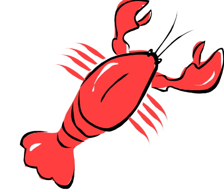
POSTCARDS FROM THE ENERGY FRONTIER

BATAVIA, ILL.

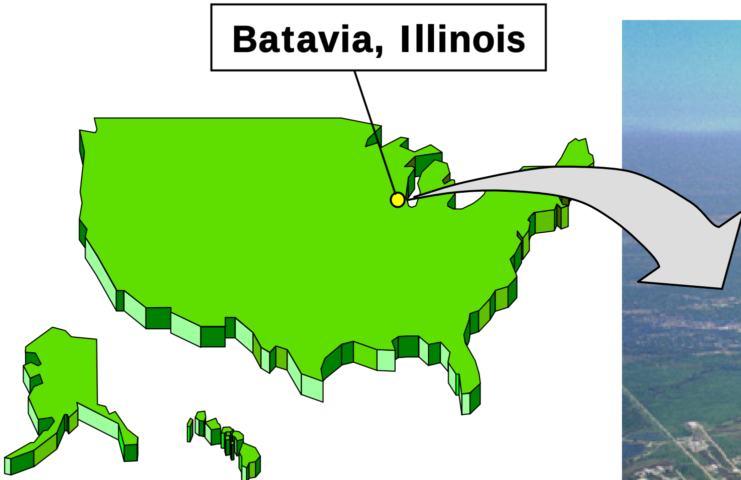
Tevatron – Part Deux

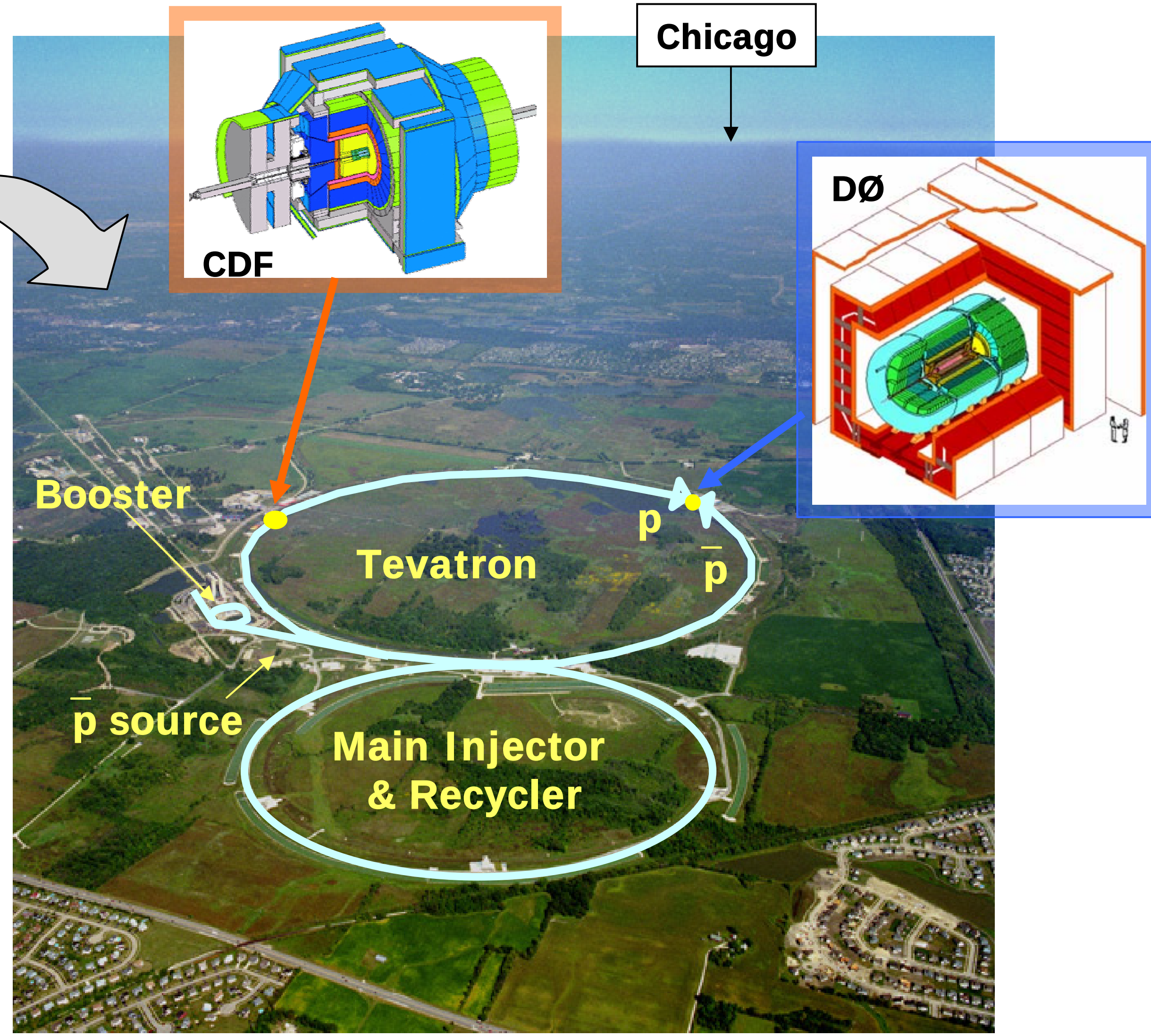
John M. Butler

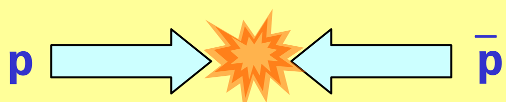
Boston University



Fermilab





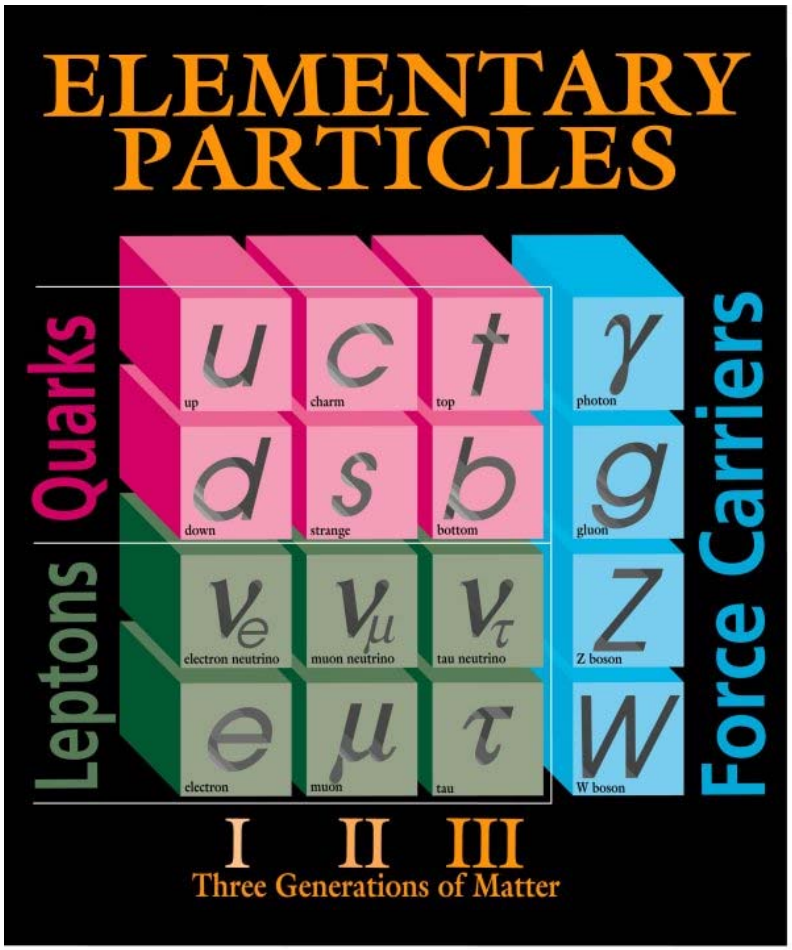


$\sqrt{s}$ = 1.96 TeV
Δt = 396 ns

Run I 1992-96
Run II 2001-09

50 × larger dataset at increased energy

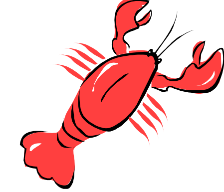
Motivation



Fermilab 95-759

- ❖ The Standard Model of particle physics is a highly successful description of Nature
- ❖ Aesthetically appealing in its elegance and simplicity
- ❖ No measurement is in significant disagreement with the SM
- ❖ Nobody believes it is the whole story

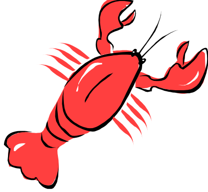
“The analysis finally agrees with the SM, let’s publish…”



- Not our job to validate the Standard Model (SM) but to find out how nature works. Much more fun to make the discovery that breaks the SM!
- The Tevatron confronts the SM with a rich* program of physics
- Measurements from a broad range of topics
  - Top quark properties
  - Strong interaction – QCD
  - CKM or “Heavy Flavor” – b and c quark studies
  - Electroweak (EW) physics
  - Searches for the Higgs boson
- Actively pursuing signs of new physics beyond the SM
  - Mechanism of EWSB – SUSY or technicolor or little Higgs or …?
  - Large extra dimensions
  - Leptoquarks
  - Excited leptons, monopoles, …
  - “Who ordered that?”

*Beware! When physicists say “rich” they often mean “vastly complicated” or “really hard” or “impossible to get a sensible result”

Abundance of Physics at 2 TeV

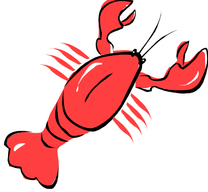


Abstracts Submitted to ICHEP'04

	Abstract Title	Session	EB
B Physics (10)			
Pub*	Measurement of B hadron lifetimes using final states containing J/ψ	CP violation and CKM	EB027
Pub	B hadron lifetime ratios in semileptonic mode	CP violation and CKM	EB006
	A study of Bd oscillations	CP violation and CKM	EB017
	Search for Bs oscillations	CP violation and CKM	EB017
Pub	X(3872) state	Hadron spectroscopy and exotics	EB007
	Upsilon (1S) bottomonium production	Heavy quark mesons and baryons	EB007
	Observation of L=1 B_J* states at the DØ experiment	Heavy quark mesons and baryons	EB028
	Observation of semileptonic B decays into orbitally excited D final states	Heavy quark mesons and baryons	EB023
	A study of the B_c meson	Heavy quark mesons and baryons	EB028
Pub*	A study of rare B meson decays using the DØ detector	Beyond standard model	EB023
Electroweak (5)			
Pub	Measurement of the W and Z production cross sections times the leptonic branching ratios…	Electroweak	EB003
	Measurement of the width of the W boson at the Fermilab Tevatron	Electroweak	EB026
	Measurement of the forward-backward charge asymmetry in Drell-Yan events	Electroweak	EB021
Pub*	Measurements of the production of photons in association with a W or a Z boson…	Electroweak	EB016
Pub	Associated production of W and Z bosons	Electroweak	EB003
Higgs (9)			
Pub*	Measurement of the Wbb production cross section and search for the Higgs in WH…	Electroweak	EB004
Pub	Search for Higgs decays to WW at DØ	Electroweak	EB005
	Measurement of the W-pair production cross section at DØ	Electroweak	EB005
	Search for technicolor particle at DØ	Beyond standard model	EB029
	Search for Fermiophobic and topcolor Higgs in the diphoton final states at DØ	Beyond standard model	EB013
Pub	Search for doubly charged Higgs pair production in the muon decay channel at DØ	Beyond standard model	EB005
Pub*	Z+j production cross section and cross section ratios of Z+b/Z+j at DØ	Electroweak	EB004/5
	Search for Z to bbar decay at DØ	Electroweak	EB018
	A search for neutral Higgs bosons at high tanβ with the DØ Detector	Beyond standard model	EB018
New Phenomena (10)			
Pub*	Searches for first and second generation leptoquarks	Beyond standard model	EB015
	Search for anomalous heavy-flavor jet production in association with W bosons	Beyond standard model	EB029
	Search for heavy stable charged particles	Beyond standard model	EB020
	Search for RPV SUSY in multilepton final states	Beyond standard model	EB014
	Search for the associated production of charginos/neutralinos in the final states with three leptons	Beyond standard model	EB014
Pub	Search for GMSB SUSY in diphoton events with large missing ET	Beyond standard model	EB013
	Search for heavy dilepton resonances with the DØ detector	Beyond standard model	EB012
	Search for large extra spatial dimensions in jets + missing ET topologies	Beyond standard model	EB019
	Search for squarks and gluinos in the jets + missing ET topology	Beyond standard model	EB019
Pub	Search for extra dimensions in the dilepton and diphoton channels	Beyond standard model	EB012

Last Updated on 5/28/2004 *Jianming Qian*

…and more and more…



Abstracts Submitted to ICHEP'04

Quantum Chromodynamics (8)

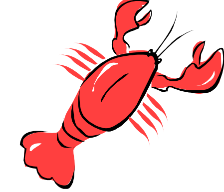
Pub	Measurement of dijet azimuthal decorrelations at central rapidities at DØ Run II	QCD hard interactions	EB002
	Measurement of the elastic slope with the DØ Detector in Run II	QCD soft interactions	EB001
	Diffractive Z measurement at DØ Run II	QCD soft interactions	EB001
	Forward proton detector status and diffractive jet production at DØ Run II	QCD soft interactions	EB001
Pub	Measurement of the inclusive jet cross section by the DØ Collaboration in Run II	QCD hard interactions	EB002
Pub	Measurement of the dijet cross section using the DØ detector in Run II	QCD hard interactions	EB002
	Measurement of the inclusive b-jet cross section using the DØ detector in Run II	QCD hard interactions	EB025
	Measurement of the dijet angular distribution using the DØ detector in Run II	QCD hard interactions	EB002

Top Physics (7)

Pub*	Measurement of the top quark pair production cross section in l+jets and ll+jets final state	QCD hard interactions	EB008/9
Pub	Measurement of the top quark pair production cross section with lifetime b tagging at DØ	QCD hard interactions	EB030
	Search for single top quark production at DØ	Electroweak	EB024
	Measurement of the top quark mass in lepton+jets channel at DØ	Electroweak	EB011
	Measurement of the top quark mass in dilepton+jets channel at DØ	Electroweak	EB011
	Measurement of the W boson helicity in top quark decays at DØ	Electroweak	EB022
	Measurement of $Br(t\to Wb)/Br(t\to Wq)$ at DØ	Electroweak	EB022

Note *: the abstract in question combines several analyses, aiming to publish a subset
Yellow indicates the existence of preliminary results while blue is for those submitted for publication.

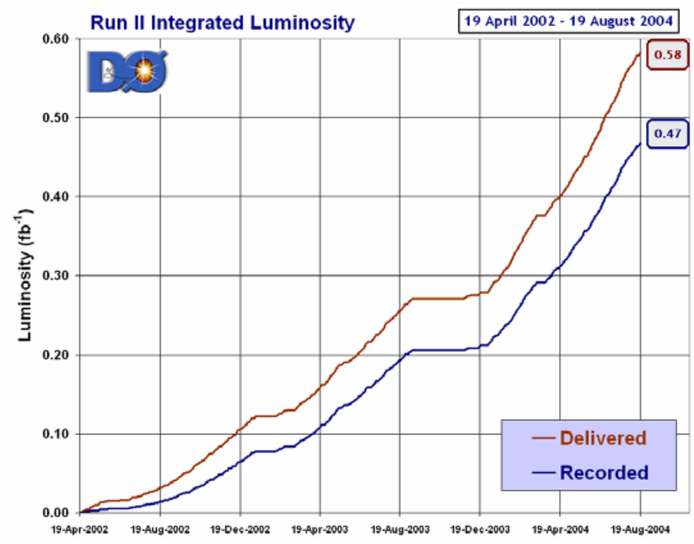
Approach for this talk



- No attempt to give a comprehensive review of latest results from CDF and DØ
- Rather, I'll present some representative measurements from the main physics areas studied at the Tevatron
  - What the data looks like and what you can do with it
- Physics Topics – my own idiosyncratic selections
  - Top quark properties – see Darien Wood's talk from Monday
  - QCD: inclusive jet cross section
  - Heavy flavor: B_s and Λ_b
  - Electroweak: W mass
  - Searches for the Higgs boson
  - Searches for new physics
    - SUSY in trileptons
    - The virtues of recycling - dileptons

Some Obvious Observations

- High energy and luminosity are good, higher is better
  - Energy Frontier: high E allows to probe shortest distance scales and directly produce new heavy states of matter
  - High L allows to observe rare processes with small cross sections
- Corollary - when LHC is running, the Tevatron is toast
- Corollary – lots of data is good, more is better
  - Now measuring integrated L in fb^{-1}
- Hadron machines are quickest, path to high E and L
  - “Discovery Machines” that also can make precision measurements
  - Dirty environment or “rich” environment?



