Tevatron *for* LHC

Aspen Winter Conference
February 15, 2006

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The TeV4LHC Workshop

organized by ***Marcela Carena*** *and* ***Steve Mrenna*** →

Four meetings were held over the course of a year:
FNAL, BNL, CERN, FNAL

Activities were organized in four categories:

- **QCD**
- **electroweak + top**
- **Higgs**
- **“Landscapes”** = physics BSM but not Higgs

and each group was run by 2-4 conveners (exp+th)

Hundreds of physicists participated.

Currently a grand report is in preparation (already over 200 pages long!).
It is meant to provide a synthesis of each group of presentations rather than an encyclopedic compendium. (This may take a while...)

Workshop Goals

(as I understand them...)

- **Exploit Tevatron data and experience for the sake of the LHC start-up.**
- **Transfer "know-how" and "wisdom" so that the LHC experimenters don't have to re-invent everything.**
    - natural, since many Tevatron experimenters are going to the LHC
    - incidentally, a very good stimulus to ongoing work at the Tevatron...
- **Boost the dialog between phenomenologists and experimenters.**
    - How would we best interpret LHC signals for new physics?
    - Where are better theoretical calculations or tools needed?
- **Make sure that critical data and other Tevatron results are on hand.**

guiding idea →

We must be ready for New Physics at start-up!

What I will say today:

- I will not try to summarize the report not organize my remarks into compartments called QCD, electroweak+top, Higgs and Landscapes.
- Rather, I will try to bring out the main general conclusions of all this work, and cull examples and illustrations from all areas.
- My apologies for excellent results left out...

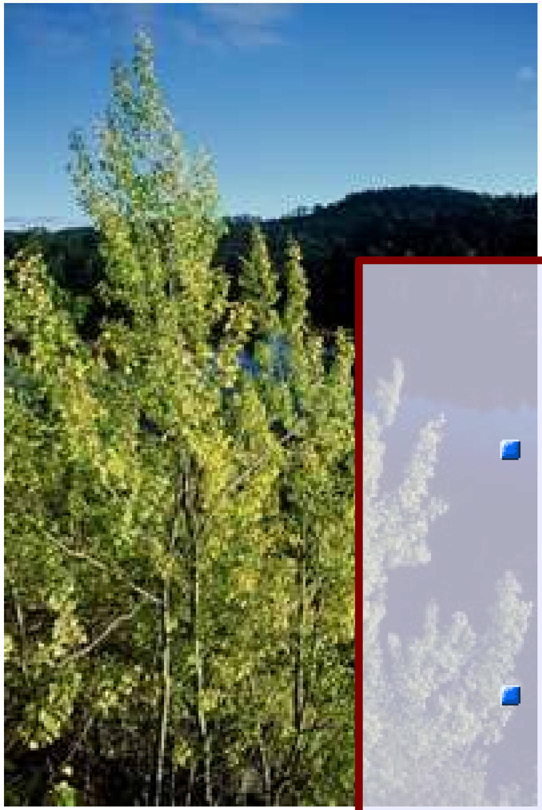
That said, it is clear that this work falls in two main categories:

- the detailed study of Standard Model processes
- discovery of new phenomen**a**

However, these cannot and should not be separated for several reasons:

- Standard Model (SM) processes are background to New Physics (NP).
- NP signals may resemble SM signatures to a degree.
- The push to observe rare SM processes is the precursor for NP searches.
- Observations of anomalies in SM measurements may lead to unexpected discoveries.
- There are many calculational issues/challenges in common
- Validation of analysis techniques (such as the calibration of sub-detectors, validation of algorithms, etc.) needed for NP will be done on basis of SM processes.

This inter-connection permeates the results from TEV4LHC.



- *Hard-Core Experimental Issues*
- *Most Relevant Tevatron Measurements*
- *Theoretical Tools, Input and Progress*
- *General Remarks*

Hard-Core Experimental Issues

electrons & photons

material in the tracker volume:

- Real understanding of electron and photon signals requires measurements of the amount of "material" in the tracker volume.
- This material causes radiation which degrades the signal.
- historically, three successful methods: 1) conversions, 2) E/p, and 3) tridents
- promising new idea: use the channel pp $\rightarrow \mu\mu\gamma$ (from $Z \rightarrow \mu\mu$)

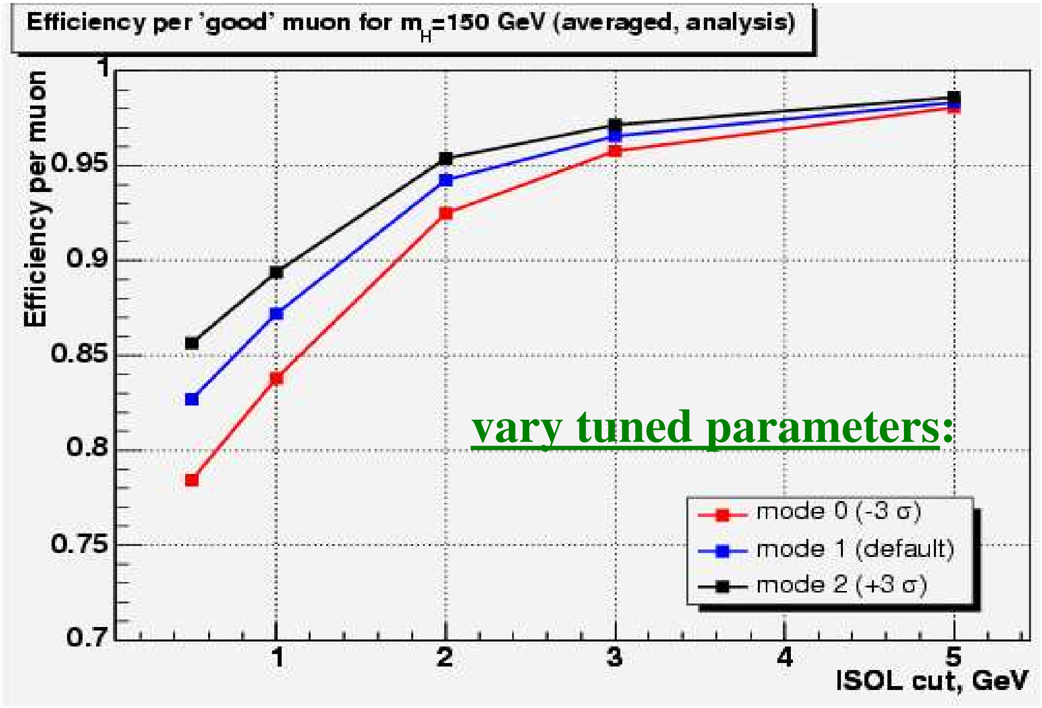
de-construct Bremsstrahlung:

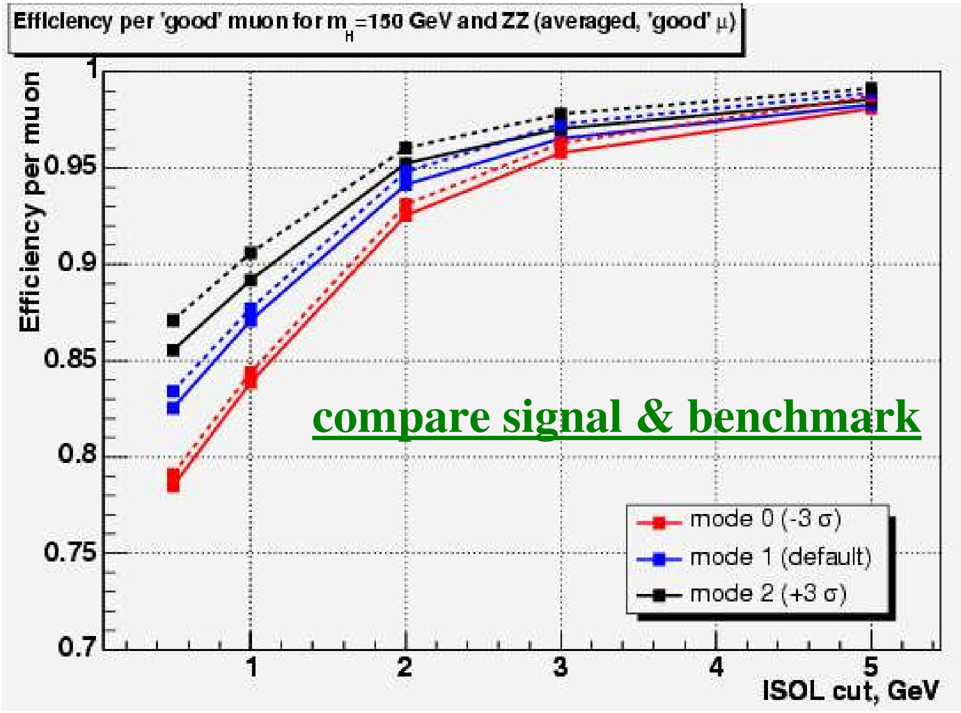
- Electron energy lost by radiation obviously degrades resolution.
- In many instances we can identify the radiated photon.
- Put that photon back into the electron, ie, construct the "parent" electron.
- This idea has been validated with real D∅ data!
- A clear reduction in tails of mass peaks is observed.
- Already implemented in CMS code.

