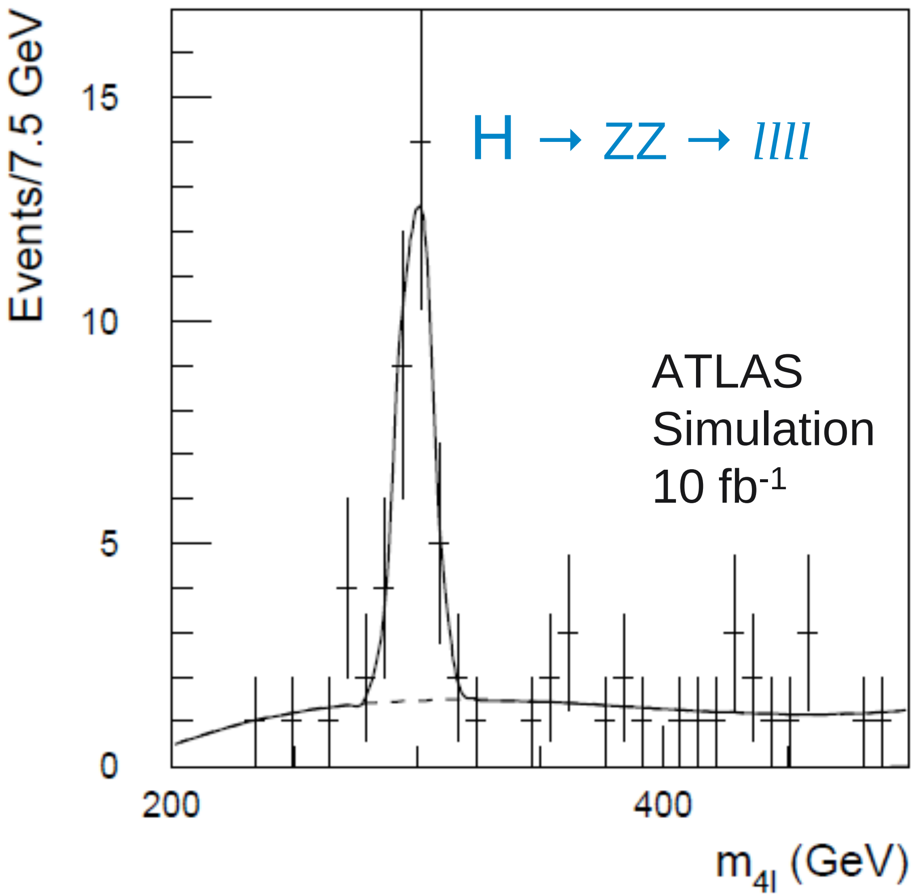
- The theory leaves the Standard Model mostly untouched
  - It adds a new Higgs boson – **which we can look for**
  - It adds a new piece to the WW → WW cross-section
    - *This interferes destructively with the piece that was already there and restores unitarity*

- In this model, the v.e.v. of the Higgs field ***is*** the Fermi constant

Searching for the Higgs Boson

Because the theory is so constrained, we have very solid predictions on where to look and what to look for.

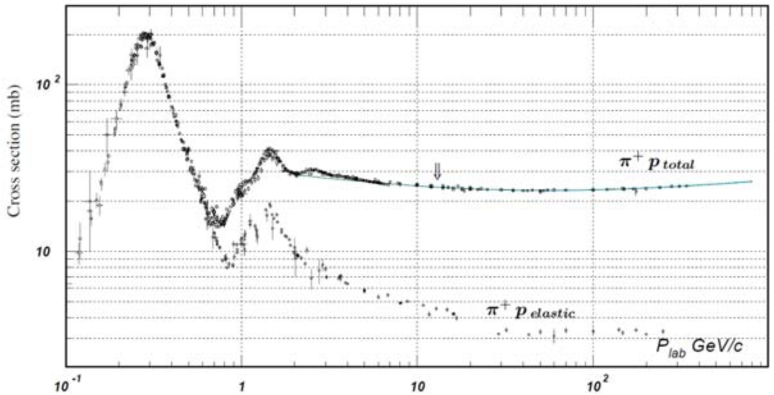




Two Alternatives

- Multiple Higgses
  - I didn't have to stop with one Higgs doublet – I could have added two
  - This provides four more degrees of freedom:
    - *Manifests as five massive Higgs bosons: h^0, H^0, A^0, H^+,H^-*
      - Usually some are harder to see, and some are easier
  - You don't have to stop there either…

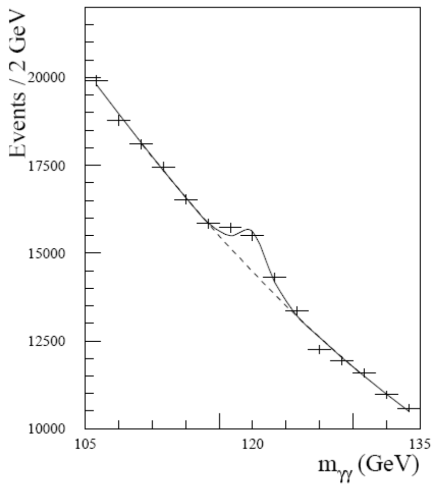
- New Strong Dynamics
  - Maybe the WW → WW cross-section blowing up is telling us something:
    - *The $\pi + p \rightarrow \pi + p$ cross-section also blew up: it was because of a resonance: the Δ.*
    - *Maybe there are resonances among the W's and Z's which explicitly break the symmetry*

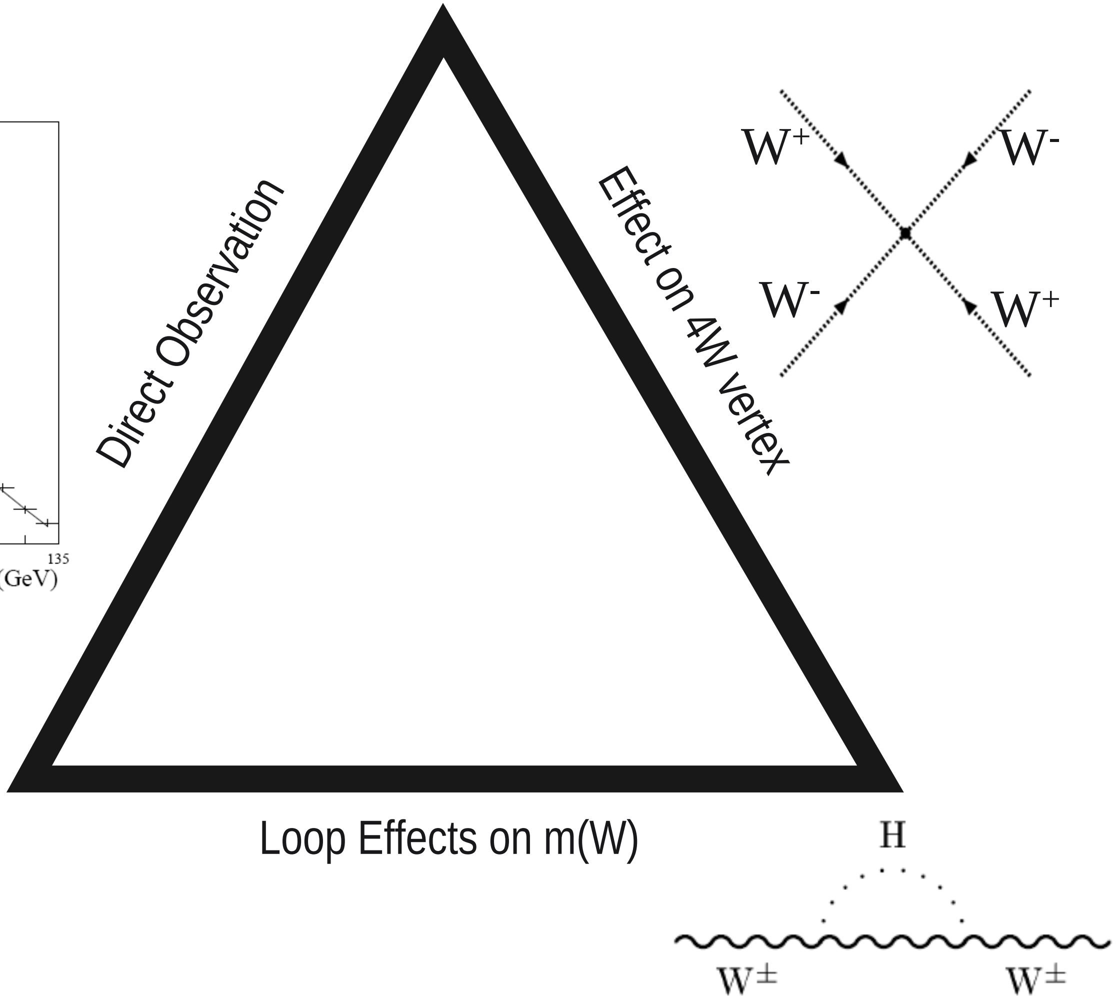


Many models: LHC data will help discriminate among them.

The Higgs Triangle

Two of the three necessary measurements are SM measurements.





Outline of the Talk

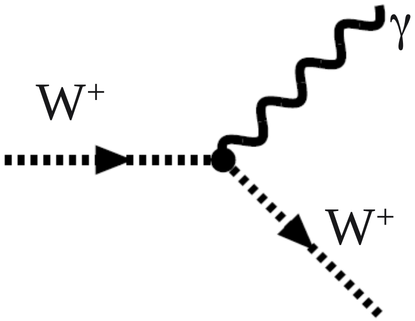
20+ slides in and ***now*** he's giving us an outline?

- The (EWK) Standard Model
  - You've just seen this
- Two of the Three Legs of the "Higgs Triangle"
  - Multiple Boson interactions
  - The Mass of the W Boson
  - There are plenty of people who can talk about the Higgs search
- Interrupt me with questions!
  - I'd rather this be a dialog than a lecture
  - I talk too fast anyway

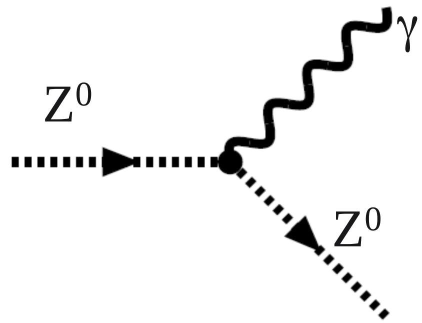
I'll probably overuse ATLAS and CDF plots, simply because they are easiest for me to find.

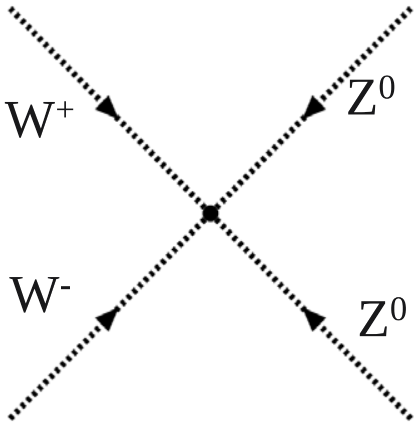
Which Model is the Standard Model?

The (Electroweak) Standard Model is the theory that has interactions like:



but not





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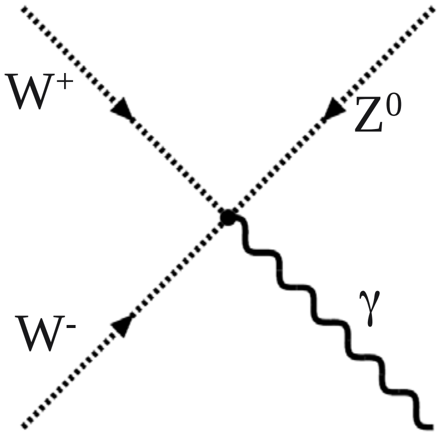
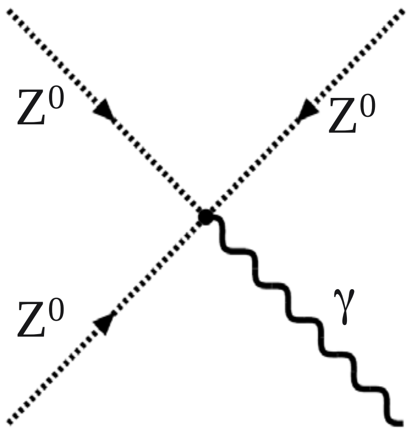


but not:



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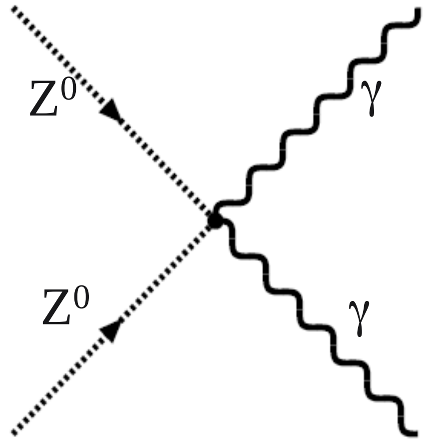
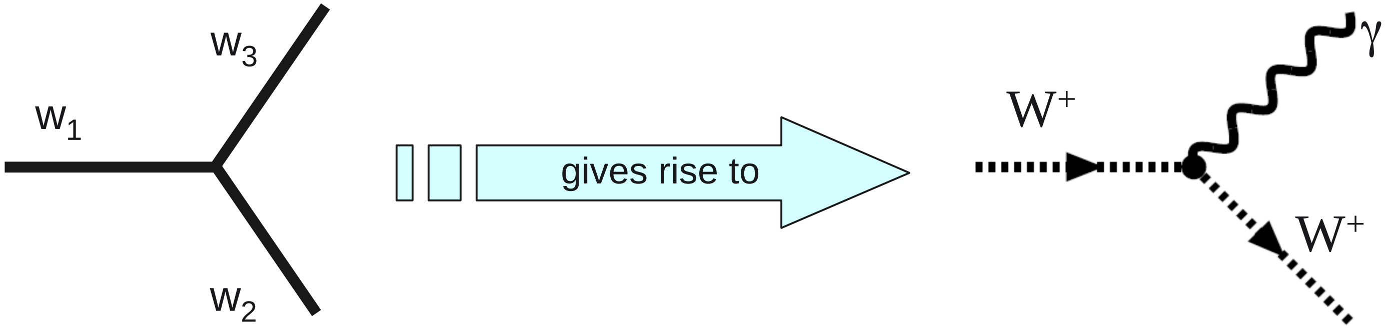
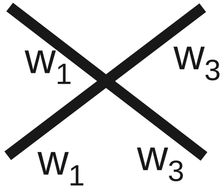


Only three parameters - G_F, α and $\sin^2(\theta_w)$ - determine **all** couplings.

