Measuring Top
from an Experimentalist's View

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2009 CTEQ Summer School

Outline

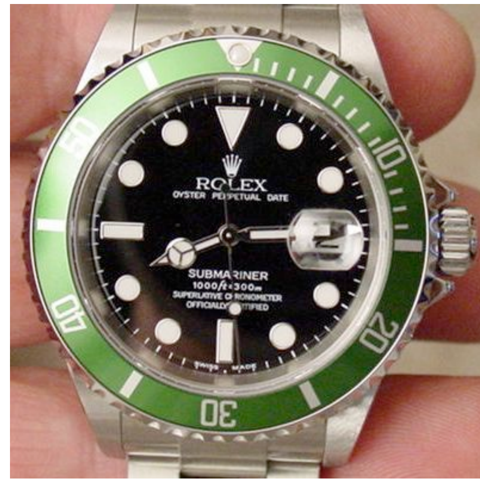
Theory Overview on Top Physics in Zack Sullivan's lectures from Friday and Saturday

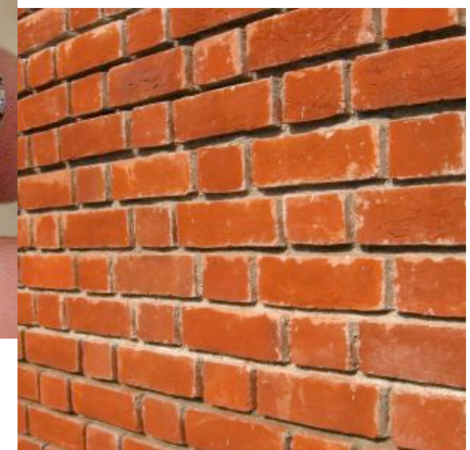
- **Being an Experimentalist**
- **Acquiring Top Events**
- **Measuring the Top Mass**
- **Finding Single Top**
- **Conclusions**

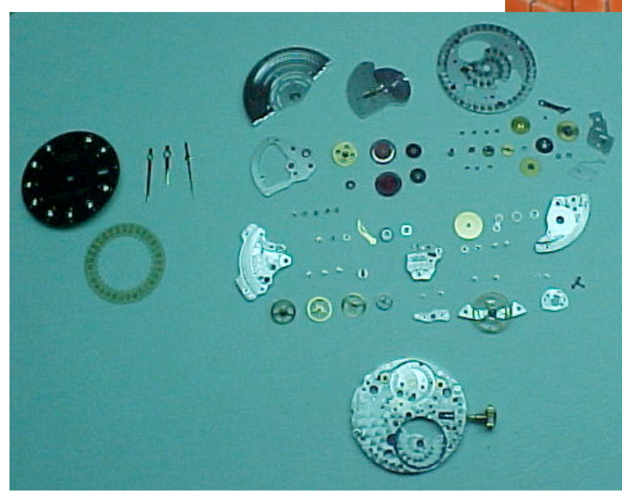
Caveat: Will focus on measurements from the Tevatron with a CDF bias

How Does a Rolex Work?

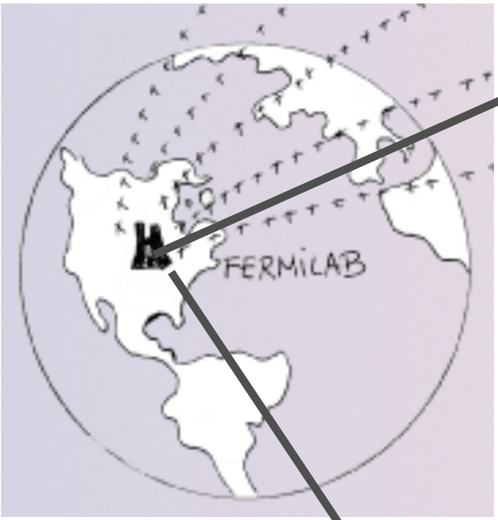
- **An HEP experimentalist would do the following:**
  - **Purchase many watches -- ten of thousands!**
  - **One at a time, throw them at**
    - **a brick wall (fixed target)**
    - **or another watch (colliding beams)**
  - **After each collision observe the remaining pieces**
  - **Statistically collect information for all the collisions**
  - **Draw conclusions on how the watch works.**