ins and outs of efficiency measurements: explained by Heidi Schellman.

muons

- <u>ISOLATION</u> is and will be crucial for lepton-based analyses (SM & NP).
- Study done to compare impact of the underlying event on isolation efficiency.
- How do we simulate the U.E. correctly? Use Tevatron data.
  Specifically, use the tune on PYTHIA by CDF and vary relevant parameters.
- Impact on, for example, $H \to ZZ \to \mu\mu\mu\mu$ is not small...
- A SM benchmark process can be used to improve tunes at the LHC.

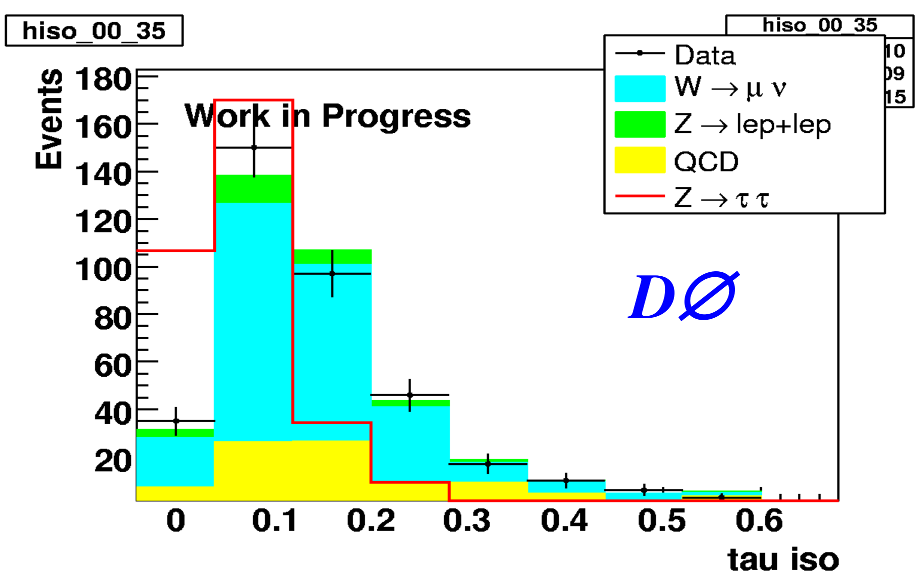


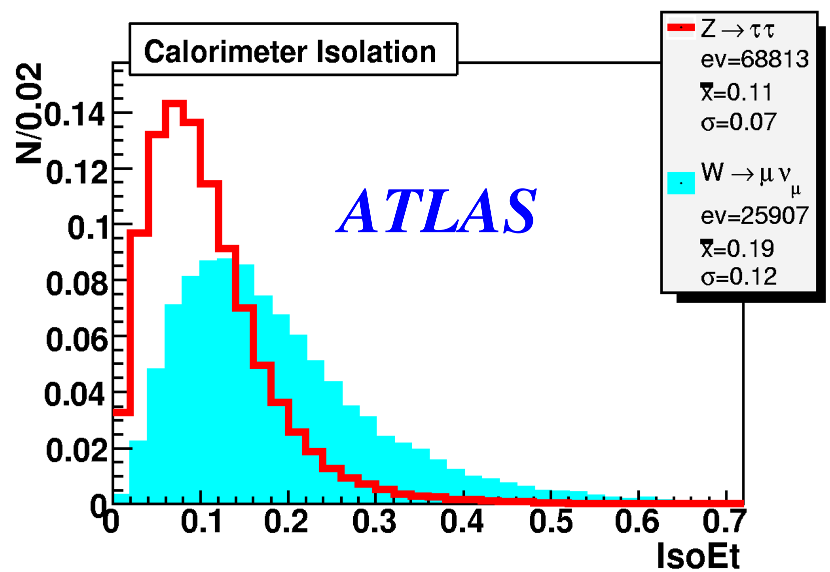


τ leptons

"τ-identification, from DØ to ATLAS"

- τ-reconstruction and identification is complicated: several different final states
  - hadronic states are difficult to distinguish from quark & gluon jets
  - many kinematic and topological quantities must be used
- tremendous progress has been made by CDF and DØ during Run II
  - requires advanced techniques, such as artificial neural networks
- use DØ real data and simulation to gauge how reliable ATLAS simulation might be
  - compare and contrast the DØ and ATLAS algorithms on ATLAS simulations
  - work still in progress; here is an example:





Use *W*→μν to calibrate *Z*→ττ, a benchmark for *A*→ττ.

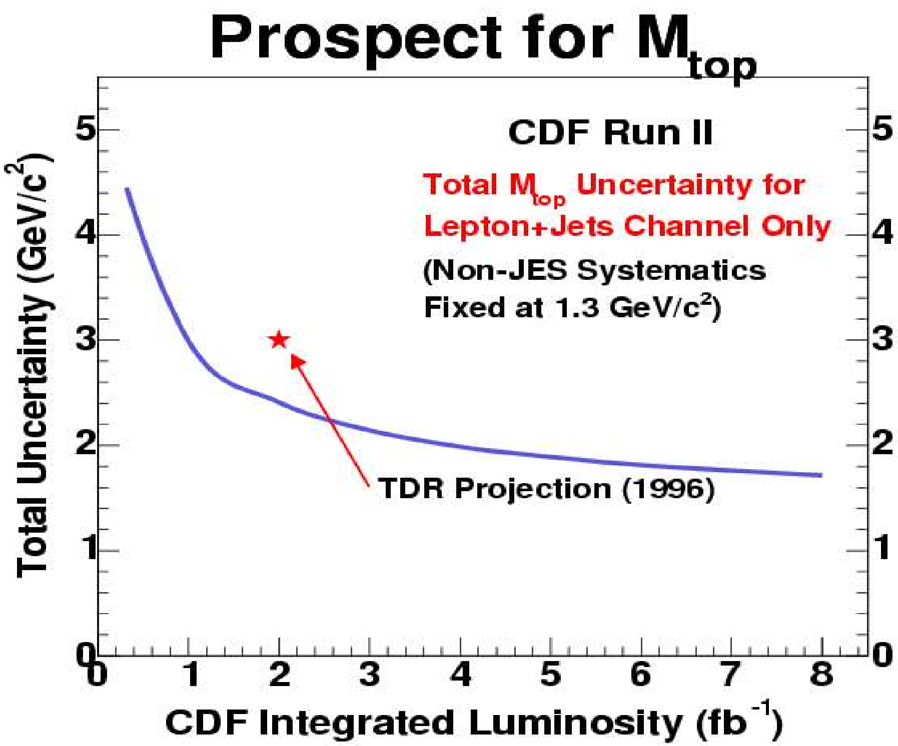
Jet Energy Scale (JES)