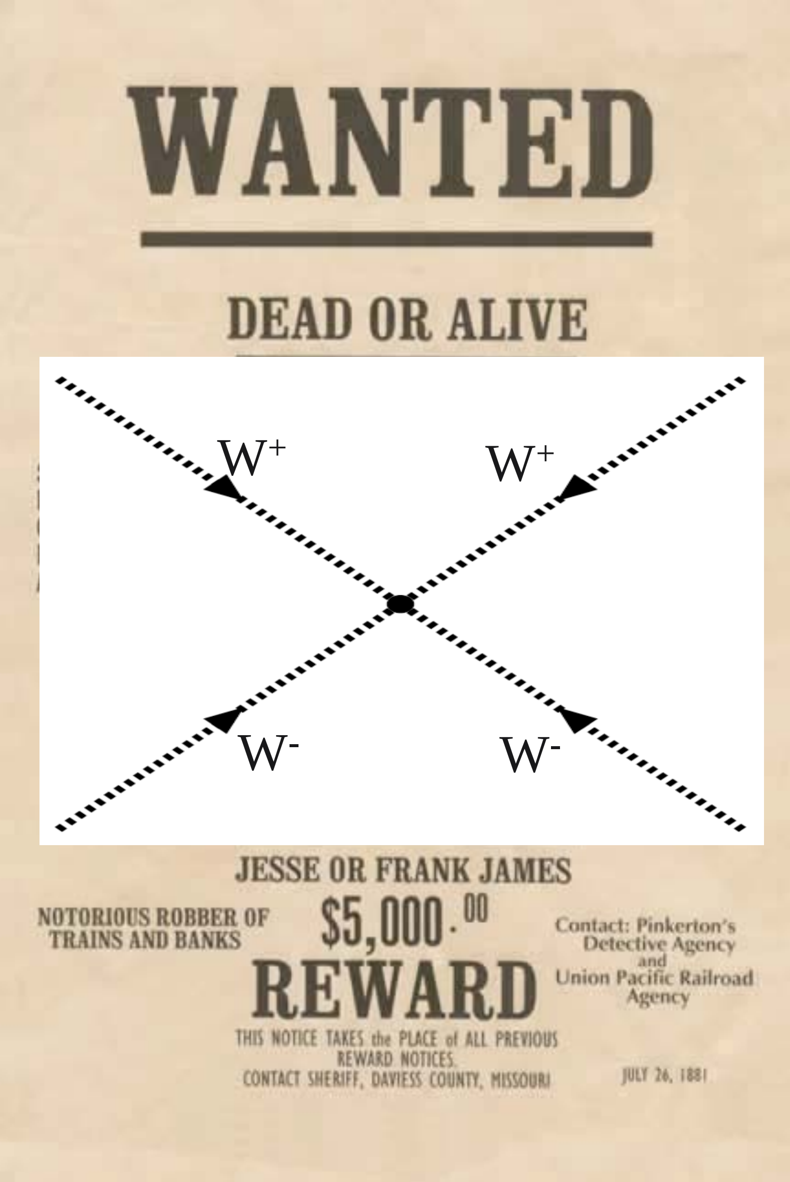
Under The Hood

- The Electroweak Gauge Group is $SU(2)_L x U(1)_Y$
  - U(1) – "weak hypercharge"
    - *a close analog of electromagnetism*
  - SU(2) – "weak isospin"
    - *A Non-Abelian Group*
    - *Same Group as Angular Momentum*



Note: diagrams like  give rise to the quartic gauge couplings as well.

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.

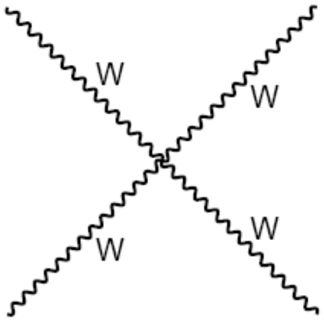
Yields are not all that great

$M_{\rm Higgs}$ (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

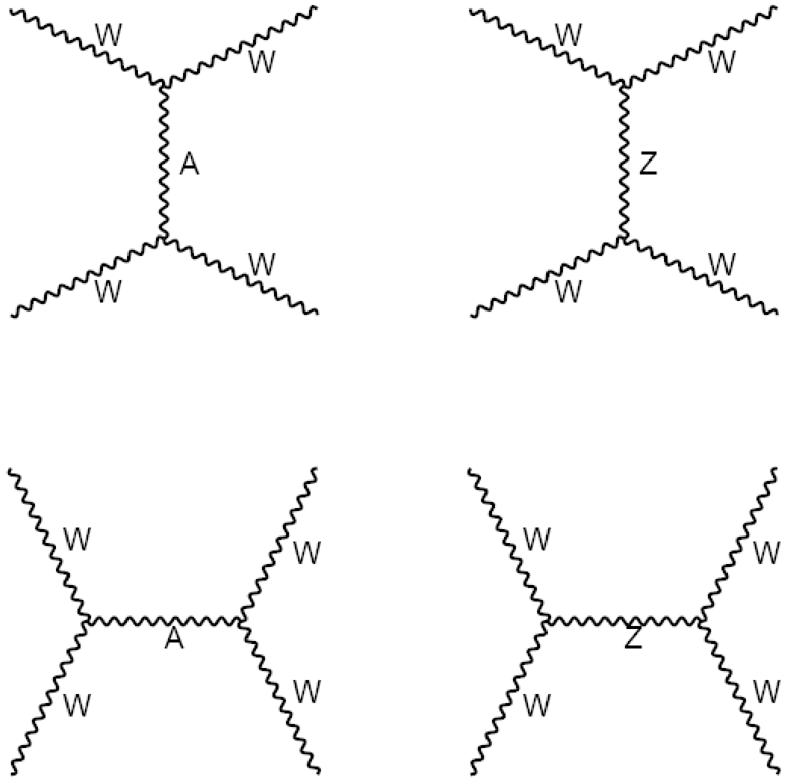
100 fb-1, all leptonic modes inside detector acceptance

A Complication



If we want to understand the quartic coupling…

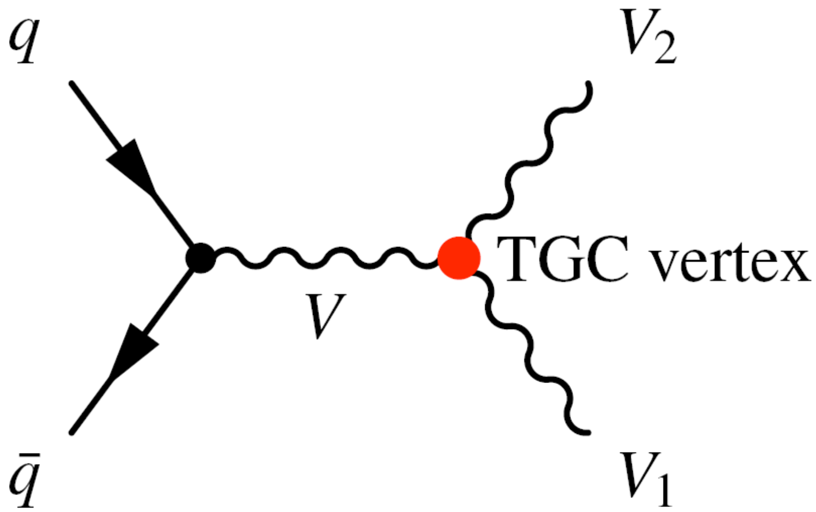
…first we need to measure the trilinear couplings



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

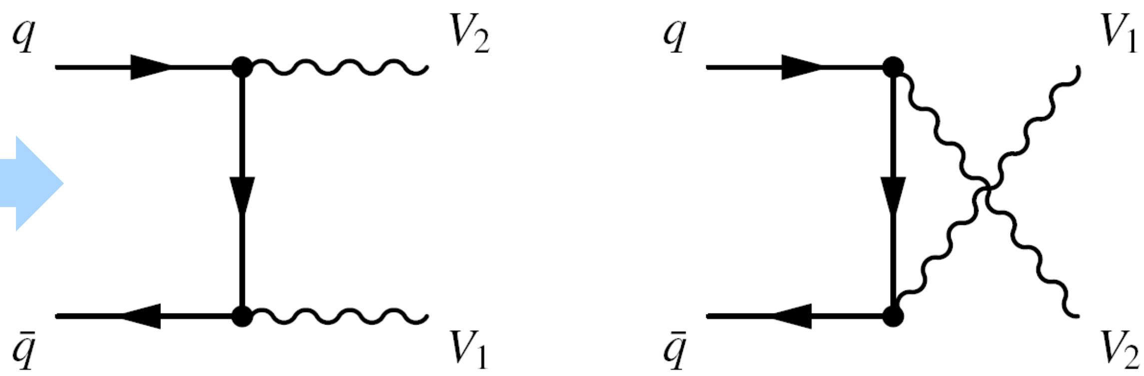
Trilinear Couplings

Of course, one doesn't look at anything that complicated to probe TGC's.



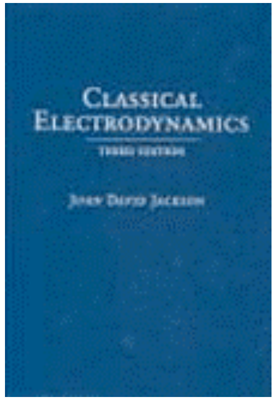
- Final states involving photons
  - $W\gamma$, $Z\gamma$
- Final states involving heavy bosons
  - *WW*, *WZ*

There are, however, backgrounds



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

Tevatron Yields

Process	Source	L fb^{-1}	observed events	background events	σ(data) [pb] $\pm$ (stat)$\pm$(sys)$\pm$(lum)	σ(theory) [pb]
W^+W^-	CDF [21]	0.83	95	38$\pm$5	13.6$\pm$2.3$\pm$1.6 $\pm$ 1.2	12.4$\pm$0.8
$(ee, \mu\mu, e\mu)$	D0 [22]	0.25	25	8.1$\pm$.5	13.8$\pm$4.1$\pm$1.1 $\pm$ 0.9	"
$W^\pm Z$	CDF [23]	1.1	16	2.7$\pm$0.4	$5.0^{+1.8}_{-1.4} \pm 0.4$	3.7$\pm$0.3
$(\ell^\pm \nu \ell^+ \ell^-)$	D0 [24]	1.0	13	4.5$\pm$0.6	2.7 +1.7−1.3 (total)	"
$Z\gamma$	CDF [25]	0.2	72	4.9$\pm$1.1	4.6 $\pm$0.6 (sta+sys) $\pm$ 0.3	4.5$\pm$0.3
$(\ell^+\ell^-\gamma)$	D0 [26]	1.0	968	117$\pm$12	4.96 $\pm$0.3 (sta+sys) $\pm$ 0.3	4.7$\pm$0.2
$W^\pm\gamma$	CDF [25]	0.2	323	114$\pm$21	18.1 $\pm$3.1 (sta+sys) $\pm$ 1.2	19.3$\pm$1.4
$(\ell^\pm\nu\gamma)$	D0 [27]	0.16	273	132$\pm$7	14.8 $\pm$1.9 (sta+sys) $\pm$ 1.0	16.0$\pm$0.4
ZZ	CDF [28]	1.9	2	0.014	$1.4^{+0.7}_{-0.6} \pm 0.6$	1.5$\pm$0.2
$(\ell^+\ell^-\ell^+\ell^-)$	D0 [29]	1.0	1	0.13	< 4.4	"

Note: LEP also shows sensitivity to many of these couplings – in fact, the Tevatron and LEP rates depend on different combinations of them.

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$(ee, \mu\mu, e\mu)$	D0 [22]	0.25	25	8.1±.5	13.8±4.1±1.1 ± 0.9	"
$W^\pm Z$	CDF [23]	1.1	16	2.7±0.4	$5.0^{+1.8}_{-1.4} \pm 0.4$	3.7±0.3
$(\ell^\pm \nu \ell^+ \ell^-)$	D0 [24]	1.0	13	4.5±0.6	2.7 +1.7−1.3 (total)	"
$Z\gamma$	CDF [25]	0.2	72	4.9±1.1	4.6 ±0.6 (sta+sys) ± 0.3	4.5±0.3
$(\ell^+\ell^-\gamma)$	D0 [26]	1.0	968	117±12	4.96 ±0.3 (sta+sys) ± 0.3	4.7±0.2
$W^\pm\gamma$	CDF [25]	0.2	323	114±21	18.1 ±3.1 (sta+sys) ± 1.2	19.3±1.4
$(\ell^\pm\nu\gamma)$	D0 [27]	0.16	273	132±7	14.8 ±1.9 (sta+sys) ± 1.0	16.0±0.4
ZZ	CDF [28]	1.9	2	0.014	$1.4^{+0.7}_{-0.6} \pm 0.6$	1.5±0.2
$(\ell^+\ell^-\ell^+\ell^-)$	D0 [29]	1.0	1	0.13	< 4.4	"

Note: LEP also shows sensitivity to many of these couplings – in fact, the Tevatron and LEP rates depend on different combinations of them.

Tevatron Yields

Process	Source	L fb^{-1}	observed events	background events	σ(data) [pb] $\pm$ (stat)$\pm$(sys)$\pm$(lum)	σ(theory) [pb]
W^+W^-	CDF [21]	0.83	95	38±5	13.6±2.3±1.6 ± 1.2	12.4±0.8
$(ee, \mu\mu, e\mu)$	D0 [22]	0.25	25	8.1±.5	13.8±4.1±1.1 ± 0.9	”
$W^\pm Z$	CDF [23]	1.1	16	2.7±0.4	$5.0^{+1.8}_{-1.4} \pm 0.4$	3.7±0.3
$(\ell^\pm \nu \ell^+ \ell^-)$	D0 [24]	1.0	13	4.5±0.6	2.7 +1.7−1.3 (total)	”
$Z\gamma$	CDF [25]	0.2	72	4.9±1.1	4.6 ±0.6 (sta+sys) ± 0.3	4.5±0.3
$(\ell^+ \ell^- \gamma)$	D0 [26]	1.0	968	117±12	4.96 ±0.3 (sta+sys) ± 0.3	4.7±0.2
$W^\pm \gamma$	CDF [25]	0.2	323	114±21	18.1 ±3.1 (sta+sys) ± 1.2	19.3±1.4
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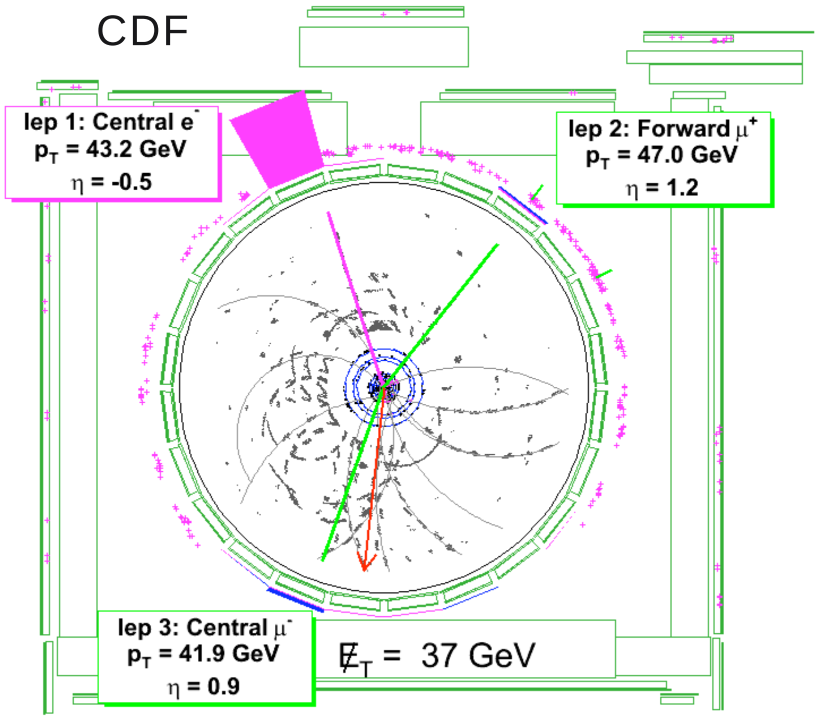
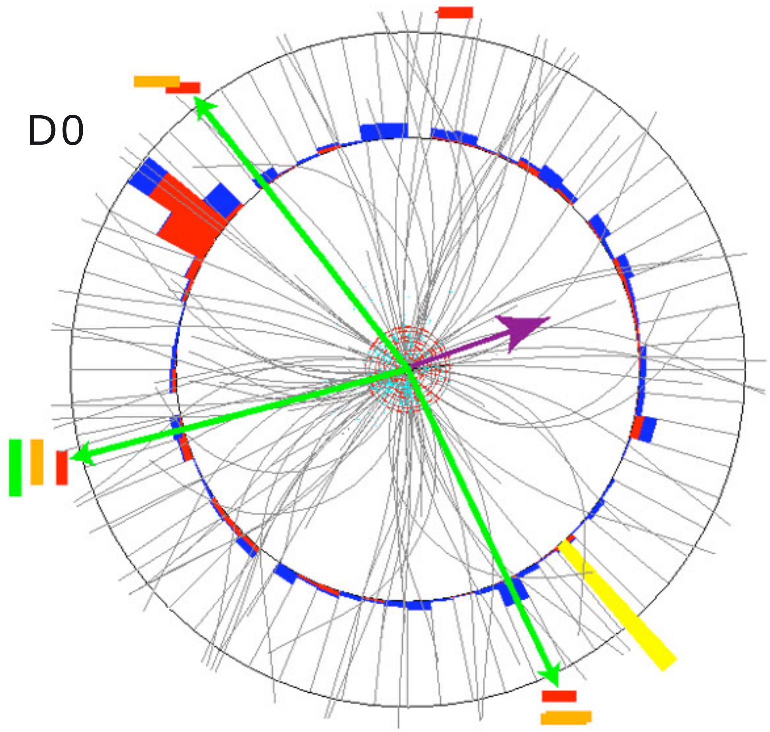
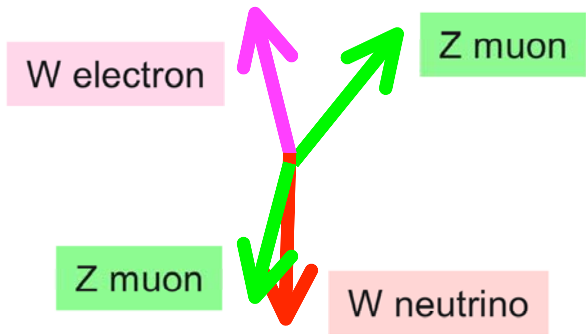
ZZ	CDF [28]	1.9	2	0.014	$1.4^{+0.7}_{-0.6} \pm 0.6$	1.5±0.2
$(\ell^+ \ell^- \ell^+ \ell^-)$	D0 [29]	1.0	1	0.13	< 4.4	”

Note: LEP also shows sensitivity to many of these couplings – in fact, the Tevatron and LEP rates depend on different combinations of them.

