Combining Search Results: The Tevatron Higgs Search

- ✗ Constructing the problem
- ✗ Modelling of systematic effects
- ✗ Combining search channels
- ✗ Interpreting your results
- ✗ Assumptions & limitations

Or, *Discussions within the TEVNPHWG*

Wade Fisher

Fermilab

CMS J-Term

January 15th 2009

Steps to Calculating Limits

- ✗ Performing the data analysis for a search **#1**
  - Understanding your data
  - Selection & optimization

Matt Herndon & Mike Eads

- ✗ Assembling all the pieces **#2**
  - Identifying and calculating systematic uncertainties
  - Compatibility of analyses to be combined
  - Interpretation of results
  - Limitations

This talk

- ✗ Statistical machinery **#3**
  - How to construct a hypothesis test
  - Statistical theory aspects

Luc Demortier

The General Problem

- ✗ If possible, use data to distinguish two hypotheses:
  - ✗ **H0** ⇨ null hypothesis: background-only model, eg Standard Model
  - ✗ **H1** ⇨ a test hypothesis: presence of a new particle, coupling, etc.

H0 is a compound hypothesis, with some set of systematic uncertainties

H1 has the same form, but add model params and extra nuisance params

Simple Example: **H0** describes the Standard Model background expectation for the result of an analysis. Nuisance parameters can be luminosity, acceptance, Standard Model cross section, etc…

H1 is the same as **H0**, but add a new physics signal. The model can be parametrized by particle mass / cross section / etc, and extra systematic uncertainties come from signal acceptance, model parameters, etc…

Two versions of the problem

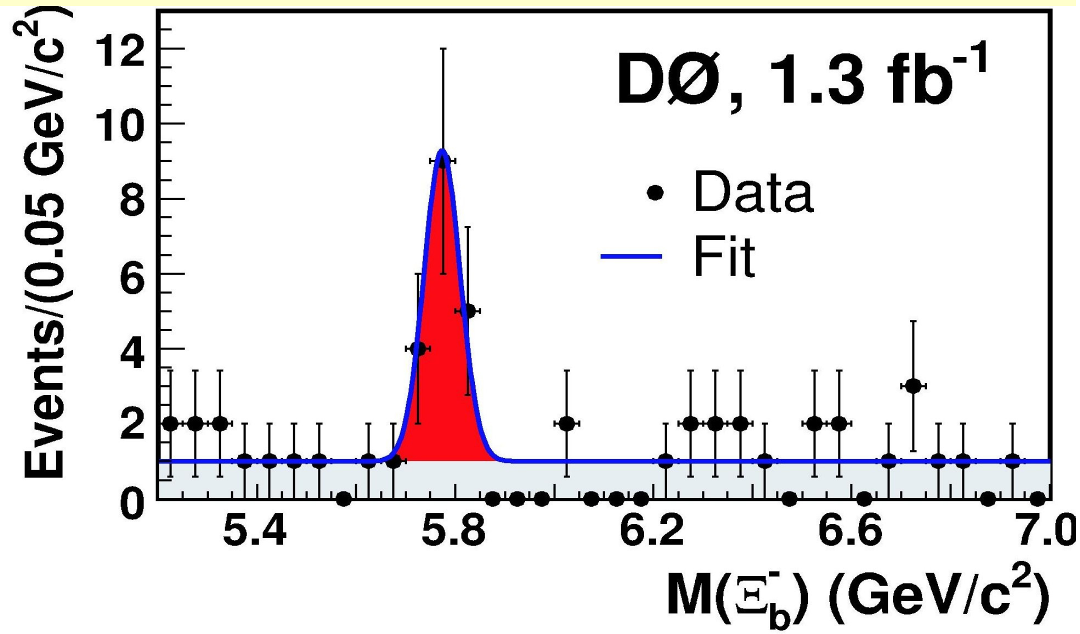
A simplifying assumption: We have reduced obvious backgrounds and done our best to classify events. Now look to see what we find.

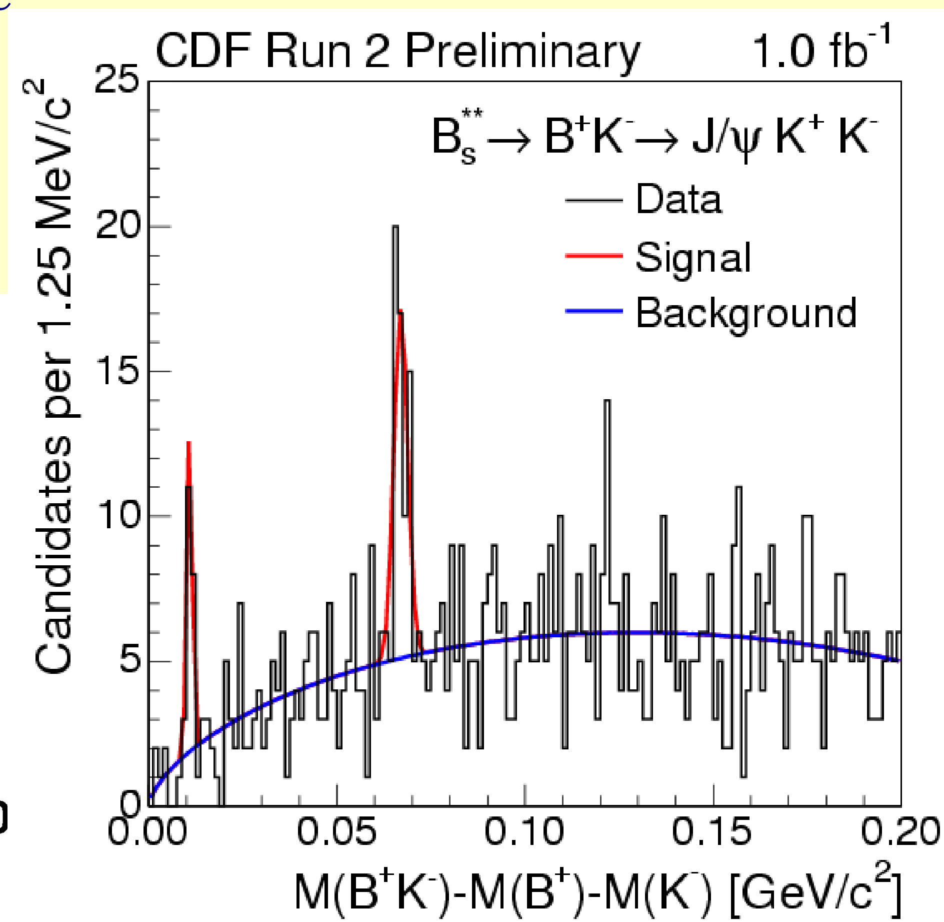
There is no "smoking gun" for the Higgs at the Tevatron

Must rely upon careful statistical analysis to determine search significance

A "rare" example

- Sometimes statistical significance is relatively unambiguous
  - DZero: $\Xi_B^{\pm}$ baryon, CDF: B_s^{**} meson
  - Large signal & small, well-behaved backgrounds
- This type of search is somewhat rare
  - Large S/B ratios
  - Powerful constraints on background shape & rate