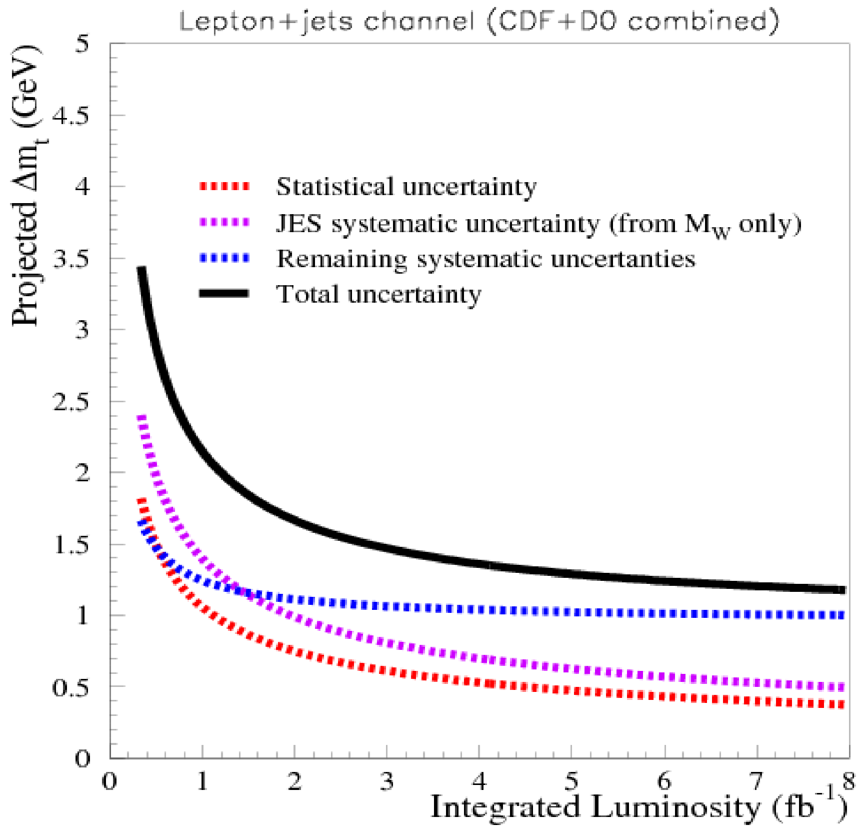
One expects $\delta M_t < 1.3$ GeV by the end of the Tevatron program.

- There are several levels of jet energy corrections, now thoroughly understood at Tevatron.
- However, standard energy scale techniques not good enough for top mass measurement.

"Make a virtue of necessity."

- In the "lepton+jets" sample, two jets come from a *W* decay.
- Constrain those jets to give the *W* mass (within resolution and B-W shape).
- Tie also *b*-jets to that derived scale, albeit with an adjustment factor (*b*-jets are different).
- A hard systematic now scales with luminosity.
- Prospects for a very precise measurement are excellent: (see: Andrew Ivanov)



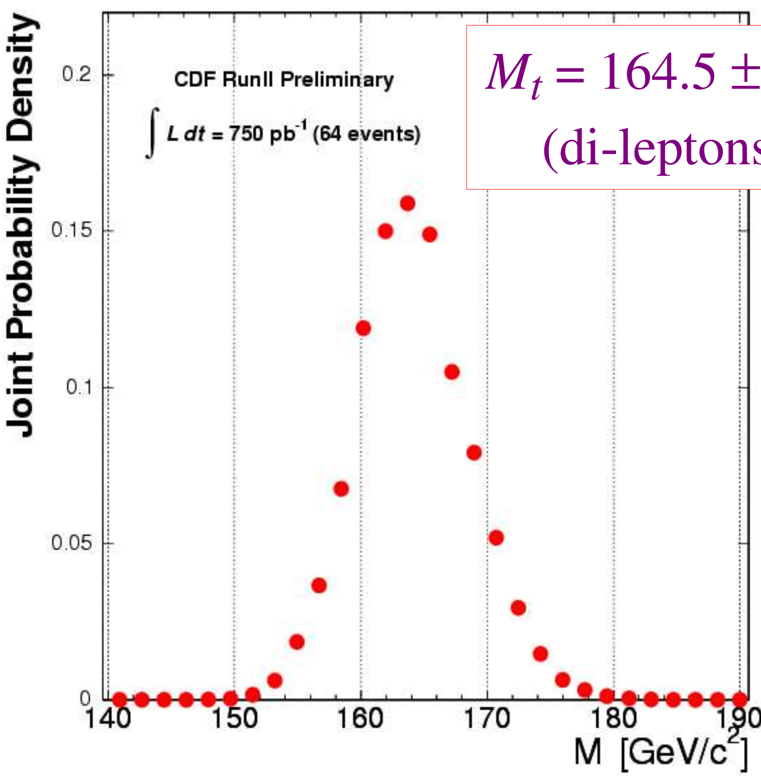


Matrix Element Methods for M_t

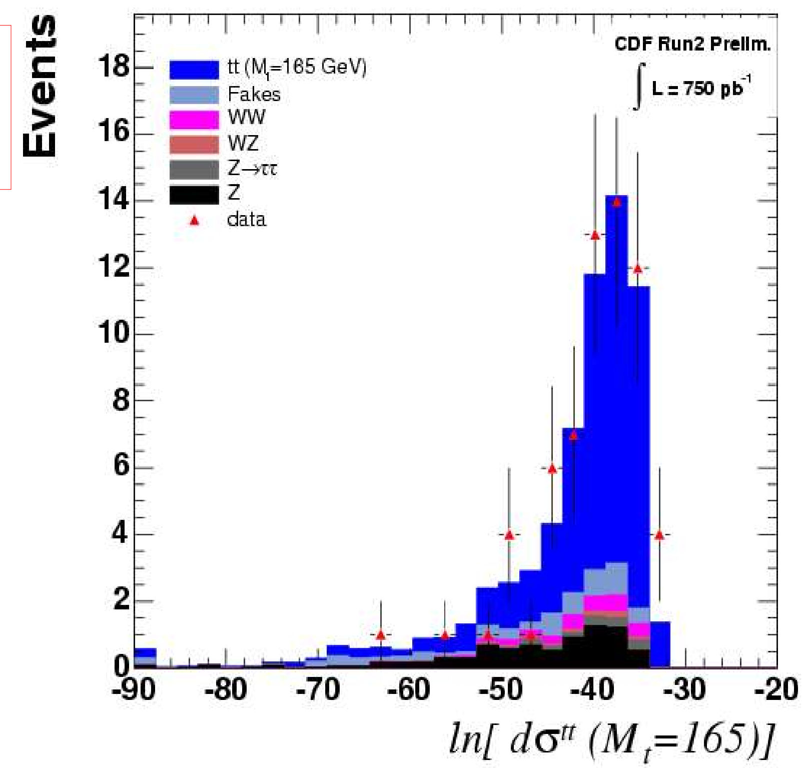
(cf: Andrew Ivanov and Heidi Schellman)

- It's smart to get the most out of your data!
- All kinematic features come from the matrix element.
- New technique introduced by D∅ and taken up by CDF uses M.E. directly, in place of "simple" kinematic quantities such as the invariant mass.
  - use M.E. as the PDF on an event-by-event basis
  - M_t enters parametrically
  - minimize the global likelihood w.r.t. M_t
- A huge boost to the statistical power of the data.