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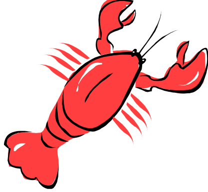
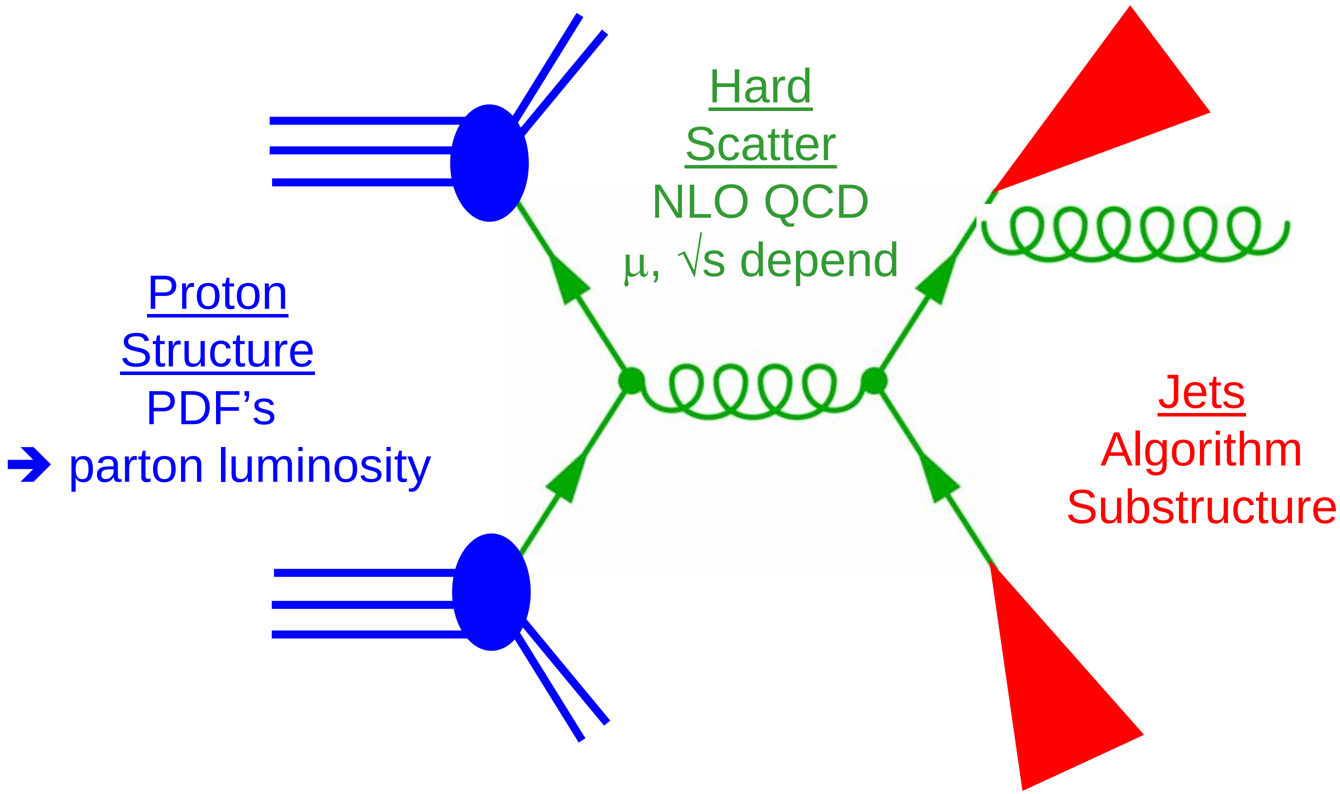


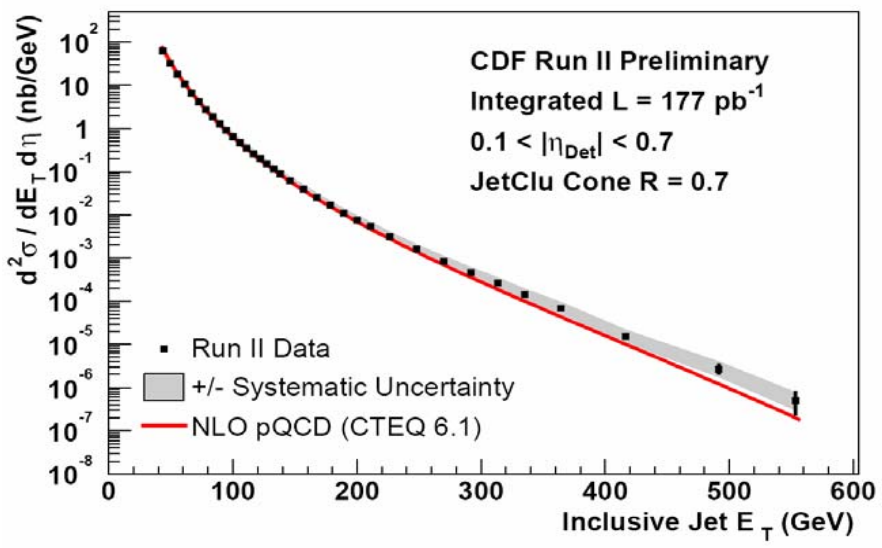
QCD

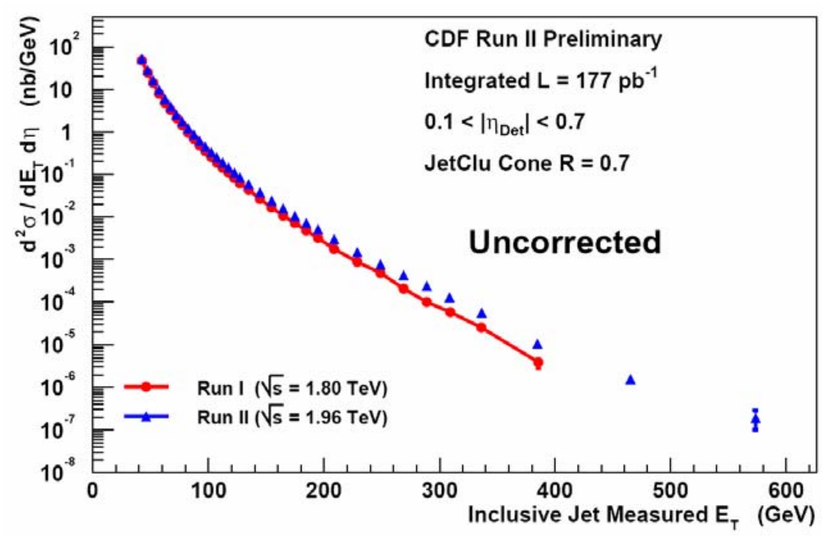
Studying Strong Interactions at the Tevatron

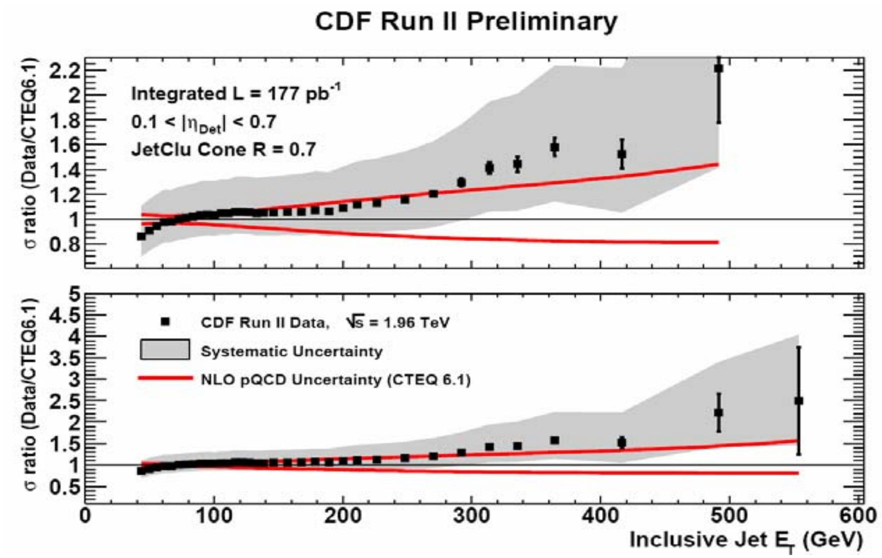


Inclusive Jets

- Inclusive jet production tests pQCD and structure of the proton through the Parton Distribution Functions (PDFs)
- Highest $E_T = E \sin\theta$ jets probe distance scale of order 10^{-19} m
- Sensitive to new physics, e.g. quark compositeness

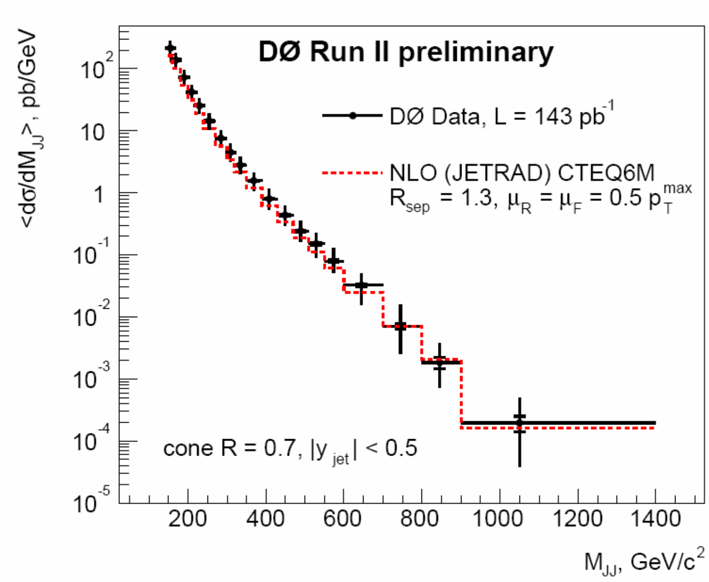


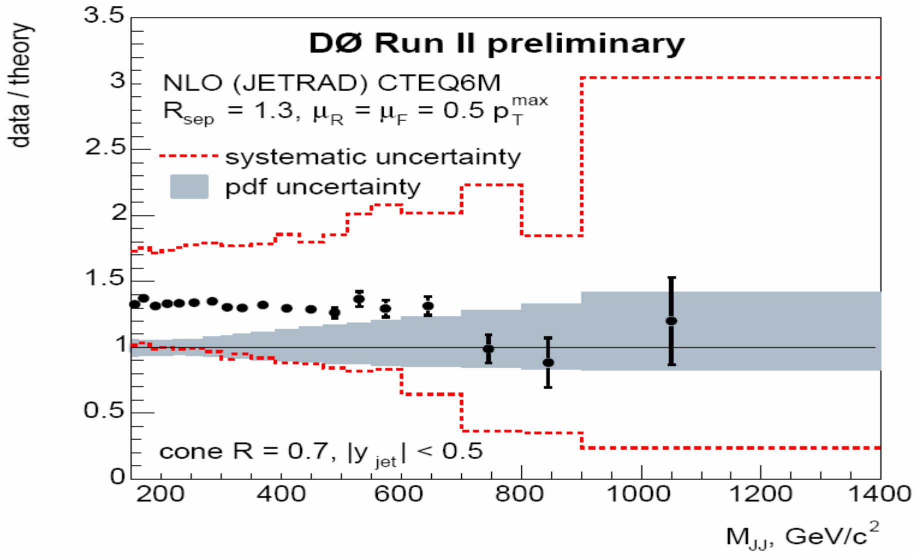




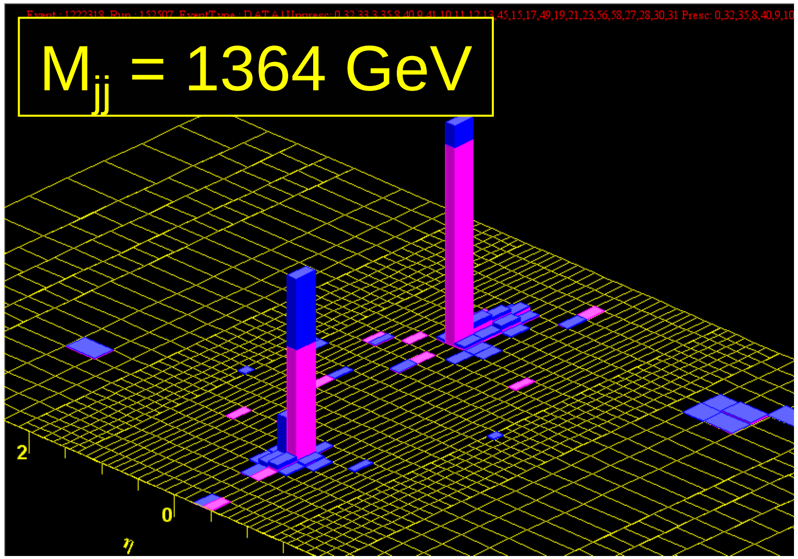
Inclusive Dijets

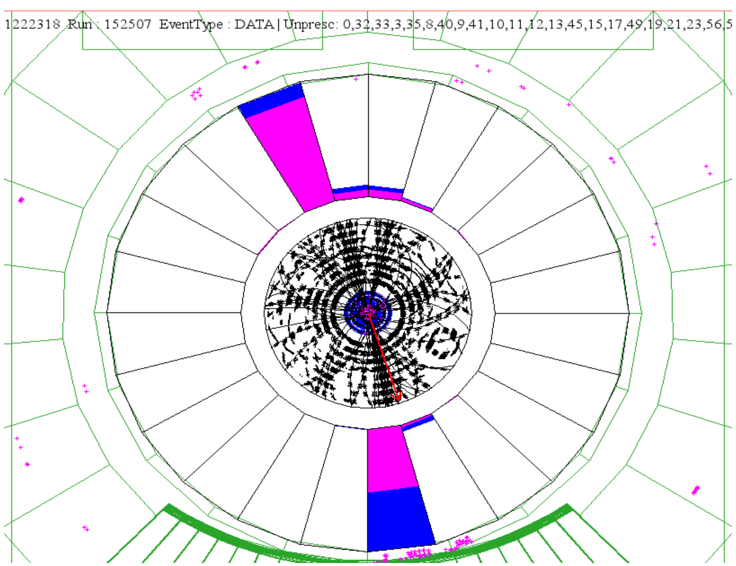
- Again sensitive probe of PDFs
- Look for excess or "bump hunting" at high M_{jj}
  - Very hard to see W,Z → jj
- Energy scale systematic uncertainty dominates the experimental error
  - Careful! A case where the errors are nearly 100% correlated point-to-point
  - Requires a detailed understanding of your detector