W+Z Events



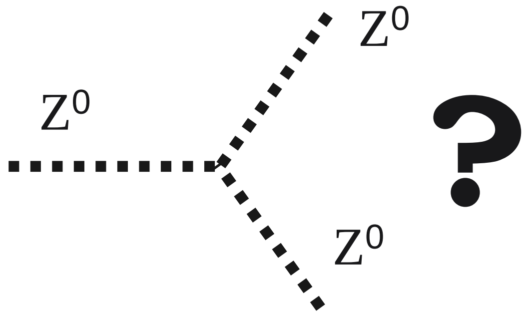




About three dozen such events in the two experiments.

Within uncertainties, rates are consistent with the Standard Model.

Why No All-Neutral Couplings?



Here's where thinking about the unbroken symmetries helps.

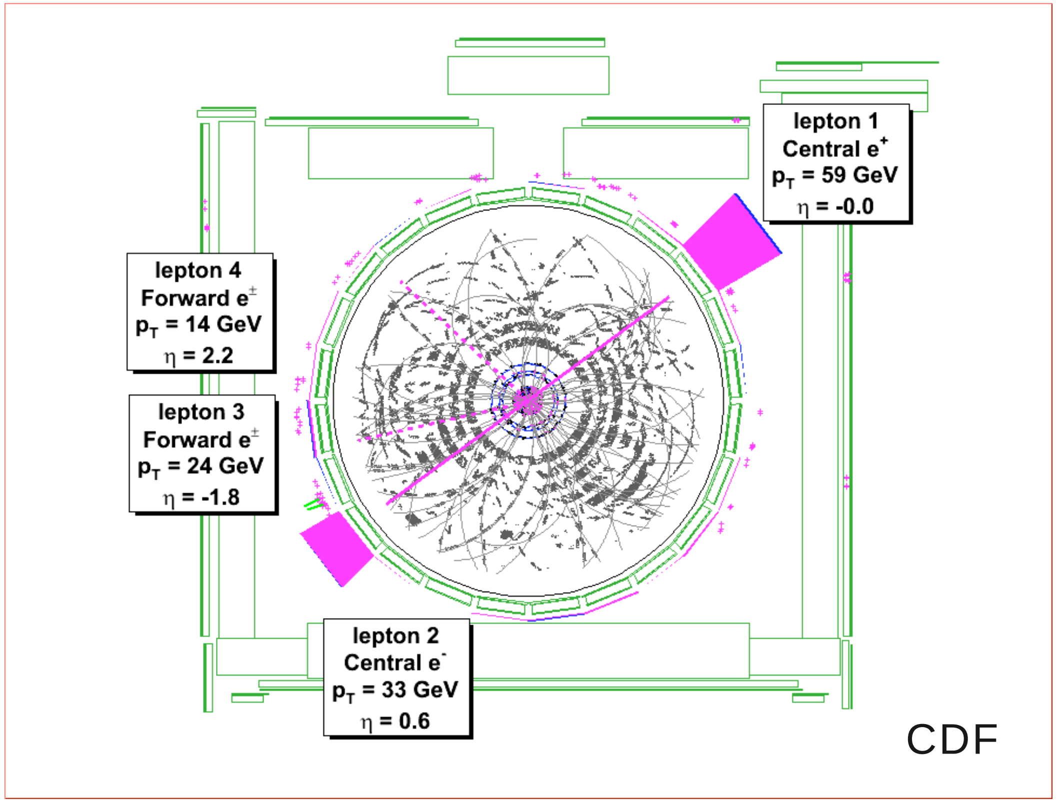
- Trilinear Coupings
  - B-B-B: zero because U(1)'s are Abelian, Furry's Theorem, C, P…
  - B-B-w_3
  - B-w_3-w_3

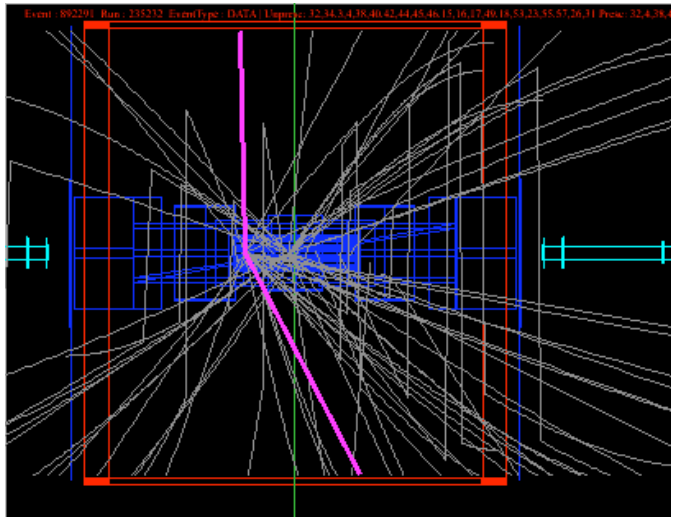
  The w's don't carry hypercharge, and the B doesn't carry isospin. So the "mixed couplings" are zero

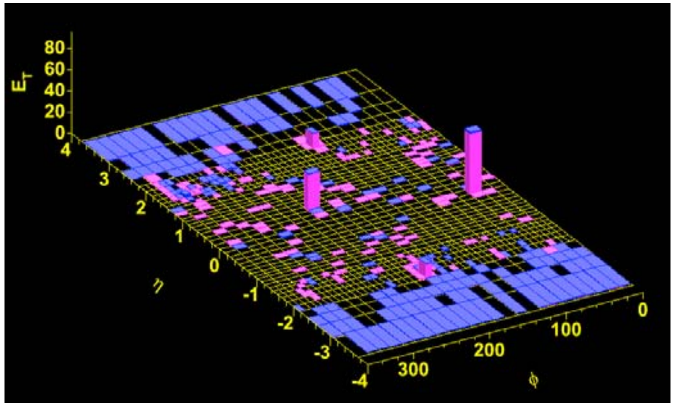
  - w_3-w_3-w_3
    - *This is where the SU(2) symmetry comes in handy*
    - *The Clebsch-Gordon coefficient for (1,0)+(1,0)=(1,0) is **zero**.*
      - (Recall angular momentum is SU(2) symmetric)
- Quartic Couplings
  - B-B-B-B: zero because U(1)'s are Abelian
  - w_3-w_3-w_3 -w_3 : zero in SU(2)
  - All mixed couplings: zero

These are all zero. Any linear combination (like the γ and Z) of zeros is still zero.

So, Does This Event (and its siblings) Kill the SM?



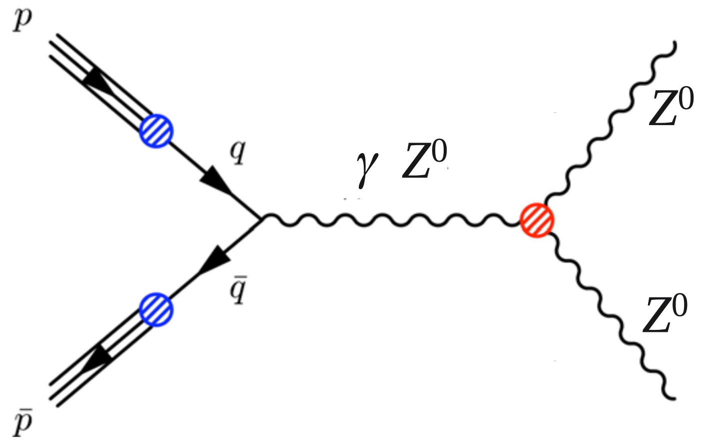




$$\bar{p}p \to ZZ + X\,, ZZ \to eeee$$

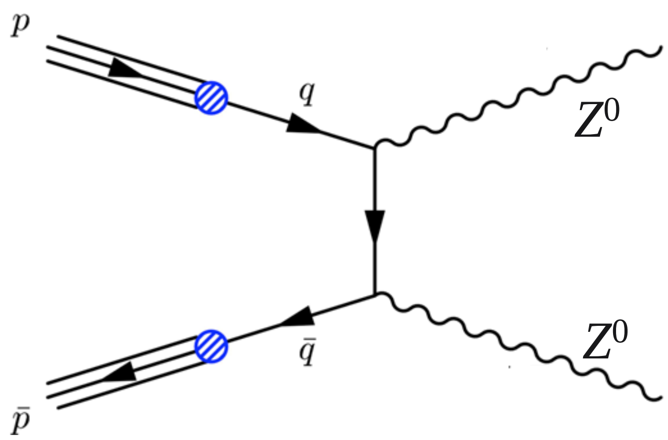
No…Experiments Measure Rates, Not Couplings

The experiments are hoping to see this – evidence for a non-zero ZZZ or γZZ coupling.

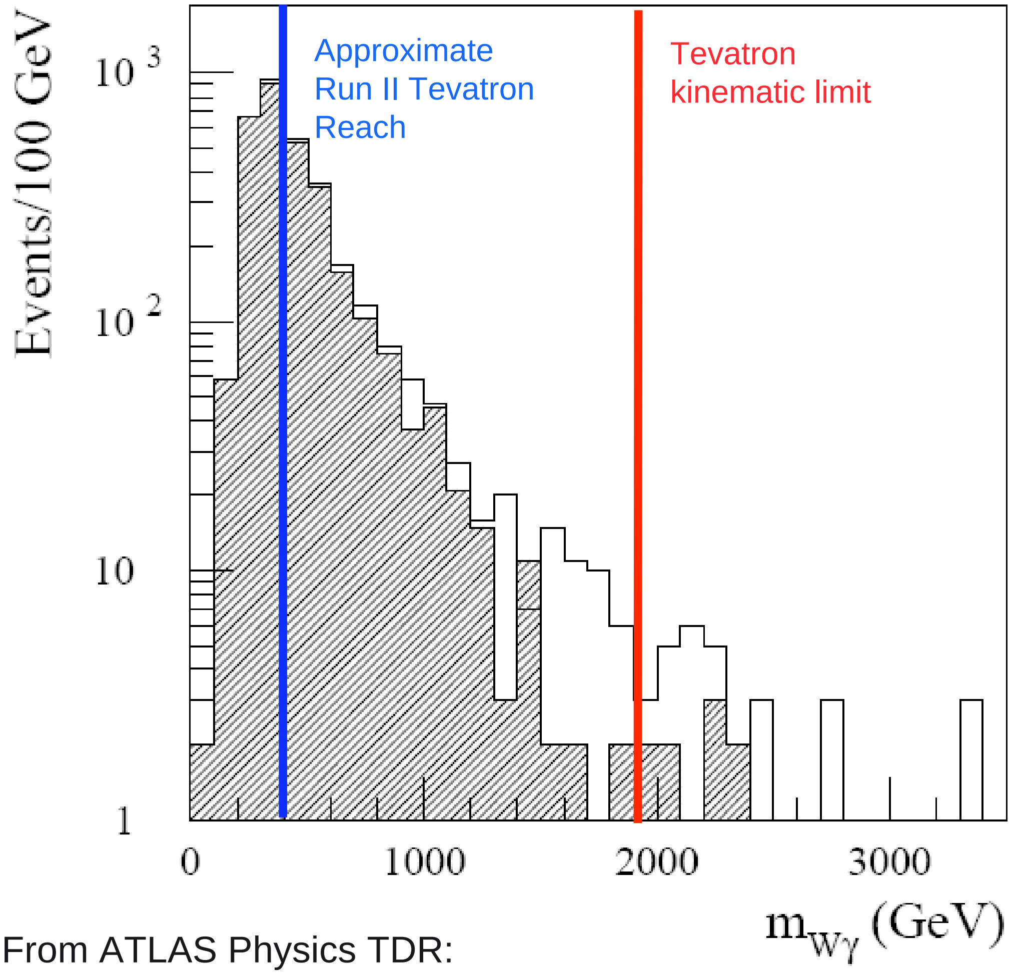


However, the exact same final state can occur by this (ordinary SM) process.

Experiments need to look for an excess of events beyond the SM prediction, and/or events at high m(ZZ), where the SM prediction is small and new physics would be larger.