$$P(x|M_t) = \frac{1}{\sigma(M_t)} \frac{d\sigma(M_t)}{dx}$$

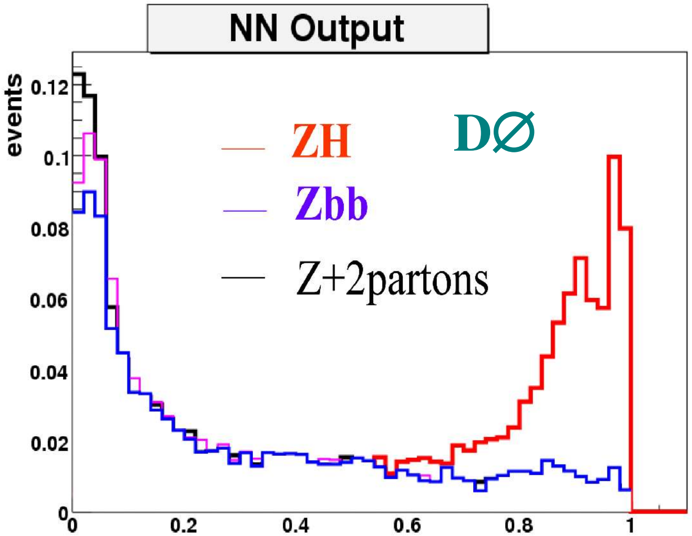


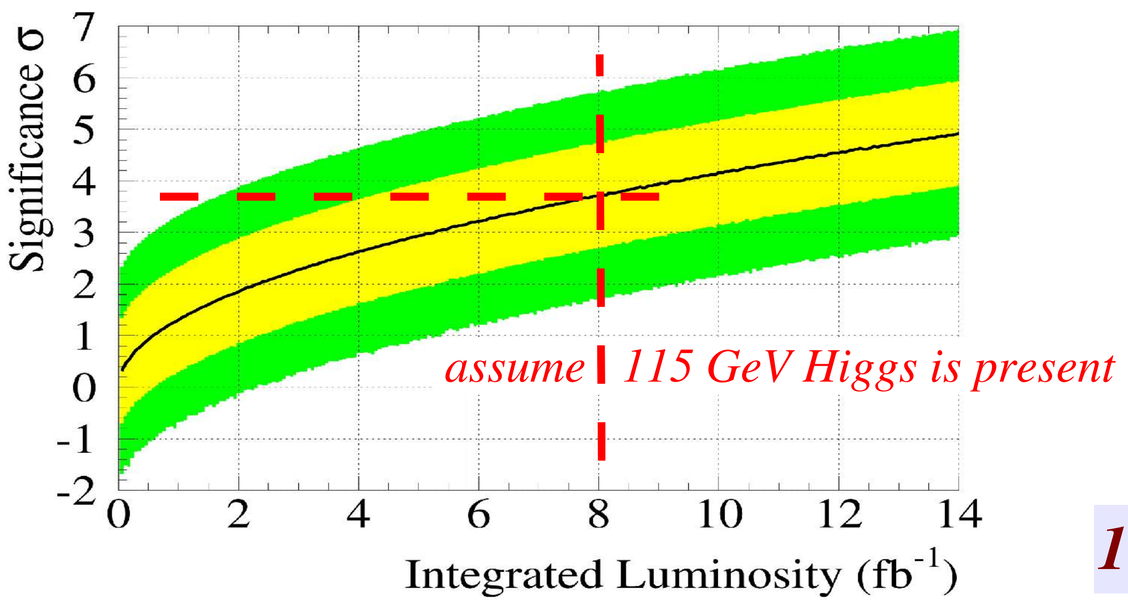
$M_t = 164.5 \pm 4.5 \pm 3.1$ GeV
(di-leptons, 750 pb^{-1})



Higgs Searches at the Tevatron

- The search for the SM Higgs boson remains a priority at the Tevatron.
- But it is clear that current analyses, even with a lot more data, won't make it.
- A number of "hard core" improvements seem to be in hand --
  if realized, then the Tevatron will be **very relevant** for Higgs searches.
  - improved *b*-tagging, making use of 3D vertexing and forward jets
  - extend lepton-ID in the forward direction
  - optimize lepton-ID criteria, esp. as regards the "loose" lepton
  - improve the di-jet mass resolution
  - employ multi-variate methods
  - re-optimize for cross-channel "signals" (e.g., *WH* in *ZH*)
- Together these may amount to a factor 5 – 10 improvement in the
  per event sensitivity of the Tevatron Higgs search.

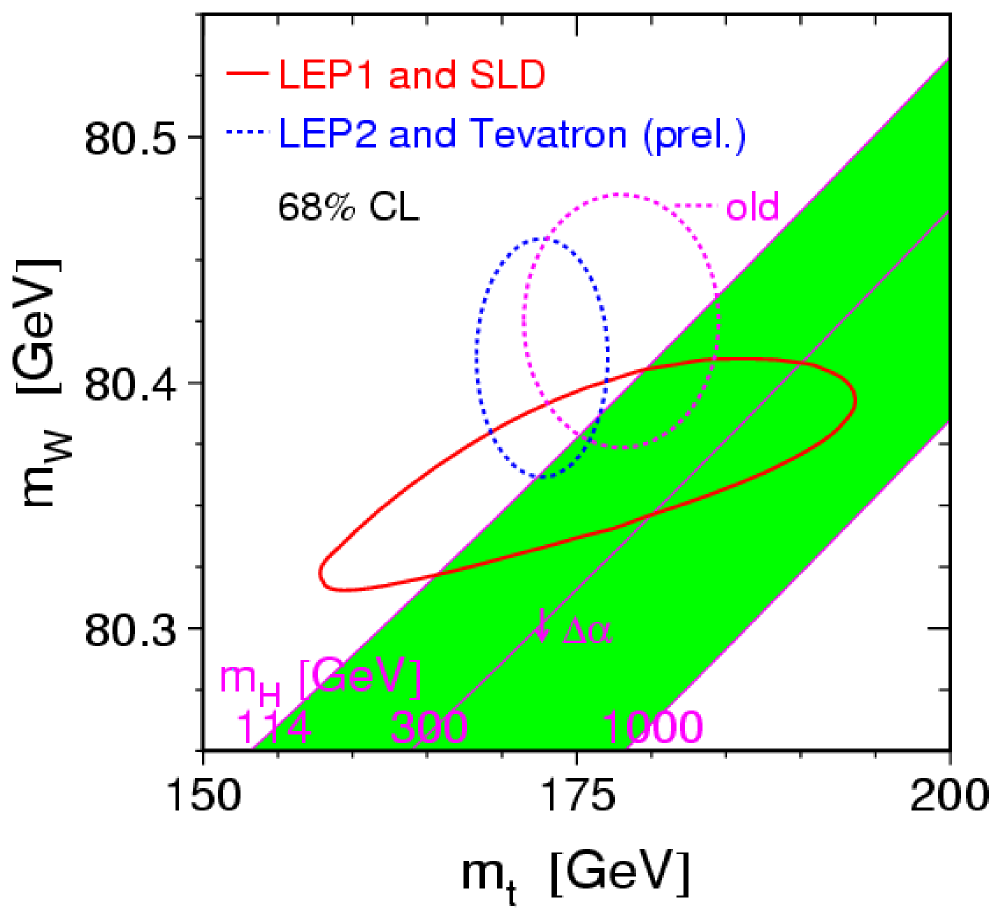




Most Relevant Tevatron Measurements

M_t and M_W

These "nuisance" parameters enter the most important theoretical calculations of the day, esp. those aimed at the LHC.



Theoretically they are intimately related to the (SM-like) Higgs boson, so measurements of M_t and M_W are central in the indirect constraints on M_H.

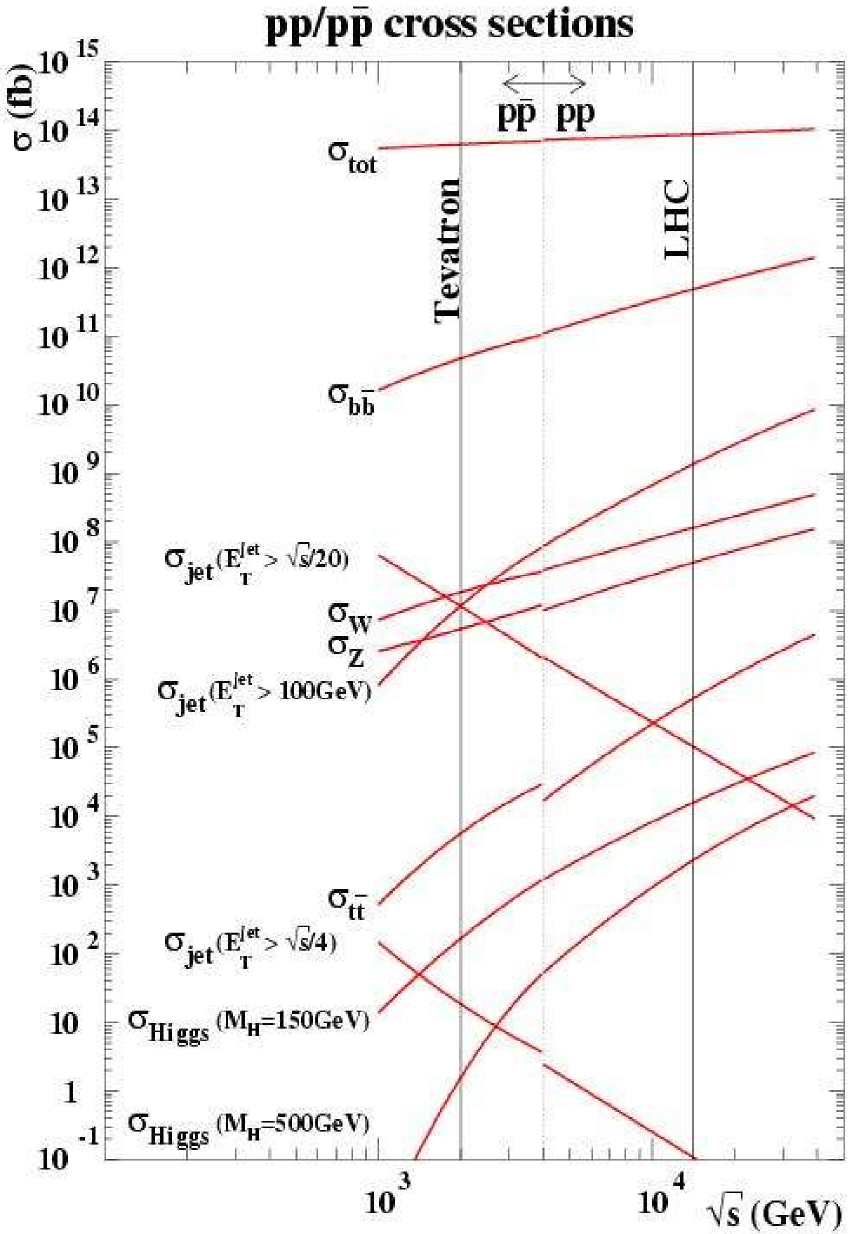
Tevatron will provide the best measurements for many years.

$$\delta M_t \rightarrow 1.5\, GeV$$
$$\delta M_W \rightarrow 30\, MeV$$

(Laura Reina pointed out that this will improve $\Delta M_H / M_H$ by a factor of 2 w.r.t. LEP + Run I!)