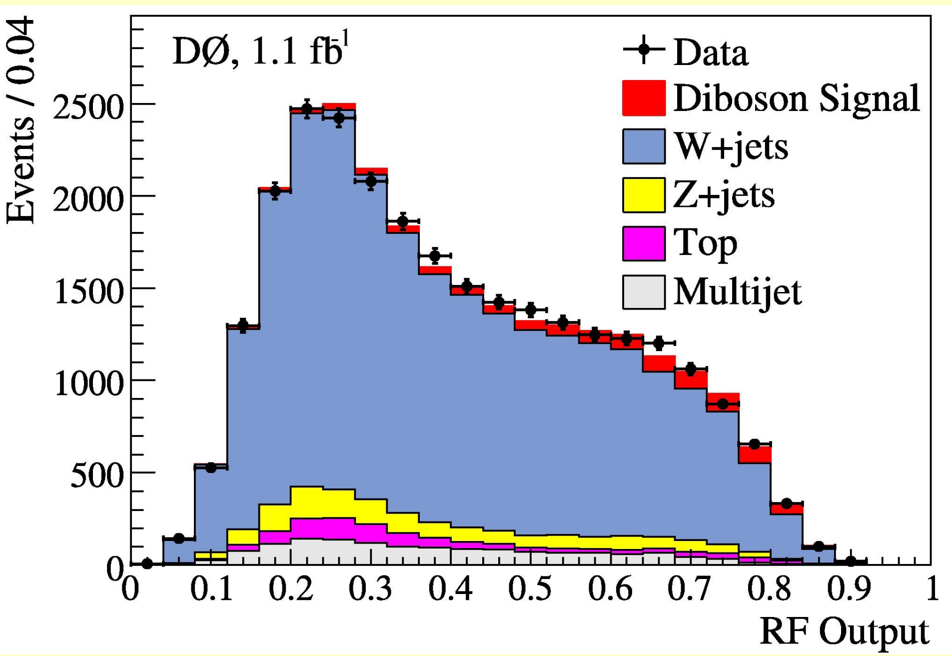




A more common example

- A search in an environment with large systematic uncertainties
  - Signal-size fluctuations have drastic degrading impact on significance
  - *Obtaining appropriate measurements of systematic effects is often difficult!*

<u>DZero:</u> First evidence for WW/WZ→lvjj decays



	Expected Events	Theory Uncertainty	Experimental Uncertainty
Signal	770	77	53.9
Background	27800	5838	3058
S/sqrt(B)	4.62		
S/σ(B)	0.12		

Similar values for WH→lvbb search

Systematic Uncertainties

- Three basic classes of systematic uncertainties:
  - Type I – Acceptance normalizations, constrainable via control samples, scale roughly with luminosity
    - Gaussian uncertainties on efficiencies may not be Gaussian in acceptances
  - Type II – Arise from poorly understood features of data measurement (eg, experimental resolution). Often manifest as "shape" uncertainties.
    - Like it or not, your NN or BDT convolutes systematics in unpredictable ways
  - Type III – Originate from uncertain theoretical modelling aspects
    - Kinematic effects and normalization effects must be handled coherently
- Issues surrounding systematics will only become more important
  - As the data sample grows (*ie, statistical uncertainty falls*)
  - As we get closer to excluding a model (*ie, when people will expect bullet-proof systematics studies*)

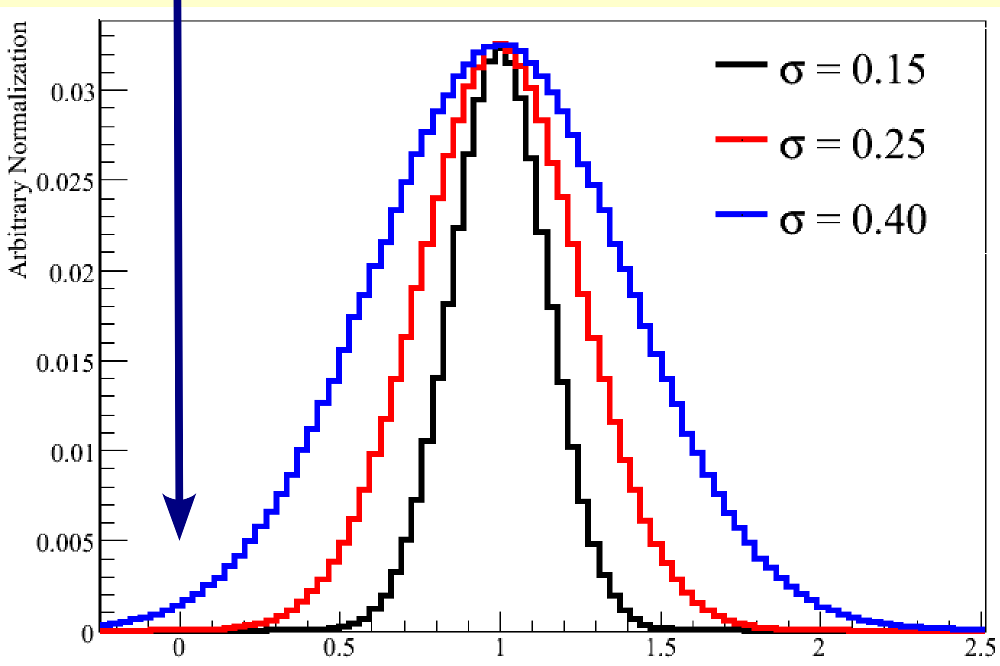
Gauging your Situation

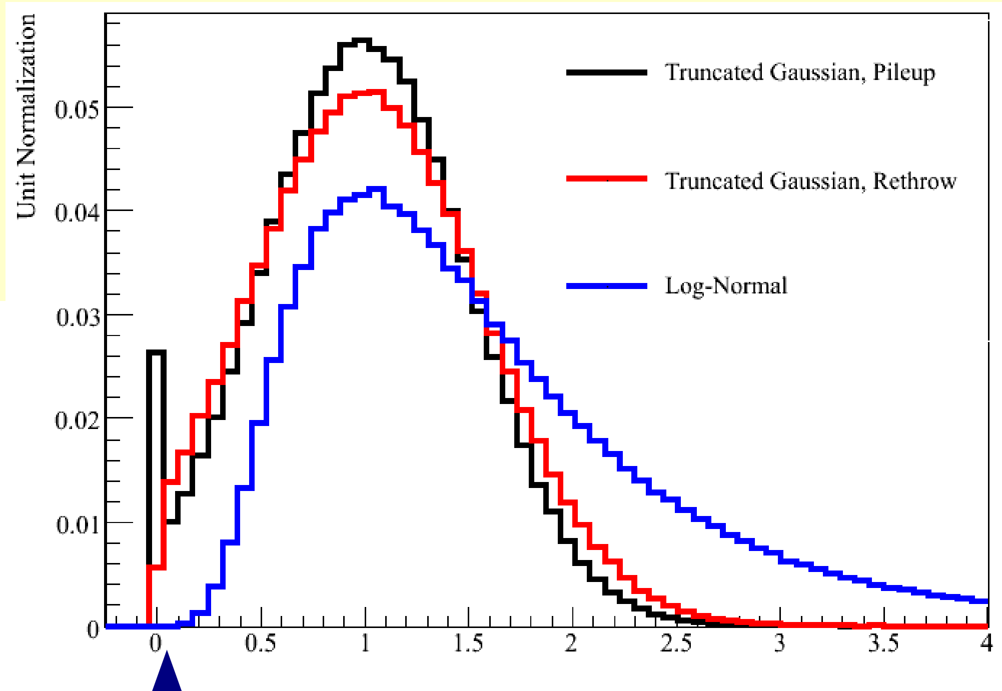
- First questions to ask yourself:
  - What precision for systematics does your analysis goal demand?
  - What sources of uncertainty contribute on this level?
- Rules of thumb on precision requirements
  - *Two major aspects contribute: background statistics and signal significance*
  - Systematics of the same order as your background Poisson uncertainty are important (not just 1/sqrt(B), depends on binning!)
  - Systematics that reproduce your signal size at your required significance level are important (e.g., for a 95% CL limit of 5× signal rate, systematics of ~5/2× signal rate matter!)
- Sources of uncertainty
  - Every analysis is unique, but in general analyzers need to be careful to identify orthogonal (*uncorrelated*) sources
  - Systematics need to be taken into account in analysis design: *can you make yourself insensitive to large or dominating systematics?*

Systematics Example 1

- What are the consequences of large background uncertainties
  - Consider Gaussian parametrization centered at 1.0
  - Lesson: Large systematics have implications beyond the obvious ones

Non-physical, negative values populated as σ grows.