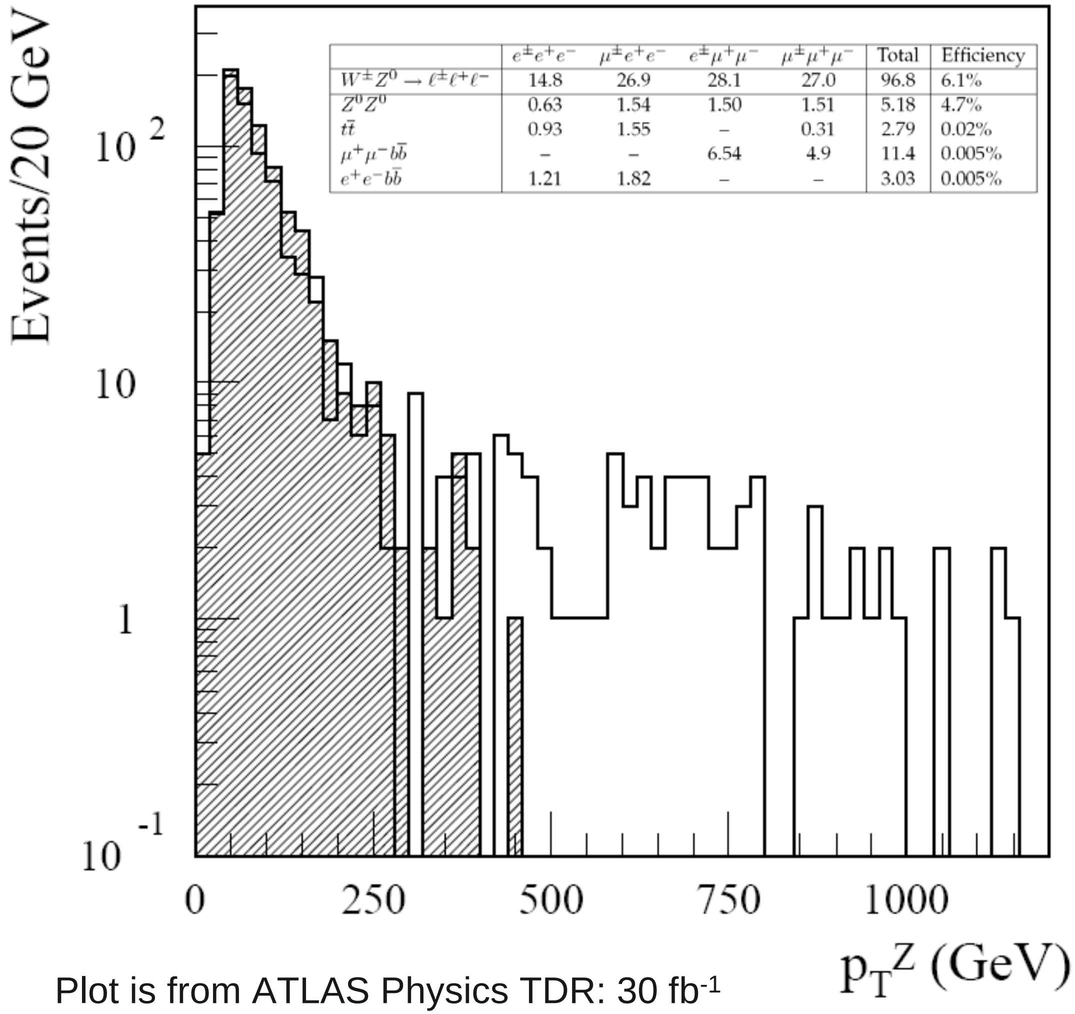
Why Center-Of-Mass Energy Is Good For You



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

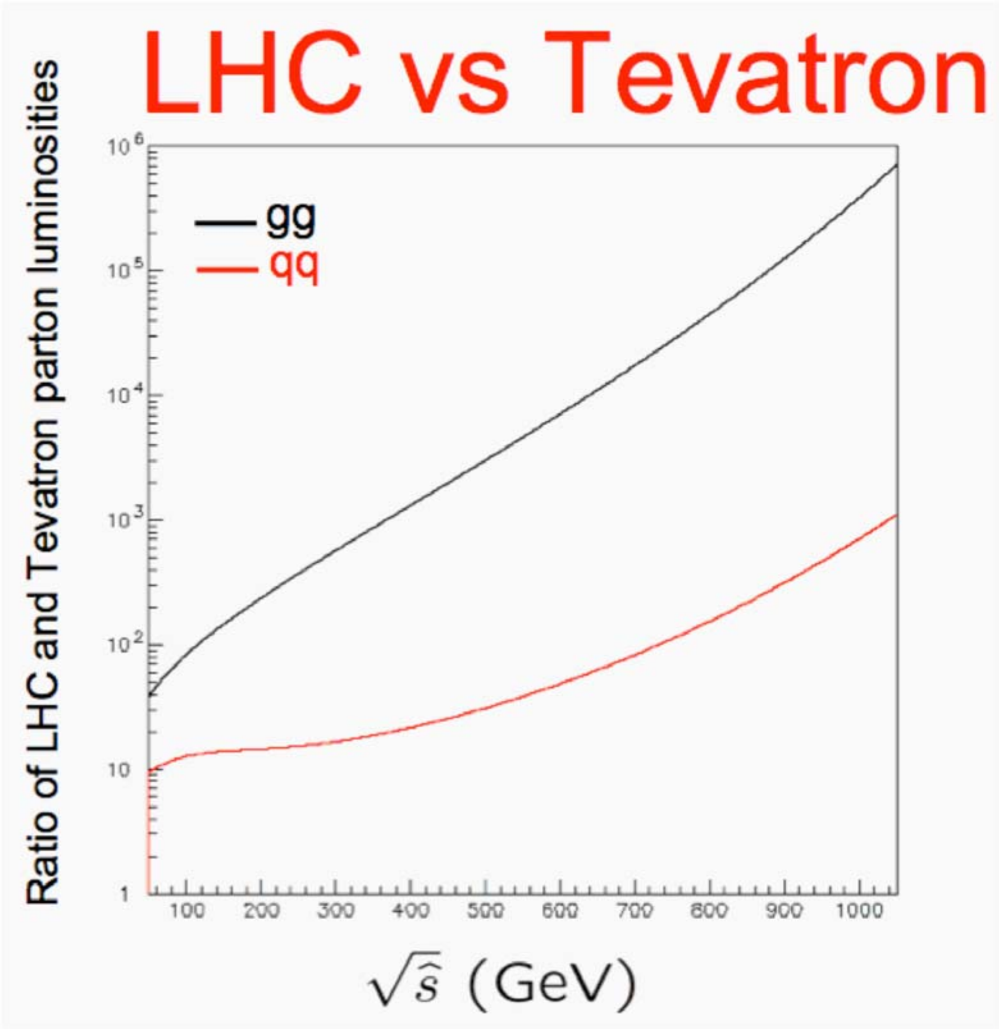


	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency
$W^\pm Z^0 \rightarrow \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1%
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.18	4.7%
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02%
$\mu^+\mu^- b\bar{b}$	–	–	6.54	4.9	11.4	0.005%
$e^+e^-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

TGC's – the bottom line

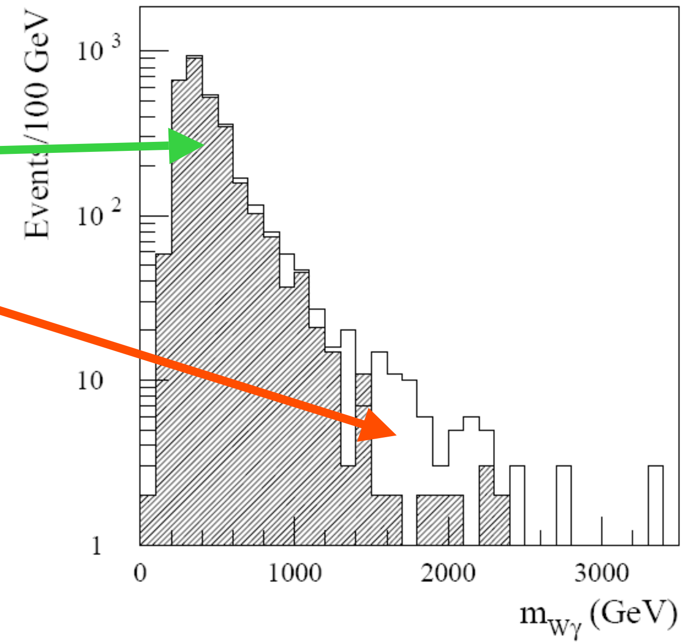
Coupling	Present Value	LHC Sensitivity (95% CL, 30 fb-1 one experiment)
$\Delta g_1{}^Z$	$-0.016^{+0.022}_{-0.019}$	0.005-0.014
$\Delta\kappa_\gamma$	$-0.027^{+0.044}_{-0.045}$	0.03-0.076
$\Delta\kappa_Z$	$-0.076^{+0.061}_{-0.064}$	0.06-0.12
λ_γ	$-0.028^{+0.020}_{-0.021}$	0.001-0.0035
λ_Z	$-0.088^{+0.063}_{-0.061}$	0.0028-0.0073

- Not surprisingly, the LHC does best with the Dimension-6 parameters
- Sensitivities are ranges of predictions given for either experiment

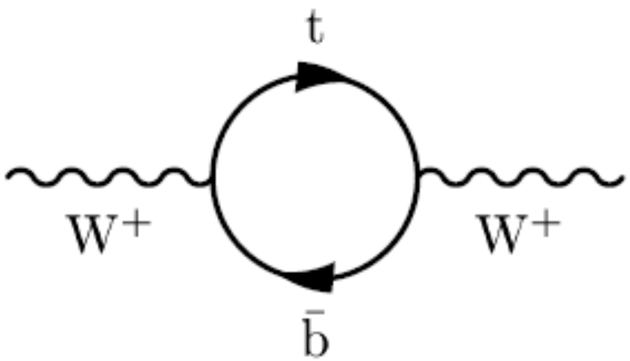
Early Running

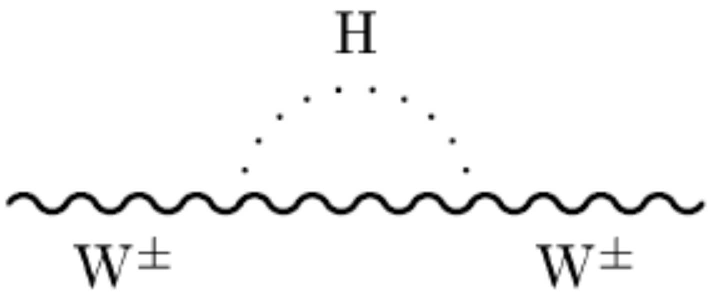
- Reconstructing W's and Z's quickly will not be hard
- Reconstructing photons is harder
  - Convincing you and each other that we understand the efficiencies and jet fake rates is probably the toughest part of this

- We have a built in check in the events we are interested in
  - The Tevatron tells us what is happening over here.
  - We need to measure out here.
- At high E_T, the problem of jets faking photons goes down.
  - Not because the fake rate is necessarily going down – because the number of jets is going down.



The W Mass

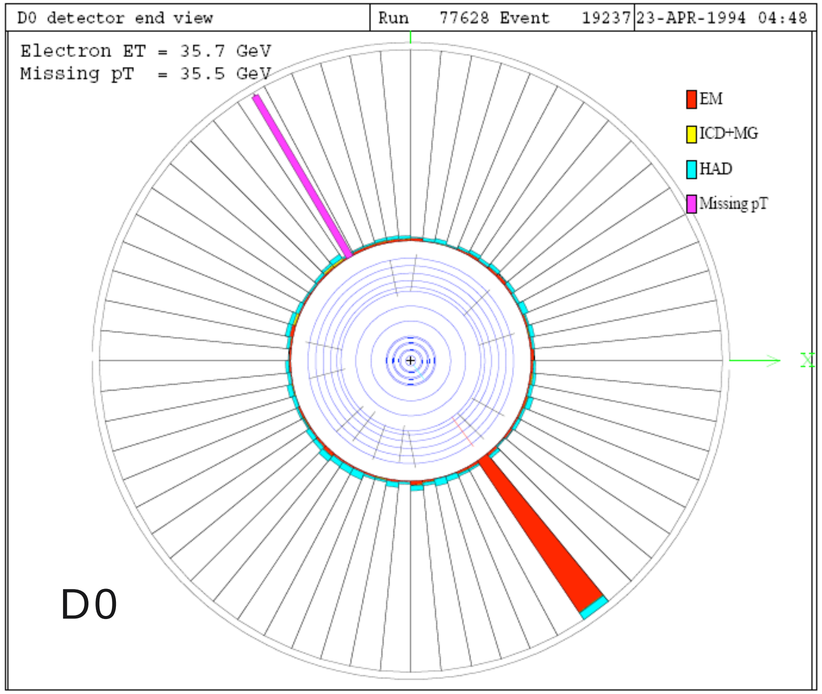




I am not going to try and sell you on the idea that the LHC will reach a precision of [fill in your favorite number here].

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

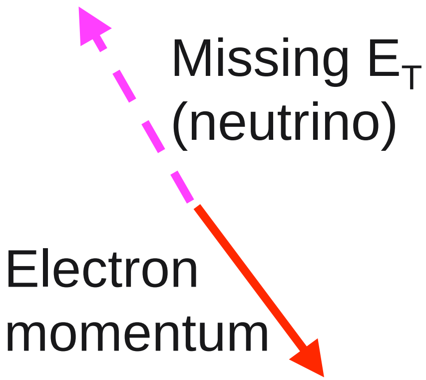
Measuring the W Mass at a Hadron Collider

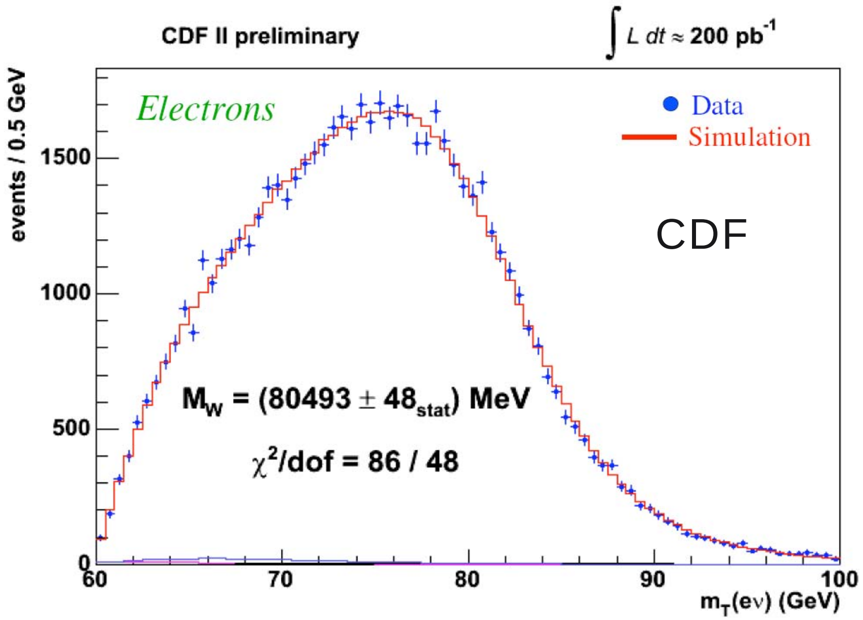


p_z for the neutrino isn't measured, so we can't measure m(W). The best we can do is the transverse mass.

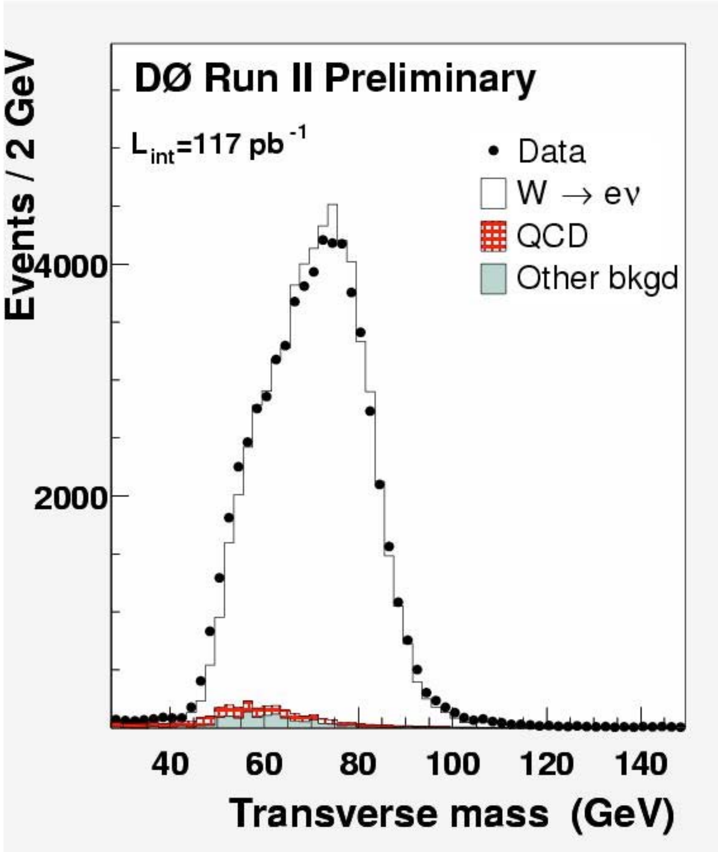
$$m_T = \sqrt{E^2 - p_x^2 - p_y^2}$$

Fortunately, the transverse mass distribution is a function of the true mass.