Will future Tevatron measurements increase this "tension" to the breaking point?

σ_W and σ_{DY}



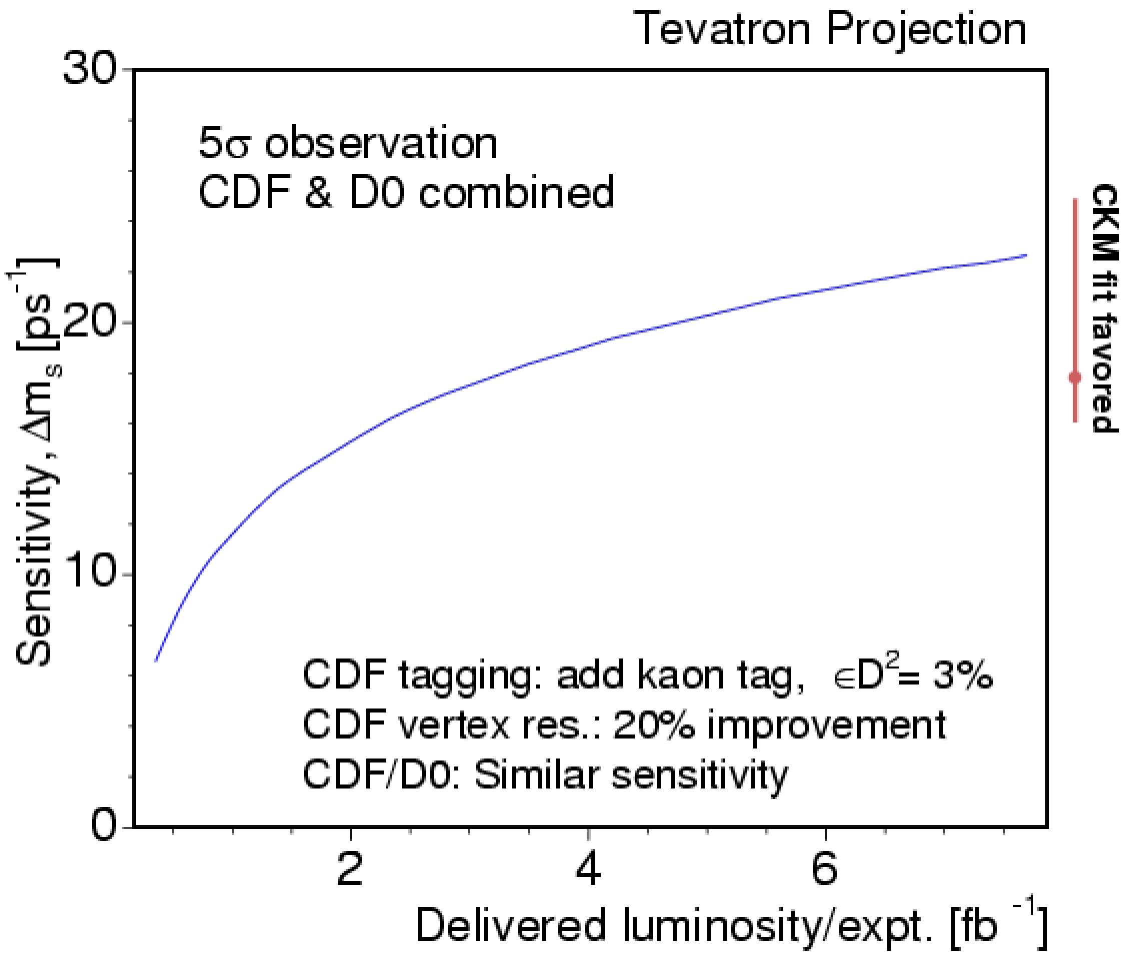
- an important test of advanced QCD and EWK theory
  especially differential cross-sections probe theory
  (cf: Laura Reina)

- measured to 2% or better, aside from luminosity error
  → use these as the **definition** of luminosity
  (cf: Heidi Schellman)

- These are not easy measurements –
  getting them right shows that detector & algorithms
  are understood – a validation of basic data analysis

B_s - mixing

oops, this was not covered!



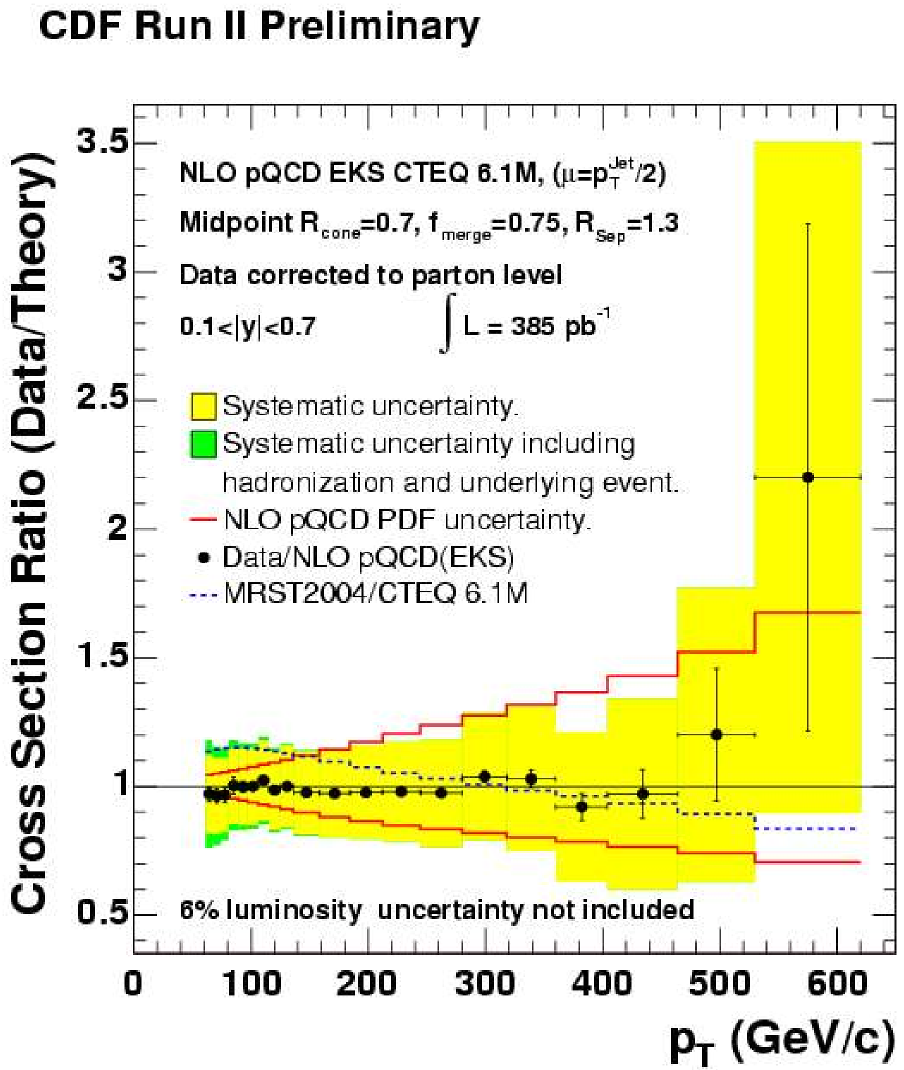
Notice that the SM-favored region will be covered.

Suppose Δm_s is not there – new physics in the flavor sector?

PDF's

(parton distribution functions)

- essentially all cross sections depend on these, esp. *g(x)* is important!
- excellent information is coming from HERA (cf: Roberto Carlin)
- Certain Tevatron measurements can provide powerful constraints, too:
  - W charge asymmetry (*u/d*)
  - direct photon production (HF)
  - high-E_T jet production (*g*)



- yellow bars are experimental systematics, mainly jet energy scale
- red lines show PDF uncertainties
- blue dotted line compares MRST2004 and CTEQ6M
- These data are on the verge of constraining the PDF's tightly.