Must choose appropriate model for uncertainties as you approach zero event rate.

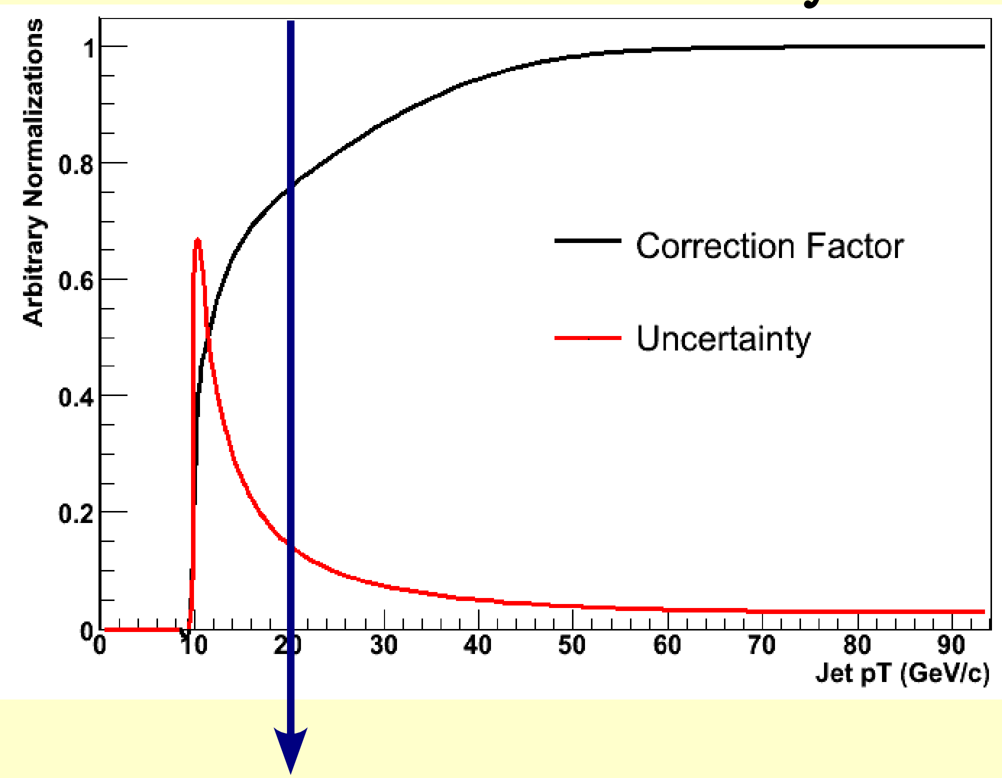
Systematics Example 2

- Problem: Jet reconstruction efficiency different between data & Monte Carlo
- *Question: What is the uncertainty on the acceptance of two jets?*

Systematics Example 2

- ✗ Problem: Jet reconstruction efficiency different between data & Monte Carlo
- ✗ *Question: What is the uncertainty on the acceptance of two jets?*

Jet Reco Correction Factor and Correction Uncertainty



Typical jet p_T cut

Graduate Student Solution:

(1) $$\epsilon_{corr} = \epsilon_{jet1} \times \epsilon_{jet2}$$

(2) $$\frac{\sigma_X^2}{X^2} = \left(\frac{\sigma_A^2}{A^2}\right) + \left(\frac{\sigma_B^2}{B^2}\right) + 2\frac{\sigma_{AB}^2}{AB}$$

(3) $$\epsilon_{jet1} \simeq \epsilon_{jet2}, \sigma_{jet1} \simeq \sigma_{jet2}$$

(4) $$\sigma_{corr}^2 = 4\sigma_{jet1}^2$$

(5) $$\sigma_{corr} \sim \sqrt{4}\sigma_{jet1} \sim 2\langle\sigma_{jet}\rangle$$

Type I??

Postdoc Solution:

(1) Vary correction factor by $-1\sigma, 0\sigma, +1\sigma$

(2) Model using *assymetric, shape-dependent* Gaussian

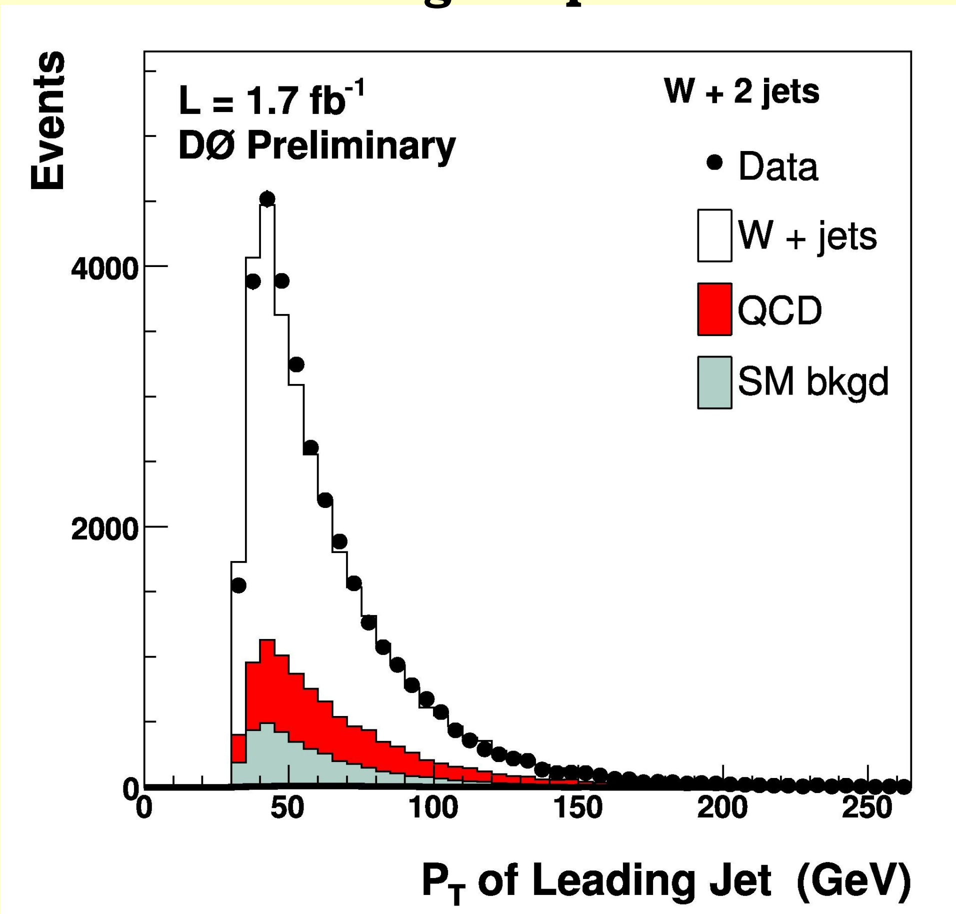
(3) $N\sigma = N \times 1\sigma$

Type II??