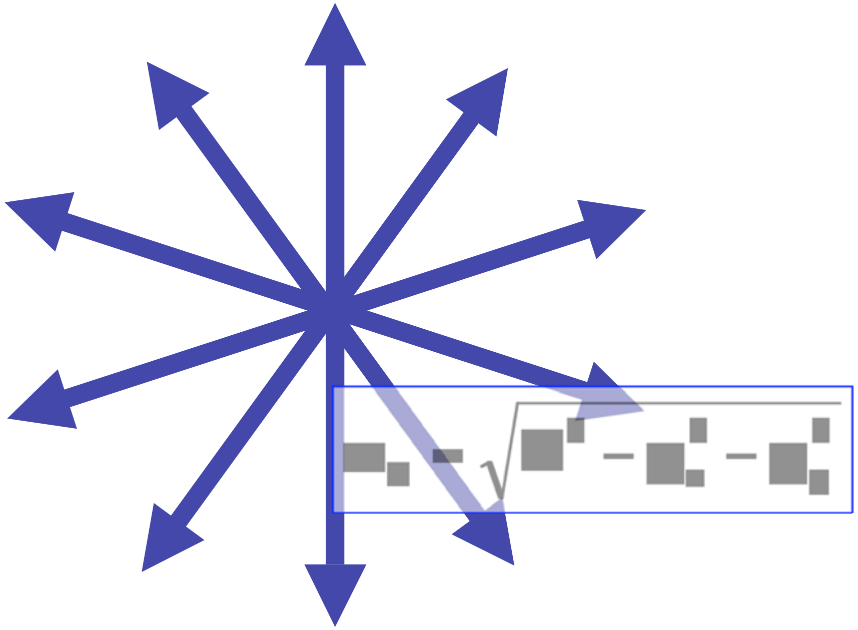




Why the Odd Shape?



The $W \rightarrow l+\nu$ decay is a two-body decay, whose axis can point in any direction.

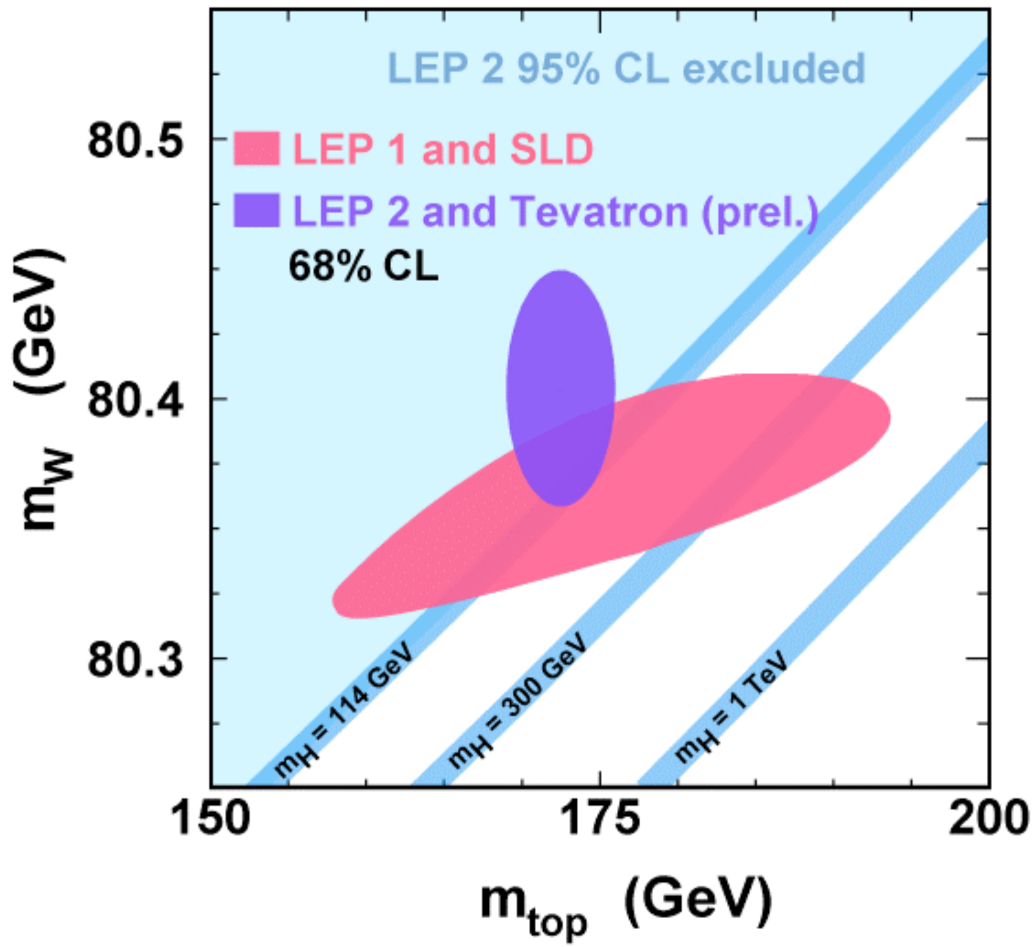


The momentum components depend on the decay angles – and p_z for the neutrino remains unmeasured.

The Jacobian peak that results is a consequence of the decay angle of the W. The position of this peak is (fortunately!) a strong function of the W mass.

Constraints on Higgs Mass

- To obtain equivalent constraint on M_H
  - $\Delta M_{top} \sim 1.5$ GeV/c^2, ~ 1% on M_{top}
  - $\Delta M_W \sim 10$ MeV/c^2, ~ 0.01% on M_W



(A statement that a quadratic effect is bigger than a logarithmic one)

W Mass Strategies

- Reconstructing W → jj is impossible
  - Backgrounds are so large, we can't even trigger on them
  - Even if we could, Z → jj would be a pernicious background

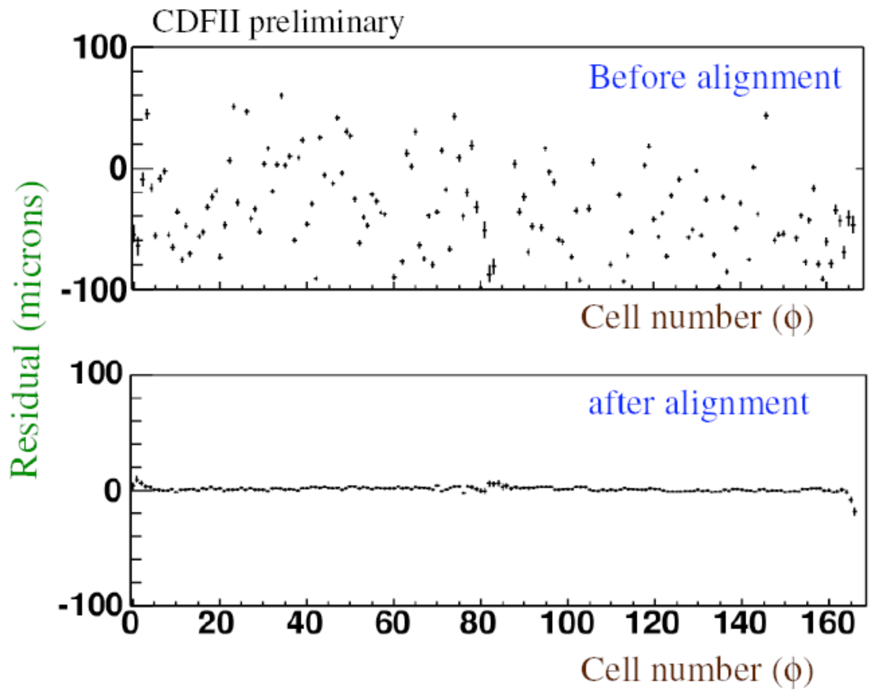
- We must use leptonic decays
  - W → $e\nu$, W → $\mu\nu$ (22% branching fraction)
  - W → $\tau\nu$ is more difficult because of the τ reconstruction
  - This requires neutrino reconstruction
- Three estimators of the W mass
  - Transverse mass m_T
  - p_T(e or μ)
  - Missing E_T
    - *an estimator for $p_T(\nu)$*

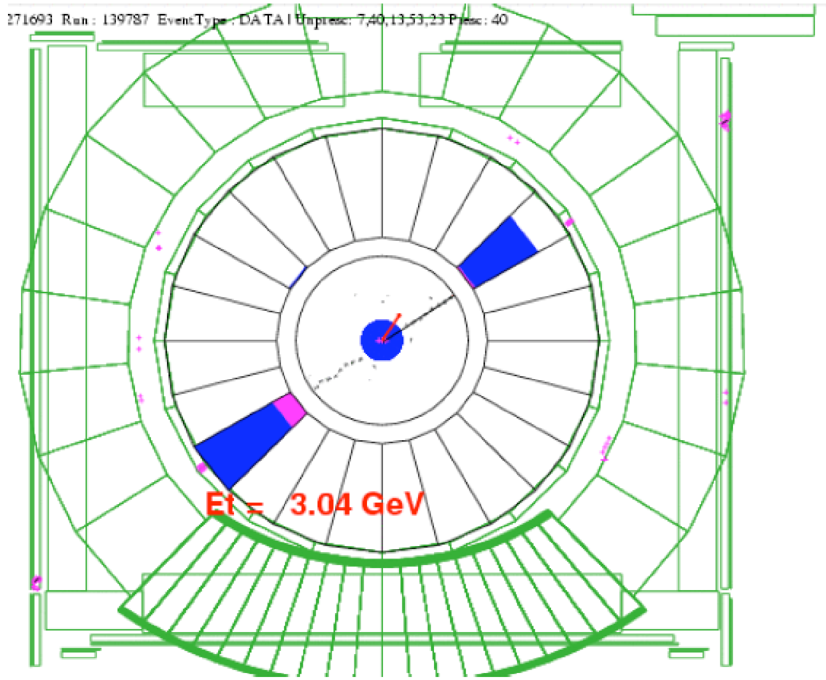
These have different systematic uncertainties associated with them.

All three are used in a fit.

Step One: Align The Detector

- Use clean sample of ~200,000 cosmic rays
  - Do a “bi-helix” fit – fit both legs simultaneously



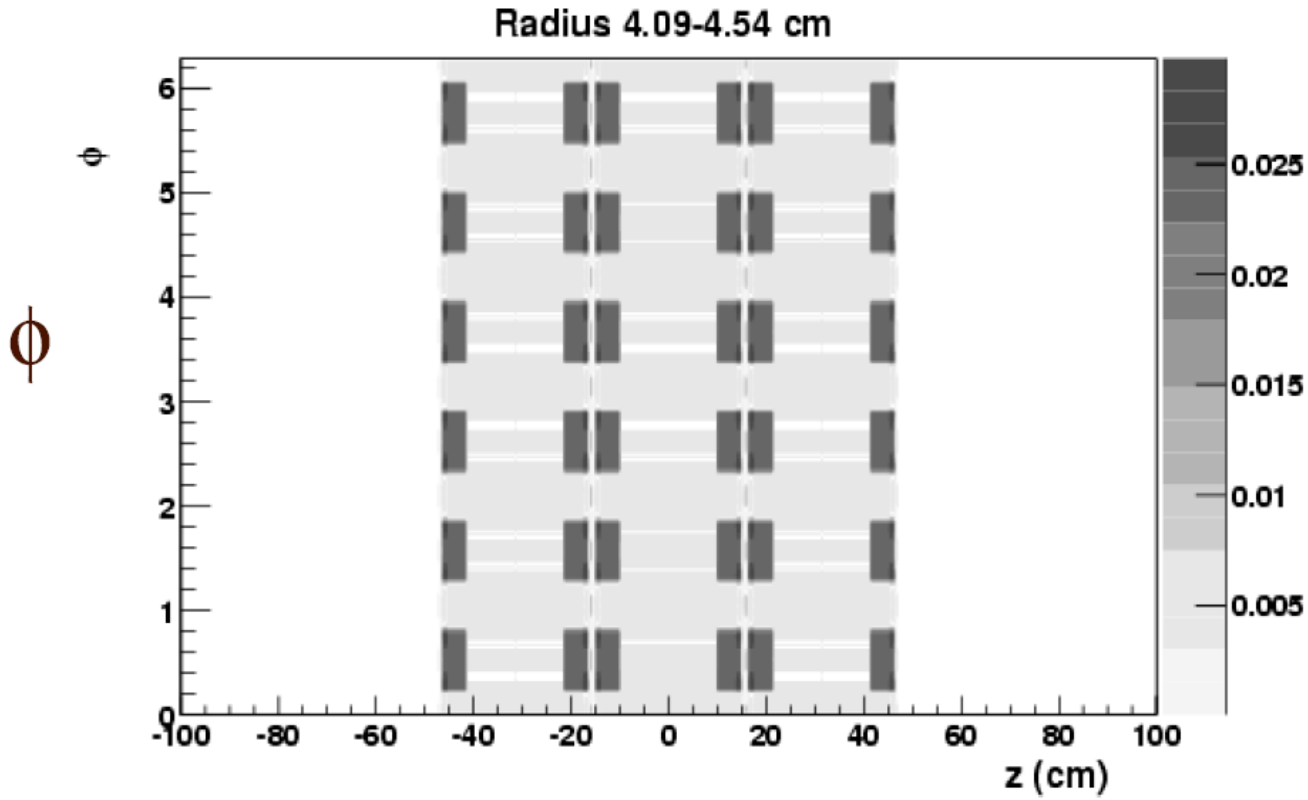


This aligns the tracking to within about 5 μm.

We cross-check by comparing the measured momentum of positrons and electrons of the same measured energy.

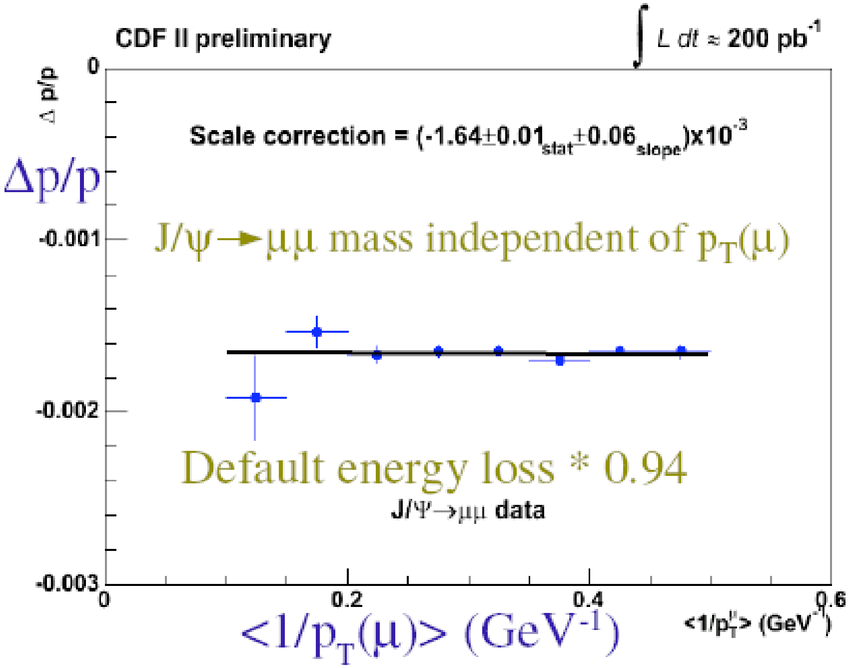
Understanding the Detector Part 2

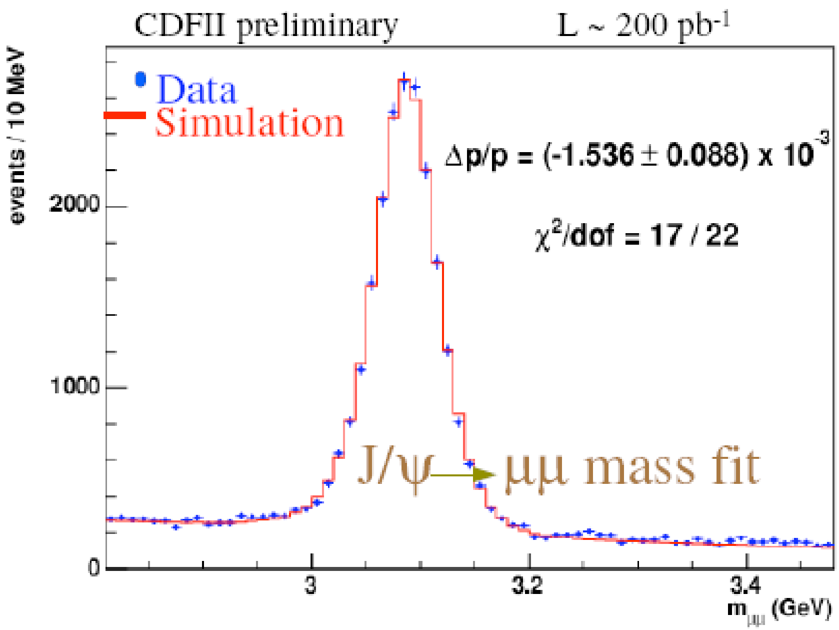
- We have a very, very detailed material map
  - Wafers, hybrids, bulkheads, port cards, water in cooling lines…
  - This is used to model the energy loss
  - We will check this with J/ψ's and electrons (details in later slides)