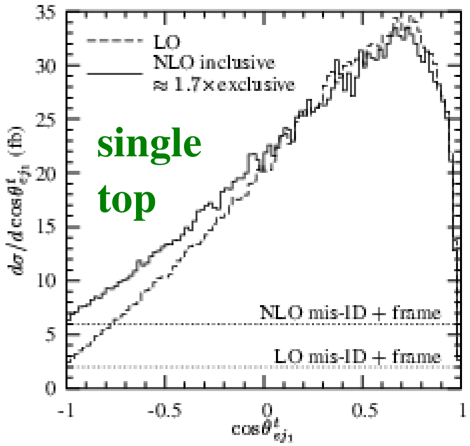
Theoretical Tools & Input

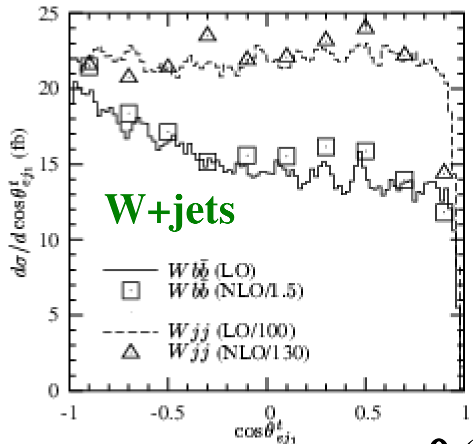
- The LHC program will not succeed without theoretical input !!!
- Tevatron data provides the impetus for some of the “down-to-earth” work.

Cross-Sections, BF's and Angular Distributions

- Experimenters need specific improvements in the calculation of certain (differential) cross sections, branching fractions and angular distributions.
- mainly a question of radiative corrections + higher orders, but these are not easy!
  - example: NNLO $d\sigma/dy$ for inclusive vector bosons (Dixon *et al.*)
  - example: one-loop QCD multi-parton processes (G. Zanderighi *et al.*)
- Sometimes rad. corr. can have a crucial effect:
  - QCD corrections to inclusive vector boson production,
  - Δh_b in Higgs decays
- We also need to evaluate residual theoretical uncertainties especially for precision electroweak measurements.
- Accurate simulations of events may require **matrix elements** rather than **parton showers**.

Example: lepton-jet corrections for single-top search

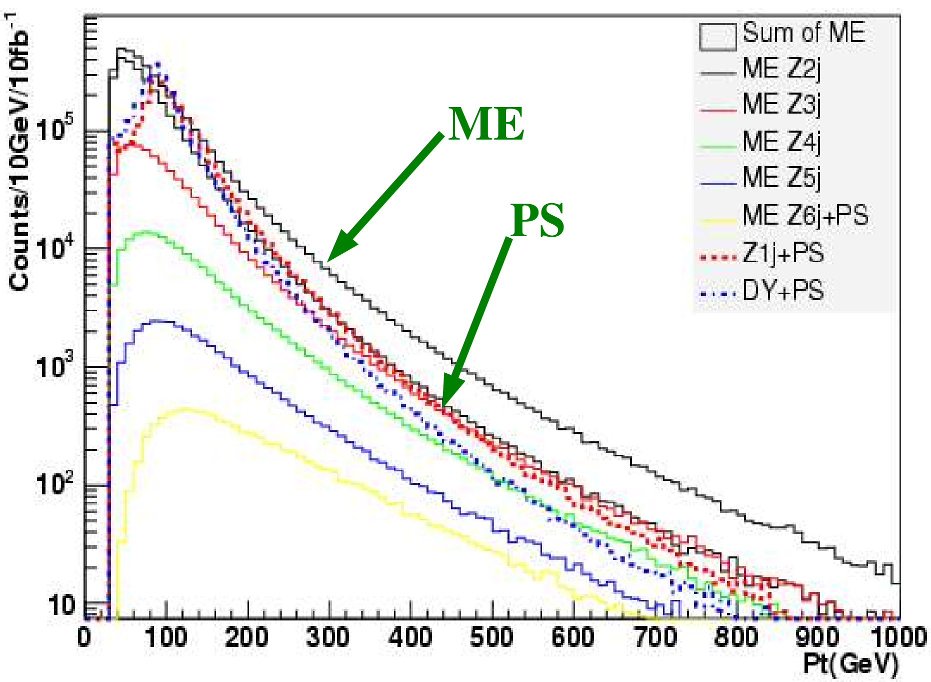




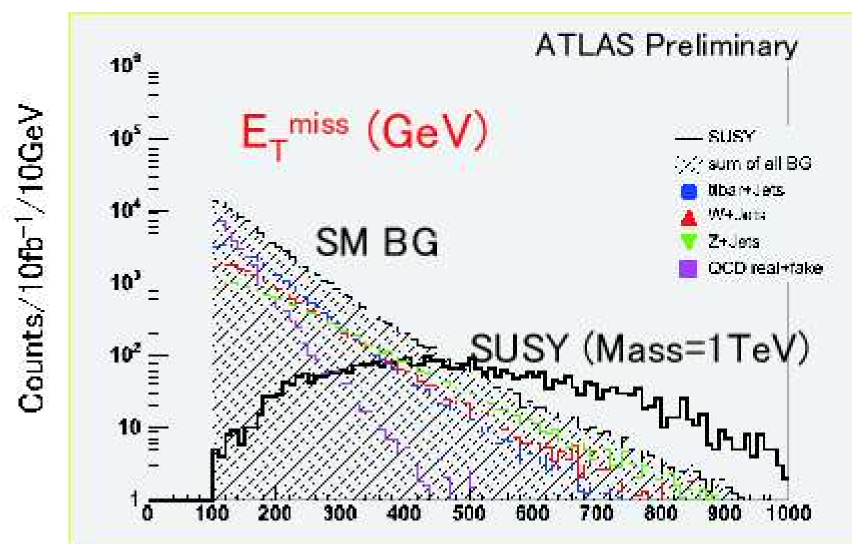
cos θ (e-jet)

For this case it turns out that the NLO distributions are similar to the LO scaled by a fixed *K*-factor. Tevatron data can test this.

Example: matrix elements vs. parton showers for Jets+MET Search



p_T(Jet)



ATLAS Preliminary

New, Improved Event Generators

(for details, see Peter Skands, hep-ph/0601103)

- **MCFM, RESBOS, ALPGEN:** these go beyond the PYTHIA/HERWIG models and include real matrix element calculations. They are being improved today.

- **MC@NLO, CKKW:** generate inclusive jets at NLO

- **MadGraph/MadEvent, WhiZard/O'Mega, Sherpa/Amegic++ :** these are very complete and sophisticated event generators for MSSM processes.
  - spin amplitudes!
  - efficient generation of codes for reduced CPU load
  - multi-channel adaptive sampling of phase space
  - structure functions for incoming partons
  - interface to, e.g., PYTHIA for hadronization (Sherpa does this itself)
  - These three programs have been shown to agree! (hep-ph/0512012)

Matching Schemes

(cf: Steve Mrenna & others, hep-ph/0509127, 0312274, ...)