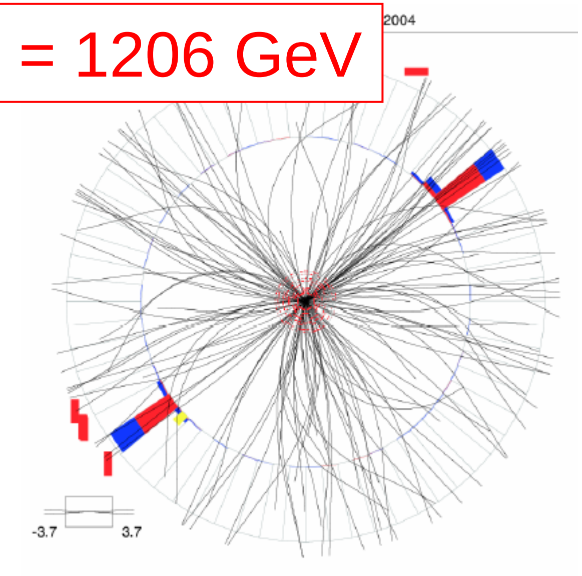




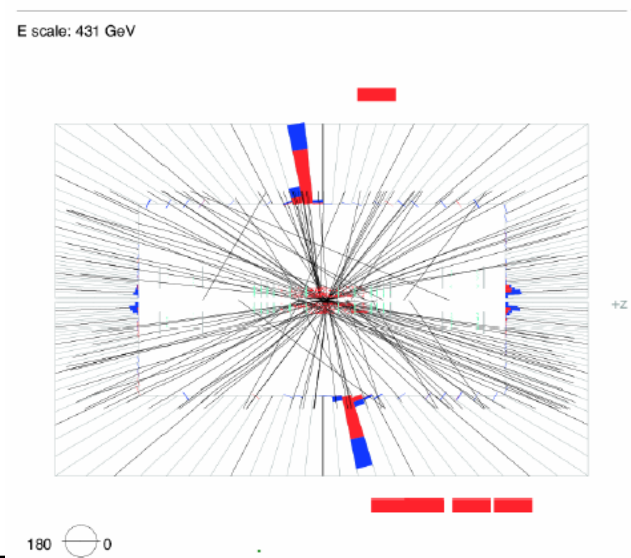
Highest ET Events



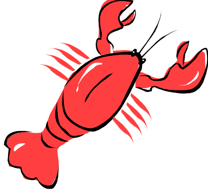




x-y view

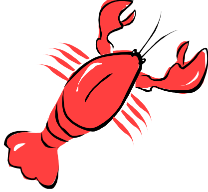


r-z view



Heavy Flavor

B Physics at the Tevatron



- Complementary to the e^+e^- B Factories (Dallapiccola & Morii – Friday)
- Hadron colliders have some advantages…
  - *Lots* of b quarks produced $\sigma(b\bar{b}) \sim 100\ \mu b$
    - 10,000 Hz @ $L = 10^{32}$
    - More b's than tape
  - All species produced B_u, B_d, B_s, B_c, Λ_b, …
- …and some disadvantages
  - $\sigma(b\bar{b}) \ll \sigma(p\bar{p})$ ➔ must trigger on b's
  - "Rich" environment
  - Limits the final states that are accessible for study
- Topics include
  - Masses
  - Lifetimes
  - Oscillations
  - CP violation
  - Rare decays

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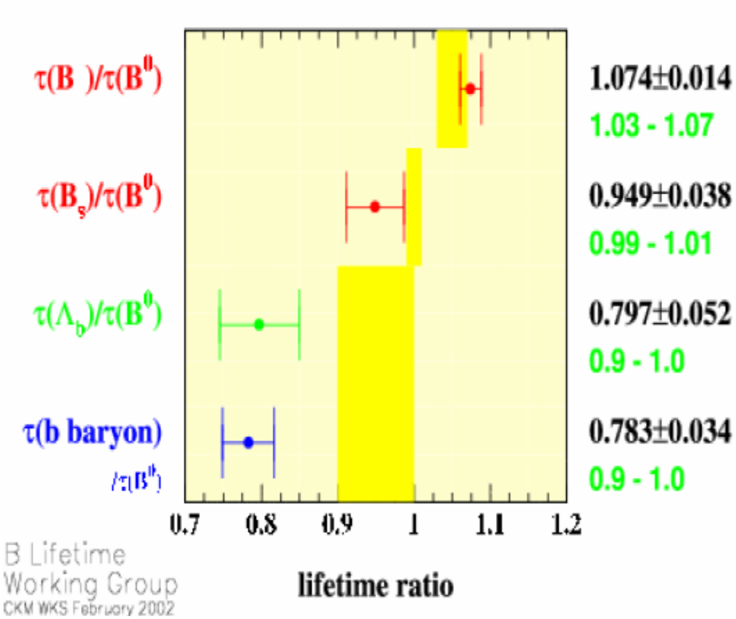
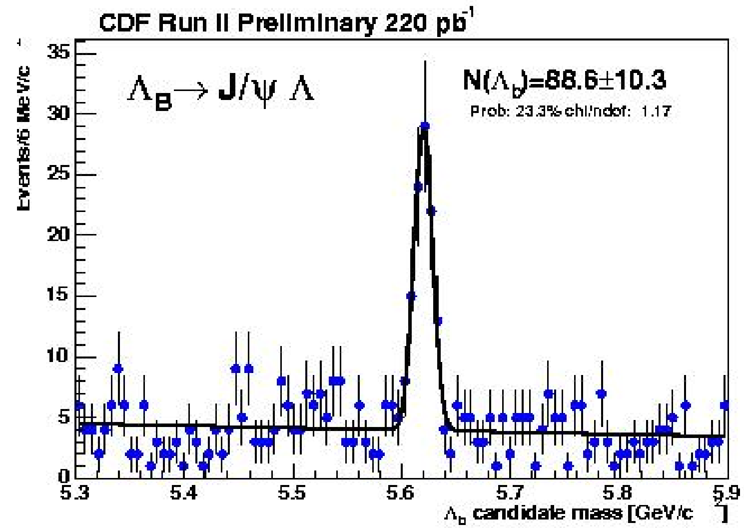
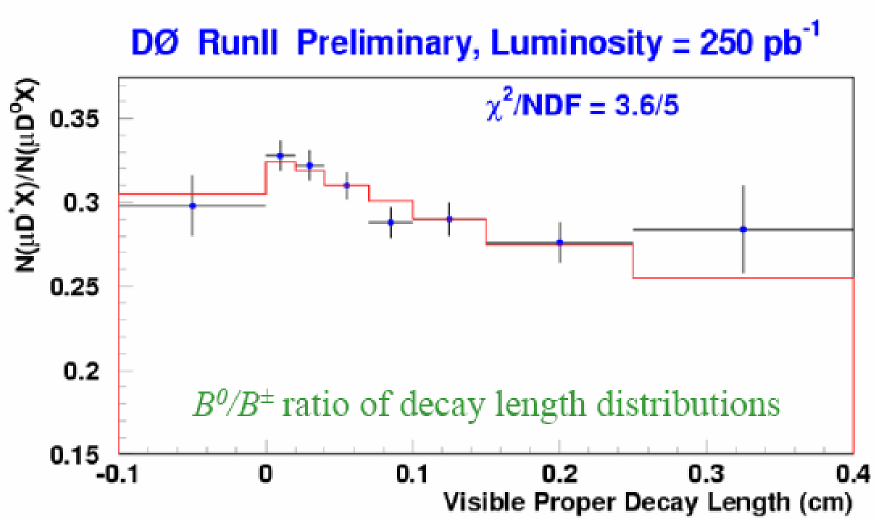
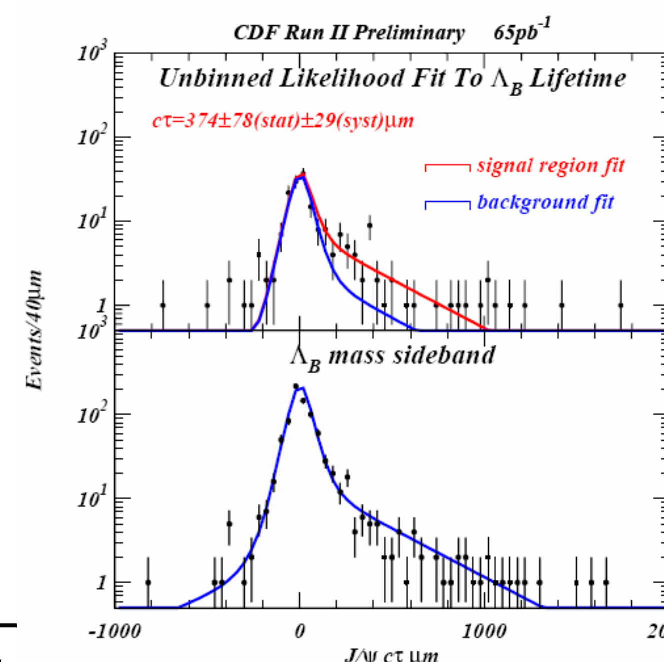
Masses and Lifetimes

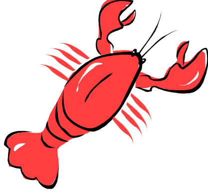


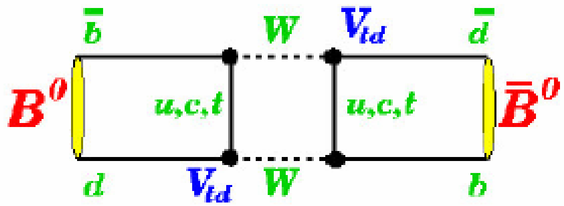




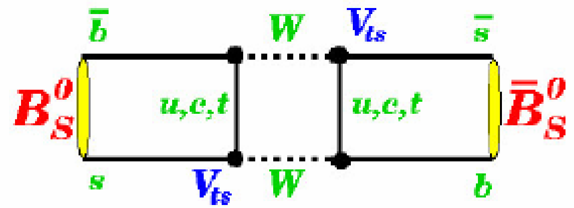


B_s Oscillations

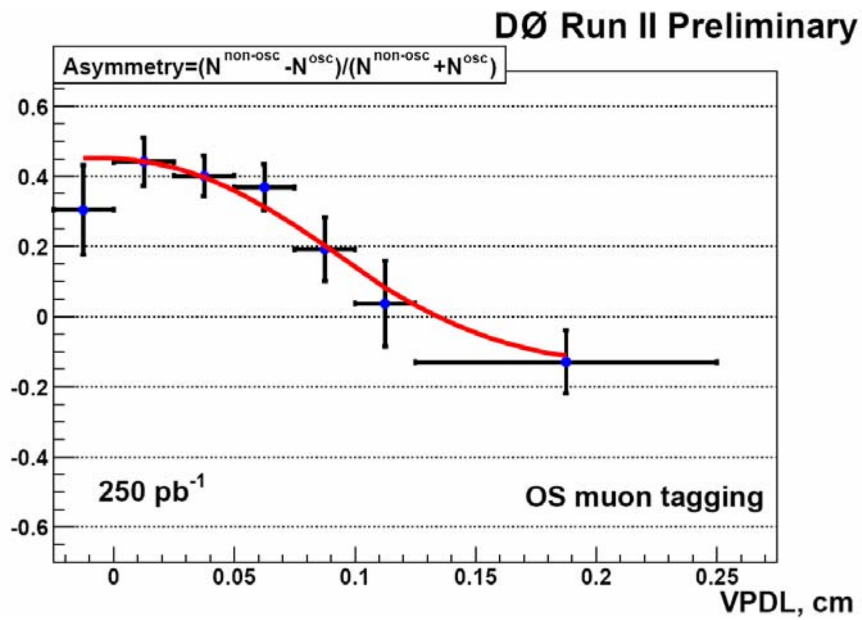


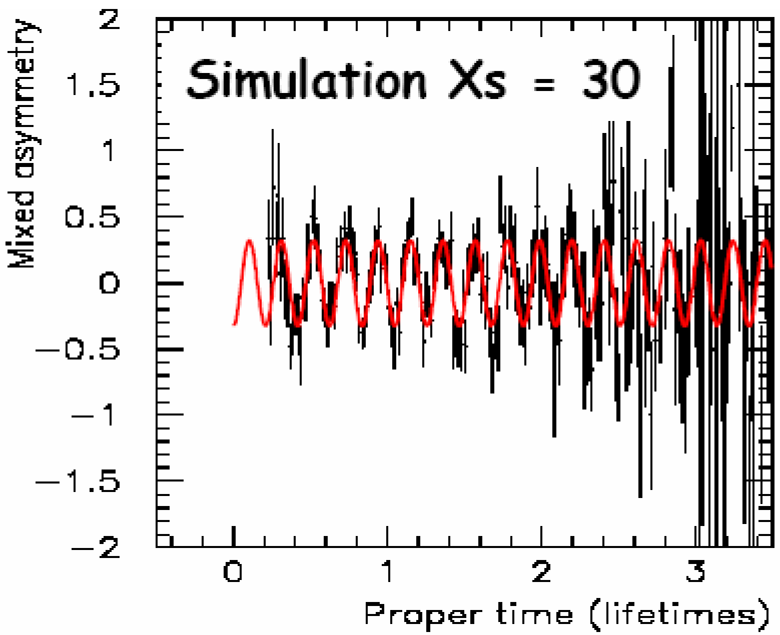


VS



$\Rightarrow$ B_s oscillates >25 times faster than B_d





B_d mixing is Tevatron proof of principle

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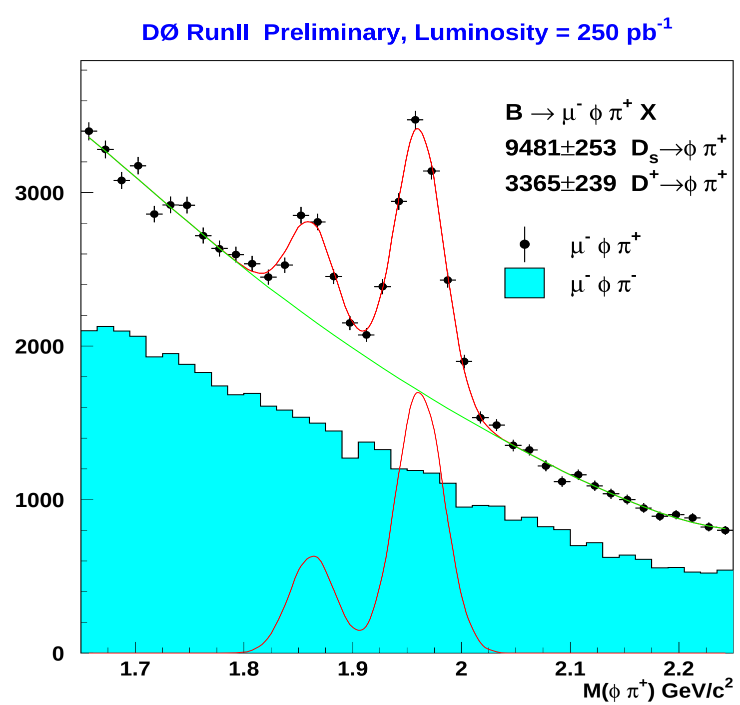
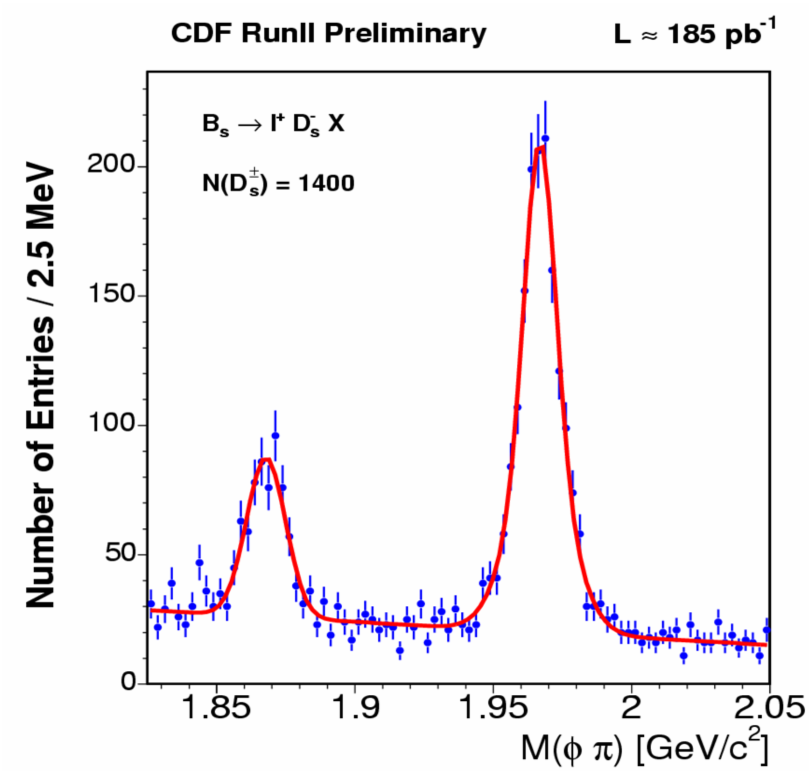
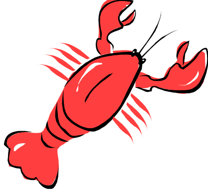
$B_s \to \mu\nu D_s(\to\phi\pi)$

Pro: easy to trigger on
Con: neutrino in final state
Nice illustration of different detector strengths







Electroweak

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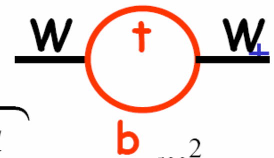
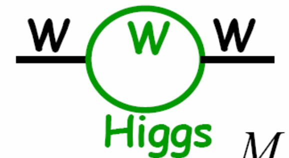
Measuring the W Mass