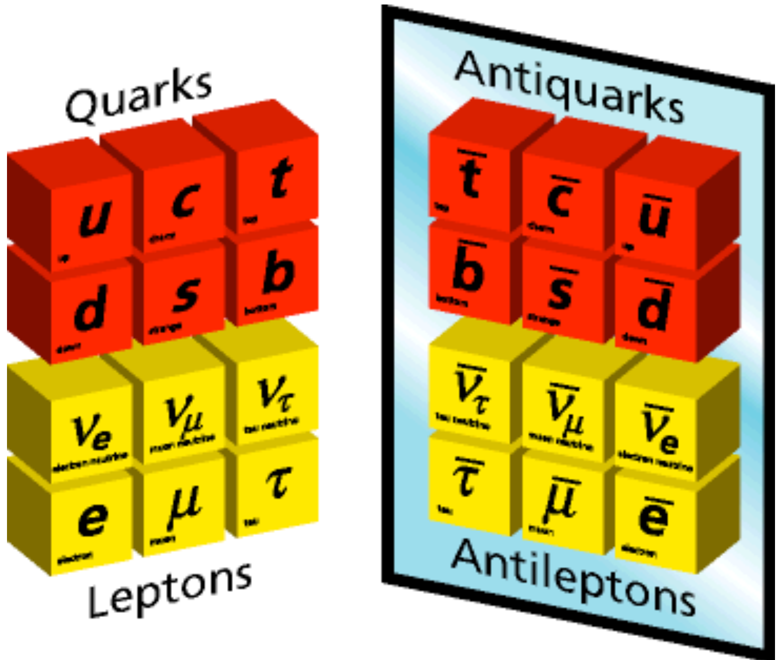


Fermilab


FERMILAB

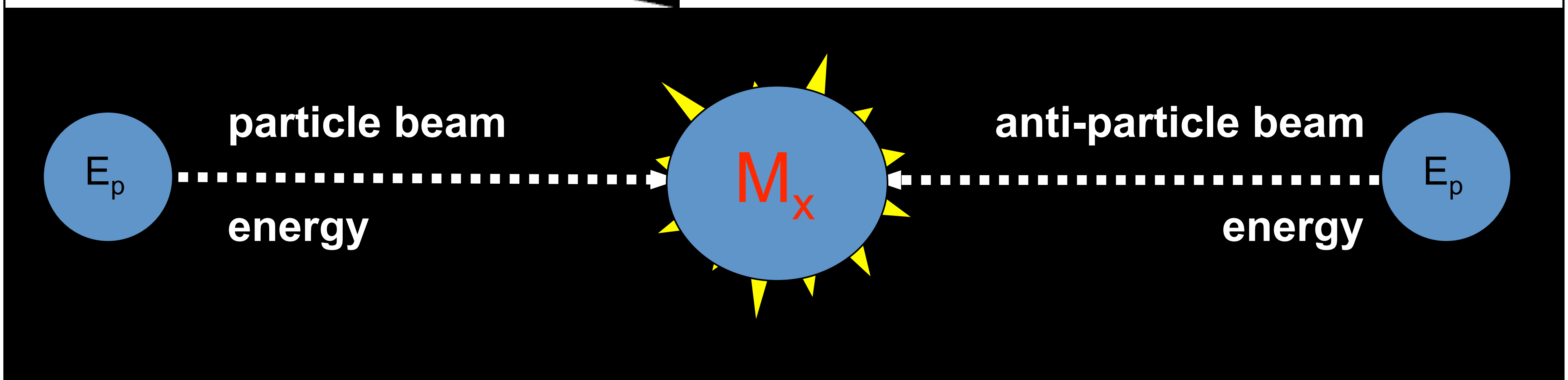

Wrigley Field
Chicago
p
$\bar{p}$
1.96 TeV
CDF
DØ
Tevatron
Main Injector

Making Particles

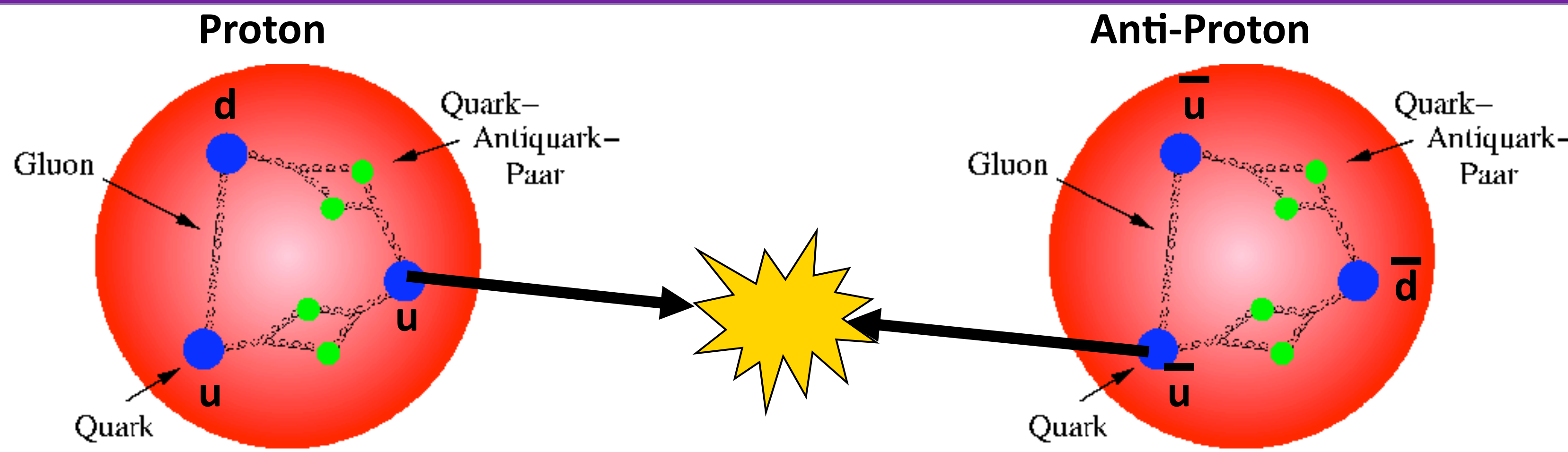


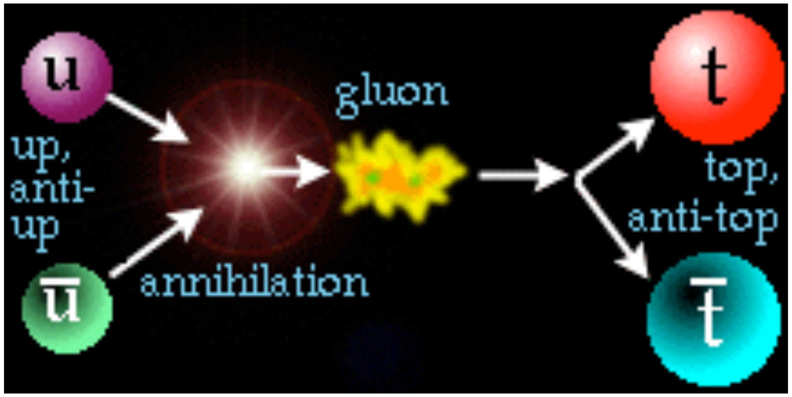
$$E = mc^2$$

$$E_p + E_{\bar{p}} > M_x c^2$$



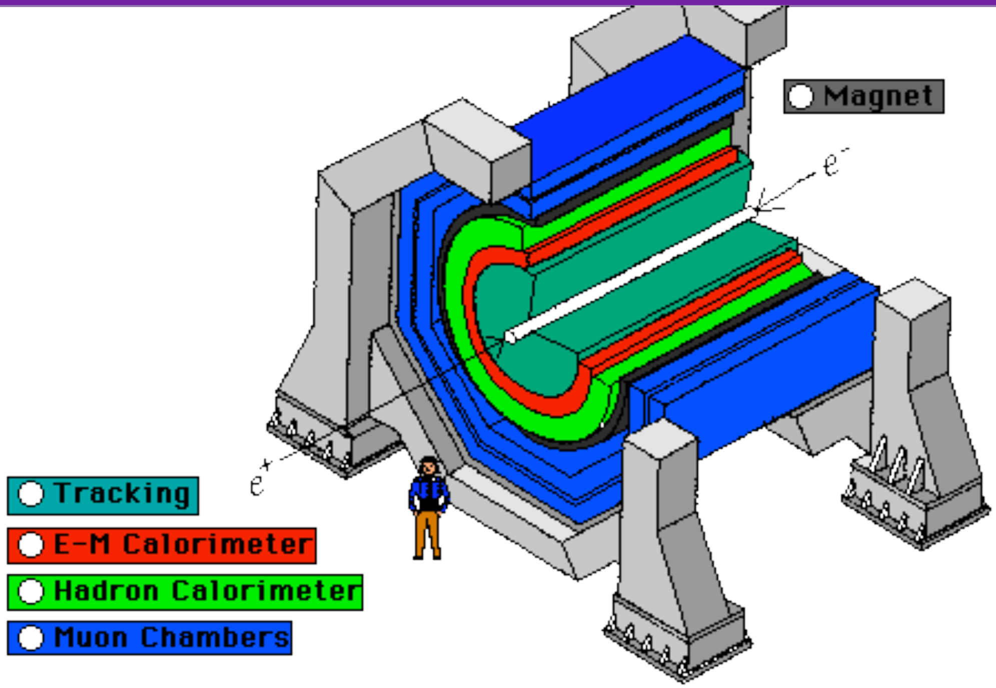
It’s a Bit More Complicated





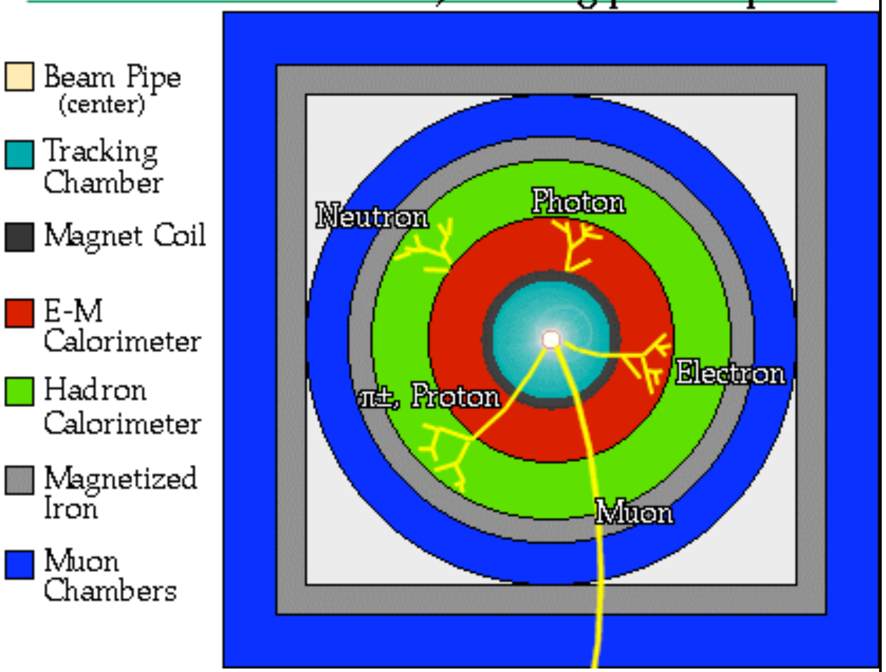
$$E_u + E_{\bar{u}} >> M_t + M_{\bar{t}}$$

Hadron Collider Detectors



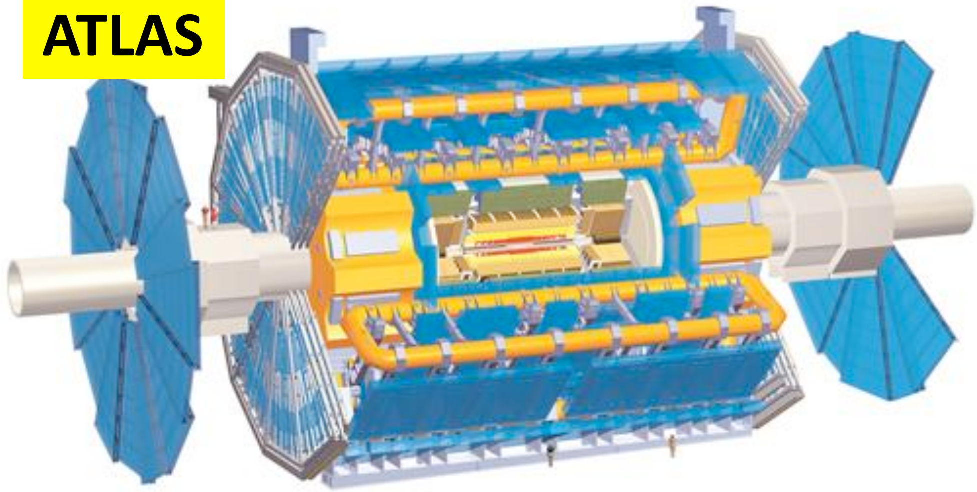
See Steve Kuhlmann's talk on Detector Basics from Monday

A detector cross-section, showing particle paths

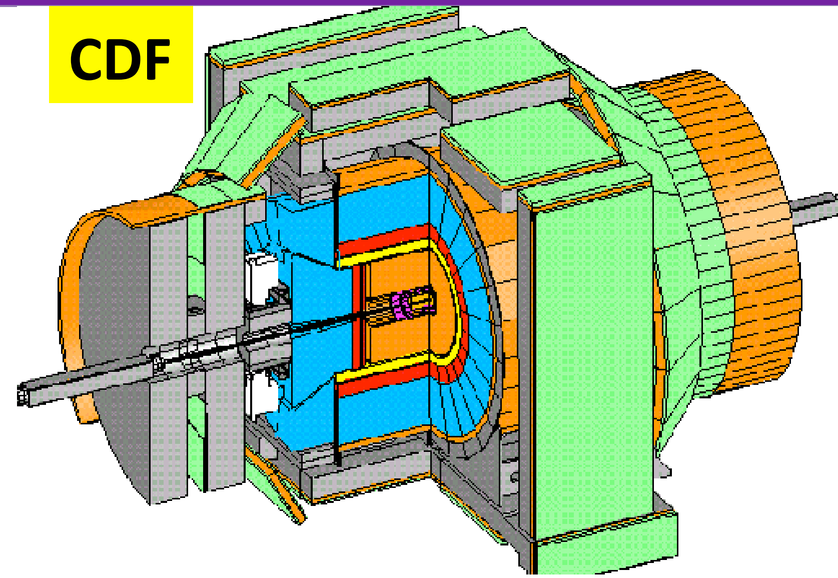


Hadron Collider Detectors

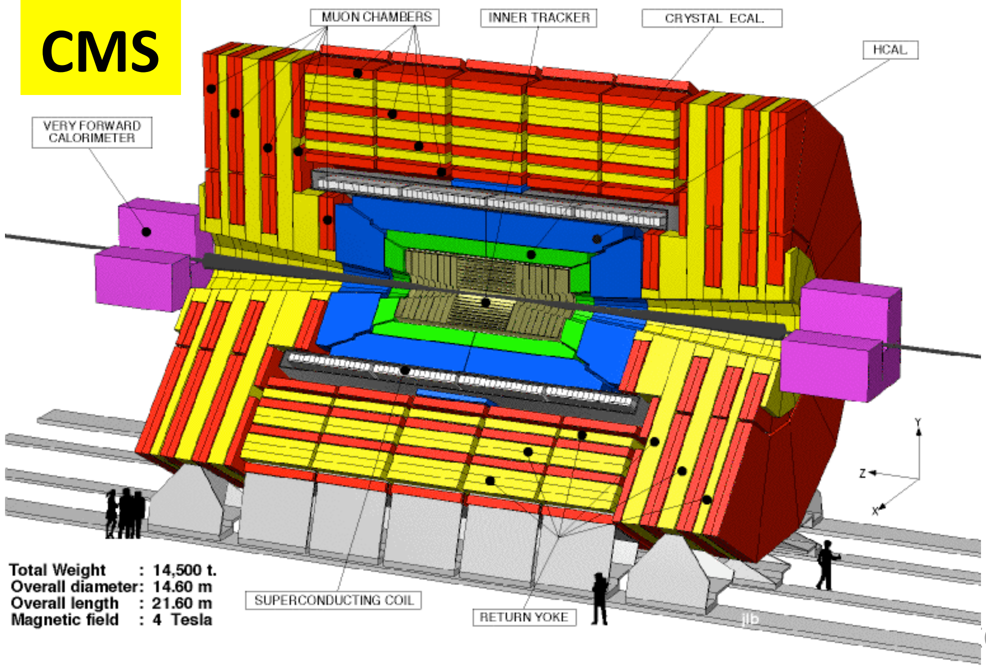
ATLAS



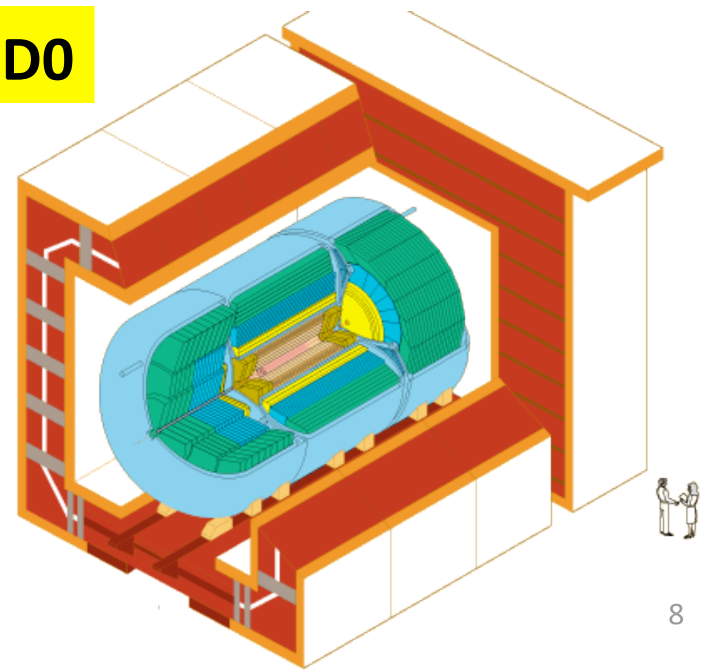
CDF



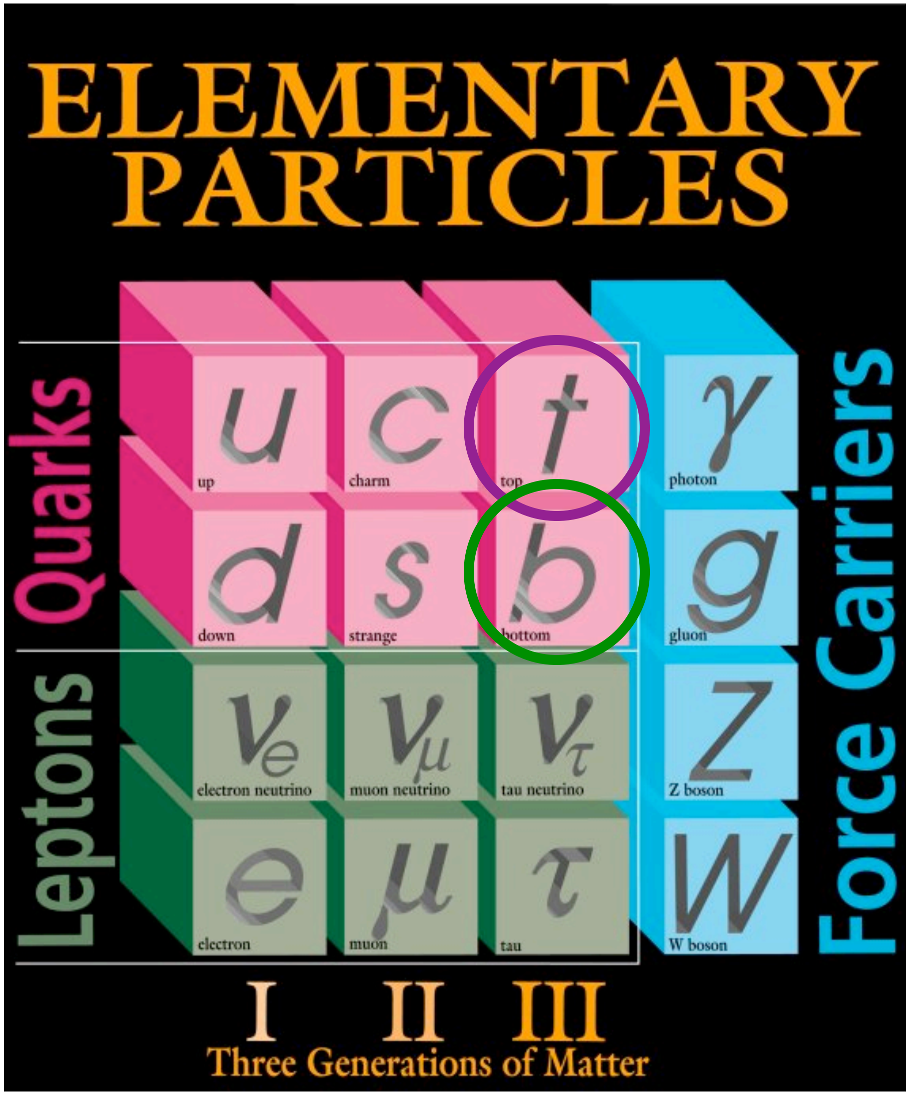
CMS

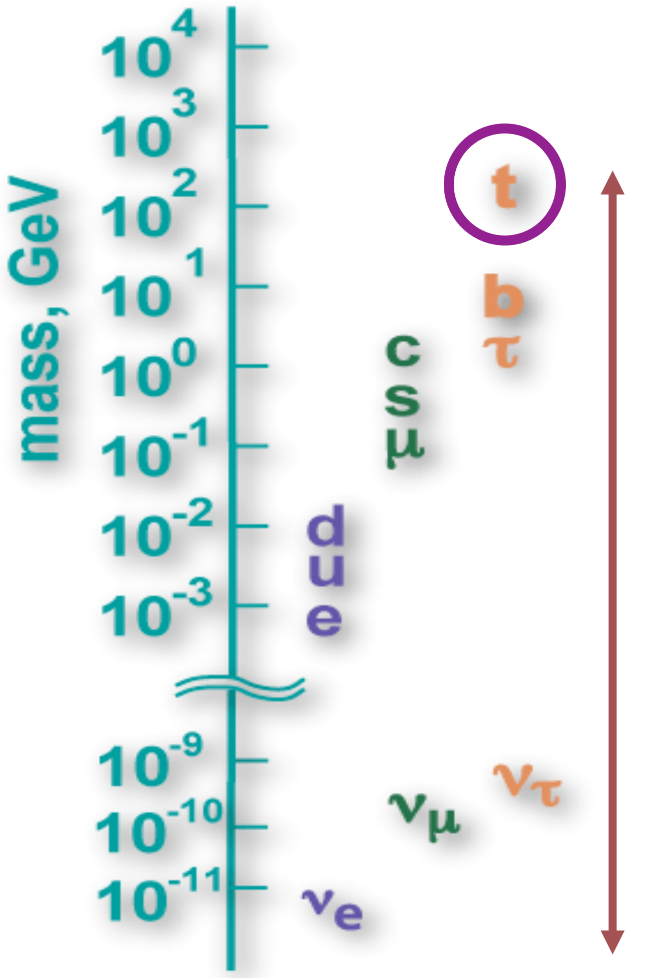


D0



Standard Model and Top Quarks





5 orders of magnitude!