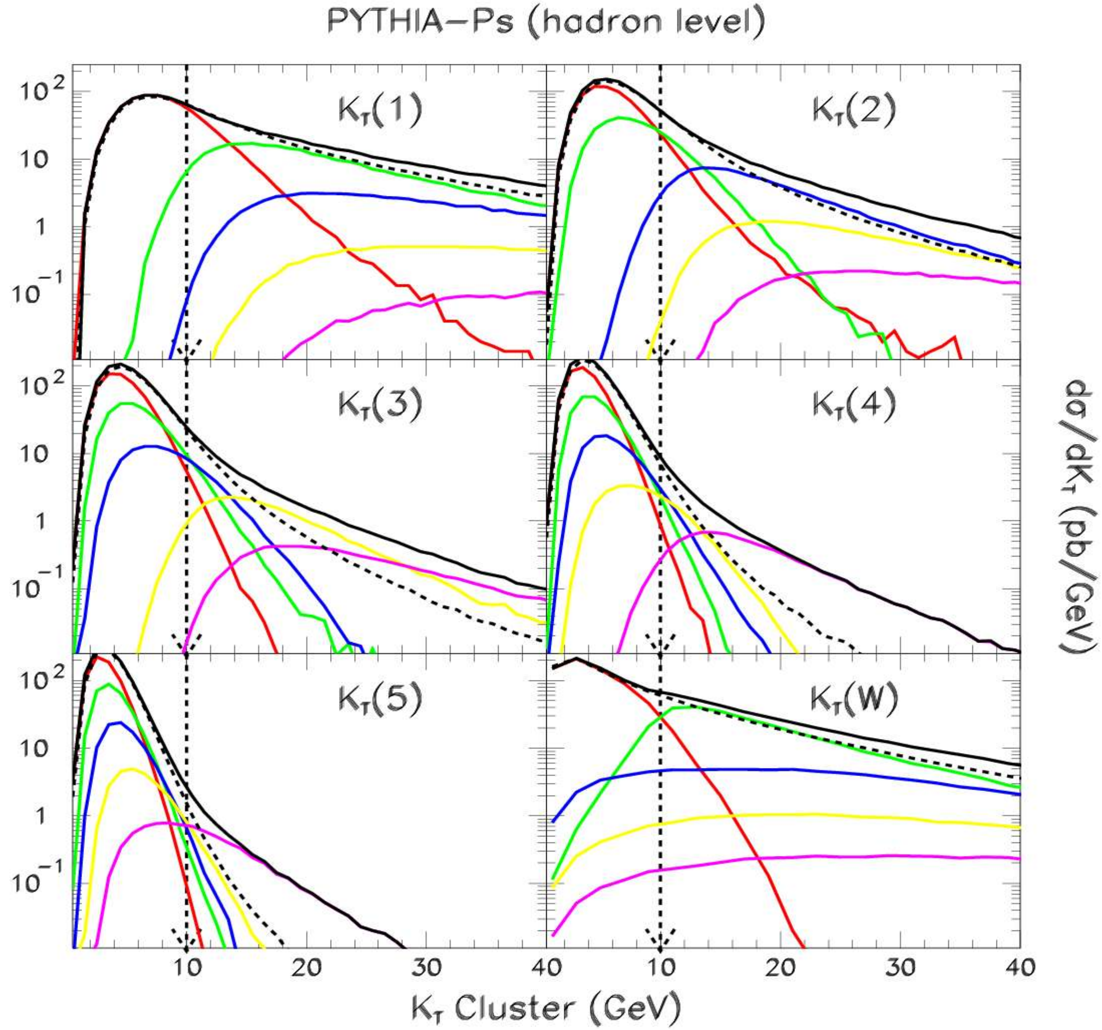
- There is a well-known thorny problem faced by experimenters: When it comes to *N* partons, where do PS end and ME begin?
- A typical case is "W + jets" production at the Tevatron. The uncertainty from this theoretical issue is not small compared to systematics. LHC will produce even higher numbers of partons in the final state...

Theorists are making a serious effort to tackle this problem rigorously.

CKKW

- interpolate from "hard scale" ME to "soft scale" PS employing Sudakov factors and α_S
- merge the ME and PS steps inside the same rejection algorithm
- requires a clustering of partons for this merging

(**MLM** similar)



Constraining Theoretical Parameter Space

- Suppose you have observed new physics and you believe it is SUSY. How do you infer the corresponding theoretical parameters?
- This is the inverse process of Monte Carlo event generation.
- New codes address this (future) need directly.

SFITTER (hep-ph/0404282)

- interfaced to several advanced codes for sparticle properties, cross sections, etc.
- there are too many free parameters, so SFITTER entertains certain popular models of low-energy supersymmetry
- initial multi-dimensional grid avoids biases from starting point
- Authors considered LHC measurements and mSUGRA model (SPS1a), and showed that theoretical uncertainties on sparticle masses need to be reduced.
- Also, the Tevatron measurement of M_t will be very important.
- Finally, even a “hint” of the Higgs boson with $\Delta M_h = 4.5$ GeV helps a lot.

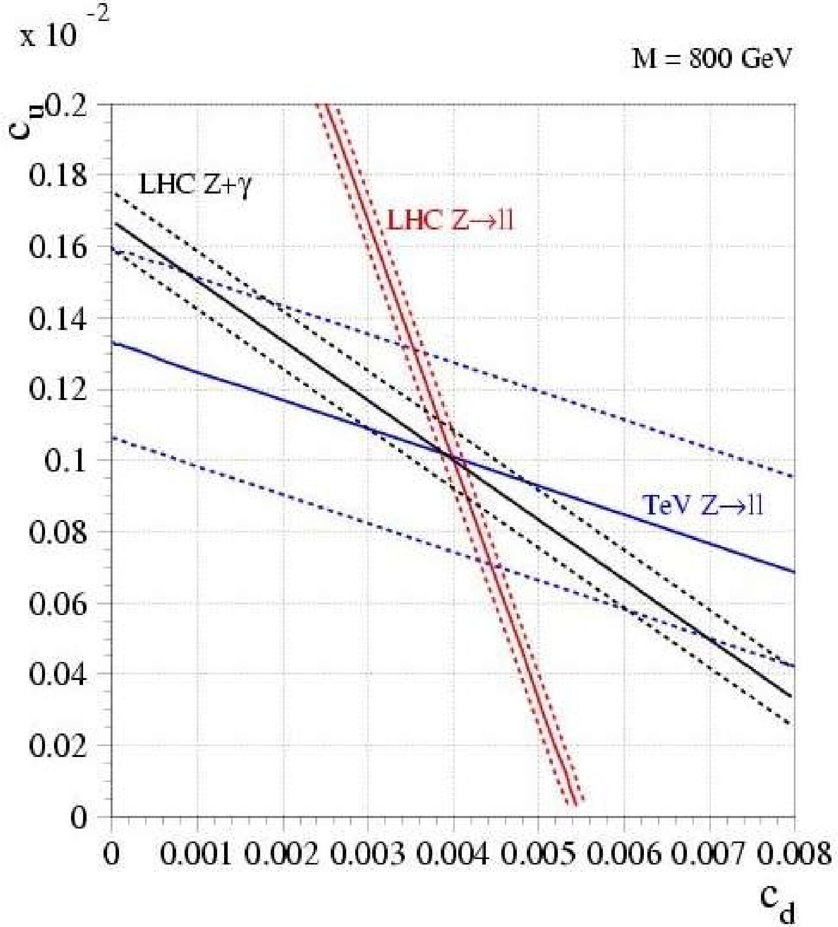
(**FITTINO** similar)

Model-Independent Parametrizations

- Perhaps one should put a buffer between observables and the models.
- Purely phenomenological formulations can encapsulate the results from experiments.
- example: $\boldsymbol{Z'}$ signals (hep-ph/0408098)
  - recent work provides a very general parametrization for the cross section:

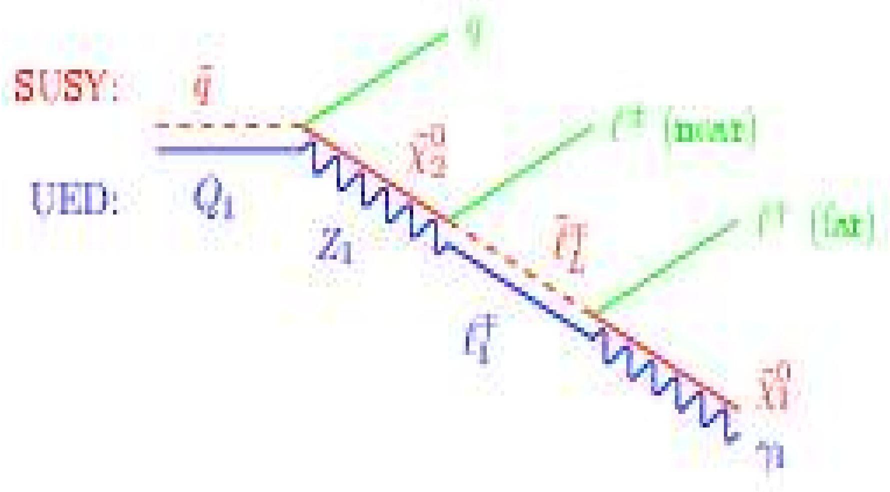
$$\sigma(Z') = \frac{\pi}{48\,s}\left[c_u w_u(s, M_{Z'}) + c_d w_d(s, M_{Z'})\right]$$