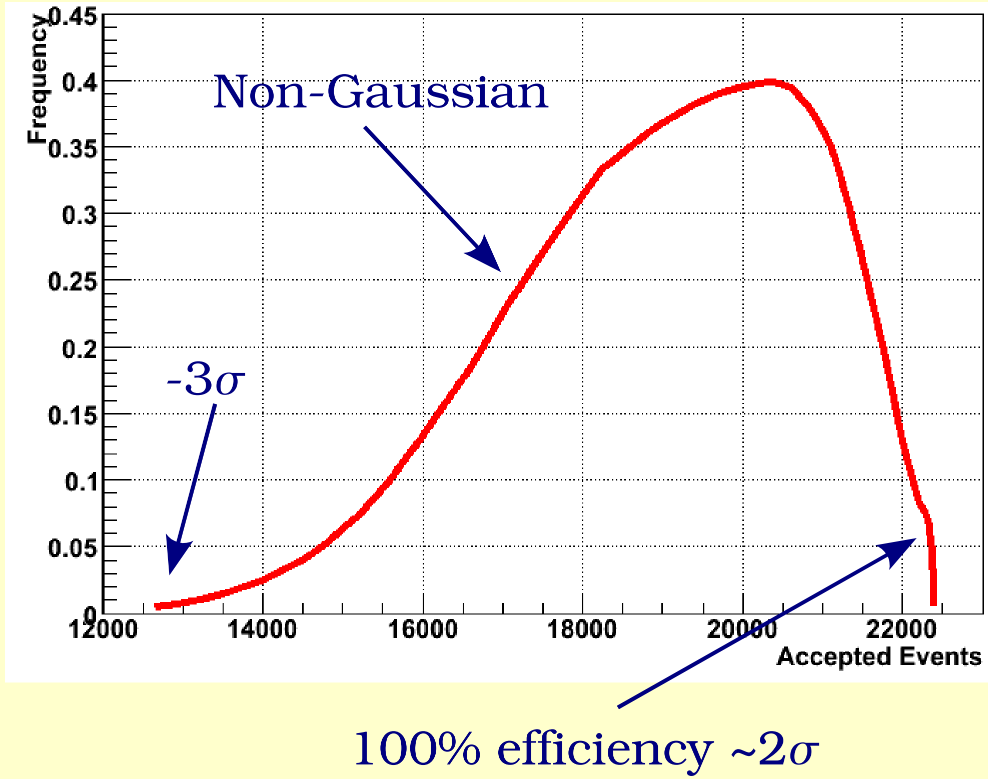
Systematics Example 2

- In reality, response function convoluted with jet pT distributions
  - Result is asymmetric, non-Gaussian, and truncated
  - Shape dependence for final variable is clearly non-trivial
  - Modeling assumption: **N×(1σ) = Nσ?**

Leading Jet pT



Acceptance Response Function

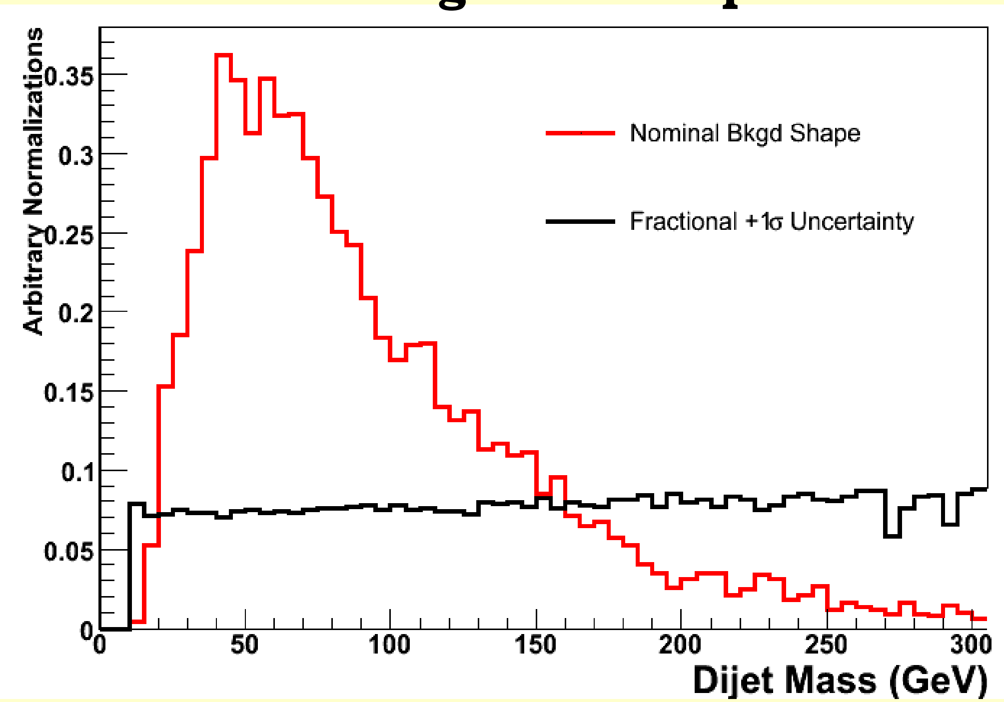


Systematics Example 3

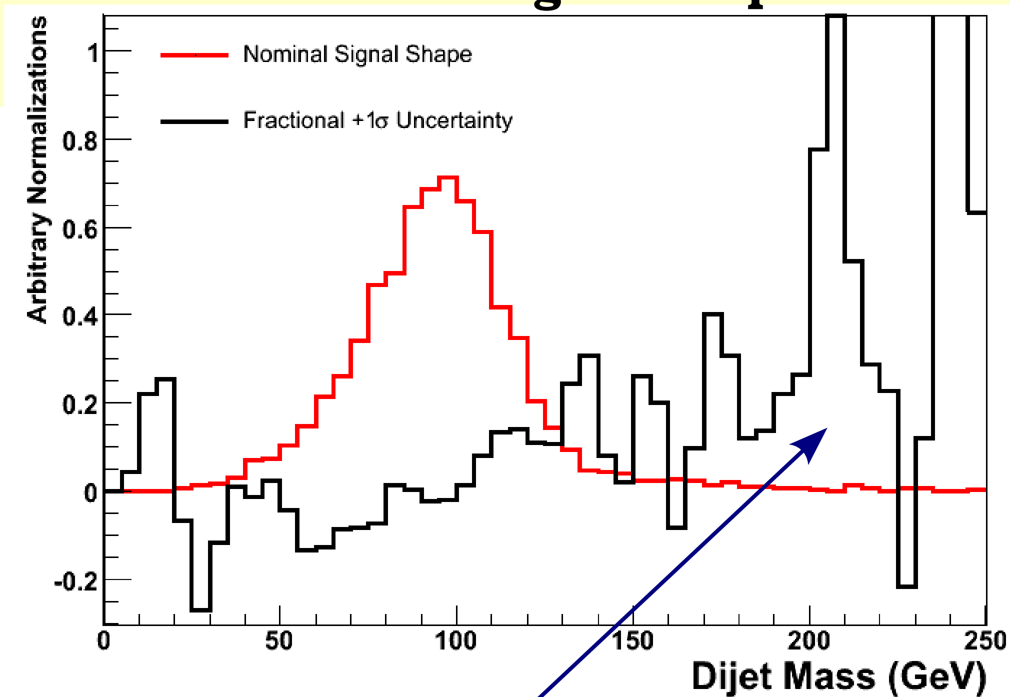
✗ Parametrization of shape uncertainties requires care