The “Golden” Quark

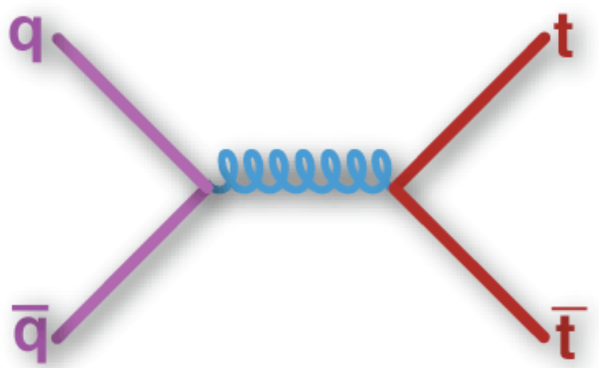
- **Size of gold atom** $M_{top} \approx 175\ \text{GeV}$
  - Only fermion with mass near EW scale.
  - Does it play a role in EW symmetry breaking?
- **Very short lifetime** $\tau_{top} \sim 10^{-24}\text{s}\ ,\ \Gamma^{-1} \approx (1.5\ \text{GeV})^{-1}$
  - Top quarks decay before they hadronize.
    - Study the decay of a **bare** quark
    - Momentum and spin of the top are transferred to its decay products
- **Fundamental question:** Is it the **truth**, the Standard Model (SM) **truth**, and nothing but the **truth**?
  - The top quark is an ideal place to look for Beyond the Standard Model Physics!

Why physicists really want to study Top…

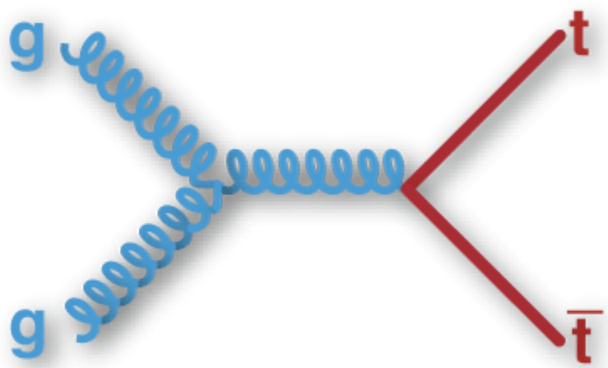
When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.

Top Quark Production

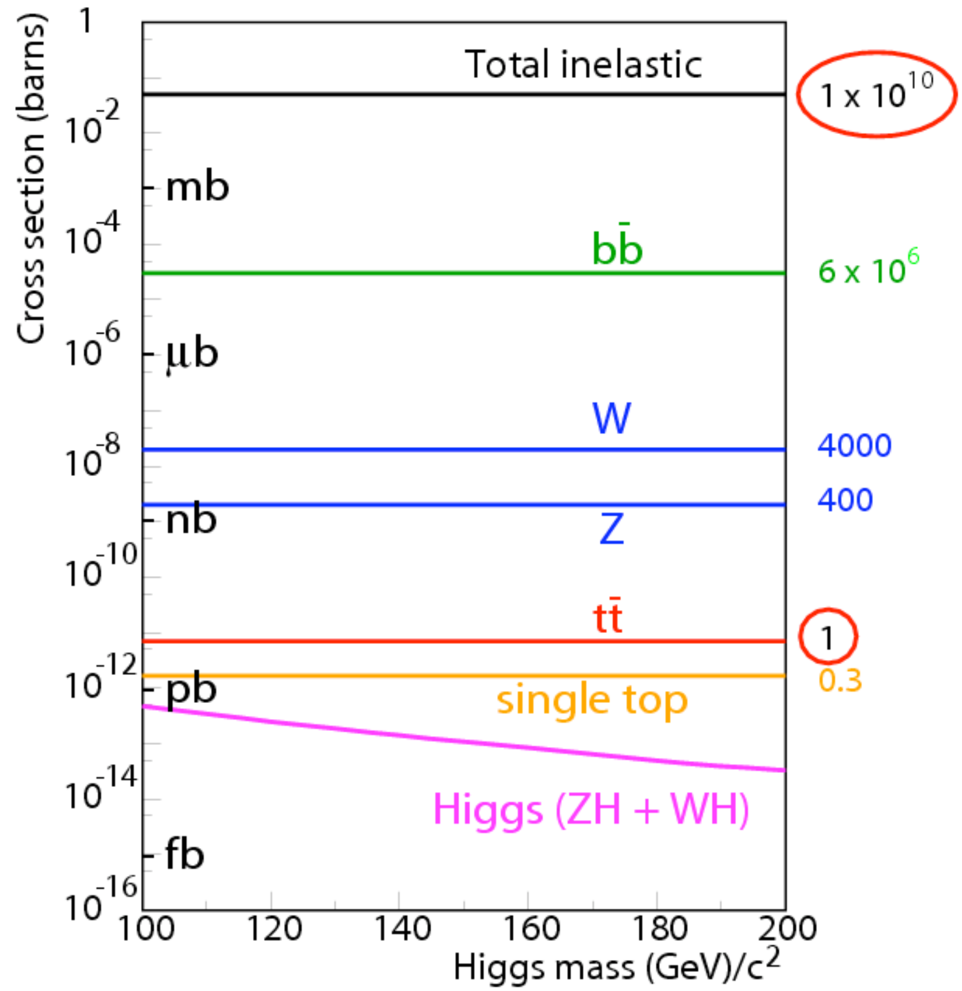
1 top pair in 10 BILLION inelastic collisions at √s = 1.96 TeV



Tevatron (1.96 TeV) ~ 85%
LHC (14 TeV) ~ 10%

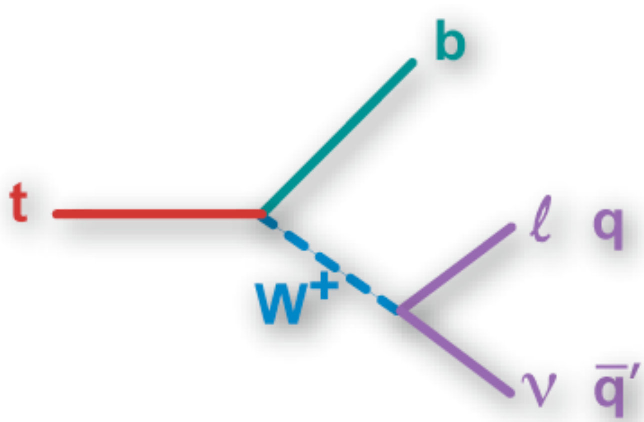


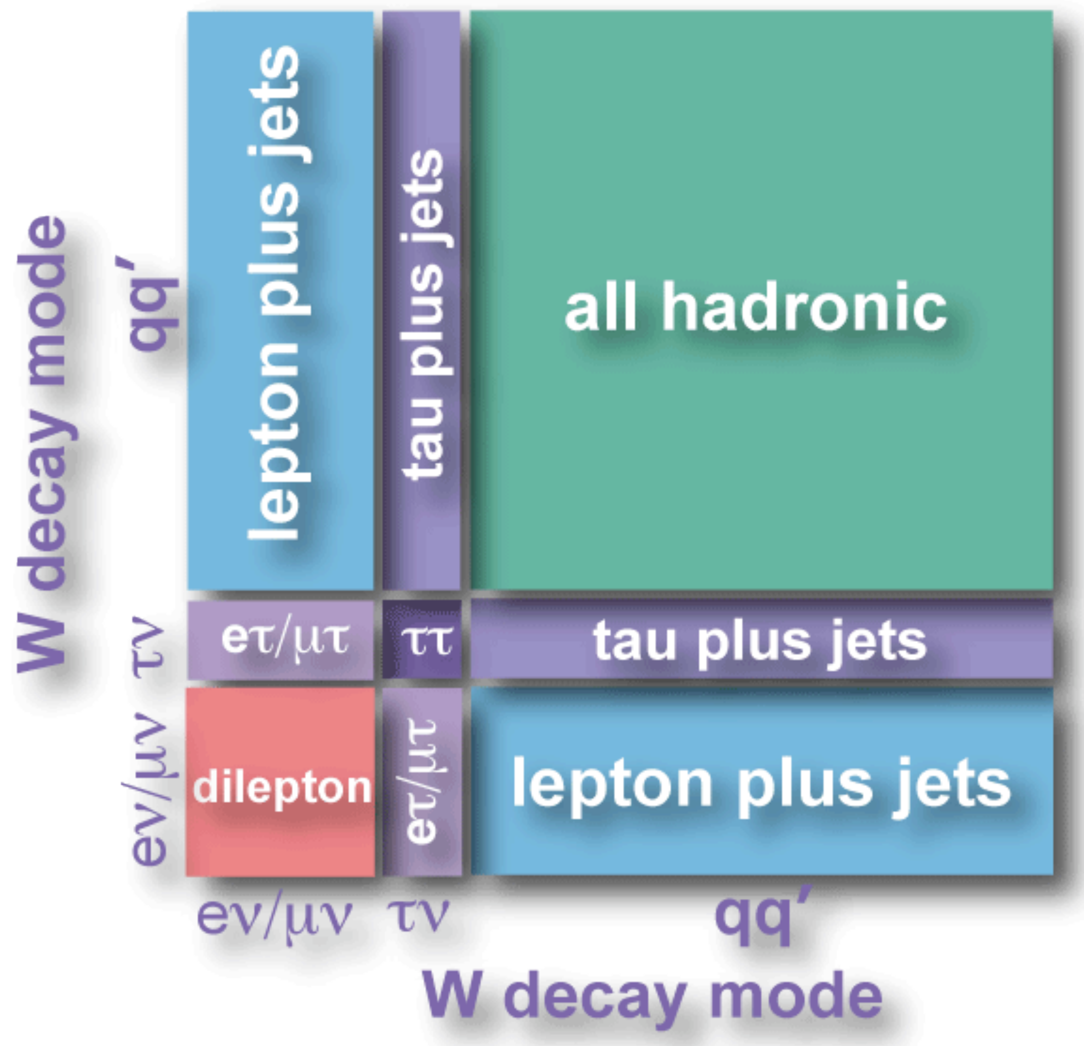
Tevatron (1.96 TeV) ~ 15%
LHC (14 TeV) ~ 90%