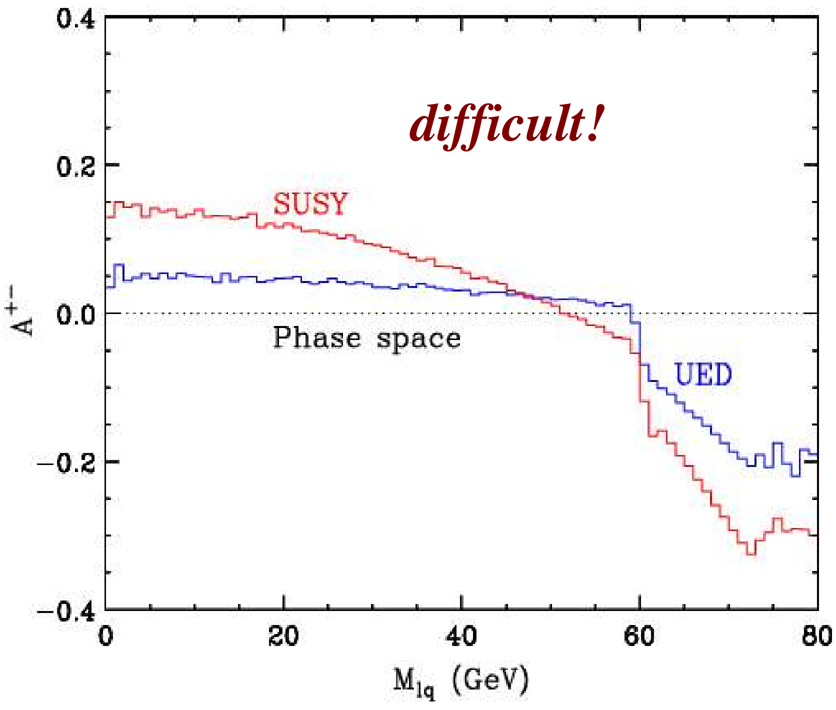
  - Z' couplings determine c_u and c_d.
  - Z' observation (or limit) places constraints in the (c_d, c_u) plane.
  - Constraints from different observables allows one to infer nature's (c_d, c_u) point.
  - From there one can test the models.
  - This already has been deployed at the Tevatron.



Phenomenological Plans of Attack

- An even more basic problem is to identify new objects (to be) observed at the LHC.
  - example: Observe significant missing energy: is it SUSY or Xtra-Dim ?
  - example: Find a resonance – what is its spin?
- Theorists have made many good suggestions about what to do with the data.
- In general, one hopes for tell-tale decays or mass spectra.
  But for a specific channel, spin correlations seem to be most promising.
- Example: $q\,\ell^+\ell^-\not{E}_T$ which may arise from SUSY or UED (hep-ph/0509246, 0405052)

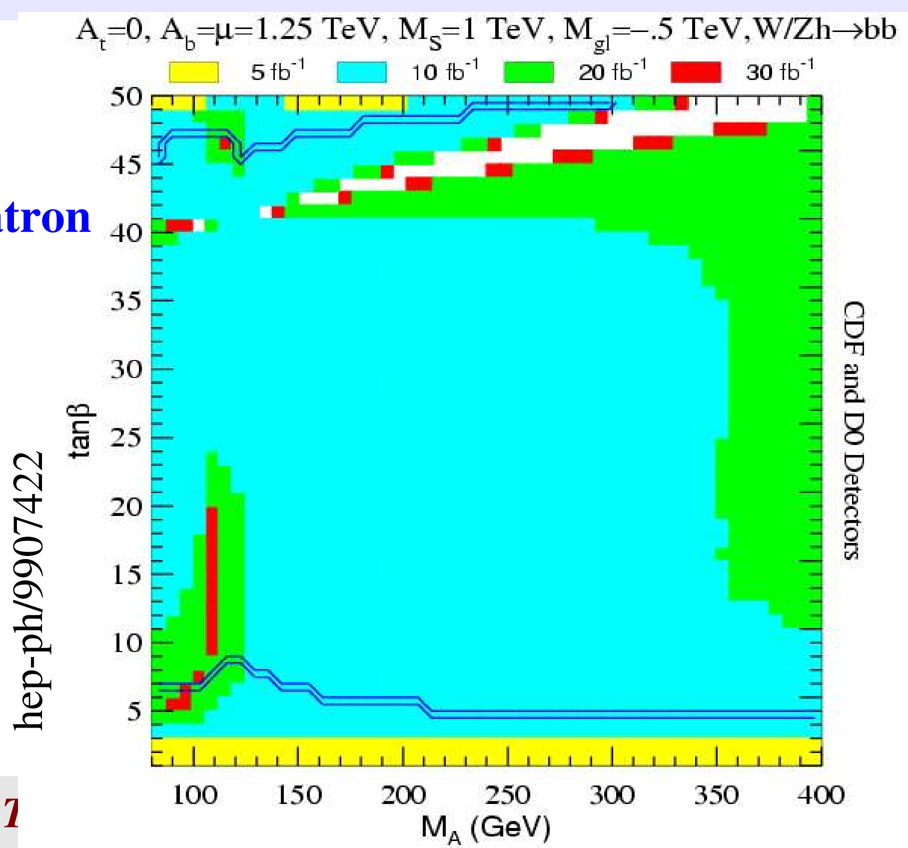


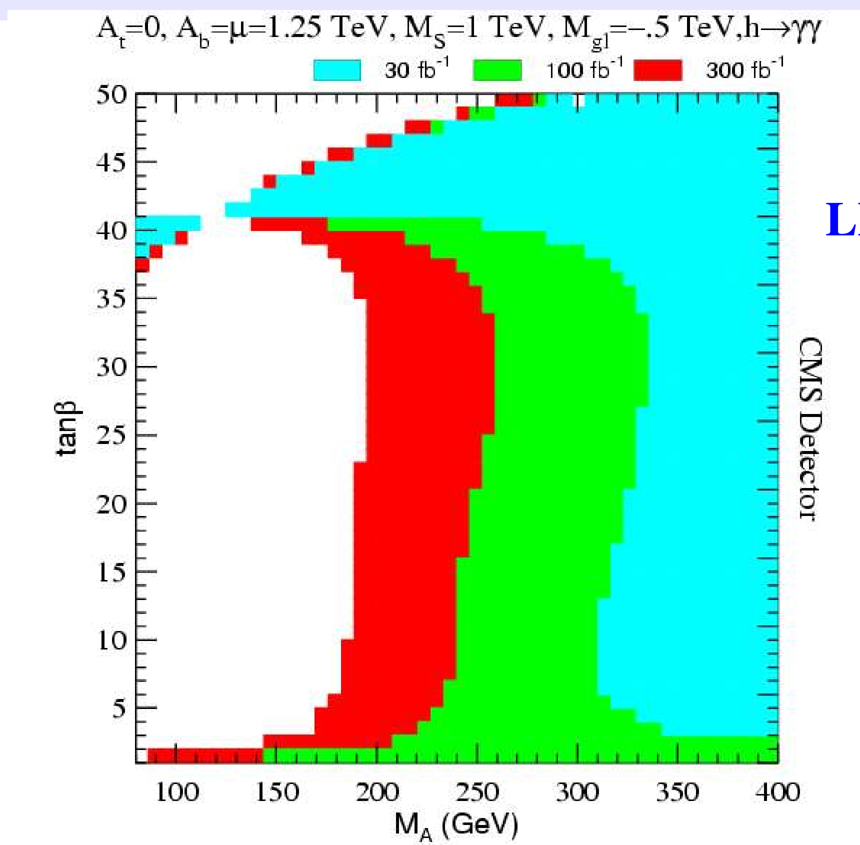


Interplay of Tevatron and LHC Channels

- Sometimes the Tevatron and LHC are not “in competition” - they complement each other.
- A nice example of this was provided 7 years ago by the organizers (MC & SM).
- Radiative corrections can modify effective Higgs couplings in a major way.
  - mixing angles can shift so that the VVh coupling is very small
  - in addition, rad. corr. to Yukawa coupling Y_{hbb} can suppress $h \to bb$
  - the rate for $pp \to h \to \gamma\gamma$ can be significantly modified
- Detrimental effects do not appear in all areas at the same instance.

Tevatron





LHC

Last Set of Remarks + Observations

- **All this is very stimulating to ongoing Tevatron efforts!**
- **Experimenters at the Tevatron continue to innovate, so pay attention, and let this be known.**
- **Questions / suggestions from theorists always provoke useful discussions!**
- **Sometimes there is a stark contrast in the Tevatron and LHC situations for a given channel.**
- **Tevatron constraints on New Physics (or discovery!) will have dramatic consequences for the LHC...**