- M_W is a fundamental parameter of the standard model
- Depends on the top quark and Higgs masses through loop effects

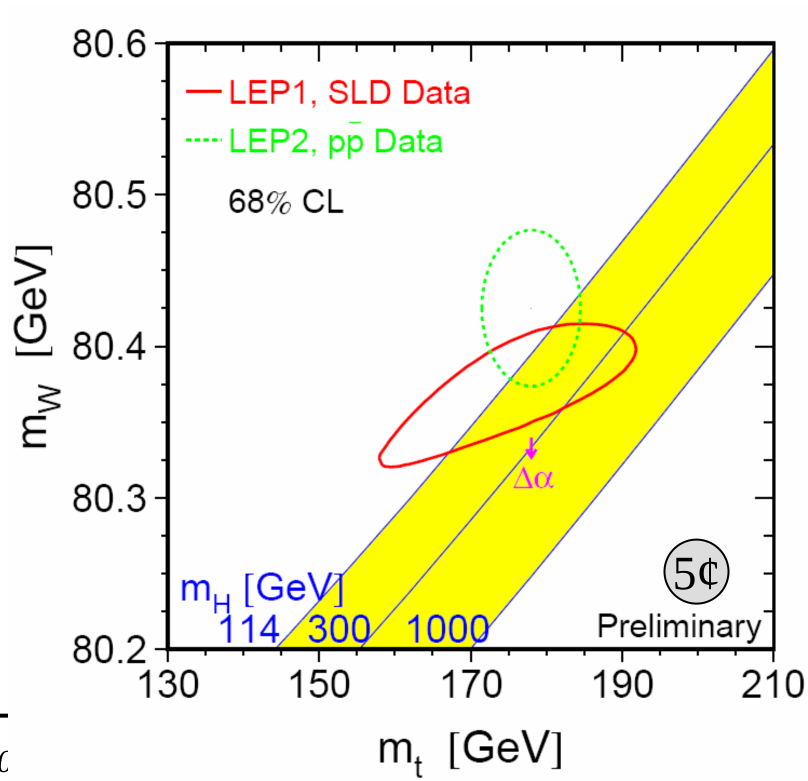
$$M_W = \underbrace{M_{tree}}_{M_Z,\ \alpha_{EM},\ G_F} +$$



$\propto \frac{m_t^2}{M_W^2}$



$\propto \ln \frac{M_H}{M_W}$



Run I data favor a low Higgs mass

Run II can indirectly determine $\delta M_H/M_H$ to 35% if δm_t = 3 GeV and δM_W = 40 MeV

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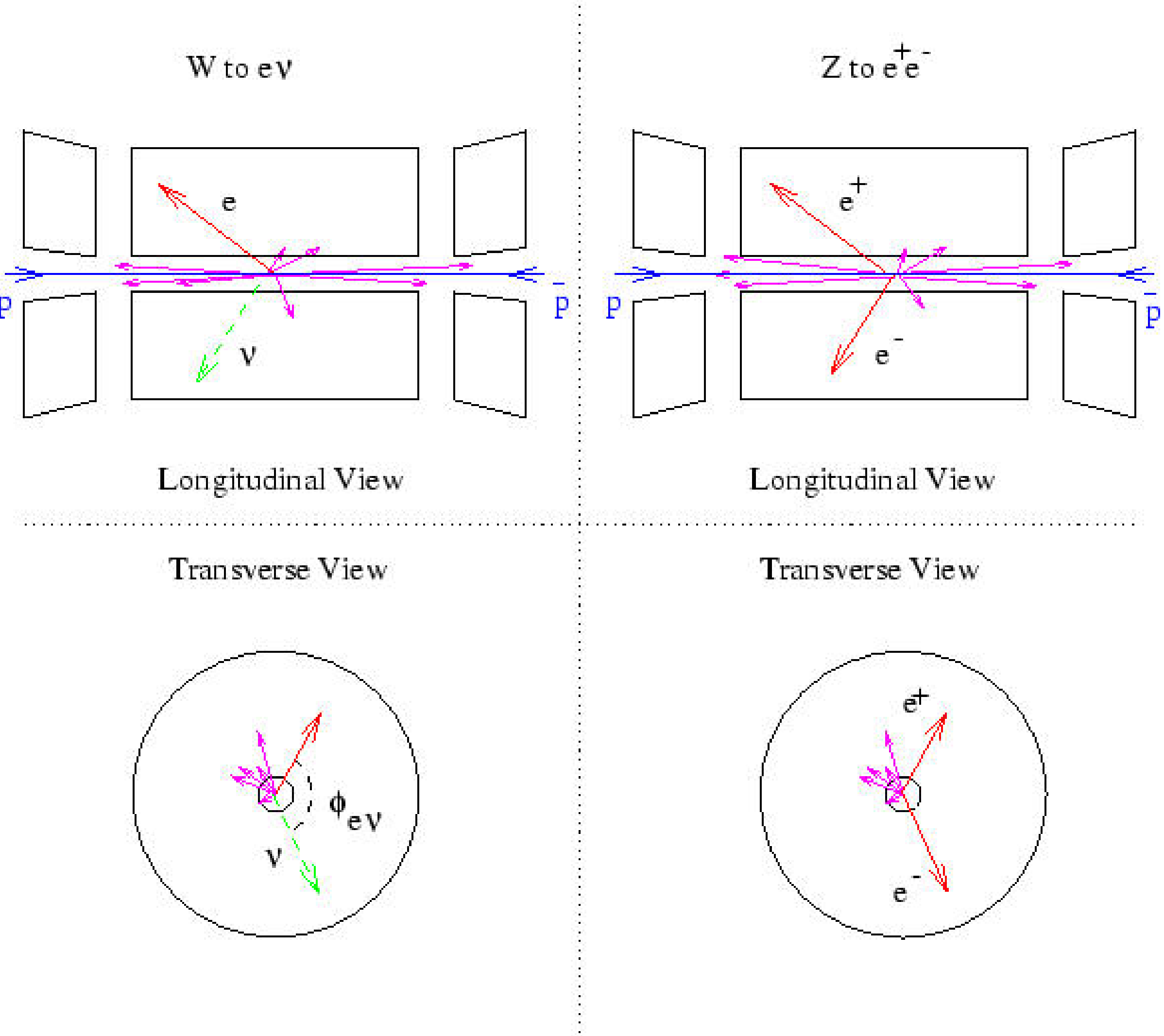
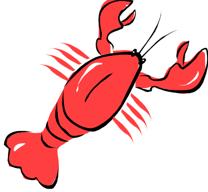
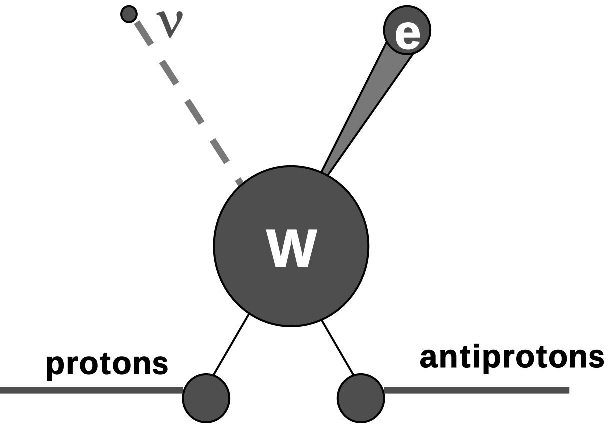
W Mass at a Hadron Collider



- Need to use leptonic decays
- Complicated by neutrino ➔ can't compute invariant mass
- Z sample is used extensively for controlling measurement

Measuring the W Mass



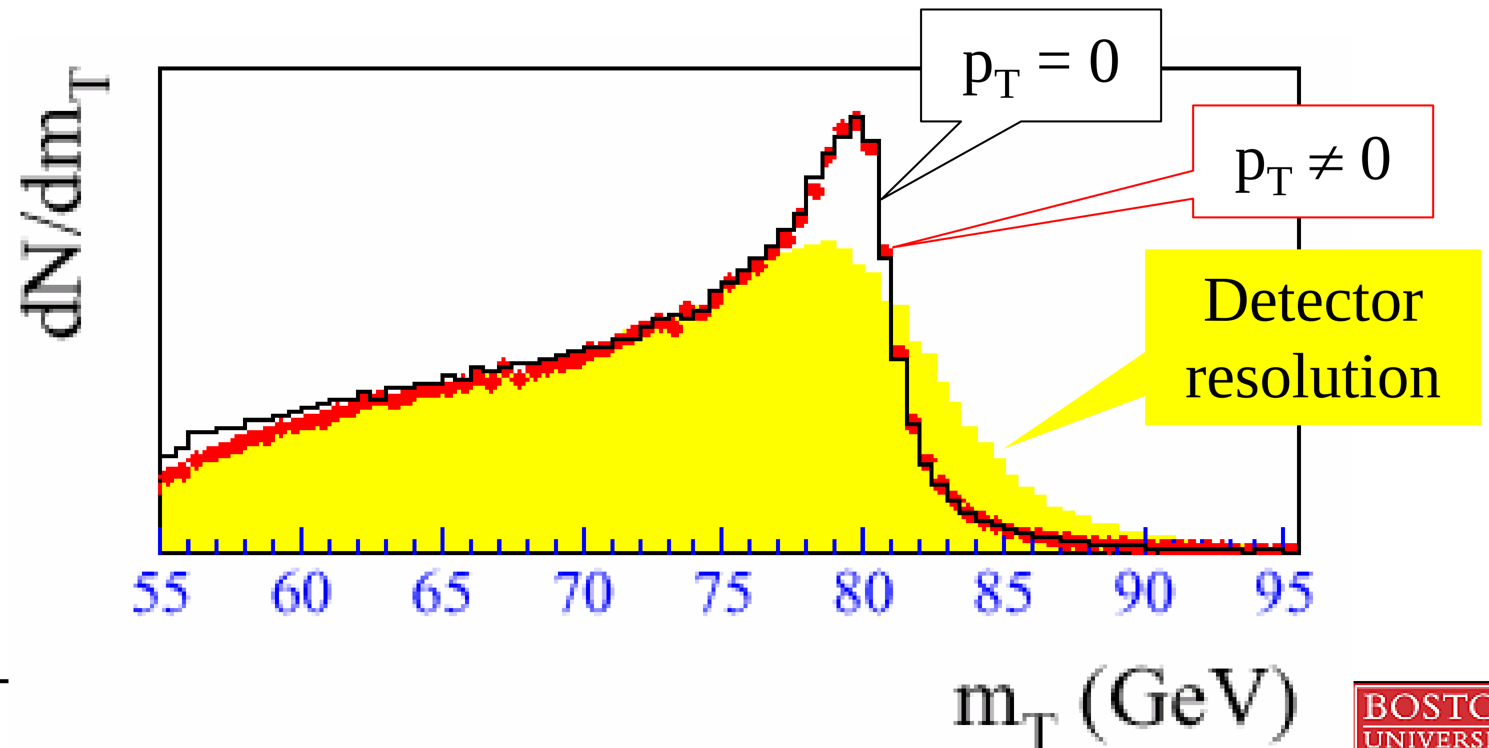


$p_z(\nu)$ is unknown $\Rightarrow$ can't calculate m_W

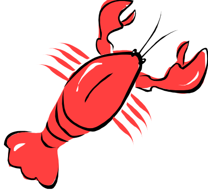
Fit to distributions of transverse quantities

$p_{Te},\ p_{T\nu} = \not{E}_T,\ m_T$

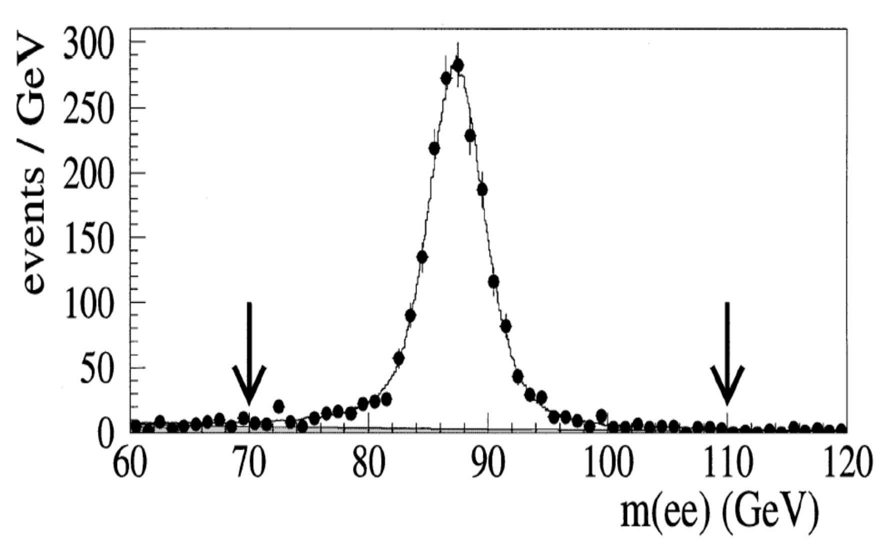
$$m_T = \sqrt{(E_{T\ell} + E_{T\nu})^2 + (\vec{p}_{T\ell} + \vec{p}_{T\nu})^2}$$
$$= \sqrt{2E_{T\ell}\not{E}_T(1 - \cos\phi_{\ell\nu})}$$

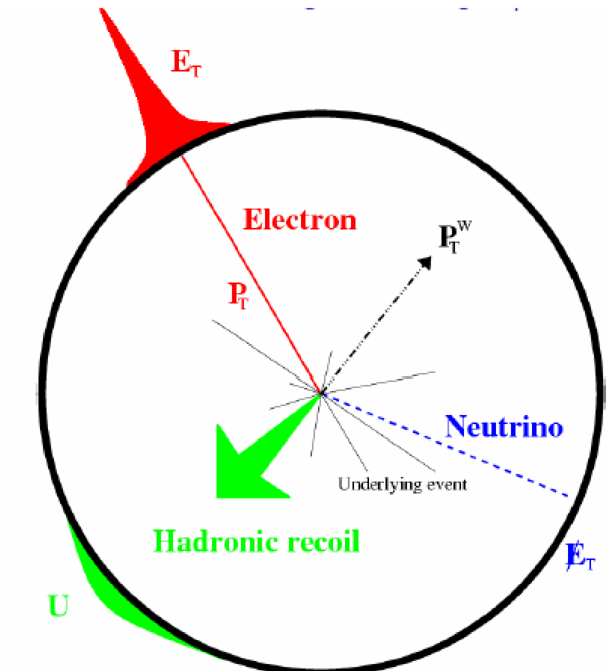


Calibration with the Z Boson



- Must use the data to determine calibration, corrections, and systematics
  - Monte Carlo and theory not good enough
- Use the decay modes
  - Z → ee and μμ
- Clear, low-background signal
- Used as the basis for energy calibrations
- p_T balance in Z events is used to understand the detector response to the hadronic recoil and underlying event