Characterize Top Events by W Decay

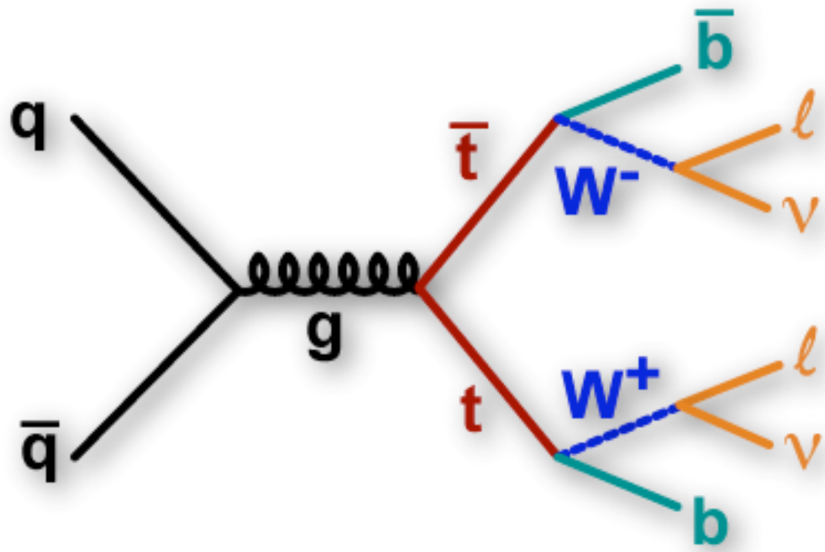
$t \rightarrow Wb \sim 100\%$

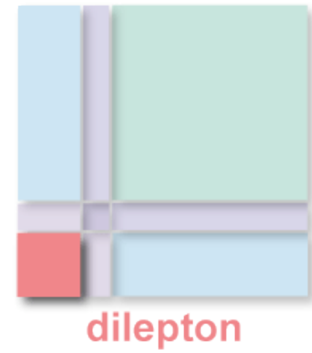


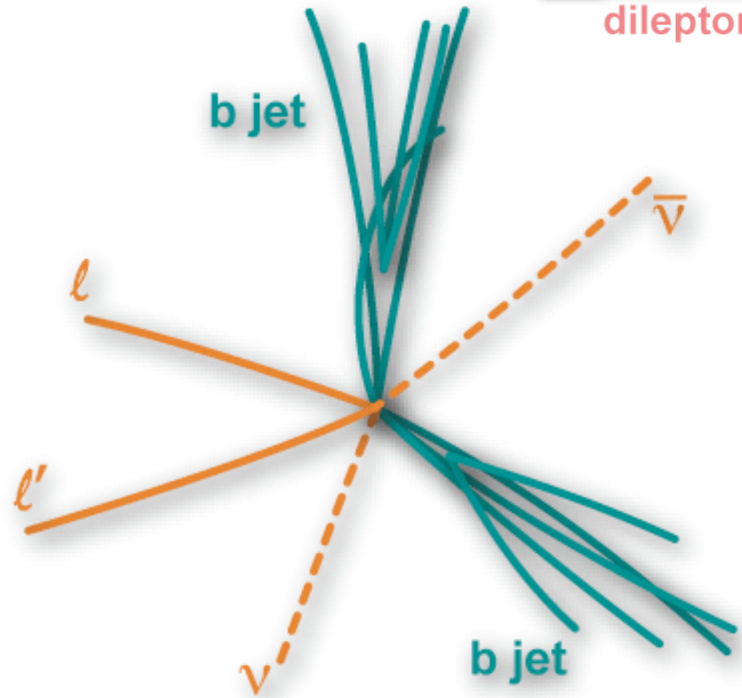


Lepton = electron or muon
Taus are treated separately

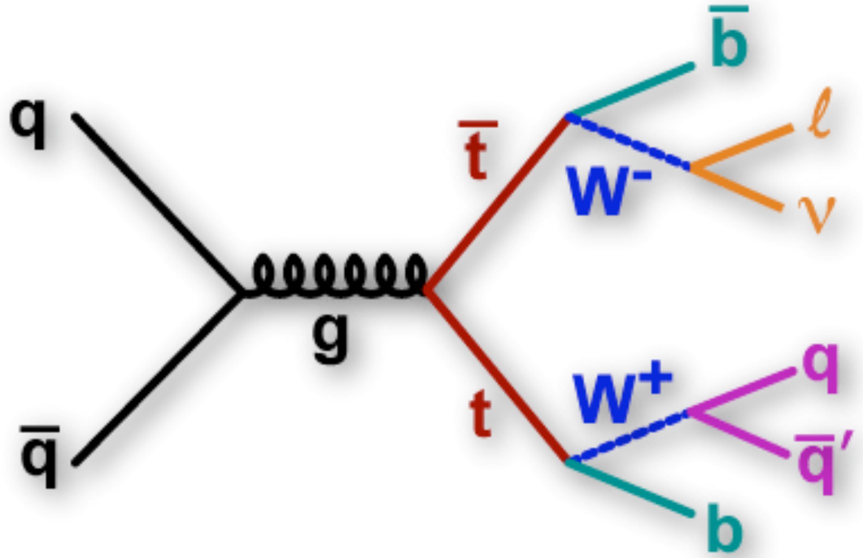
Dilepton Channel

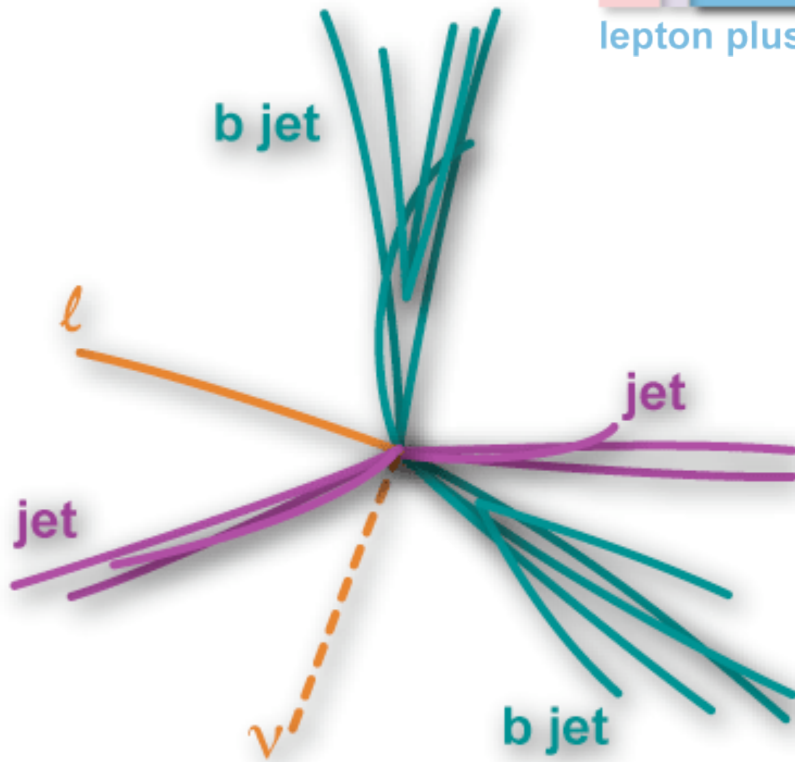




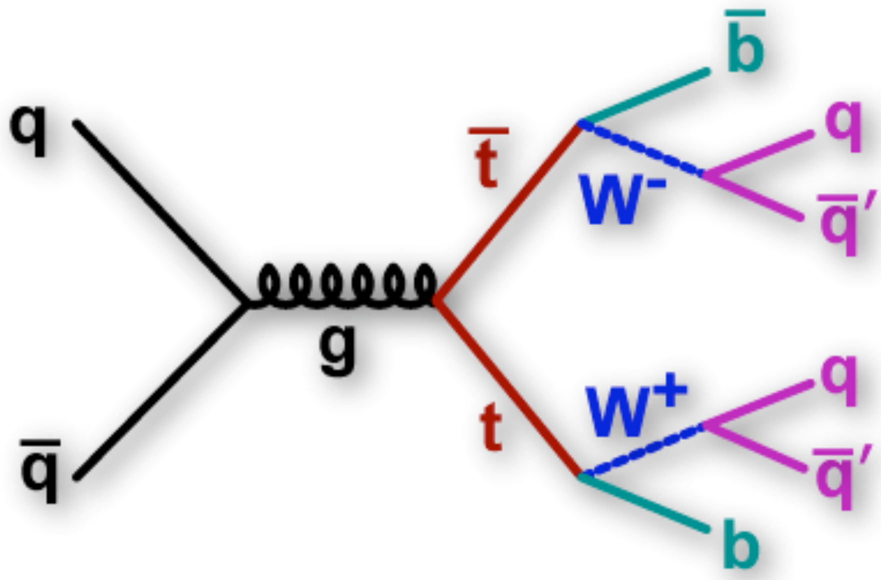


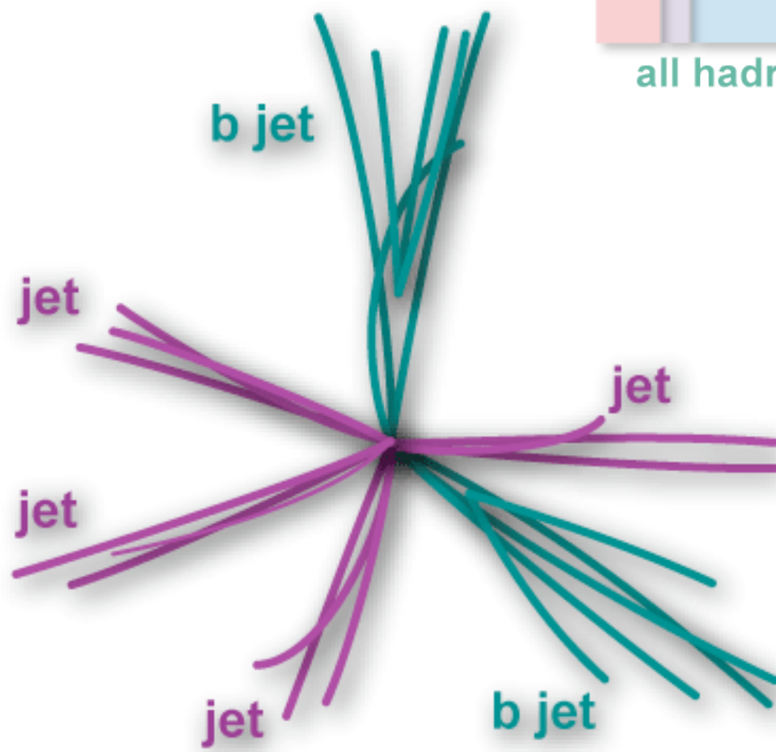
Lepton + jets Channel



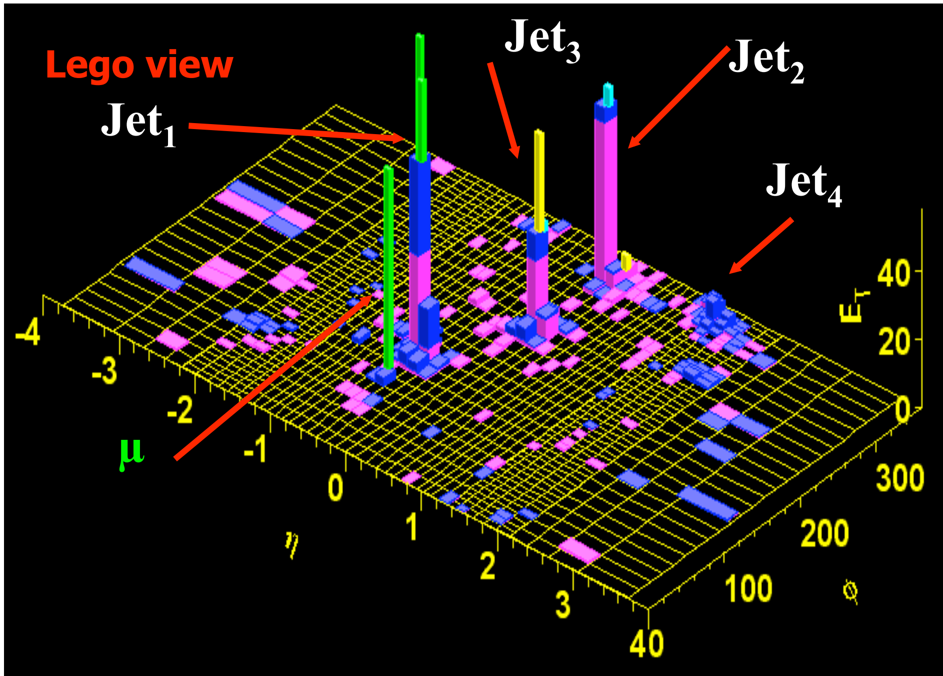


All-Hadronic Channel

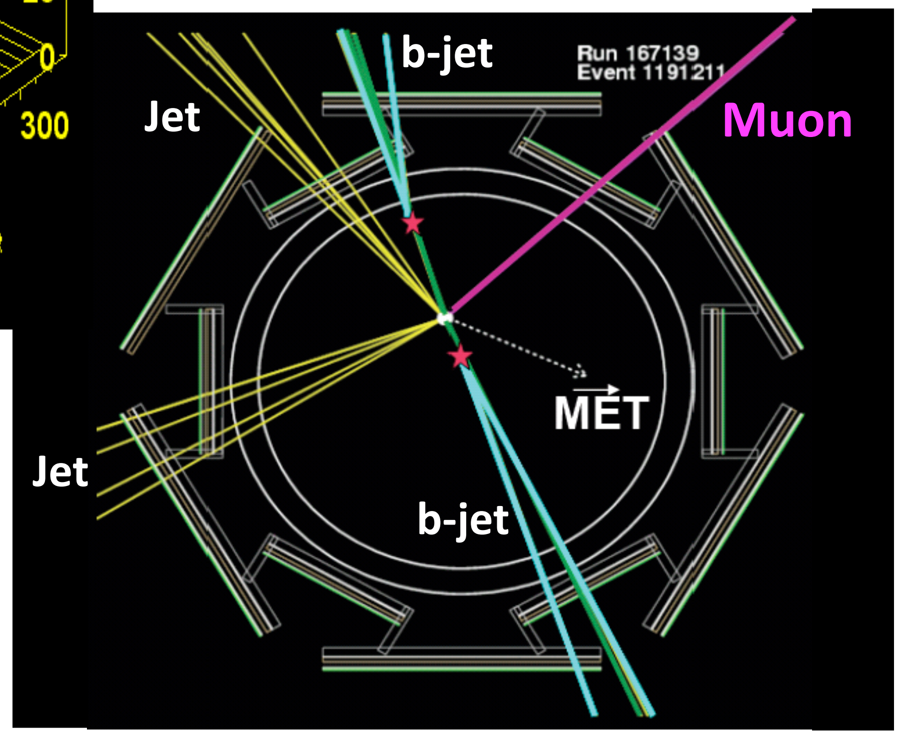


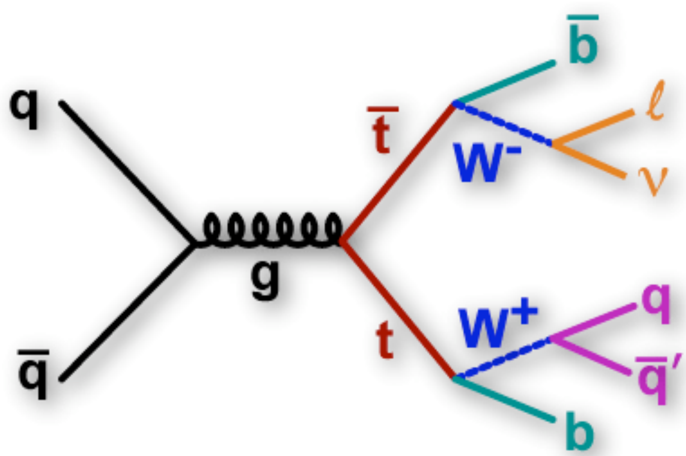


Lepton + Jet Top Event from CDF



See S. Kuhlmann's talk for event displays of simulated top events from the LHC



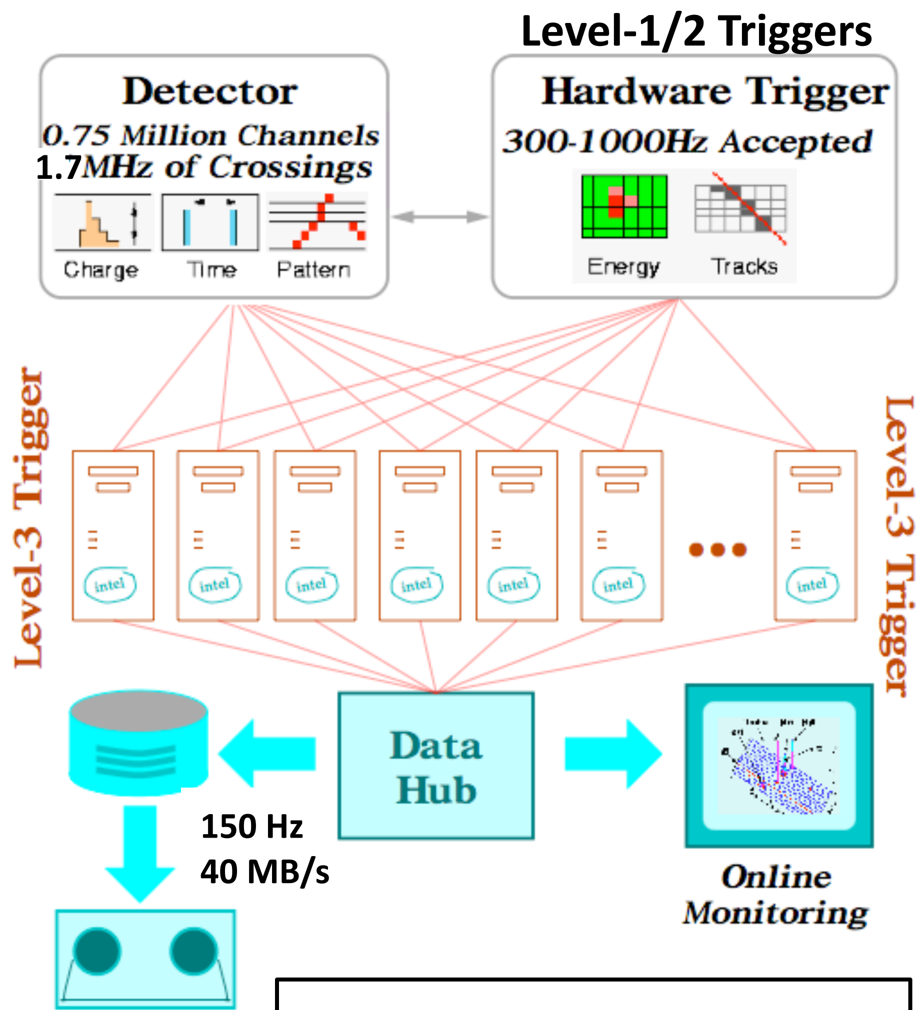


Collecting Data at CDF

- **Tevatron:**
  - 36 p x 36 p̄ bunches
  - collisions every 396 ns
  - **1.7 MHz** of crossings
- **CDF 3-tiered trigger:**
  - L1 accepts ~25 kHz
  - L2 accepts ~800 Hz
  - L3 accepts ~150 Hz

    (event size is ~250 kb)
- Accept rate **~1:12,000**

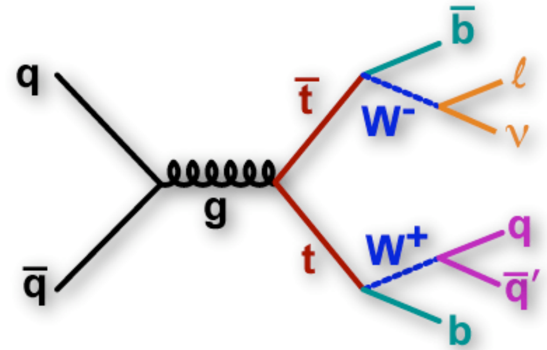
Reject 99.991%
of the events!



CDF Trigger System

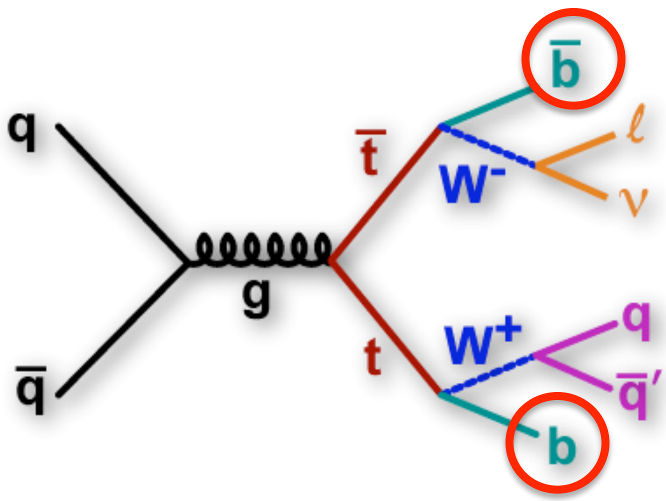
Triggering

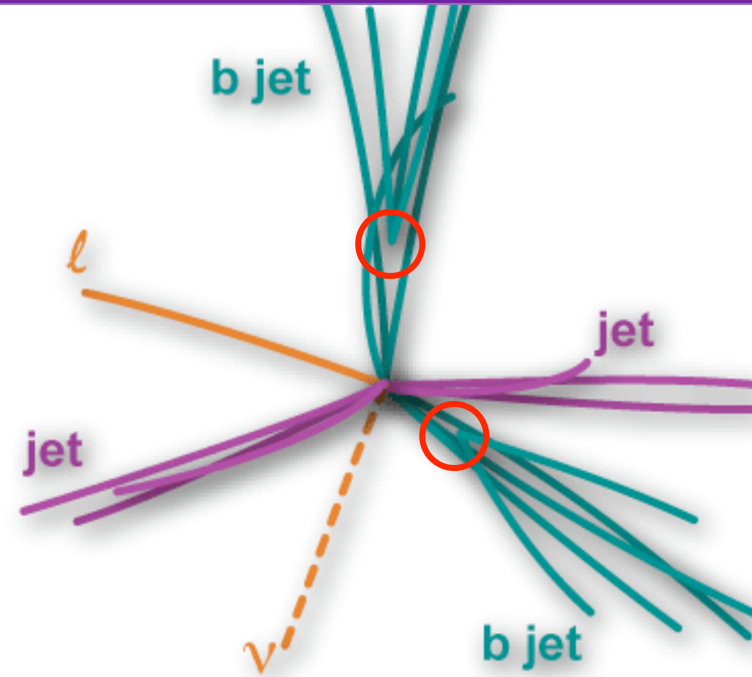