- Not all uncertainties have a flat response (*ie, equal values for all kinematics*)
- Procedure: compare shape difference between nominal and shifted distributions
- Treatment of large fluctuations in tails not Gaussian-scalable: need to measure out to N-sigma

+1σ Variation in b-quark Tagging Rate – Background Shape



+1σ Variation in Jet Energy Scale – Signal Shape

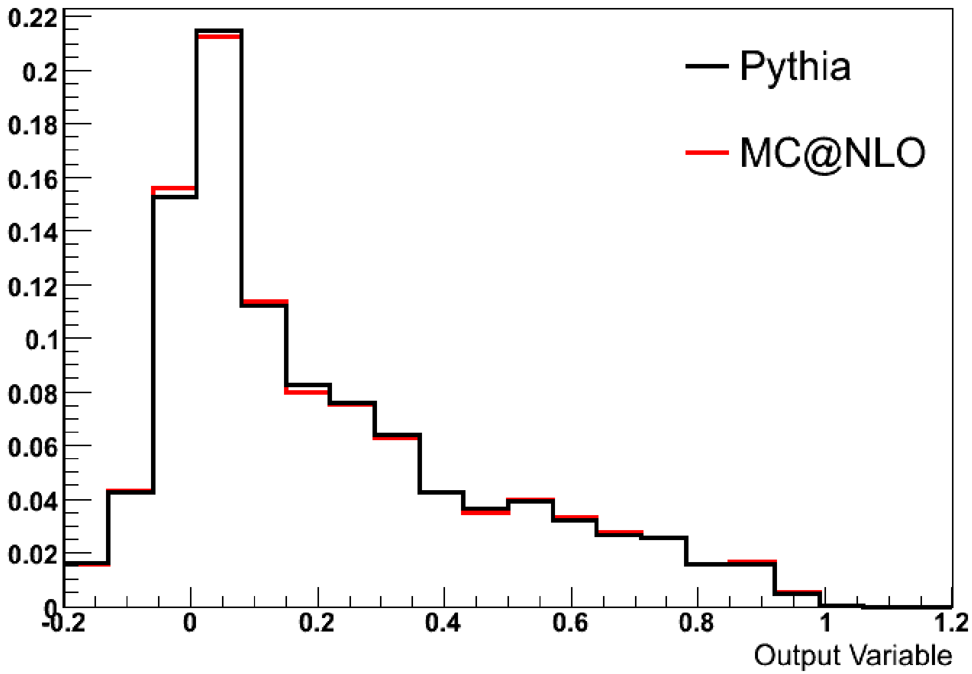


Wild fluctuations in tails!
Uncertainty larger than 100%?

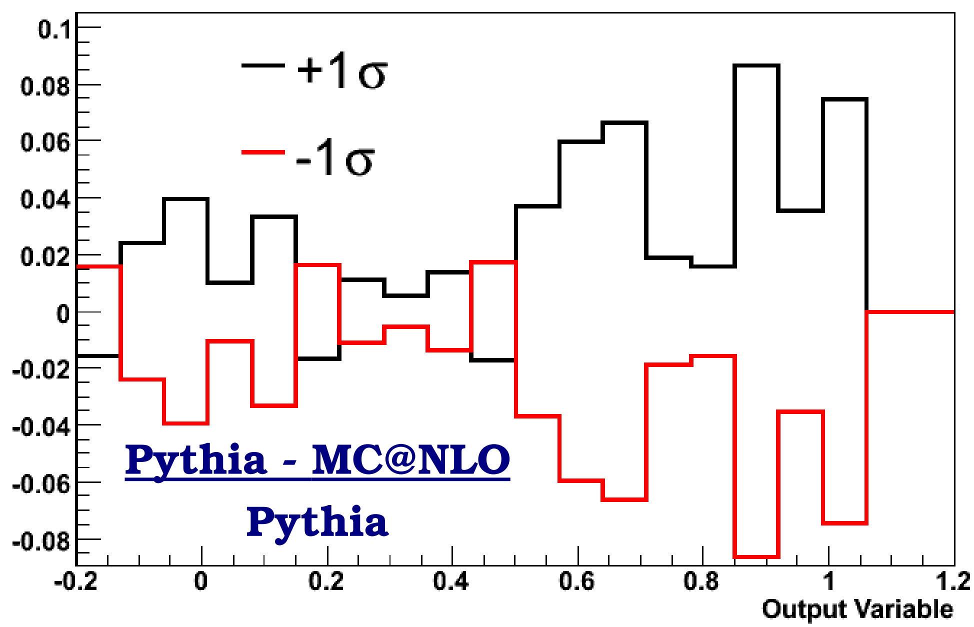
Shape Dependence

- As a specific example, consider SM WW background (diboson) to gg→H→WW. Compare events generated with Pythia vs MC@NLO
- Need good model of shape-dependence across full range of final variable
  - High-statistics region important for fitting, data/MC agreement, etc
  - Low-statistics region translates to signal region, so equally important
  - Simple look at fractional uncertainty dominated by statistical fluctuations