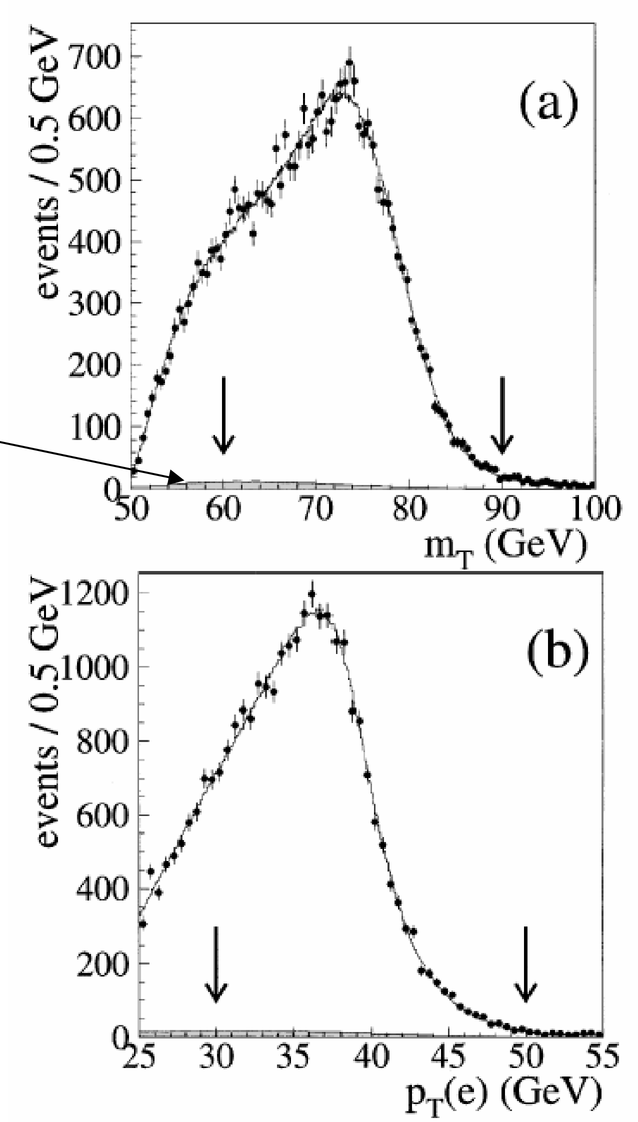




Measuring the W Mass

$W \rightarrow e\nu$

Background estimate



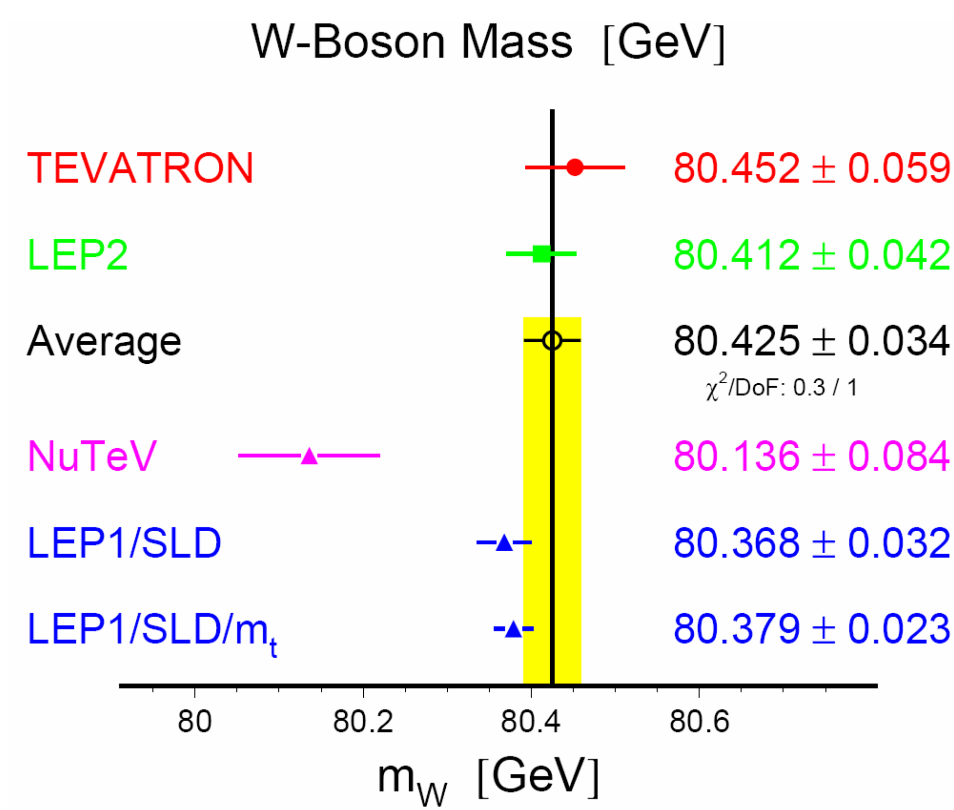
Points: data

Curves: best fit

Likelihood fits to templates of transverse mass distributions

Uncertainties on W mass

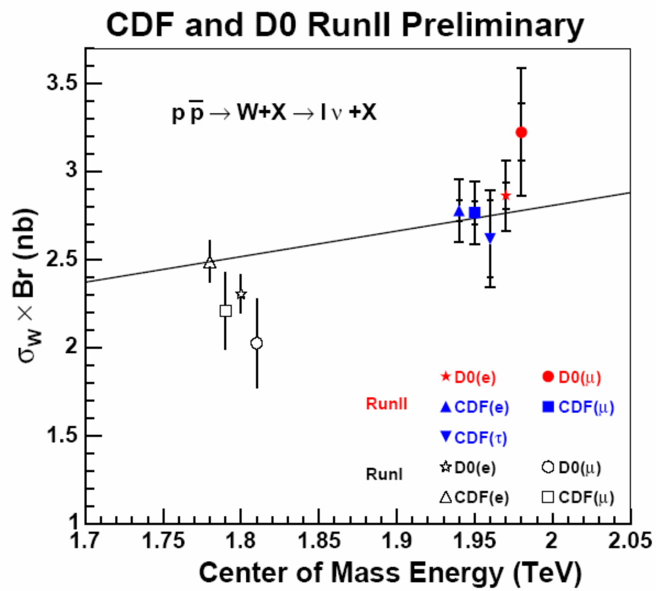
- Precision measurement
  - Effects of a few MeV are important on measuring an 80,000 MeV quantity in 2,000,000 MeV collisions
- Most systematic effects are studied using the W and Z samples
  ➔ scale with luminosity
- Goal for Run II: δM_W ~25 MeV per channel per experiment

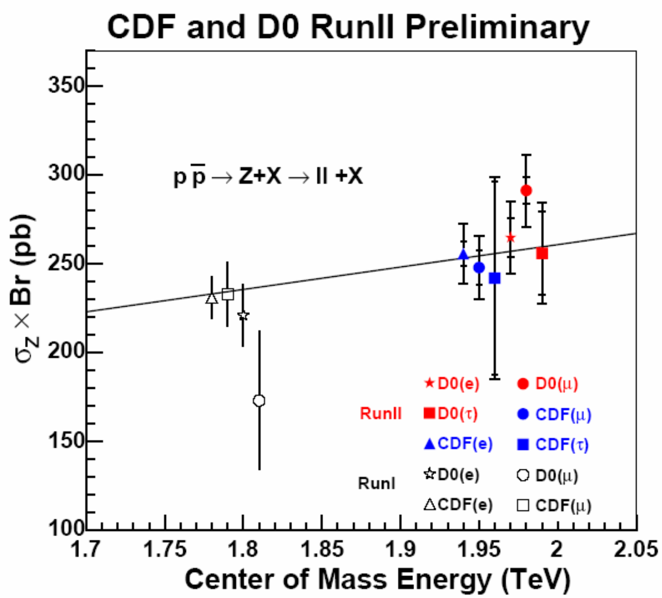


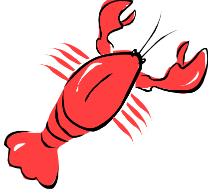
Source	δM_W (MeV)	
	M_T fit, EC	M_T fit, CC+EC
CC-EC Z mass stat.	37	16
EC-EC Z mass stat.	107	21
EC W mass stat.	179	34
CC-EC Z width stat.	47	14
EC-EC Z width stat.	56	4
Hadronic Energy Resolution	45	21
P_T^W	22	9
PDF	35	15
Hadronic Energy Scale	16	10
Electron Angle Calibration	28	7
Backgrounds	21	4
W Width	10	6
Radiative Decays	4	1

W and Z Cross Sections

- Test SM predictions for W and Z production
- Ratio of σ*B can be used to determine the W width
- Leptonic decays of the W and Z are standard candles of hadron collider physics
  - Detector calibration
  - Understanding precision measurements
  - Measure luminosity!

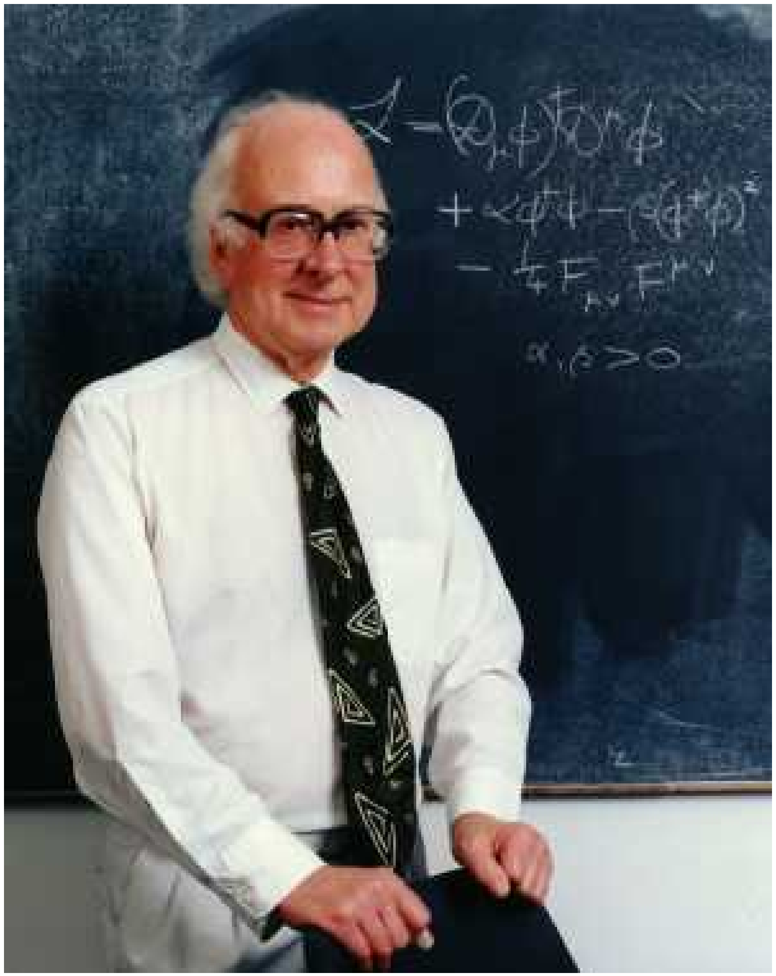






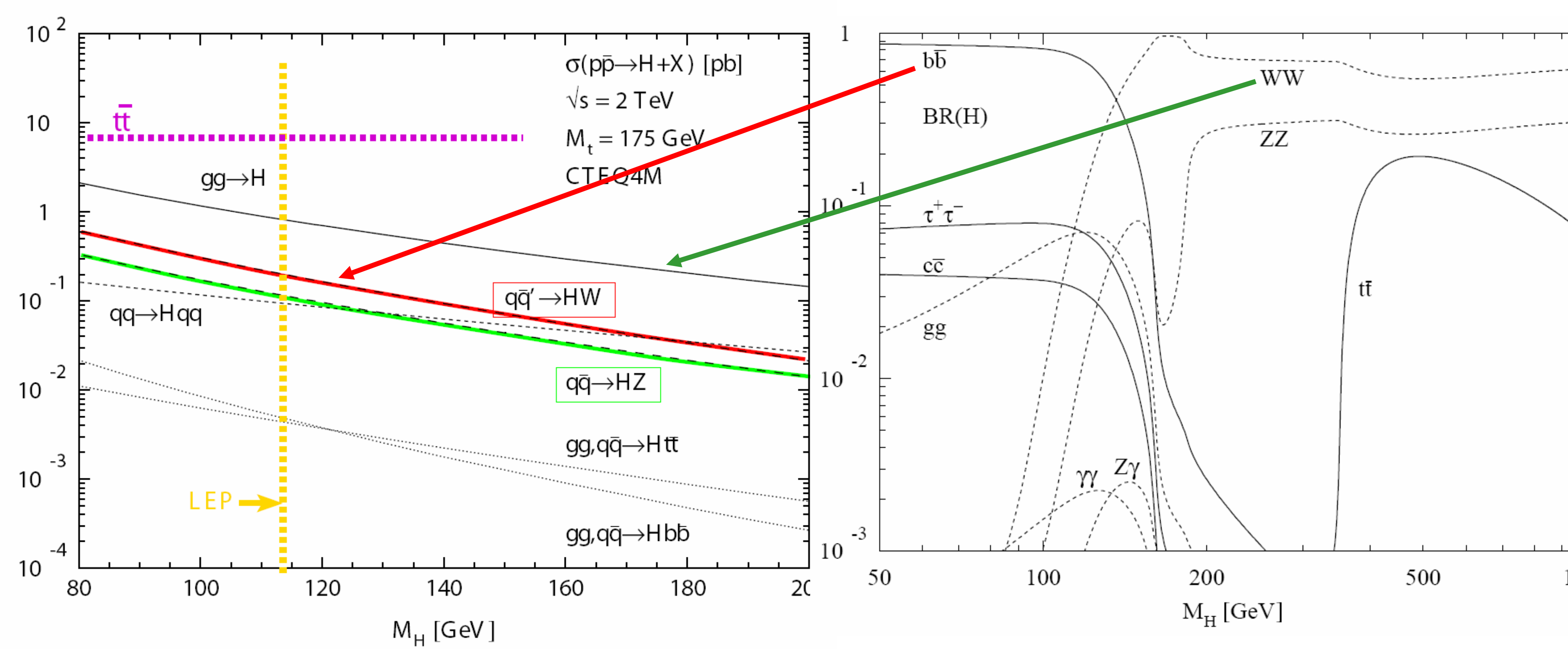
Higgs Search

The Standard Model Higgs



- ❖ Bathroom scale should be sufficient to determine the mass
- ❖ Last particle of the SM to be observed
- ❖ "Why is everybody looking for the SM Higgs? Everybody knows the SM is not the right theory!" – lunchtime conversation at BU
- ❖ Many extensions of the SM have particles that look ~identical to the SM Higgs
  - ➢ Lightest MSSM higgs h
  - ➢ Technipion π_T

Higgs Production and Decay



- Higgs search strategy at the Tevatron
  - Low mass Higgs, use Higgs-strahlung $q\bar{q} \to$ HW or HZ followed by H $\to b\bar{b}$
  - High mass Higgs, use gg $\to$ H $\to$ WW or ZZ

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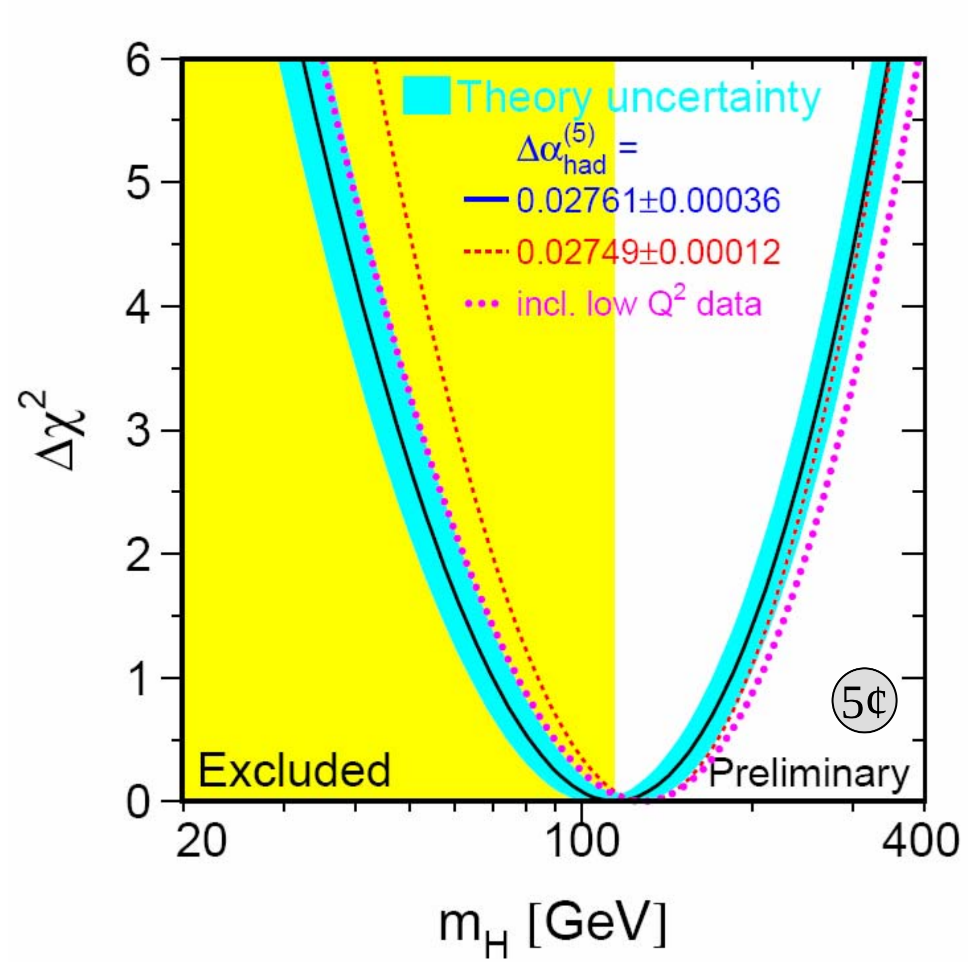
Where do we expect the Higgs?