- Want to trigger on physics information
  - # of jets, leptons, tracks
  - Amount of E_T, MET or P_T
- Example of jet trigger in a three level trigger system
  - Level 1 cut on E_T in one calorimeter tower
  - Level 2 cluster towers together to get better E_T resolution
  - Level 3 reconstruct the jet using a jet algorithm



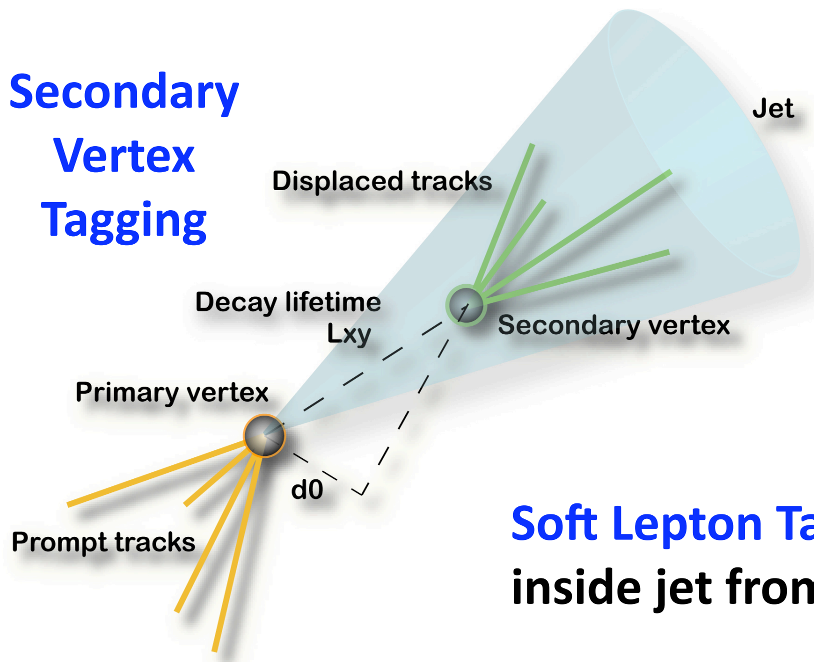
- **Top "Signal" Triggers**
  - **High P_T Leptons** (primary trigger)
  - Jets plus MET
- **Top "Background" Triggers**
  - "Looser" samples to measure efficiency of the "signal" triggers and to understand backgrounds
  - Calibration samples to measure b-tagging efficiency and jet energy scale

Tools for Finding Top (1): b-tagging





Secondary Vertex Tagging



Most backgrounds to Top do not contain bottom quarks so tag'em:

b-quark lifetime: $c\tau \sim 450\ \mu m$

b quarks travel ~3 mm before decay

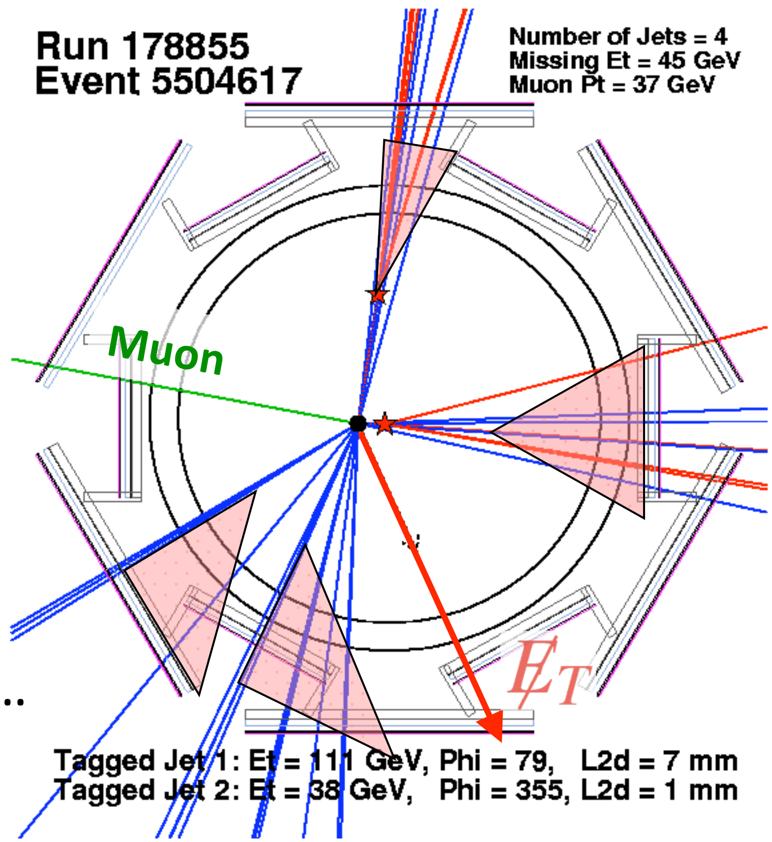
Soft Lepton Tagging – look for low P_T lepton inside jet from decay of b → c → lνX

Tools for Finding Top (2): MET

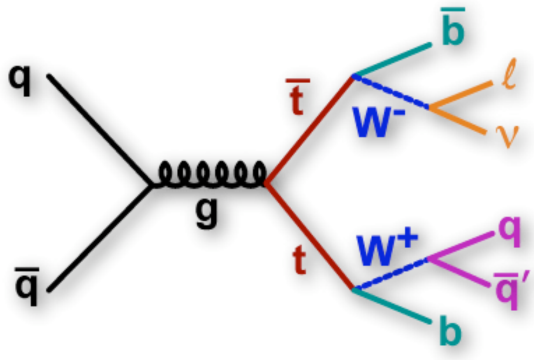
- Unlike $e^+ e^-$ colliders, we don't know what hit what.
  – We don't know p_z of the collision.
  – We do know p_x and p_y so use the "transverse missing energy" ($\not{E}_T$ or *MET*).