Step Two: Set the Momentum Scale

- Set using J/ψ → μμ, Υ → μμ and Z → μμ
  - All are internally consistent with each other
  - Large J/ψ and Υ samples let us monitor potential systematics
- Because we measure curvature (i.e. $1/p_T$, going from low p_T to high p_T is an interpolation, not an extrapolation)

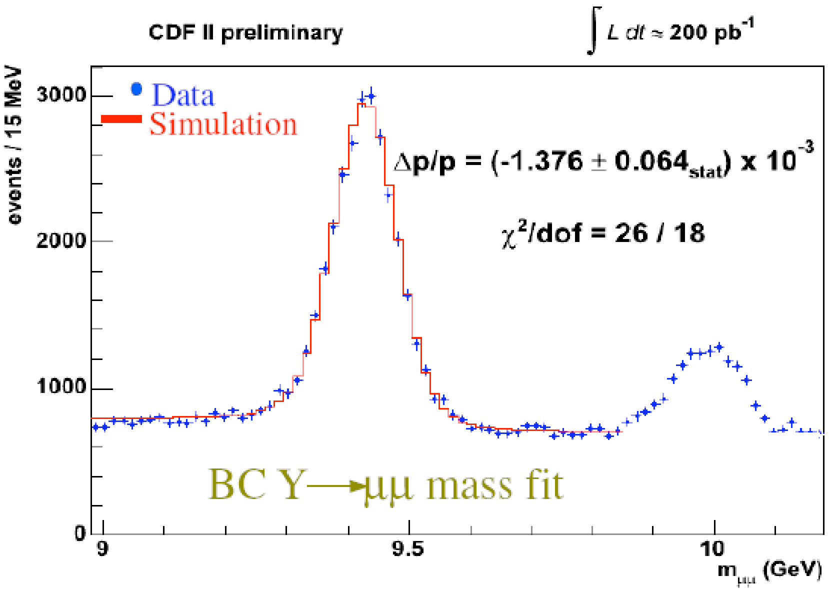


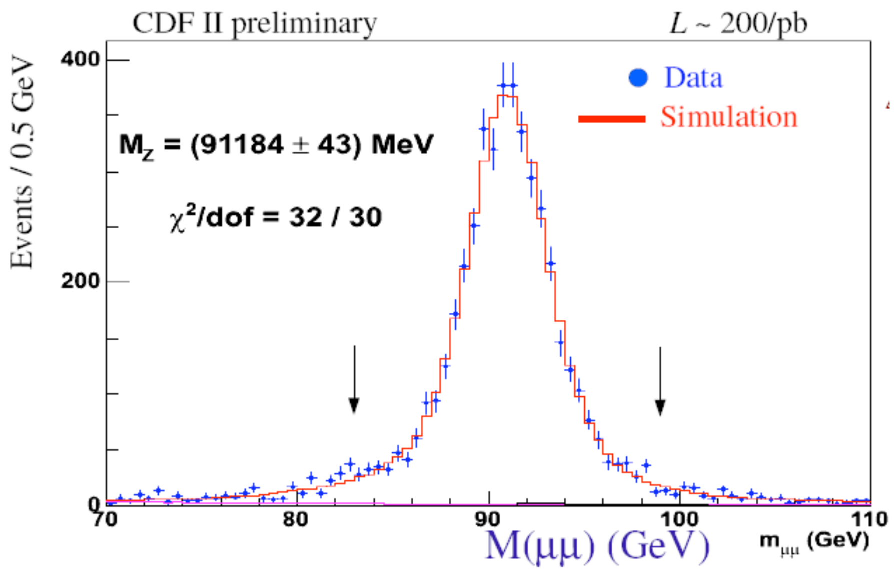


Momentum Scale Part II

- Upsilons are all produced promptly
  - Unlike J/ψ's, 20% of which are from bottom quark decays and can be up to 1 mm away from the primary vertex

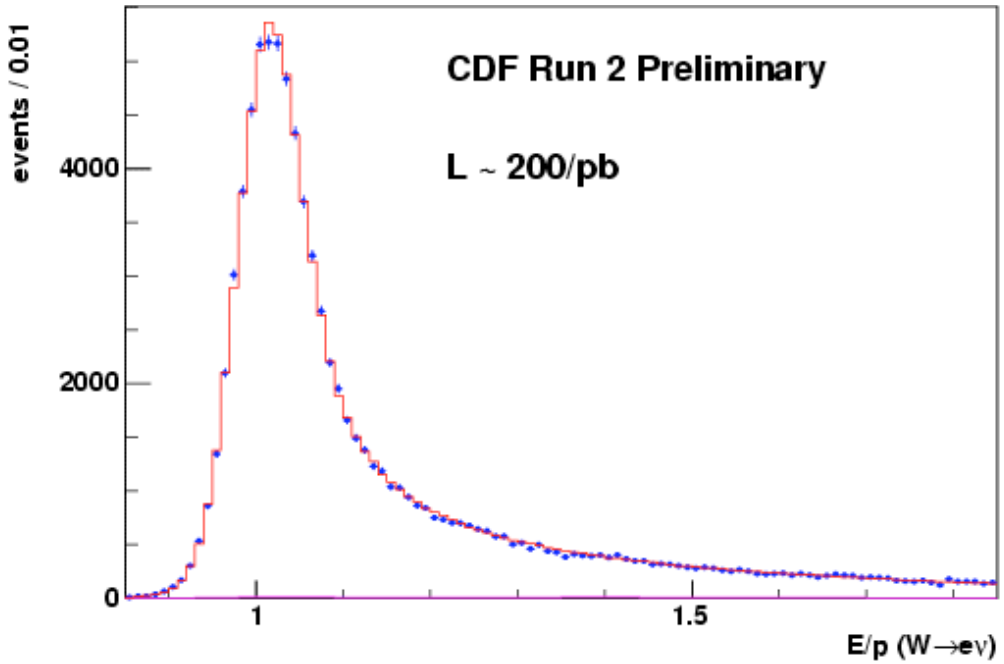
- Z's provide a final momentum scale check (which we pass)
  - Note the uncertainty – it's too large to *set* the scale. It's only a check.





Step Three: Set the Energy Scale

- Ideally, the measured energy (E) and the measured momentum (p) of an electron is the same.
  - E/p is (within resolution) equal to 1
- In a real detector, energy loss and brehmstrahlung can cause p to be lower:
  - Manifests as a tail in the E/p distribution

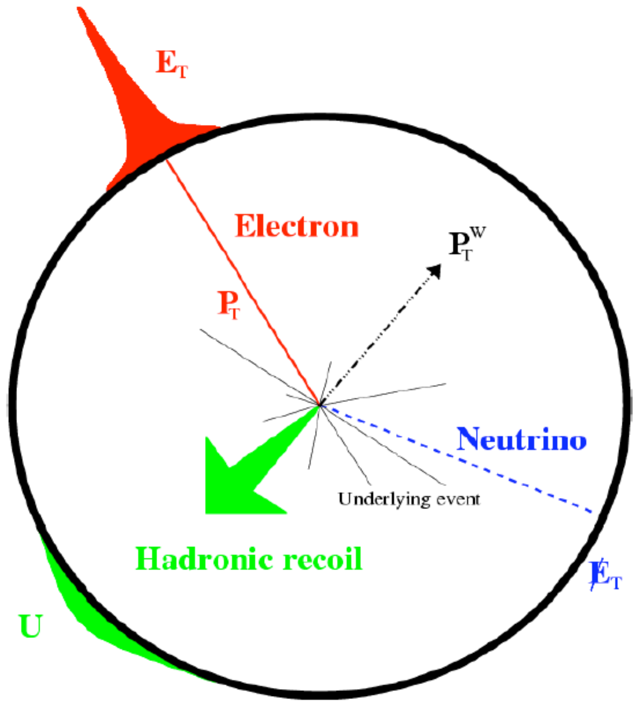


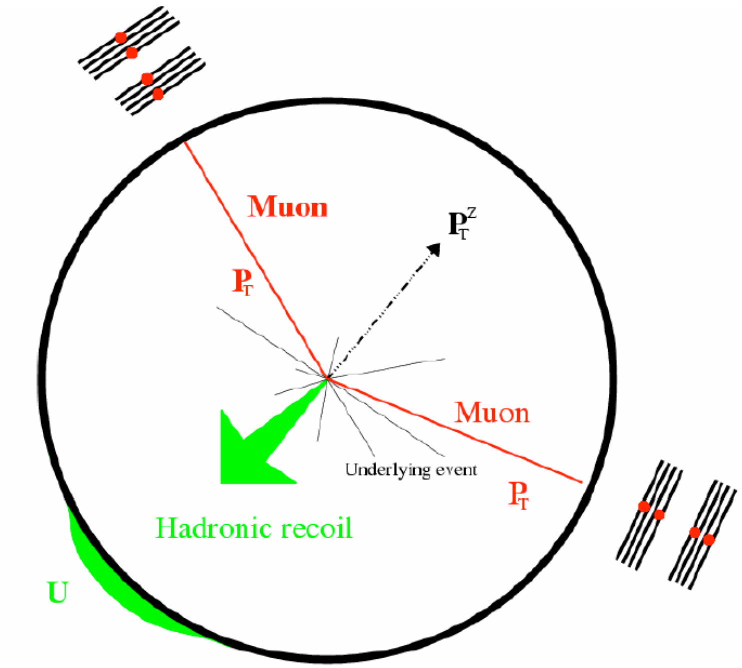
- We scale the amount of material to best fit the tail
  - Corrects for energy loss
  - Allows us to set the overall energy scale so that <E/p> = 1
  - S = 1.00000 ± 0.00025

We use the calorimeter energy (E) for the electron channel and the tracking momentum (p) for the muon channel.

Step Four: Modeling the Rest of the Event

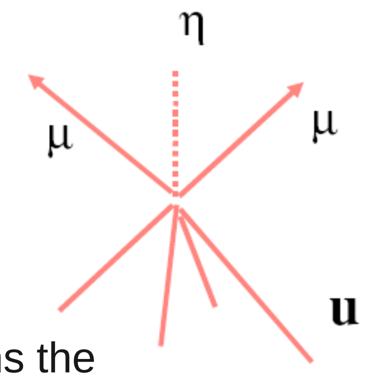
- Understanding the underlying event is critical:
  - The boost of the W affects the kinematics, and to 2nd order, the mass reconstruction
  - 2nd order may not sound like much, but we're shooting for a 0.05% measurement



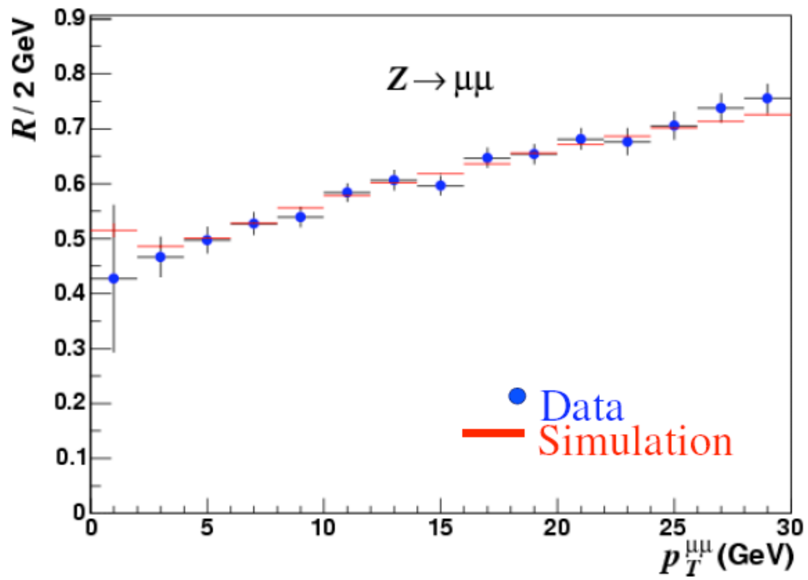


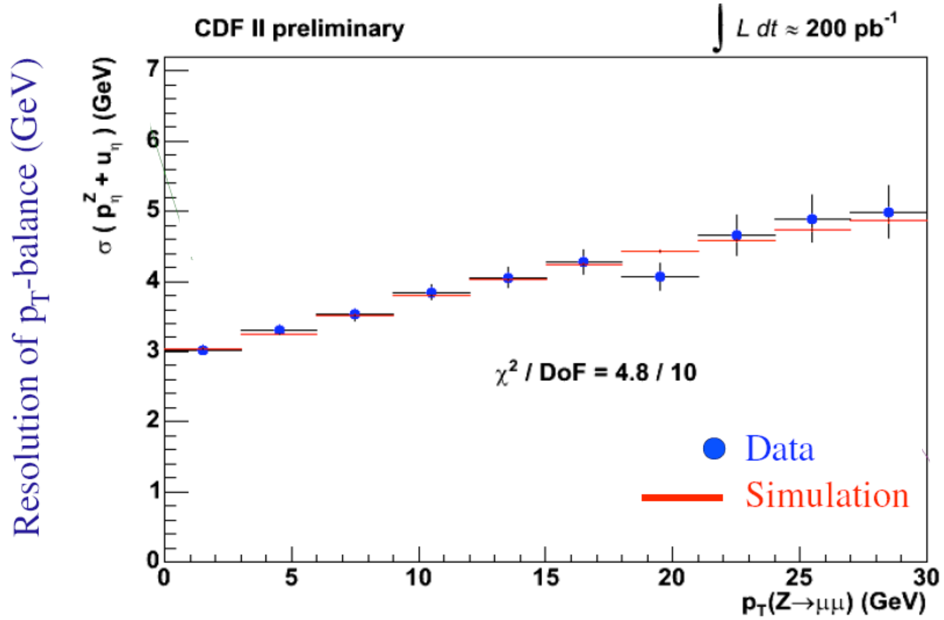
- If this were a dedicated W mass talk, ½ the talk would be on this point
- Fortunately, we can check our modeling with fully reconstructed Z's

Two (Of Many) Checks on Underlying Event Model



- Hadronic Recoil Simulation
  - Recoil "u" has two components
    - *A soft, randomly oriented one*
    - *A harder, more jet-like one*
  - R is defined as "$u_{measured}/u_{true}$"
- Recoil Resolution Modeling
  - At low p_T, this constrains the hadronic resolution due to underlying event activity
  - At high p_T, this constrains the jet energy resolution