Source Shapes



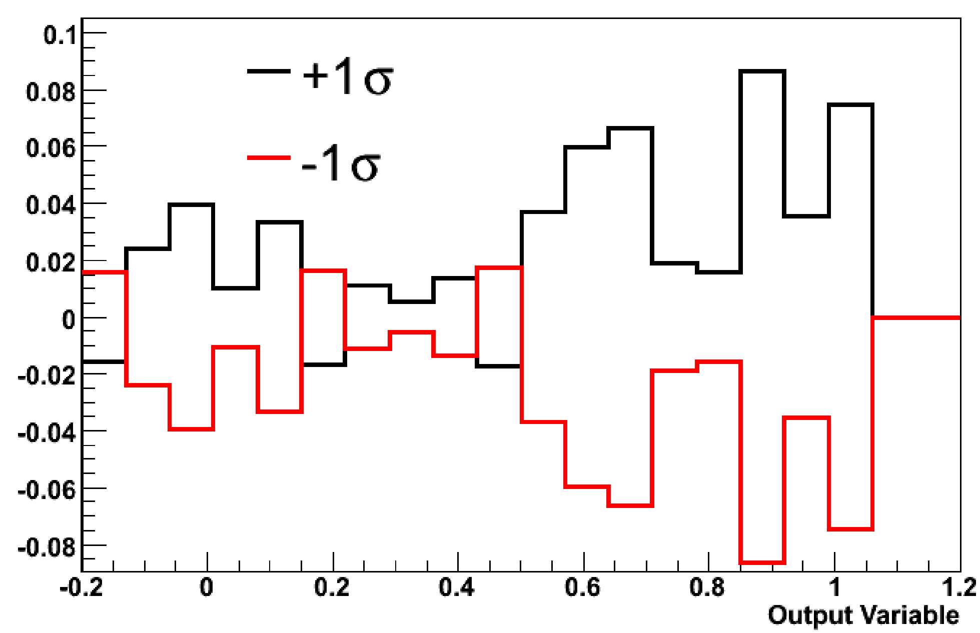
Fractional Per-Bin Uncertainty



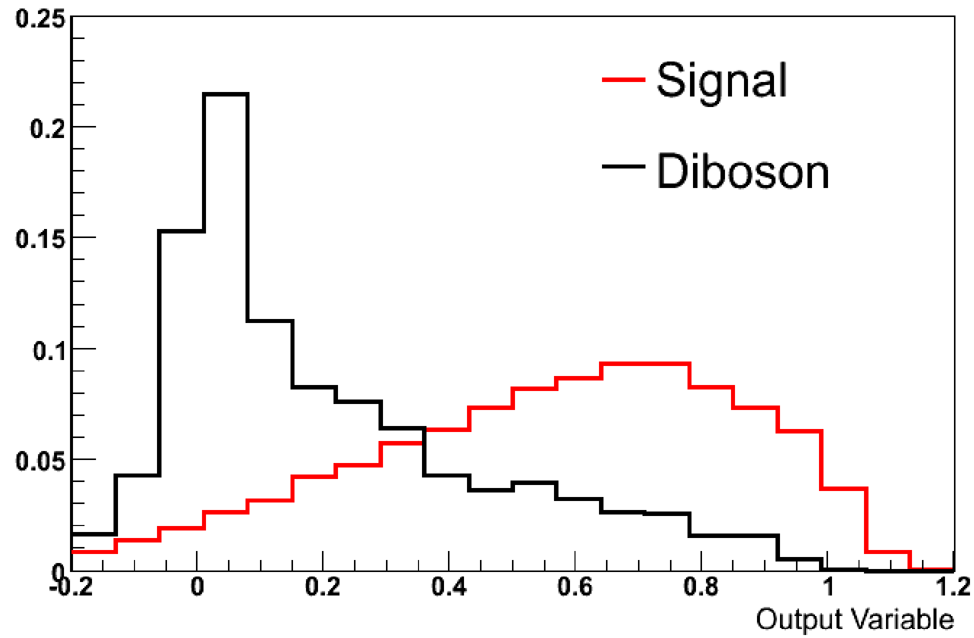
Shape Dependence

- As a specific example, consider SM WW background (diboson) to gg→H→WW. Compare events generated with Pythia vs MC@NLO
- Need good model of shape-dependence across full range of final variable
  - High-statistics region important for fitting, data/MC agreement, etc
  - Low-statistics region translates to signal region, so equally important
  - Simple look at fractional uncertainty dominated by statistical fluctuations

Fractional Per-Bin Uncertainty



Source Shapes



Alternative Shape Options

✗ If infinite statistics isn't an option, consider three alternative algorithms for determining shape dependence of systematic uncertainties:

Smoothing: Smooth all three input histograms (nominal, $+1\sigma$, -1σ) before calculating uncertainties.

Pros: Appropriate smoothing algorithms should preserve parent PDF (ie, won't introduce PDF features).

Cons: Still subject to statistical uncertainty, can eliminate PDF features.

Fitting: Choose appropriate shape and fit to observed uncertainty distribution.

Pros: Provides smoothly varying description of shape (few bin-to-bin stat. fluctuations).

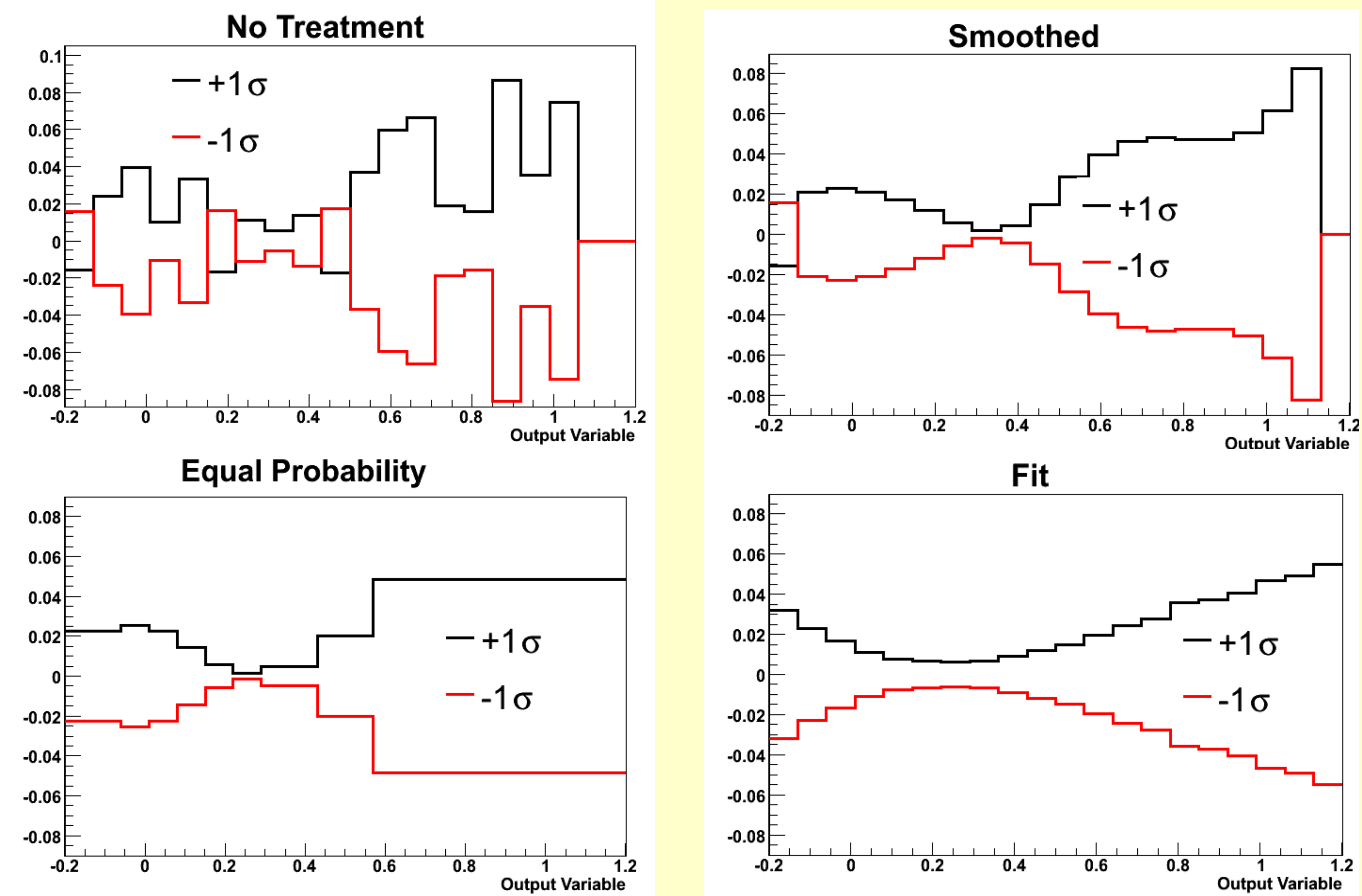
Cons: Fit depends on stat. uncertainty, can eliminate/introduce PDF features.

Equal probability regions: Define uncertainties in regions of equal statistical probability by integrating regions of low statistics.

Pros: Won't introduce PDF features, reduces bin-to-bin stat. fluctuations.

Cons: Can eliminate PDF features.