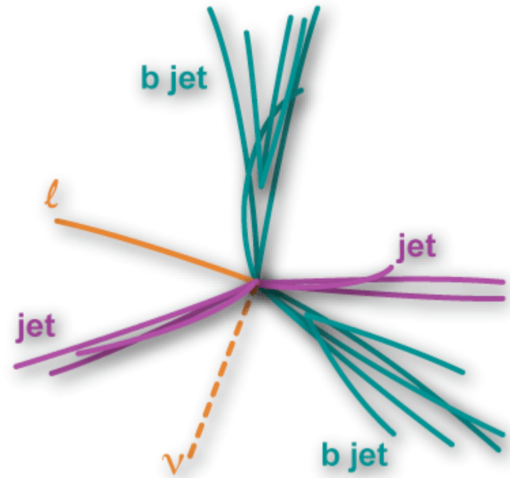
- General idea:
  – Add up all (vector) energy in the XY plane, both "*clustered*" (part of reconstructed jets, leptons, etc.) and "*unclustered*."

- Reality:
  – Need to take into account jet corrections, muons, underlying events, extra interactions (pileup), …



Tools (3): Jet Reconstruction

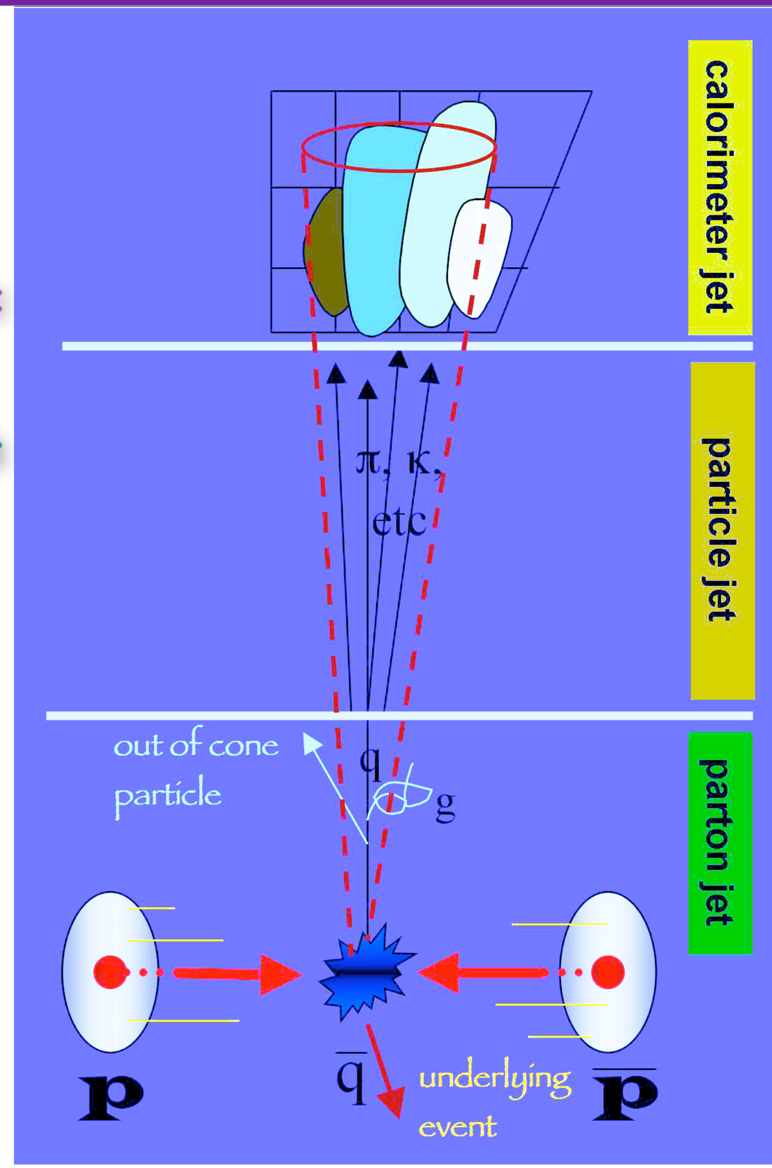




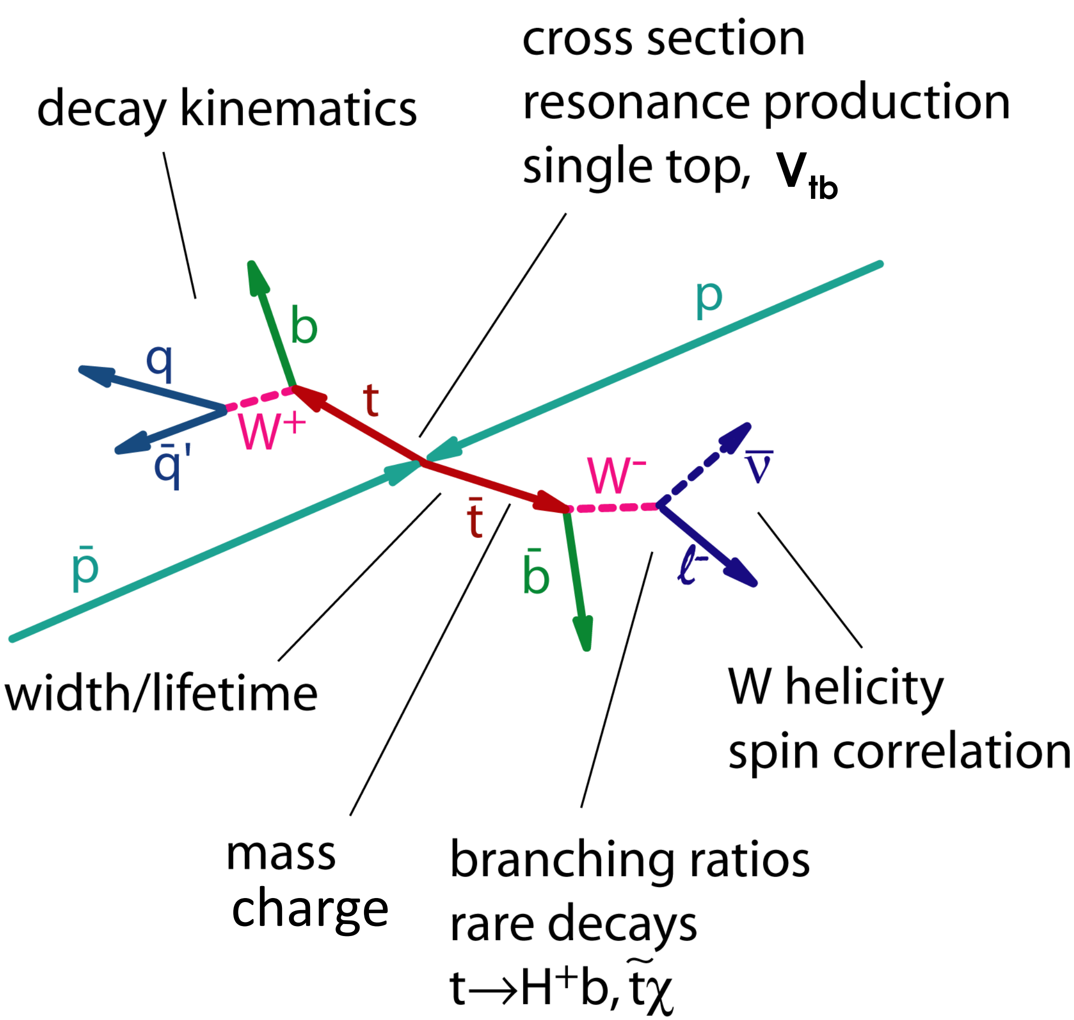
Theory **Experiment**

- Must Convert "*raw*" jets to *"corrected"* jets (Jet Energy Scale or JES)
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …

For more details on Jets see talks by Nikos Varelas on Monday and Rick Field on Wednesday



What Can We Measure about Top?



Top pairs: σ(tt) ~ 7 pb

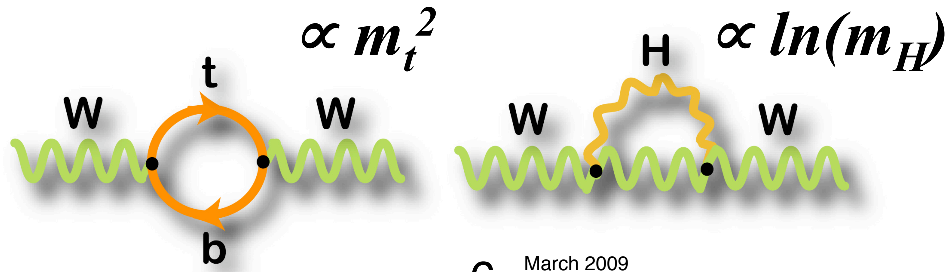
- Cross section
- Production mechanism
- Properties: Mass, Electric Charge, Width
- W helicity in top events
- New physics in X→ tt
- Anomalous couplings, new particles

Single top: σ(tb) ~ 3 pb

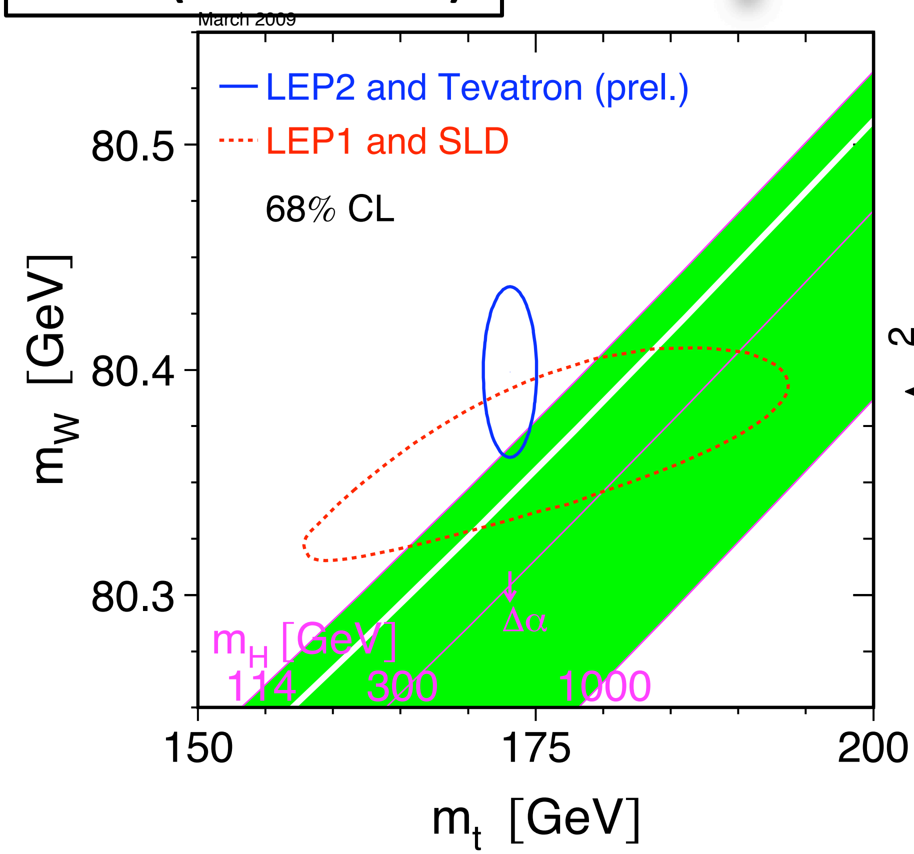
- Cross section
- $|V_{tb}|$
- Top polarization
- New physics?