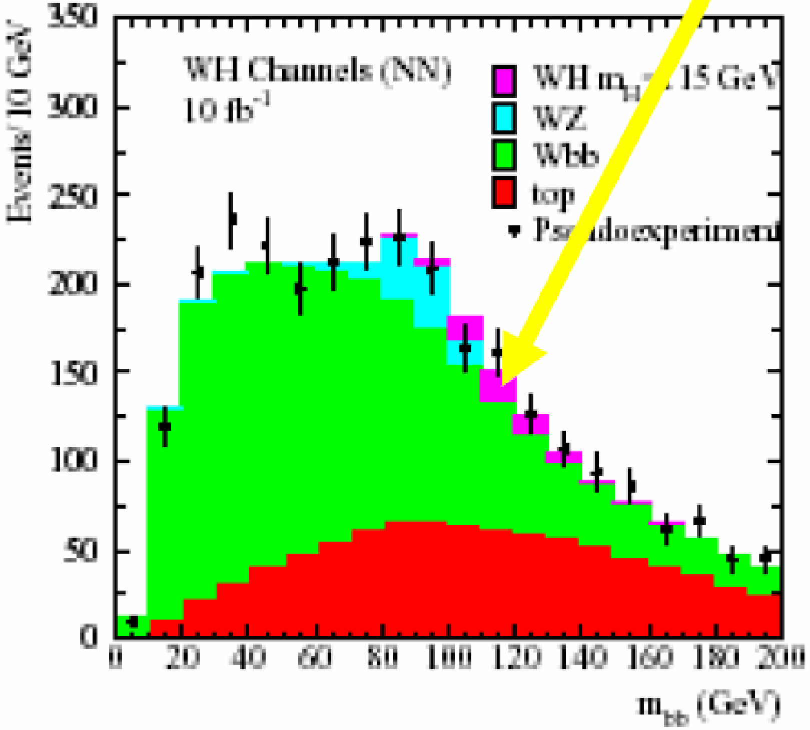
- As seen from M_W, SM parameters depend on M_H ➔ use precision EW measurements to limit allowed Higgs mass
- Result is the "blue band" plot
  - M_H > 114 GeV ruled out by LEP
  - M_H < 260 GeV from fit
- MSSM lightest Higgs < 135 GeV



LEP Electroweak Working Group:
lepewwg.web.cern.ch/LEPEWWG/

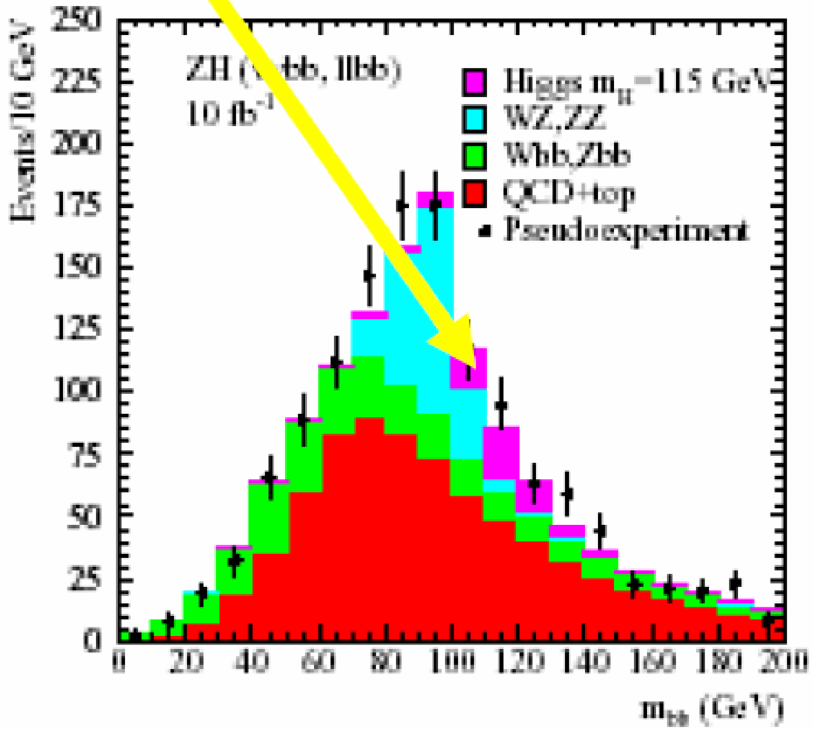
A 115 GeV Higgs signal

$p\bar{p} \to W\,h$ with $W \to \ell\nu$



This is a statistically 'unlucky' case…

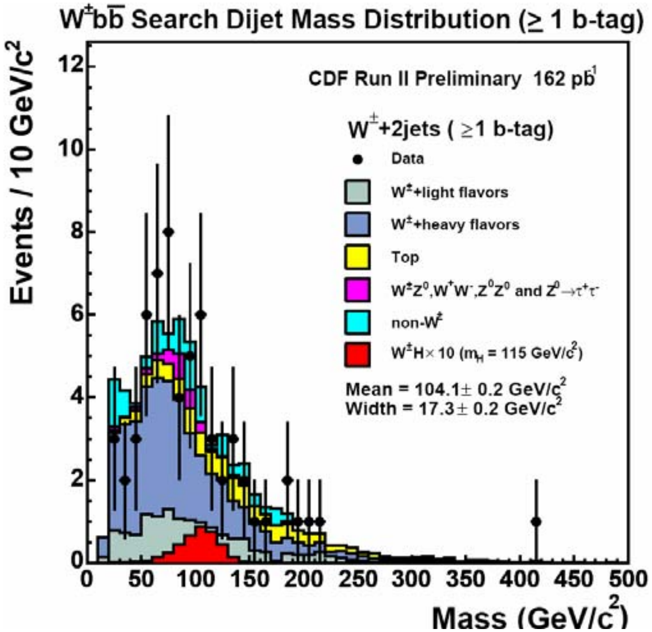
$p\bar{p} \to Z\,h$ with $Z \to \ell^+\ell^-, \nu\bar{\nu}$



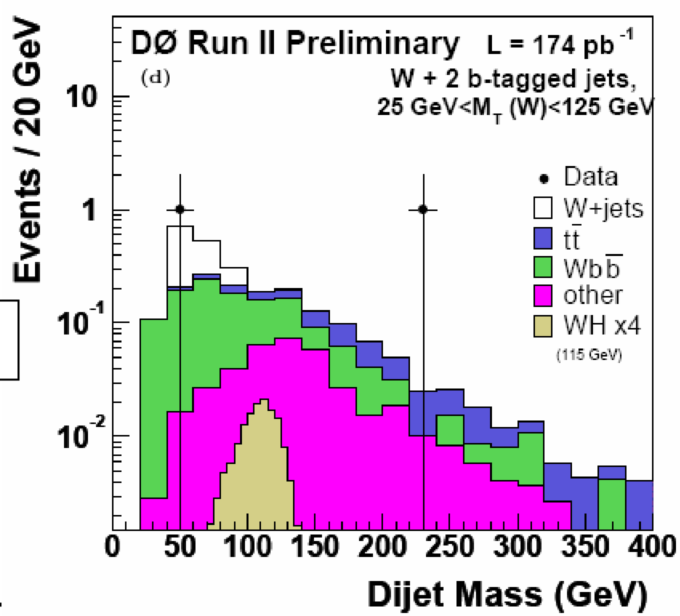
This is a statistically 'typical' case…

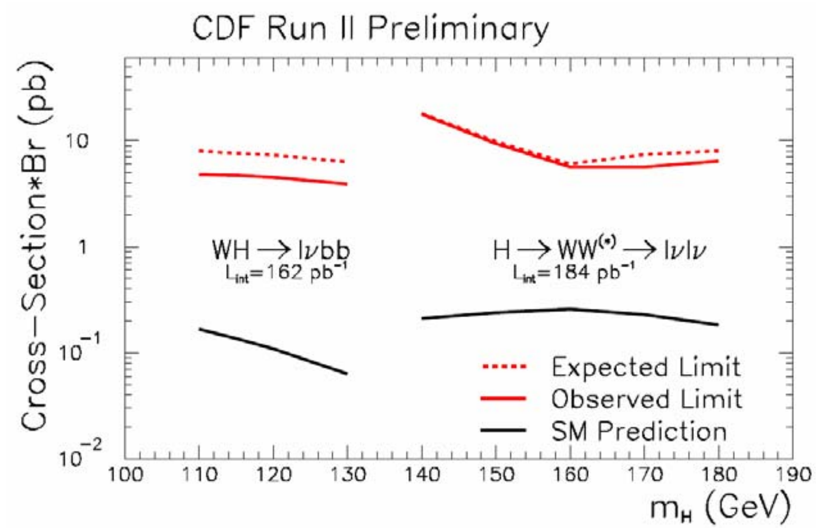
SM backgrounds are formidable ➔
must tag the b jets
need good dijet mass resolution

Single Tag

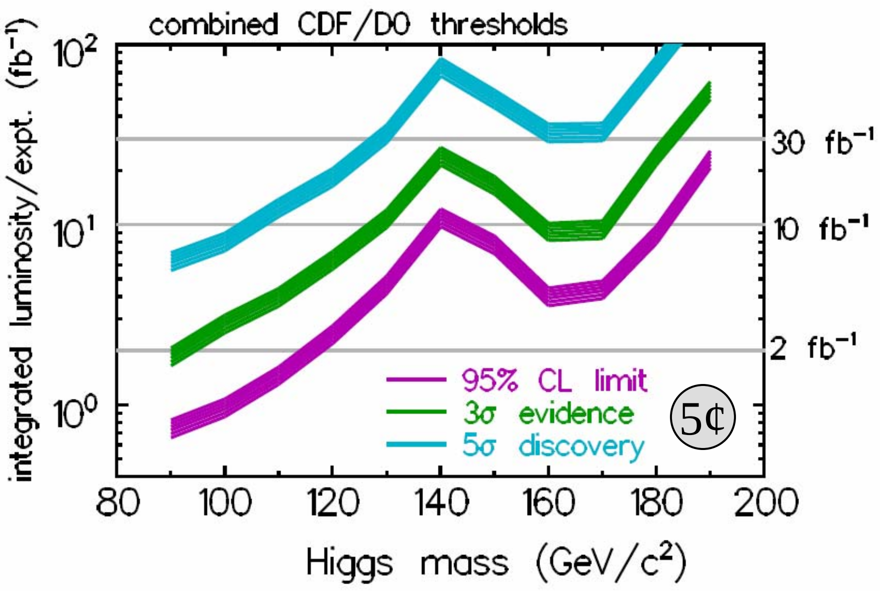


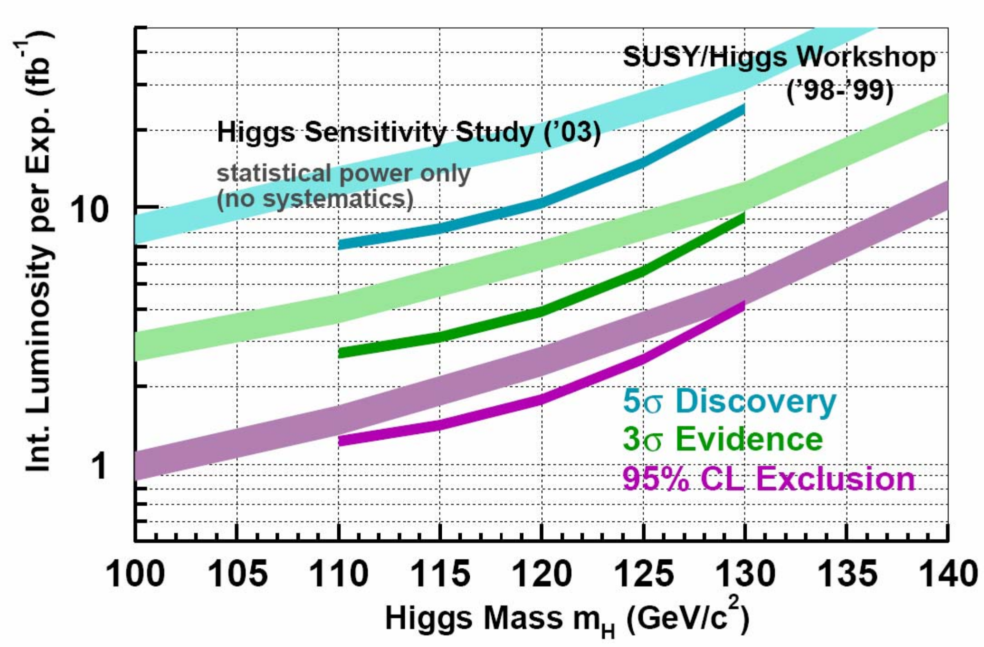
Double Tag



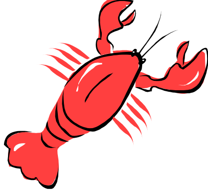


Tevatron Higgs Prospects





- It's going to be tough! May have to wait for the LHC
- Will definitively rule out the hints for a 116 GeV Higgs seen at LEP (unless, of course, the hints were right!)



Searches for Physics Beyond the SM

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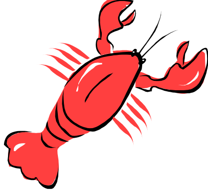
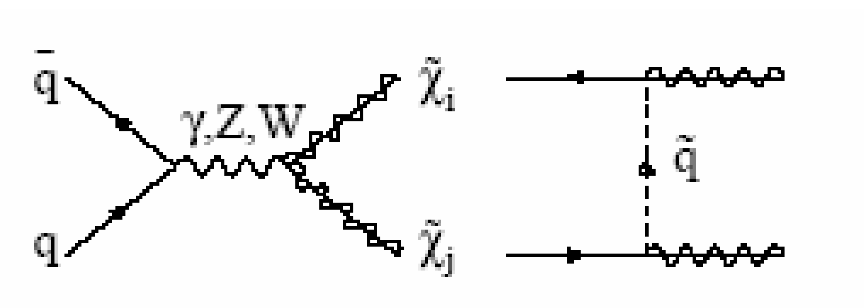
Searches for Supersymmetry

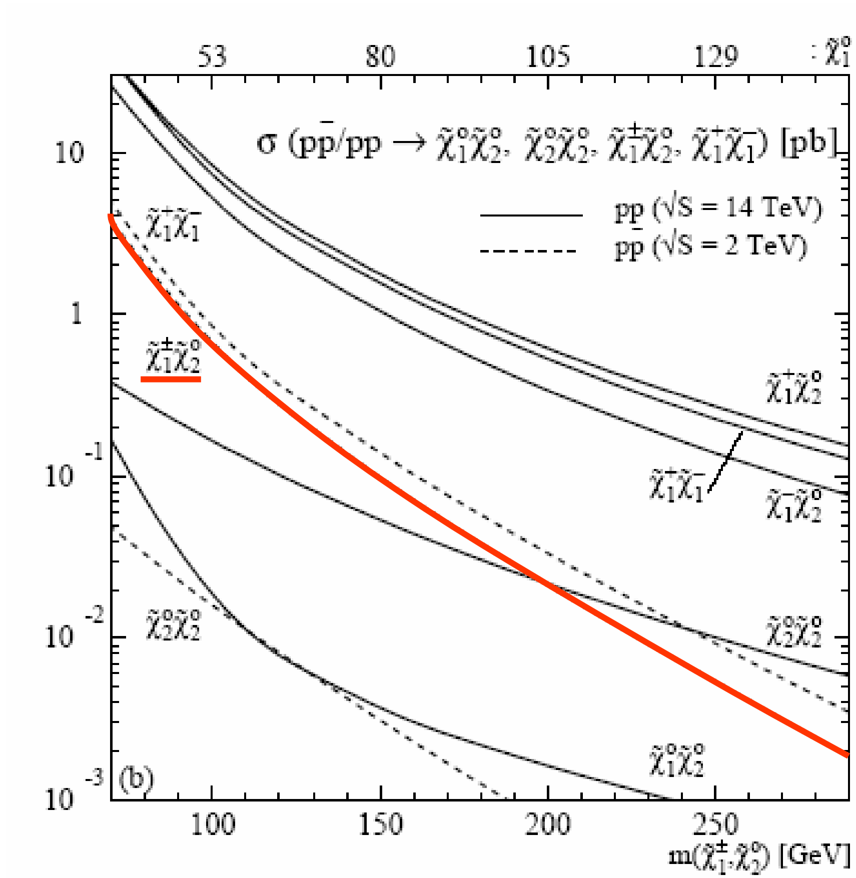


- SUSY is the current favorite idea for extending the SM
- SUSY is a postulated symmetry between bosons and fermions
  - All observed particles would have superpartners
  - Clearly, SUSY is broken
- Why people like SUSY
  - Additional particles cancel divergences in the Higgs mass
  - Allows unification of forces at higher energies
  - Lightest neutralino is a good explanation for cosmic dark matter
  - Plays well with string theory
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - Masses are unknown but expected to be in range 100 GeV - 1 TeV
    ➔ accessible at the Tevatron
- R parity = $(-1)^{3(B-L)+2S}$
  - R = +1 for SM particles
    R = -1 for superpartners
  - Conservation implies
    - Pair production
    - LSP is stable
- Gold plated channels
  - Jets + missing ET
  - Trileptons