A Word on Backgrounds

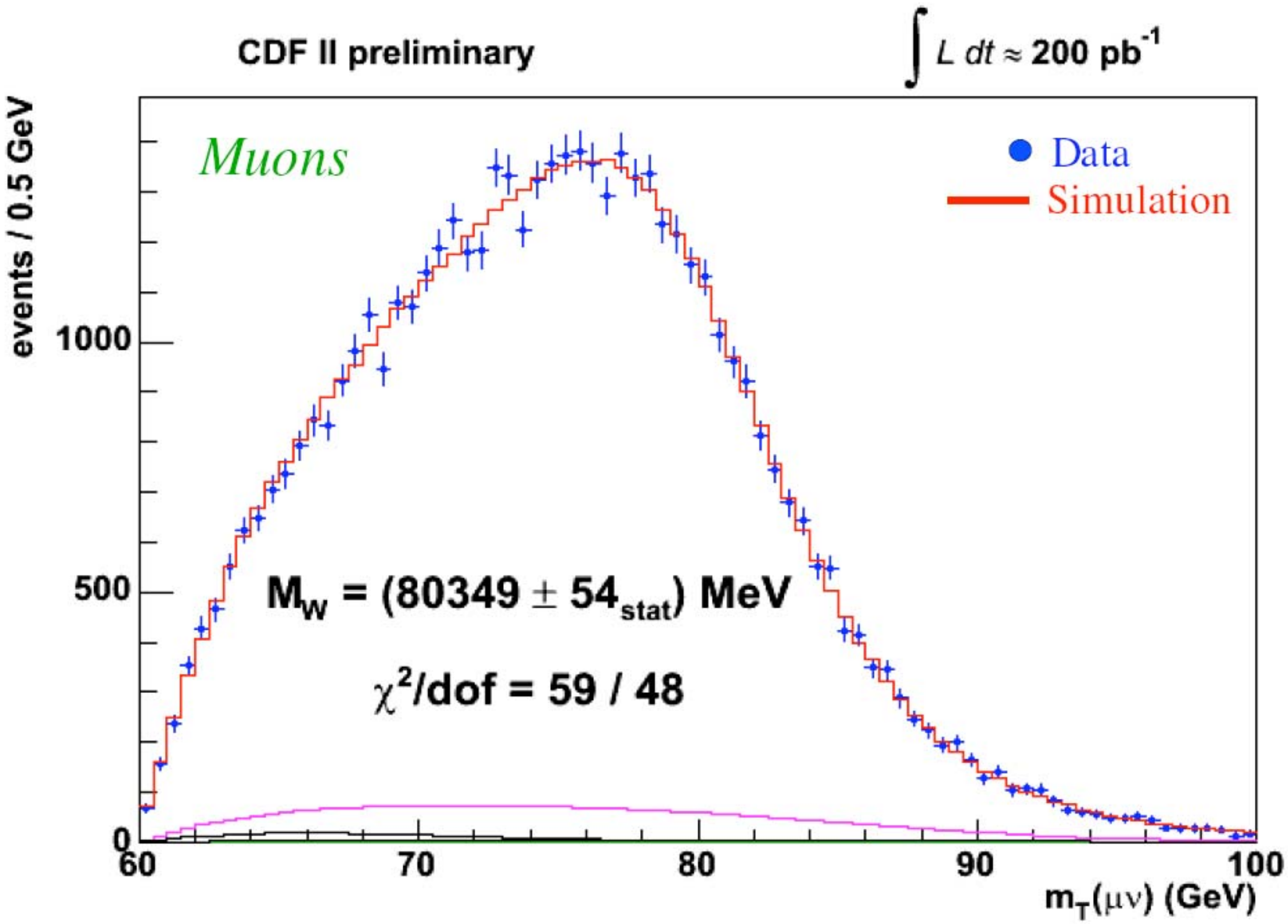
Source	Fraction ($W \rightarrow e\nu$)	Fraction ($W \rightarrow \mu\nu$)
$Z \rightarrow ll$	0.24 ± 0.04 %	6.6 ± 0.3 %
$W \rightarrow \tau\nu$	0.93 ± 0.03 %	0.89 ± 0.02 %
Jets faking a lepton	0.25 ± 0.15 %	0.1 ± 0.1 %
Decays in flight		0.3 ± 0.2 %
Cosmic Rays		0.05 ± 0.05 %

- Most of these are negligible except
  - Z decays to muons where you miss one muon
    - *Tends to drive the measured W mass too high*
  - Tau decays to electrons or muons
    - *Tends to drive the measured W mass too low*

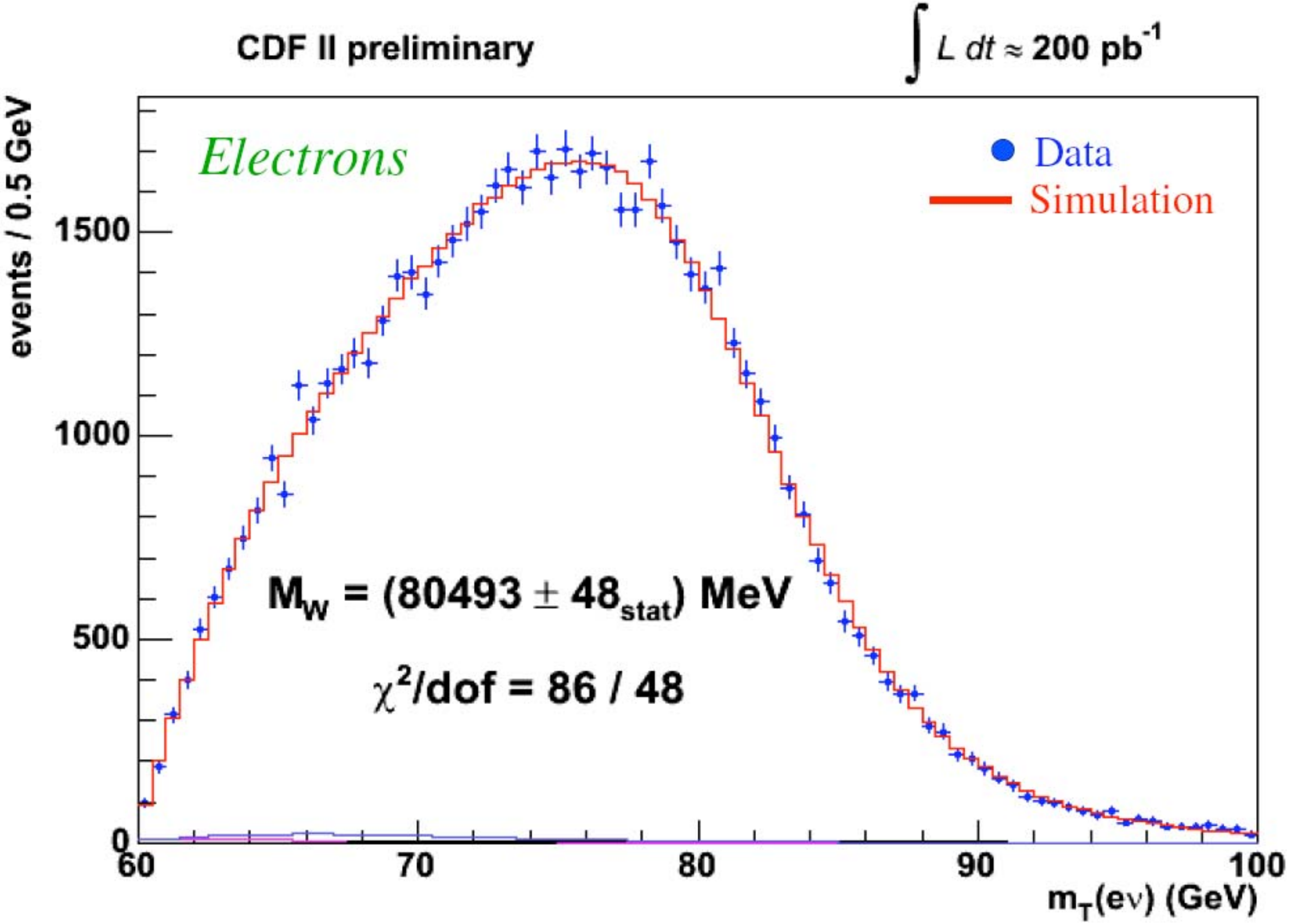
Step Five: The Final Fit

- Reminder: we fit transverse mass, lepton p_T, and missing E_T simultaneously.
  - These are not independent, but systematics affect them differently
  - Disagreements between them will naturally increase the uncertainty
- We fit electrons and muons separately
- The fit was“blind” – added a random ±100 MeV offset
  - This let us study systematics in detail, but without risking being influenced by the result
  - The last step was to remove this offset

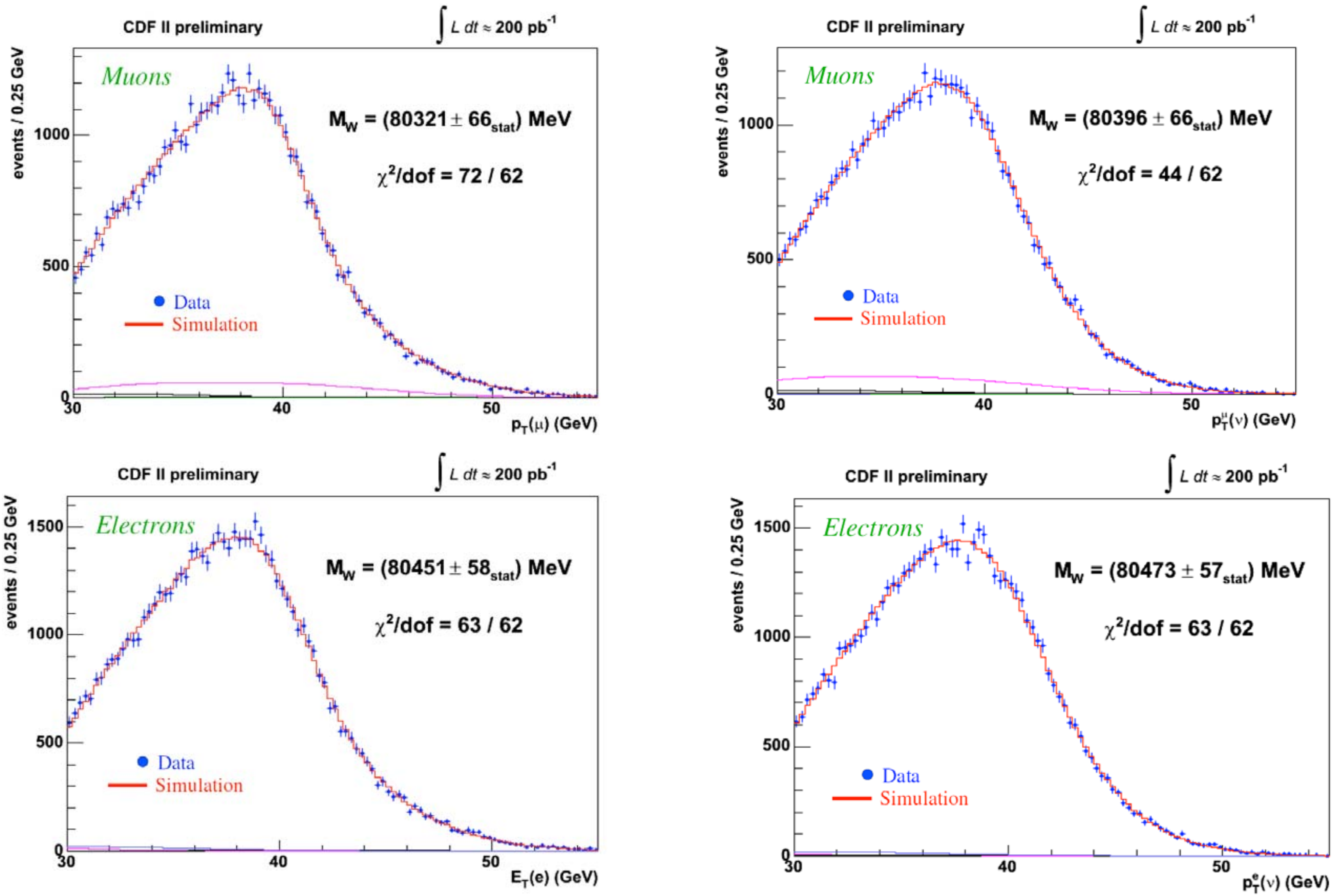
W Transverse Mass Fits



W Transverse Mass Fits



Lepton p_T and Missing E_T Fits



CDF Results: The State of the Art Today

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

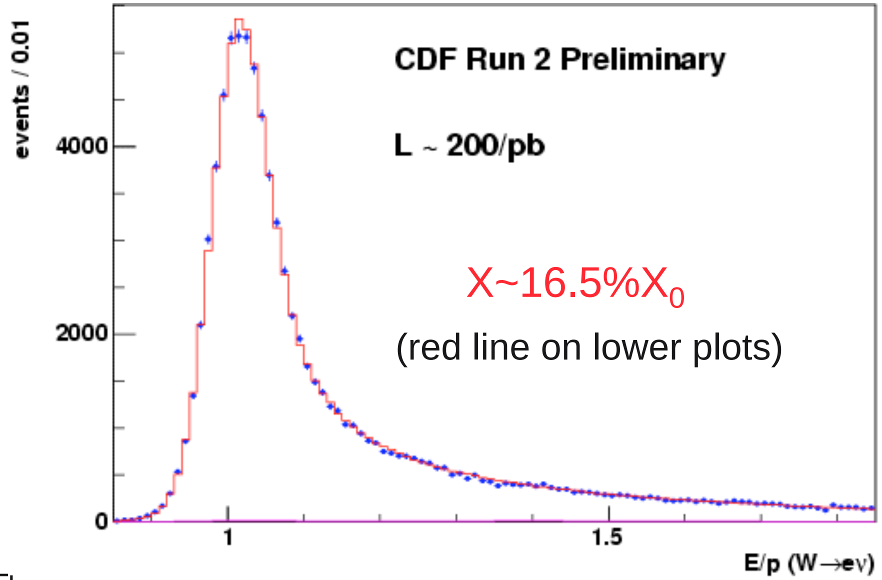
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

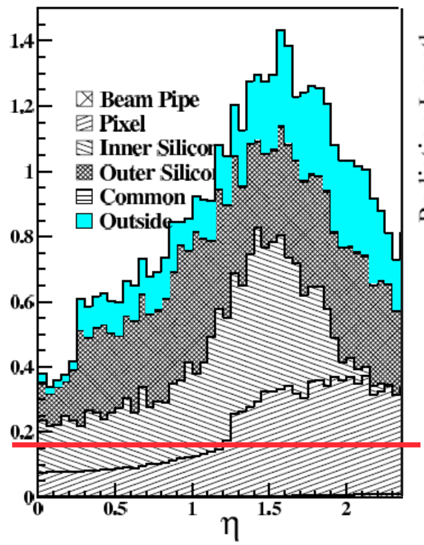
These systematics are statistically limited.

These systematics are not.