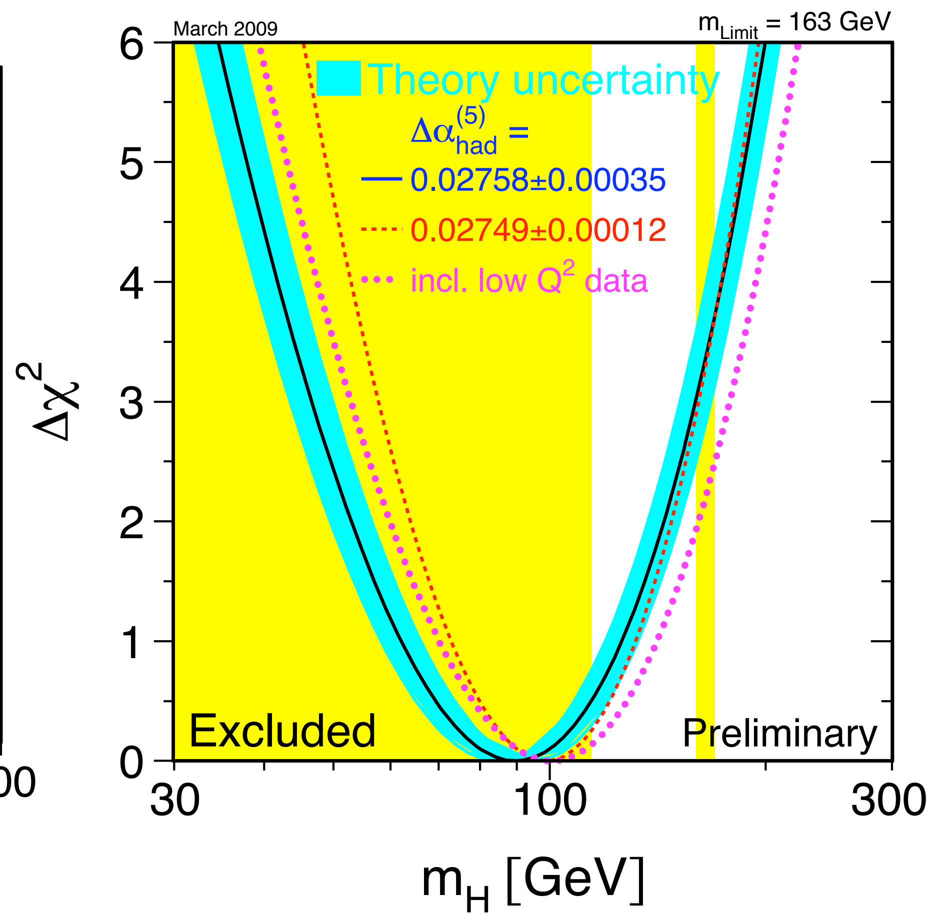
Top Mass

Why Measure the Mass

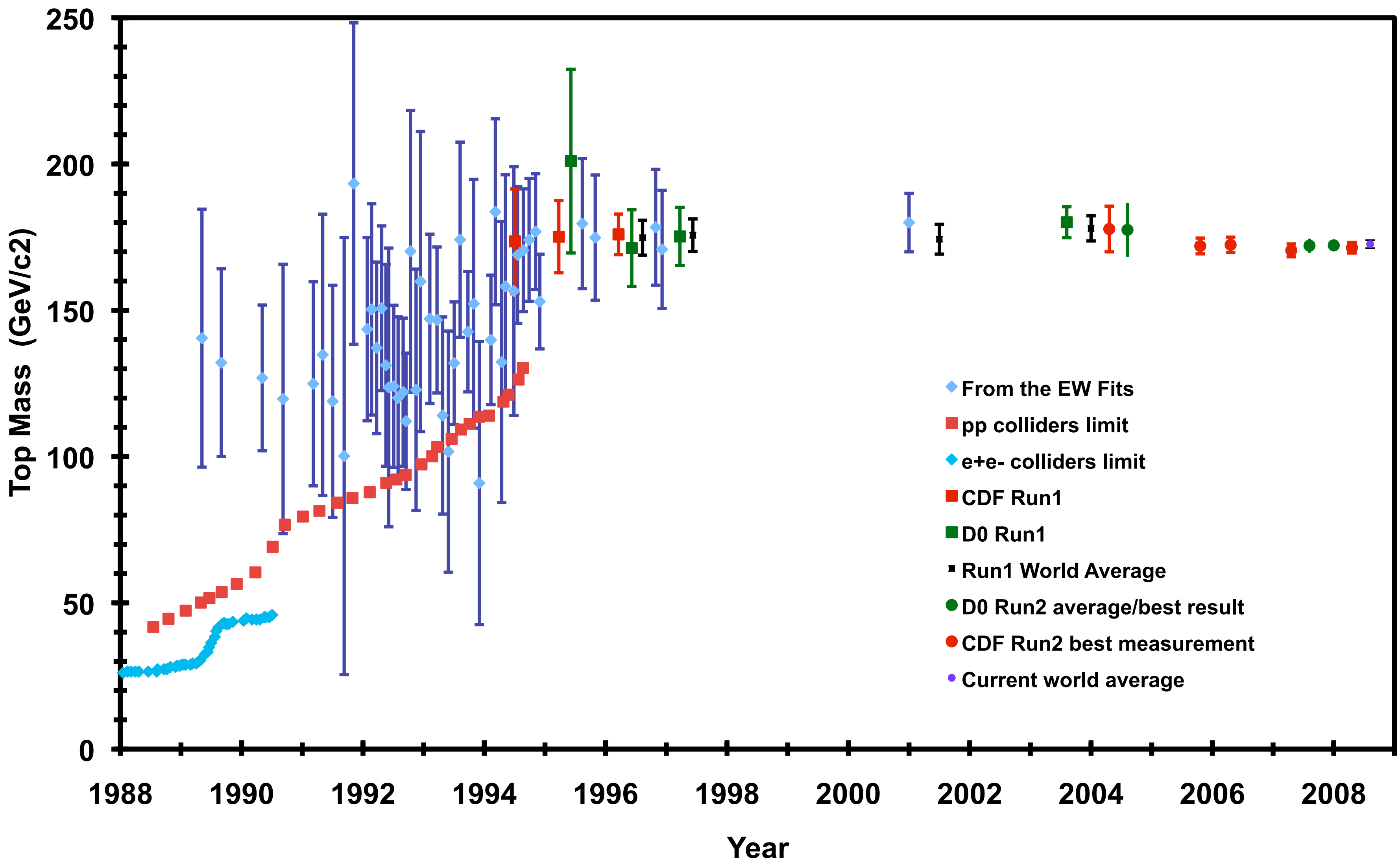


Fits use latest top mass (March 2009)





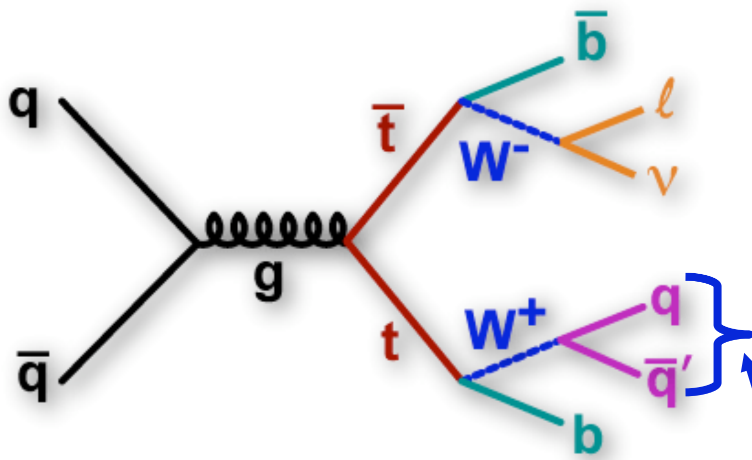
History



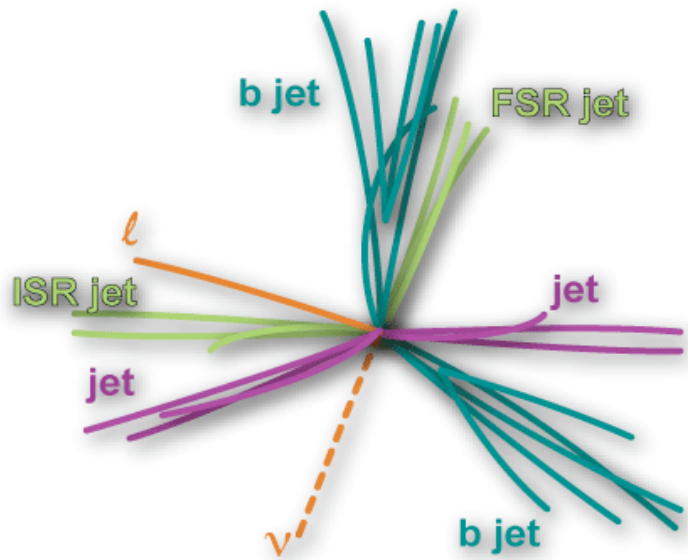
Top Mass (GeV/c2)
250
200
150
100
50
0
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
From the EW Fits
pp colliders limit
e+e- colliders limit
CDF Run1
D0 Run1
Run1 World Average
D0 Run2 average/best result
CDF Run2 best measurement
Current world average

Measuring the Mass ain't Easy

What a theorist sees…



What an experimentalist sees…



Challenges:

- **Combinatorics**
- **Jet Energy Scale (JES)**

Solutions:

- **Sophisticated analyses**
- **In-situ W→jj calibration (more on this later)**

A Simple Mass Fit: Template Method

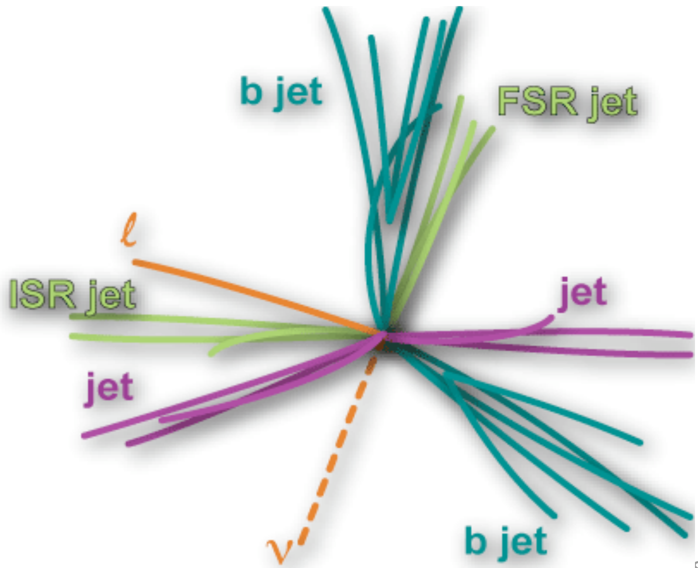
Use χ^2 fitter to reconstruct lepton+jet events:

Object Resolution — Unclustered Energy Constraints

$$\chi^2 = \sum_{i=\ell,4\text{ jets}} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{i=x,y} \frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t^{reco})^2}{\Gamma_t^2}$$

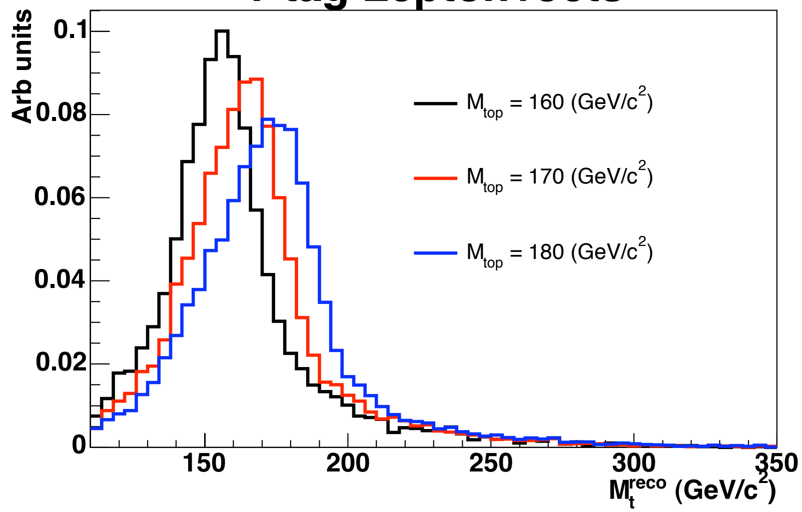
W mass constraints — Top mass "constraints"



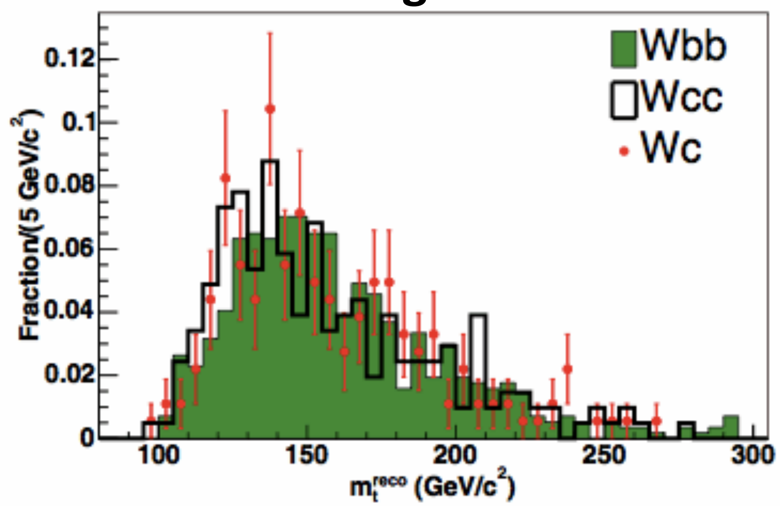
- Using 4 highest E_T jets have 24 combinations:
  - 12 correspond to the jet parton match
  - every combination has 2 solutions for neutrino P_Z
- Take lowest χ^2 combination as top mass value and make templates

Template Method (cont.)