Hadroproduction of Charginos & Neutralinos

- In R parity conserving SUSY, $\tilde{\chi}_i^{\pm}$ and $\tilde{\chi}_j^0$ are produced and decay into fermions and 2 LSP's
  - W^* exchange in s-channel
  - Squark exchange in t-channel
- $\sigma(p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)$ accessible to the Tevatron experiments





W. Beenakker et al., PRL 83, 3780 (1999)

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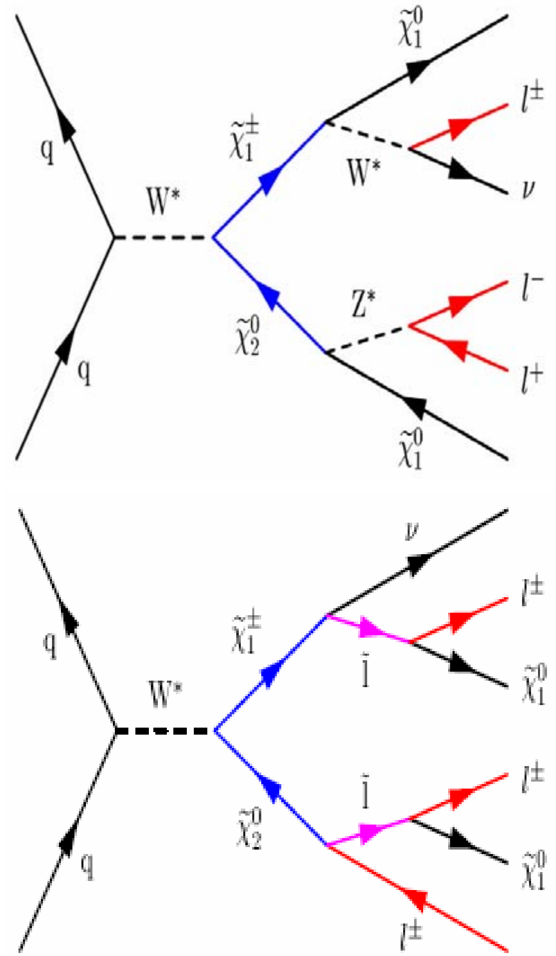
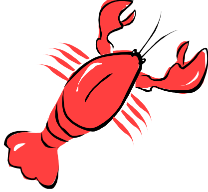
Trilepton Final State

- "Gold plated" channel
  Low standard model and
  instrumental backgrounds
- In the mSUGRA model
  $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$
  $\tilde{\chi}_1^0$ is the LSP
- SUSY parameters
  $\tan\beta = 3,\ \mu > 0,\ A_0 = 0$
  $m_0 = [72, 88]$ GeV
  $m_{1/2} = [165, 185]$ GeV
  $m_{\tilde{\chi}_1^\pm} = [97, 114]$ GeV
  $m_{\tilde{\ell}} \approx m_{\tilde{\chi}^\pm} \Rightarrow$ enchanced leptonic BR
  $\sigma \times BR \approx 0.2 - 0.4$ pb

$p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 3\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$
Signature $= 3\ell + \not{E}_T$



Search Strategies



- Observe all 3 leptons plus missing E_T
  - Tevatron Run I approach
    DØ: PRL 80 (1998) 8; CDF: PRL 80 (1998) 5275
- Clean but limited – lepton acceptance and ID efficiency, 3rd lepton can be soft, miss hadronic τ's
- Can increase search sensitivity by alternate strategies
  - Observe 2 leptons plus an isolated track
    - Gain ε by relaxing the particle ID requirement
  - Observe only 2 out of 3 leptons
    - Leptons from different generations
    - Leptons are like-sign*
- Present 3 analyses that exploit these alternate approaches

1. $e + e + \ell$, where $\ell =$ isolated charged track
2. $e + \mu$ and $e + \mu + \ell$
3. $\mu^{\pm} + \mu^{\pm}$

- Combine the results to maximize the sensitivity

*Nachtman, Saltzberg, Worcester, Int. J. Mod. Phys., A16S1B, 797 (2001)

$e + e + \ell$ Search

[DØ Note 4405]

- $\int \mathcal{L}dt = 175 \pm 11$ pb^{-1}
- Event selection

  2 good e, $p_T > 12, 8$ GeV

  $\geq 1e$ with $|\eta| < 1.1$

  16,200 events
- Reject backgrounds

  $Z \rightarrow ee$, $W \rightarrow e\nu\gamma$, $t\bar{t}$, DY

  Cut $15 < m_{ee} < 60$ GeV

  $\Delta\phi(e, e) < 2.8$

  ≥ 1 SMT or tight e likelihood

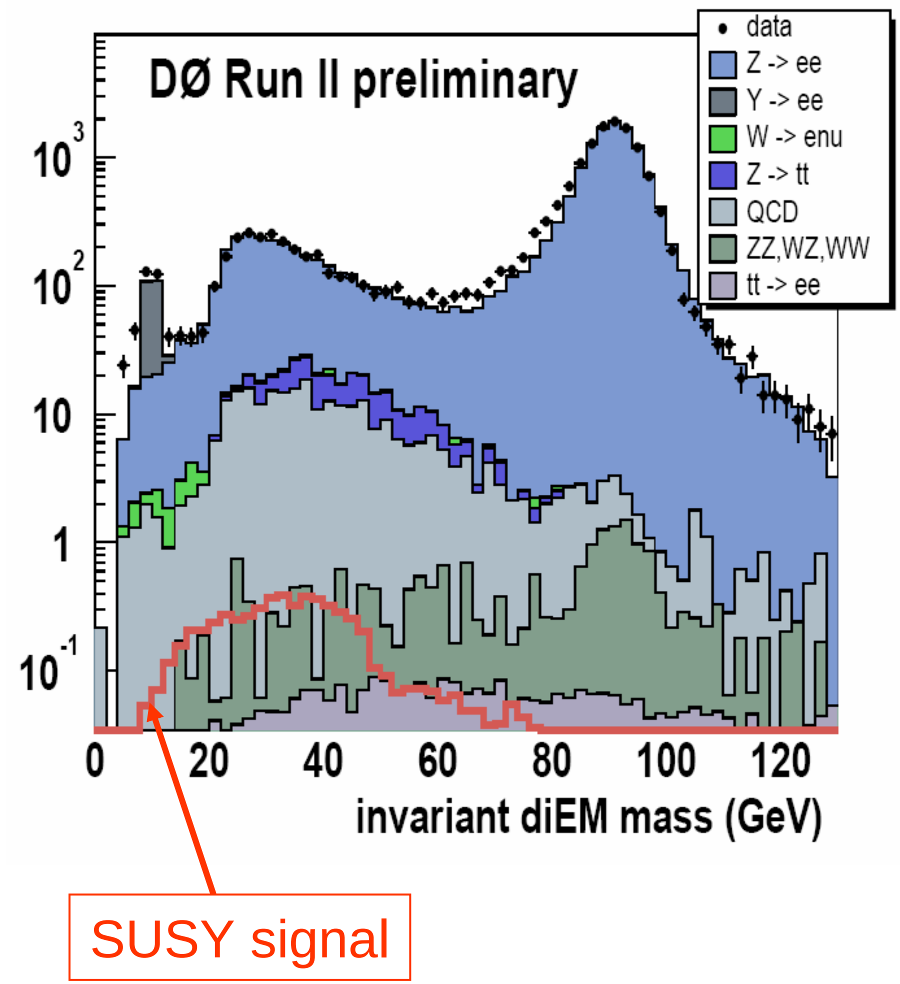
  Jet $E_T < 80$ GeV

  Scaled $\not\!\!E_T > 10$ GeV$^{1/2}$

  $M_T(e + \not\!\!E_T) > 15$ GeV

  $\not\!\!E_T > 20$ GeV

  $\Delta\phi(e, \not\!\!E_T) > 0.4$



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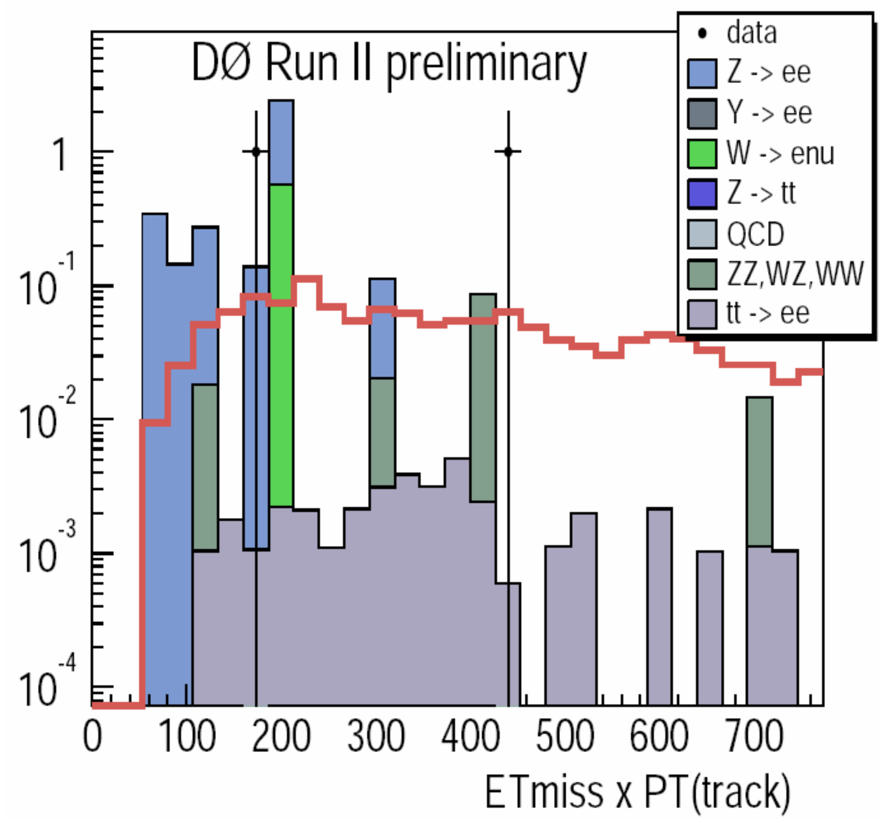
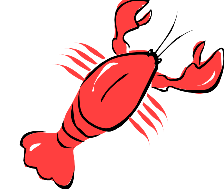
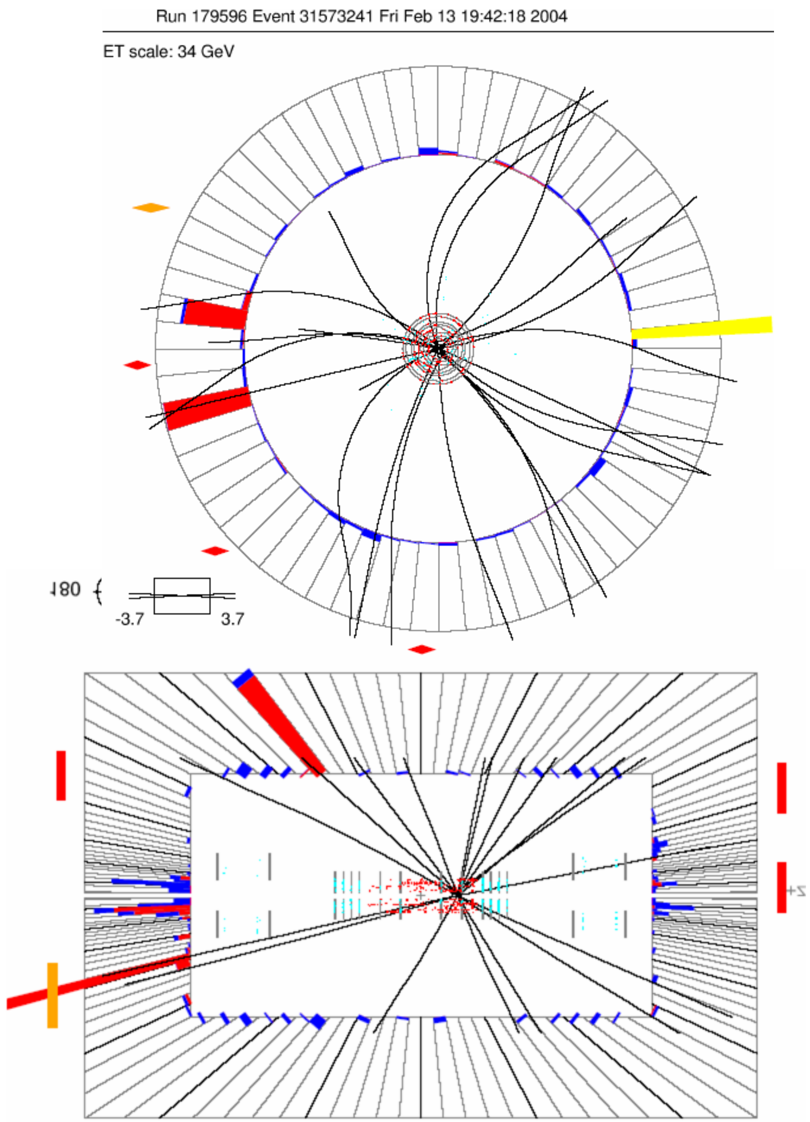
$e + e + \ell$ Search

- Isolated track, $p_T > 3$ GeV
- Residual SM backgrounds killed by requiring $p_T(\text{track}) \times \not\!\!E_T > 250$ GeV^2
  1 event remains
- Expect
  0.27 background events
  0.8-1.6 events from SUSY