Alternative Shape Options



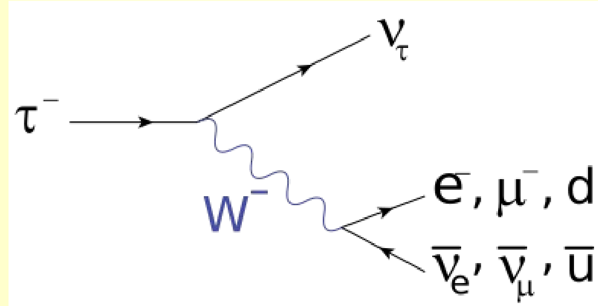
Uncertainties on Theory

- Uncertainties on theory can be *very* murky waters
  - Uncertainty sources don't necessarily translate well to analysis
    - *Uncertainty comes from generator interaction scale Q^2, not muon pT resolution*
  - Definition of size may not have rigorous motivation or estimation.
    - *What does 1-σ mean? 50% 68%? 90%?.*
  - Must be careful to separate cross section (k-Factor) from kinematics.
    - *Don't double count your uncertainty on the cross section!*
- Examples:
  - Uncertainty on interaction momentum scale often quoted as $0.5 < Q^2$ scale<2.0, with nominal value at 1.0.
  - *Is this big enough? Too big? Certainly impacts both kinematics and xsec*
  - Kinematic differences in signal/background from LO⇒NLO⇒NNLO corrections
  - *What's your uncertainty: 100% of difference? 50% of difference? 10%?*
- Need to identify an unbiased, data-driven means to resolve these issues

Channel Compatibility

- In order to combine search channels, we make a few assumptions:
  1) The channels select orthogonal sets of events.
  2) The channels specify common systematic uncertainties.
  3) The channels make the same physics assumptions.

Channel Compatibility



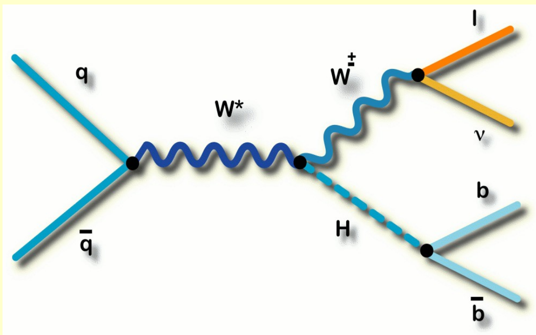
Example tau decays

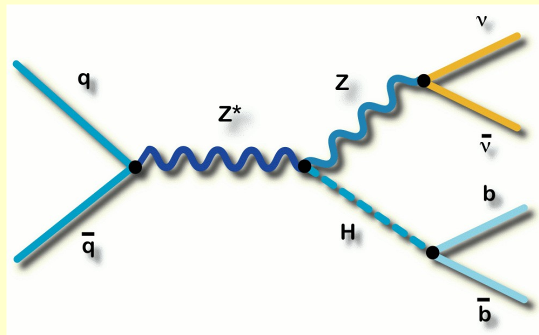
- ✗ Orthogonal event selections

  Obvious or not? Consider the Higgs signal WH→$\tau\nu$bb.

  Tau decays can look like: electrons, muon, or jets:

  This signal can appear in at least three dedicated analyses:





<u>WH→$\tau\nu$bb:</u> Tau identification algorithms should get a lot of this signal.

<u>WH→e/$\mu\nu$bb:</u> Tau decays to electrons/muons will appear as "cross efficiency".

<u>ZH→$\nu\nu$bb:</u> Un(mis)identified taus can end up in this "catch all" analysis.

Which analysis is the best place for the signal to be selected?

Depends on signal/background ratios, systematic uncertainties, etc.

Channel Compatibility

✗ Commonly determined systematic uncertainties

Can we correlate systematics amongst channels?

Within one experiment: Careful choices can make this trivial.

Amongst experiments: Limited to luminosity & theory systematics.

*Correlation amongst channels/experiments leads to greater constraints on the true parameter **(good)**, but leads to invalid limits if done incorrectly **(bad)***

✗ Physics assumptions

What cross sections did you assume (signal & bkgd)?

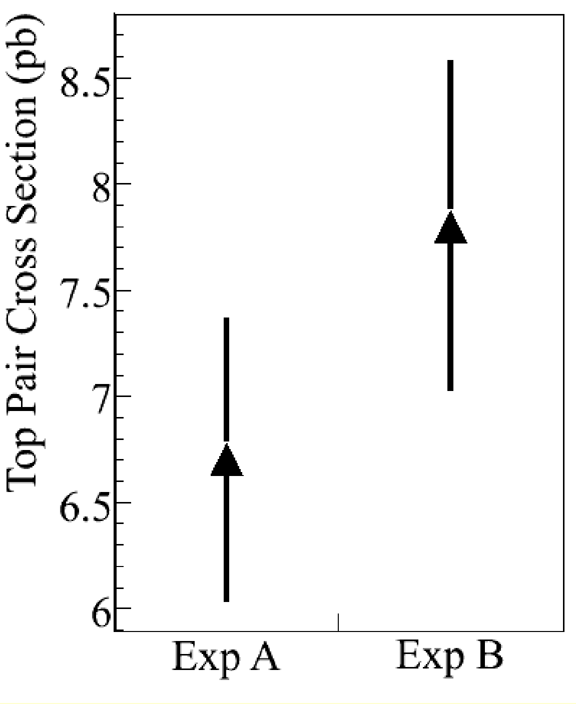
For example, top pair production cross section:

Experiment A: 6.7 ± 0.7 pb, M_{top} = 175 GeV

Experiment B: 7.8 ± 0.8 pb, M_{top} = 171 GeV

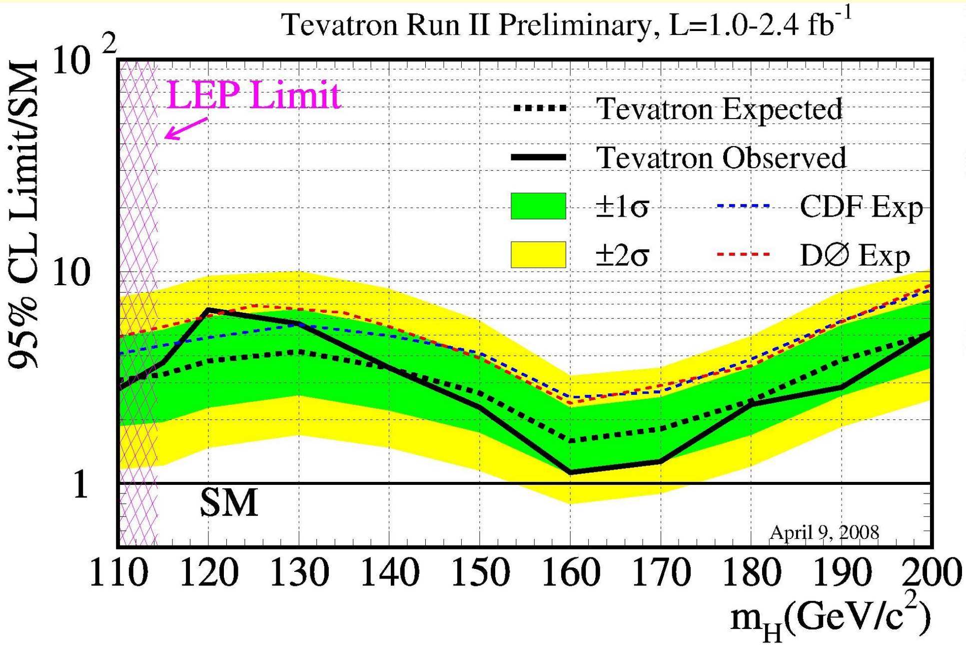
Two valid values for different top quark masses.