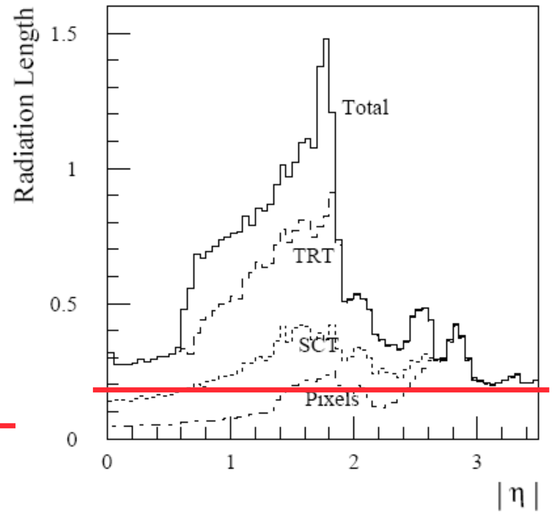
Difficulty 1: The LHC Detectors are Thicker

- 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

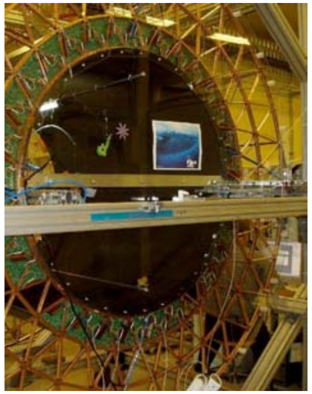




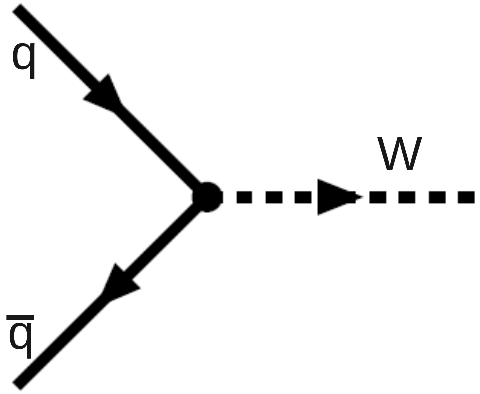
CMS material budget

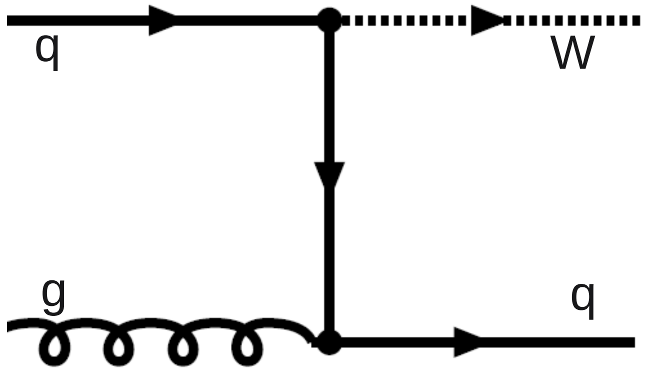


ATLAS material budget



Difficulty 2 – QCD corrections are more important





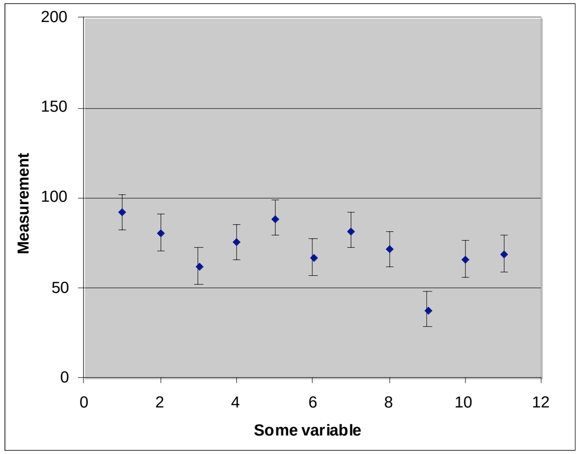
- No valence antiquarks at the LHC
  - Need sea antiquarks and/or higher order processes
- NLO contributions are larger at the LHC
- More energy is available for additional jet radiation

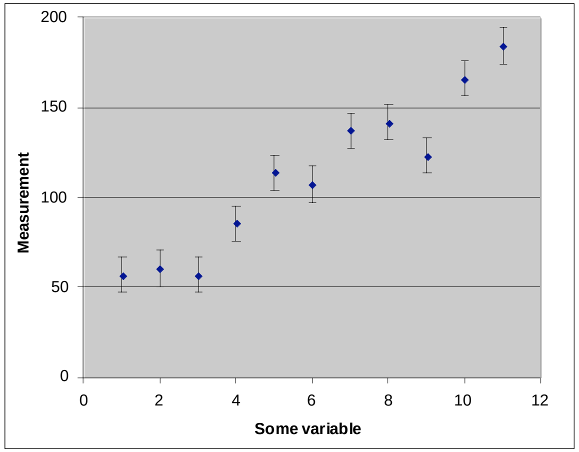
- At the Tevatron, QCD effects are already ¼ of the systematic uncertainty
  - Reminder: statistical and systematic uncertainties are comparable.
- To get to where the LHC wants to be on total m(W) uncertainty is going to require **continuous** effort on this front.

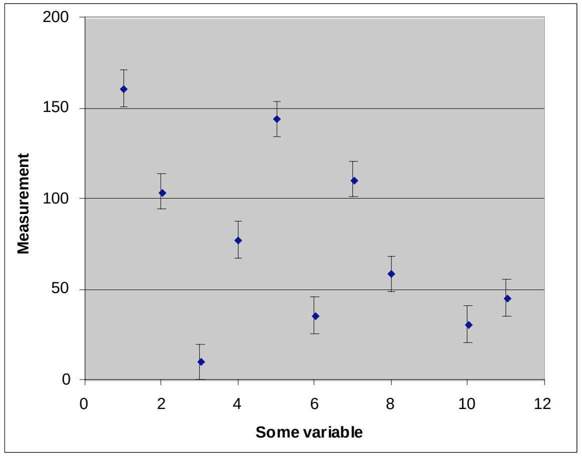
Major Advantage – the W & Z Rates are Enormous

- 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
- 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?***

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One Way Of Thinking About It

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

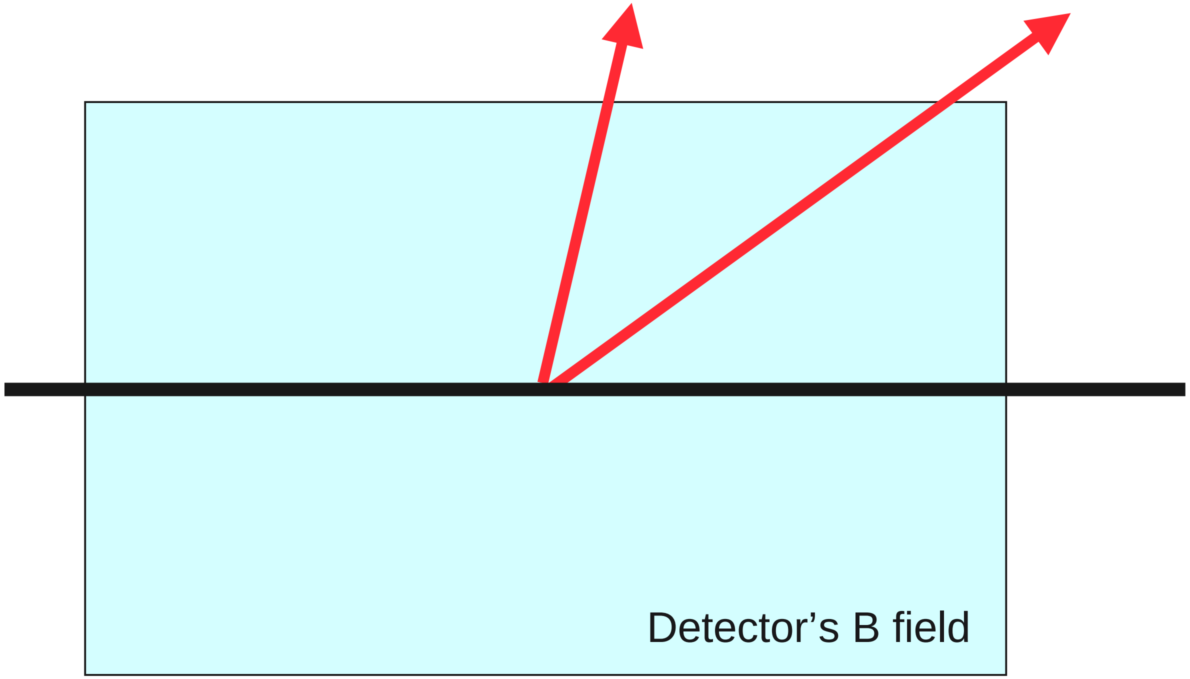
What needs to happen to get down to 5 (or 15, or 25) MeV?

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

See Besson *et al*.
arXiv:0805.2093v1 [hep-ex]

8 MeV is 100 parts per million.

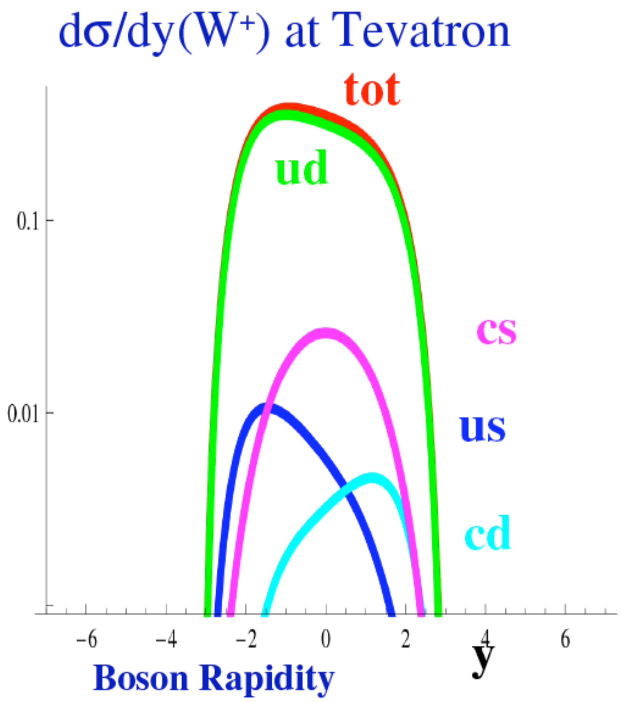
The Kind of Thing Experimenters Have To Worry About

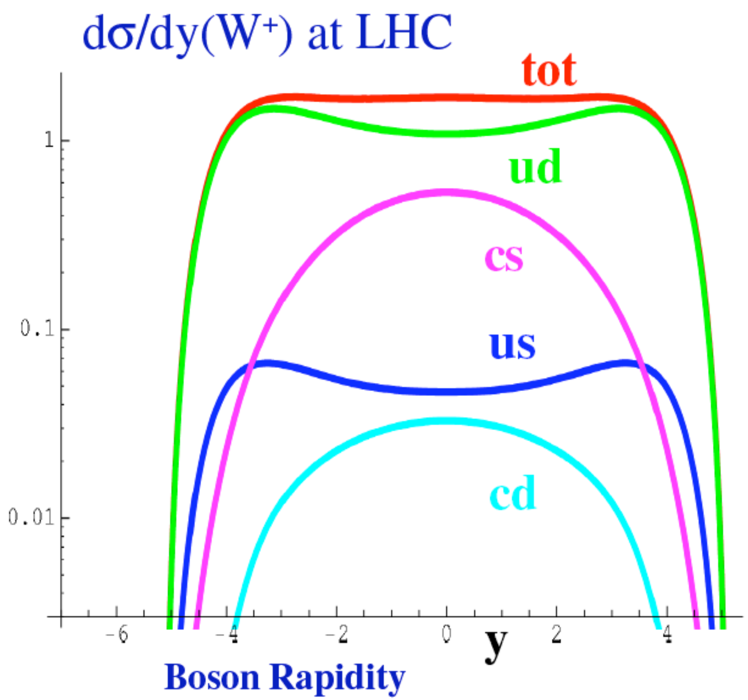


Two leptons – do they see the same field?

To 100 ppm?

One Last Slide On QCD

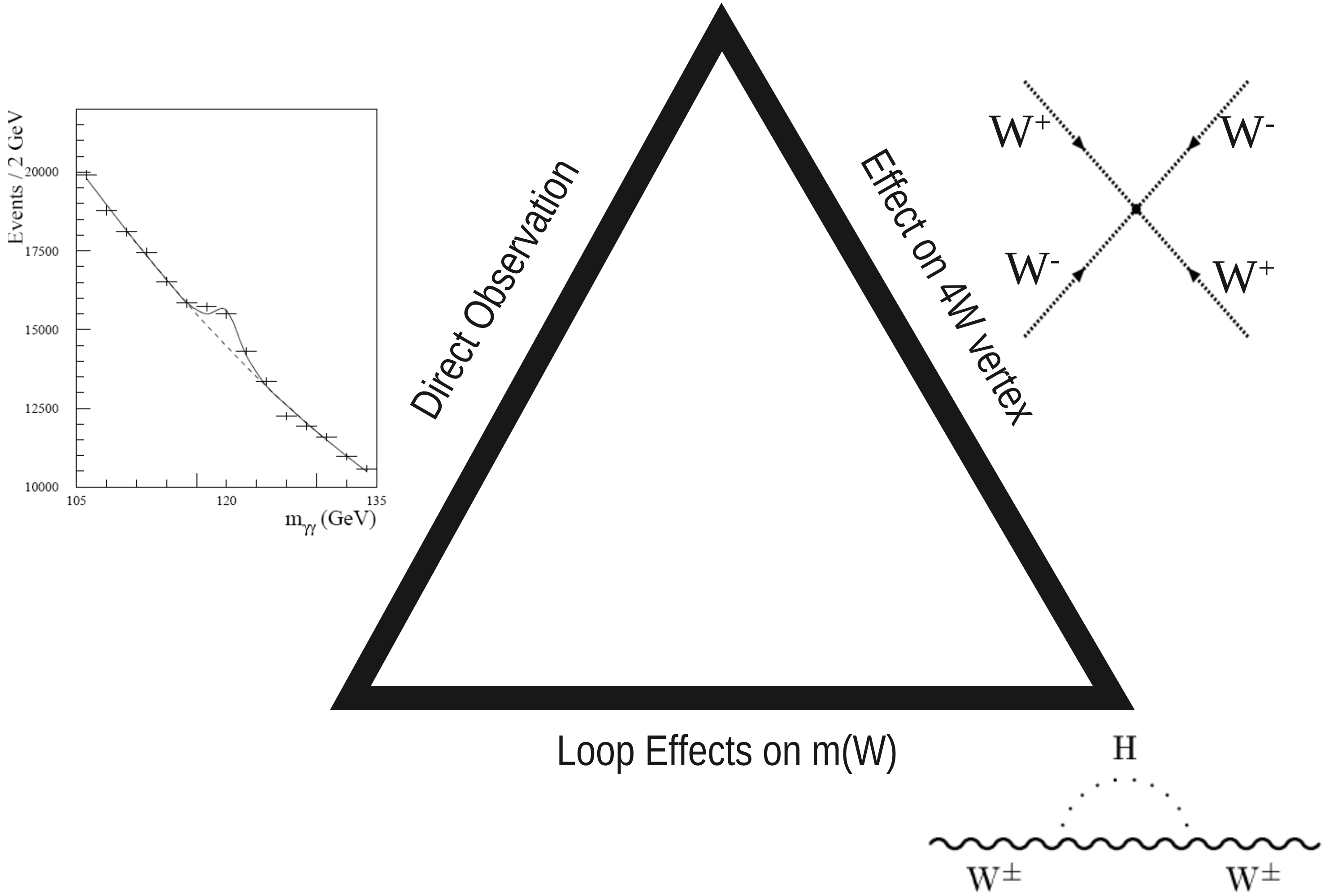




Fred Olness, SMU

- Note how much charm contributes to W production
- Unfortunately, Z production is relatively insensitive to charm
- We may need to make a number of heavy flavor QCD measurements if we want to do precision electroweak physics

Reminder: The Higgs Triangle



Summary

- Electroweak Symmetry Breaking is puzzling
  - Why is the W so heavy? Why is the weak force so weak?
- The Large Hadron Collider is in a very good position to shed light on this
  - The “no lose theorem” means *something* has to happen. Maybe it’s a Higgs, maybe it’s not.
  - Finding the Higgs is not enough. Precision electroweak measurements are needed to understand what’s going on.
    - *Multiple boson production*
    - *Mass of the W boson*
- The LHC has both advantages (energy, event rates) and disadvantages (event complexity) over previous experiments.
  - Life may not be simple, but it will surely be exciting!

Thanks for inviting me!

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The LHC: Ready or Not, Here It Comes