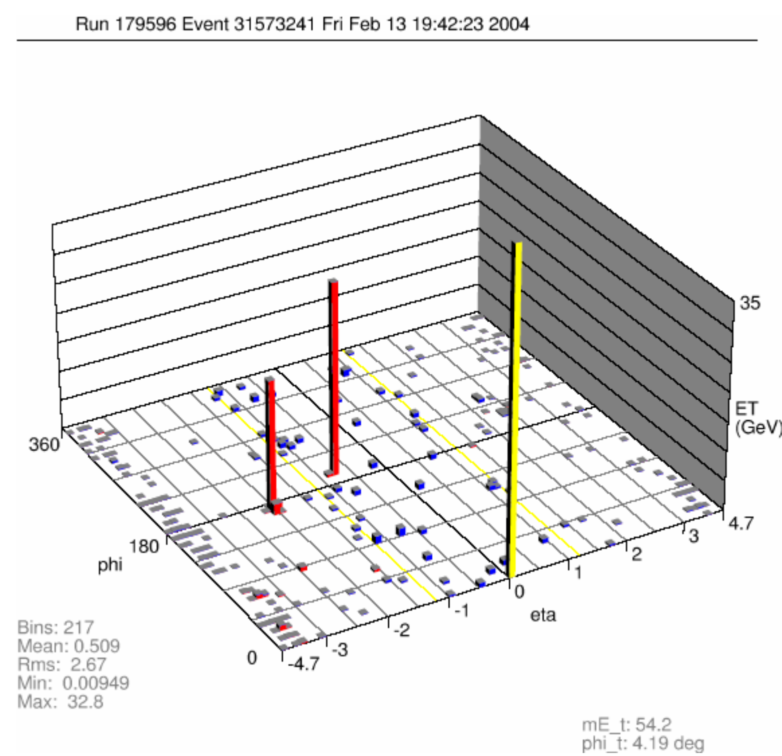
$e + e + \ell$ Candidate Event





	E_T (GeV/c)	η	ϕ
e_1	33.2	-0.97	3.37
e_2	25.7	-2.19	2.97
ℓ	8.6	0.67	5.87
$\not\!\!E_T$	52.1	–	0.12

$$m(e_1 e_2) = 39.5 \text{ GeV}$$



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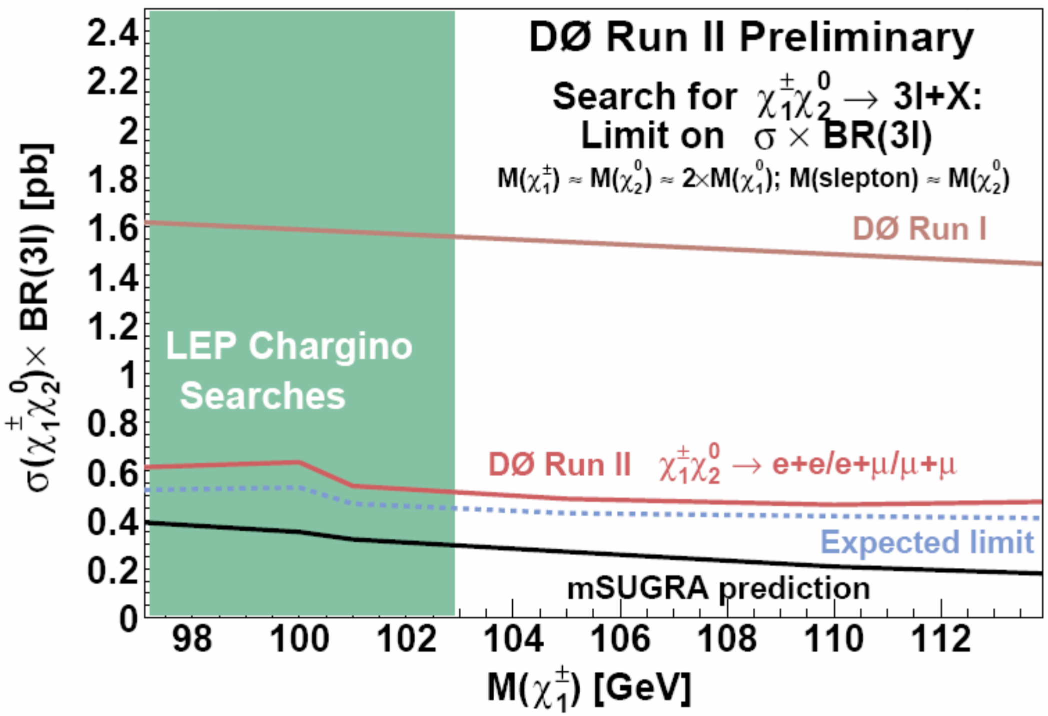
Combined Limit

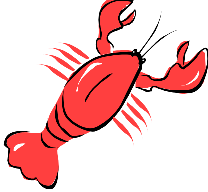
- See 3 events from data, expect 3.4 from SM sources
- Set a 95% CL limit on $\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0) \times BR(3\ell)$ using the CL_S method*
- Significant improvement over Run I results
- Can not rule out the mSUGRA prediction (yet!)
- Can use these results to constrain other SUSY models with a similar mass hierarchy

Channel	Data	Background
$e+e+\ell$	1	$0.27 \pm 0.42 \pm 0.02$
$e+\mu$	1	$2.49 \pm 0.37 \pm 0.18$
$e+\mu+\ell$	0	$0.54 \pm 0.24 \pm 0.04$
$\mu^{\pm}+\mu^{\pm}$	1	$0.13 \pm 0.06 \pm 0.02$

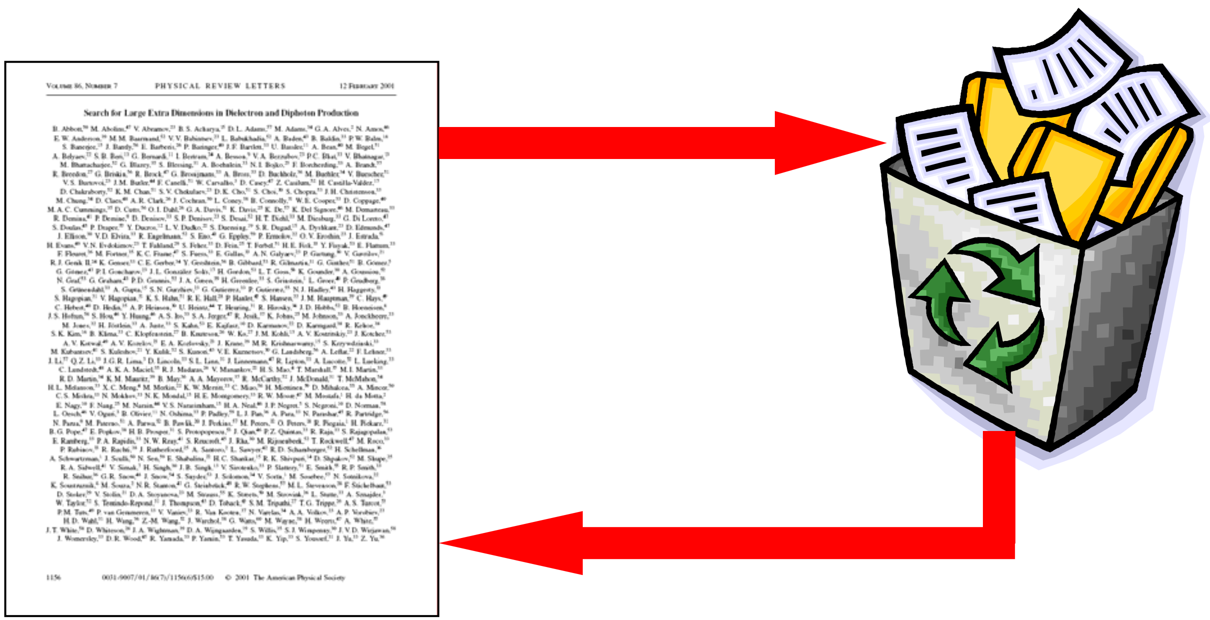


*T. Junk, NIM A434, 435 (1999).

Recycling is good!



- Signature for new physics often contain common objects
  - High pT leptons
  - Large missing ET
- Certain final states can be used to place limits on a wide variety of extensions to the SM



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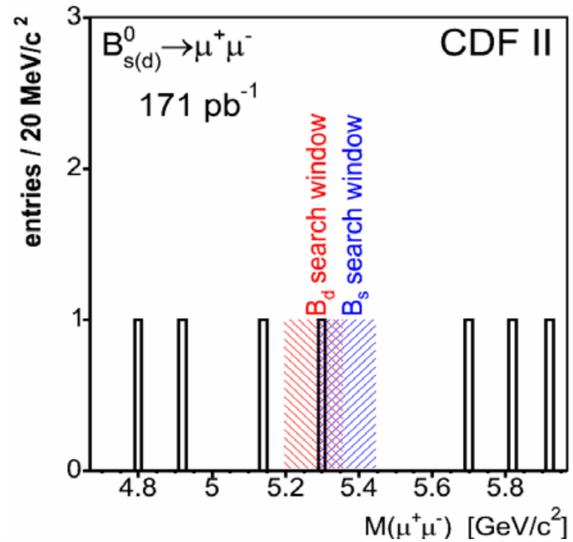
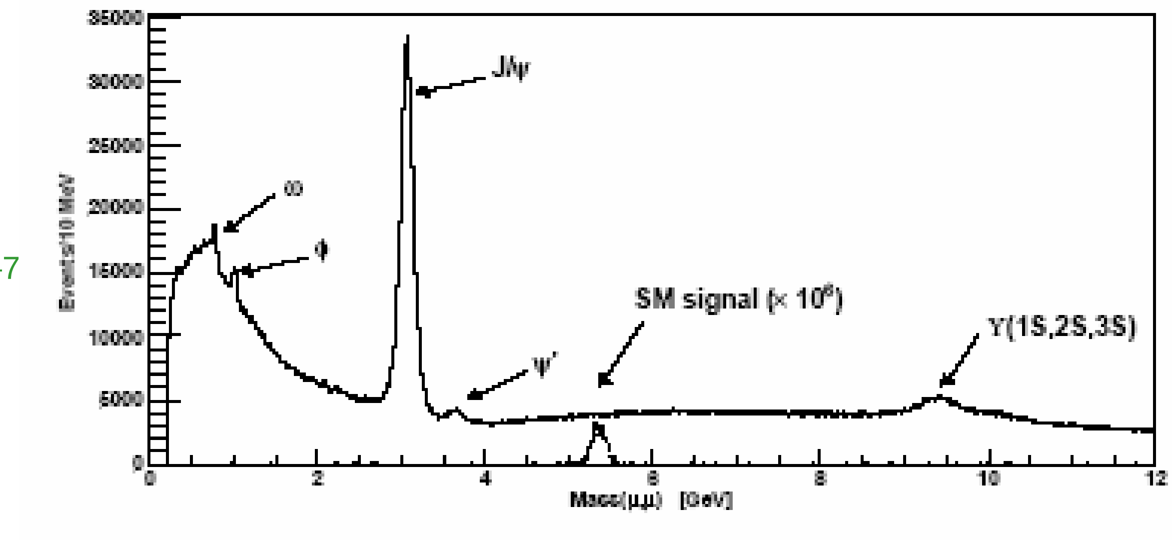
Recycling example – dileptons

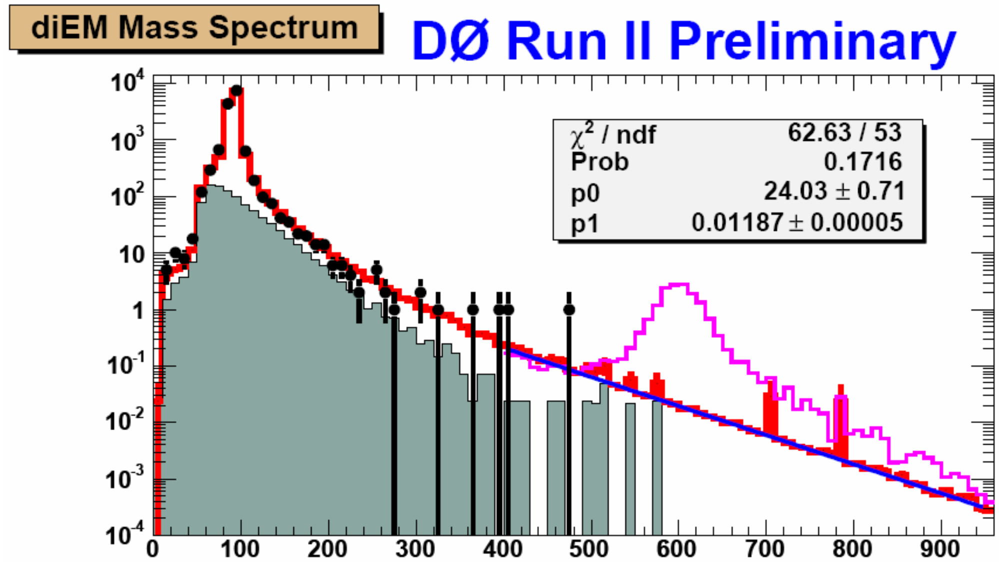
- Historically, a discovery channel
- Can use e^+e^- and $\mu^+\mu^-$ events to study many SM processes
  - b/c physics:
  - EW: e.g. Z cross section
  - top → dileptons
- Look for rare decays
  - SM B(Bs → $\mu^+\mu^-$) ~ 3×10^{-9}
  - In SUSY, can get enhancements (~$\tan^4\beta$-$\tan^6\beta$) up to factor of 1000
  - B(Bs → $\mu^+\mu^-$) < 5×10^{-7}
  - Example of analysis where SM is out of reach, any excess is new physics

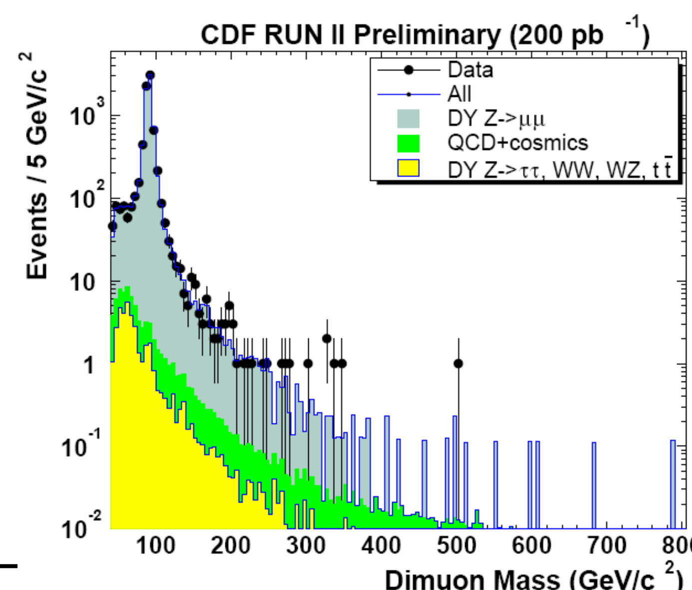




Recycling example – dileptons

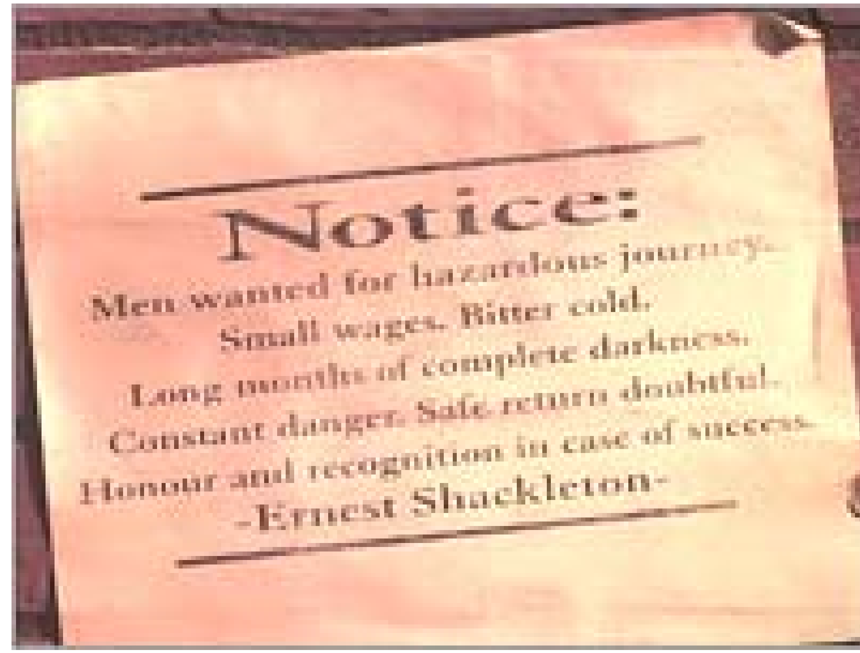
- In a wide variety of theories/models, new physics can show up as a resonance or excess of events at high dilepton mass
- Dilepton mass distributions have been used to place limits on
  - Extra dimensions (Greg Landsberg on Friday)
  - New gauge bosons: Z′
  - Technicolor: ρ_T and ω_T
  - RS Gravitons
  - RPV sneutrino
  - Little Higgs





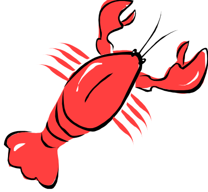
Summary

- I hope I've convinced you there is a "rich" (in the good way!) ongoing program of physics at the Tevatron
- Only in Illinois (for now)
  - Top quark
  - W mass
  - B_s, Λ_b, …
  - Search for the SM Higgs and new phenomena
  - Plus lots of other stuff I didn't have time to talk about
- Will LHC do better?
  - You bet!
  - But not yet!



Graduate student life hasn't changed much over the years!

Roll the credits



- “Borrowed” lots of slides from the excellent talks by my DØ and CDF colleagues, many thanks to them
- The talks from NEPPSR I and II are very good!
- Web sites
  - Fermilab: http://www.fnal.gov/
  - DØ: http://www-d0.fnal.gov/
  - CDF: http://www-cdf.fnal.gov/
  - LEP EWWG: http://lepewwg.web.cern.ch/LEPEWWG/
  - Tevatron EWWG: http://tevewwg.fnal.gov/
  - LEP SUSY: http://lepsusy.web.cern.ch/lepsusy/