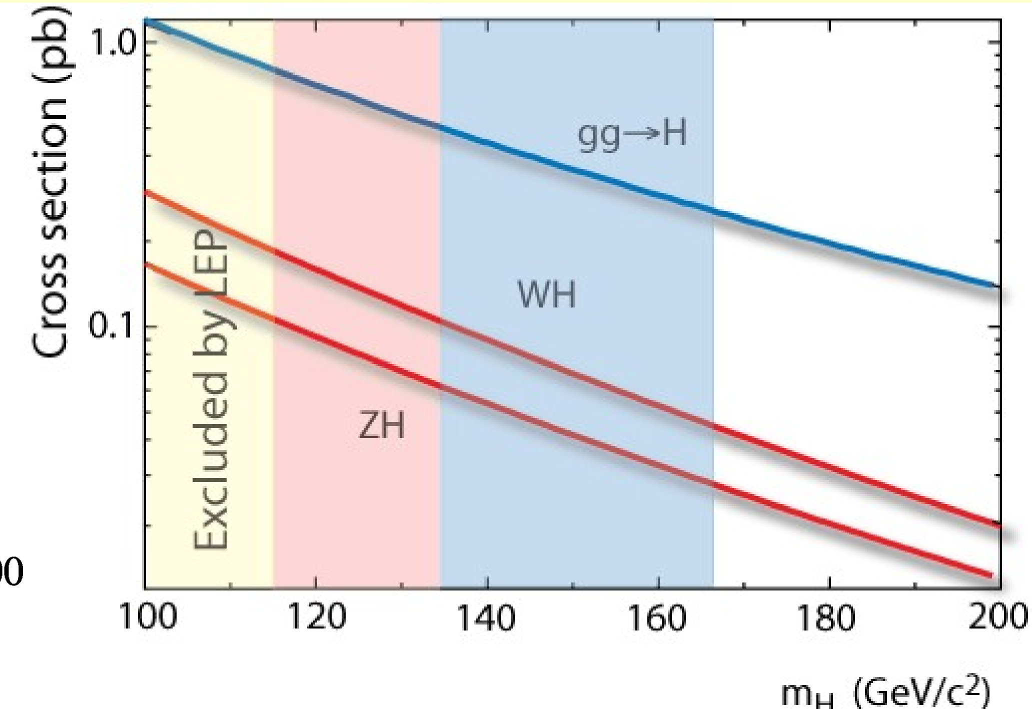
But more than 1σ apart. Valid construction?



Interpretation of Results

- ✗ When calculating upper cross section limits from many channels, what does your limit mean?
  - Tevatron Higgs: We combine WH, ZH, and gg→H production diagrams. Each has a semi-correlated cross section with uncorrelated uncertainties.
  - Solution: Report limits in units of the ratio of the 95% CL upper cross section limit to the theoretical prediction. (Exclusion when **(Limit / SM) = 1.0**)
    - *Assumes fixed cross section ratios amongst production channels.*
    - *Question: How useful is this to theorists for true model constraints?*





Limitations

✗ Total combined luminosity routinely lags behind in many channels

Reasons:

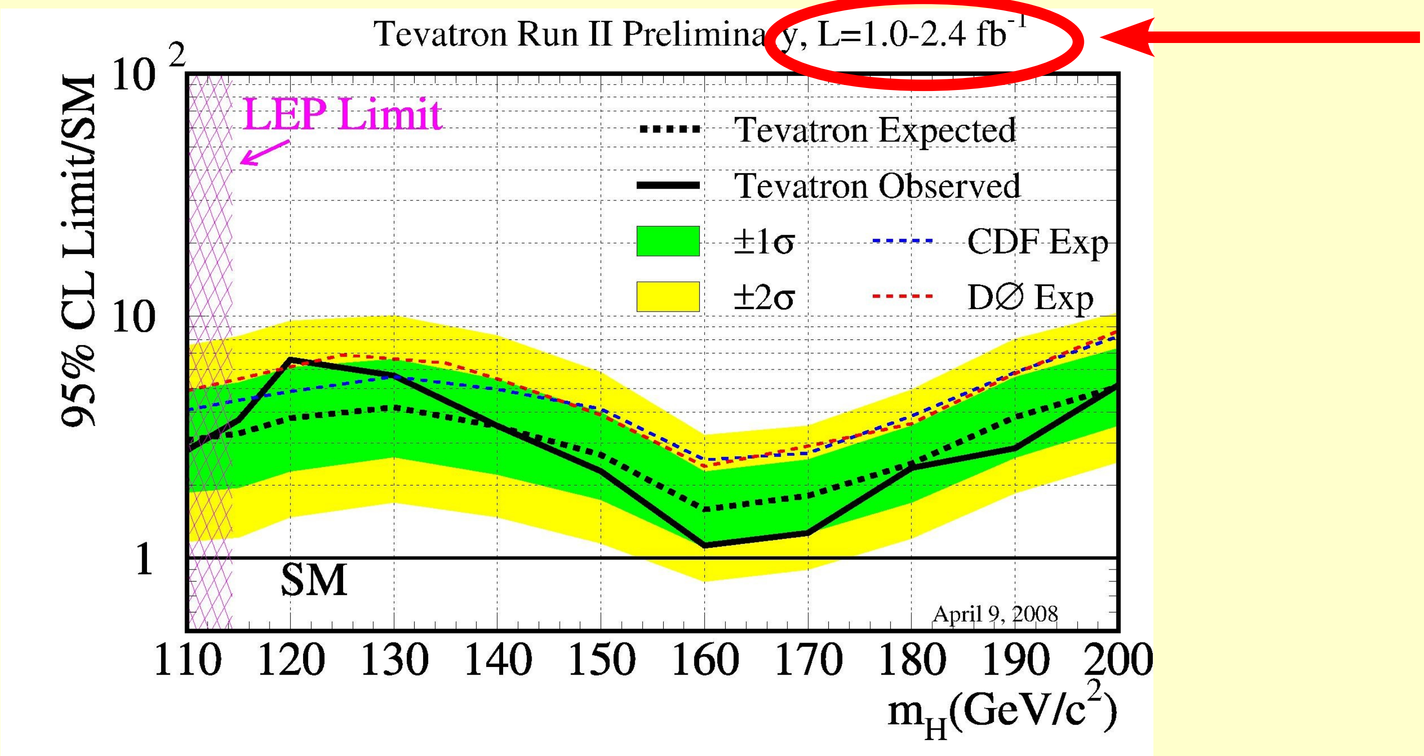
Delays in satisfactory data/MC modeling (eg, trigger turn-on curves)

Interplay of conference schedules and human schedules

Consequences:

Never truly setting limits with a fixed luminosity (*but that's OK*)

Takes more time to reach "design search sensitivity"



Summary

- ✗ This talk covered the unexpected or tricky complications in delivering a combined upper cross section limit.
  - Systematic uncertainties: estimation and interpretation
  - Compatibility of channels: analysis design & physics assumptions
  - Interpretation of results: contrasting ideas of experiment & theory
  - Limitations: realism of time scales and availability of results.

- ✗ Planning ahead helps improve the speed of analysis to limits
  - Many analyses may be systematics-limited, so plan carefully
  - As data is understood, the systematics bar rises
  - Careful analysis design can help keep things simple