1-tag Lepton+Jets

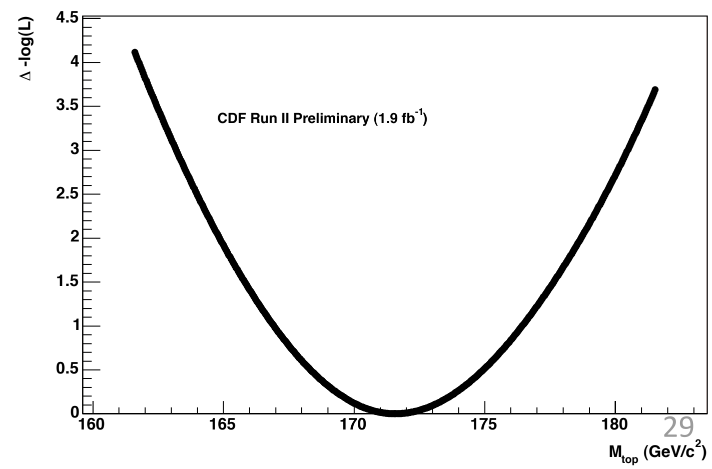


Background

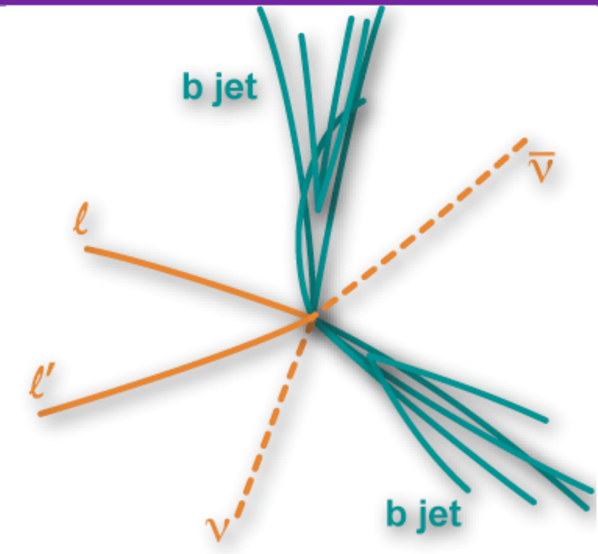


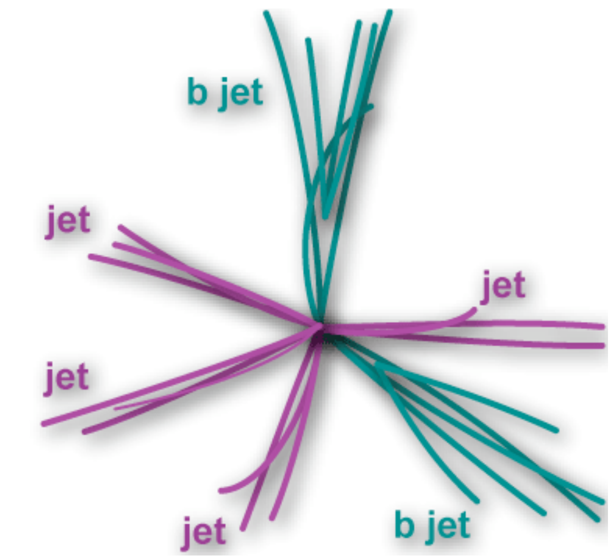
$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_i, y_i; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_i, y_i)}{n_s + n_b}$$

Minimize likelihood with respect to top mass and expected amount of signal and background events



Template Fit in Other Channels





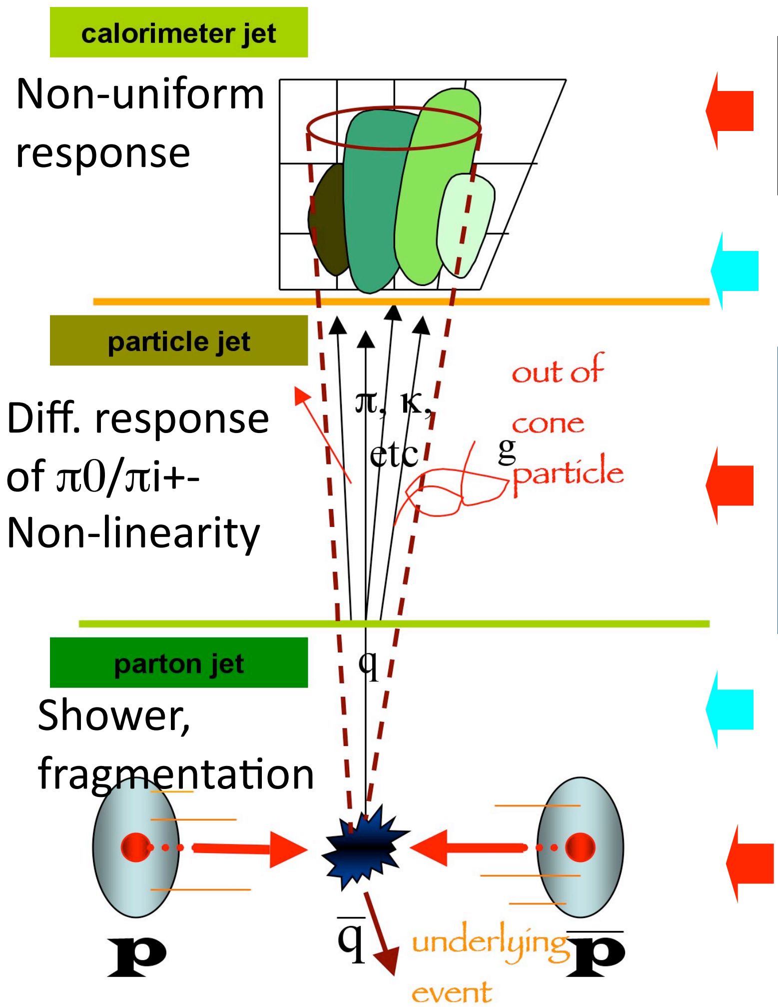
Dilepton case (under-constrained):

- Use "Neutrino weighting method"
- Assume M_{top} and η of both ν
- Solve for P_x and P_y of neutrinos
- Form weights comparing solutions to measured MET
- Sum over all solutions to get weighted M_{top}

All-hadronic case:

- Use 6 highest E_T jets but swamped by backgrounds and radiation jets
- JES systematic uncertainty large

Jet Energy Scale (JES)



Relative using dijet balance: to make response uniform in η

Multiple ppbar interactions: pileup

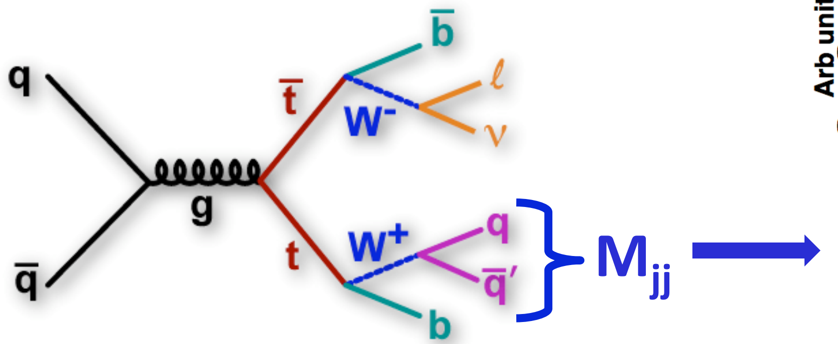
Absolute correction using dijet MC tuned for single particle E/P, material, and fragmentations: due to non-linear and non-compensating calorimeter

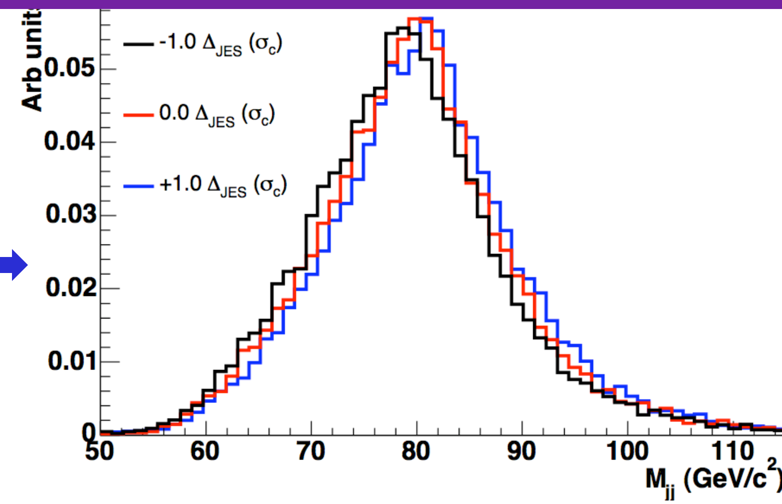
Underlying events due to spectators

Out-of-Cone : due to energy outside cone

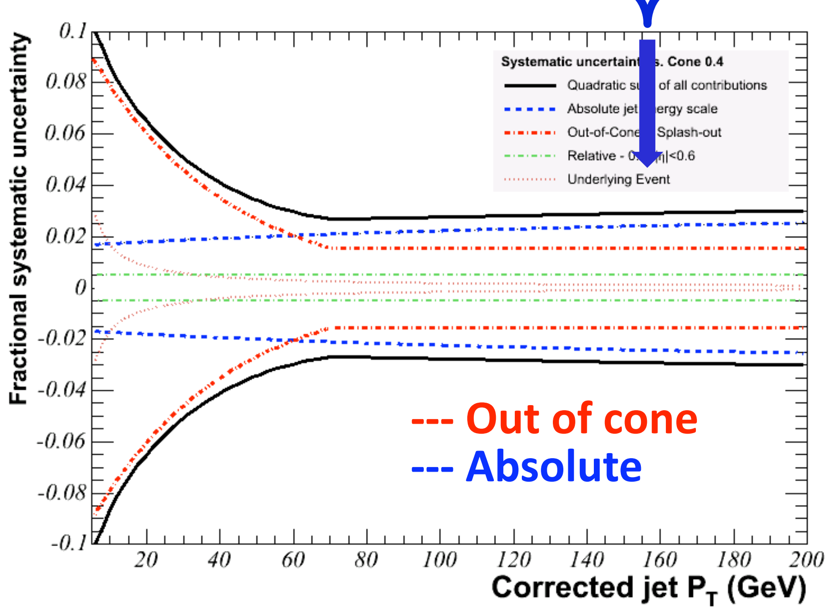
See also talks by Nikos Varelas and Rick Field

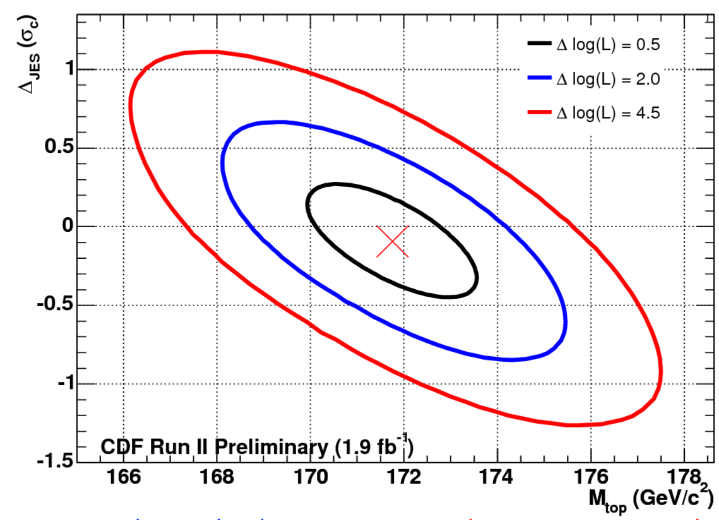
In-situ JES Measurement





$$E_{jet}=E_{meas}(1+\Delta_{JES} * \sigma_{JES}(P_t))$$





$$\mathscr{L}(m_t|\vec{x}) \Rightarrow \mathscr{L}(m_t, \sigma_{JES}|\vec{x})$$

Reconstructing the Mass

1. Template-based

Reconstruct mass for each event → Form "templates" for signal (varying M_{top}) and background using simulated events → Perform maximum likelihood fit to extract measured M_{top}

Advantages: Takes all (simulated) detector effects into account, (relatively) computationally simple

Disadvantages: Only single number (recon. mass) per event in final Likelihood, all events have equal weight

2. Matrix Element-based

Form per-event probability using matrix element → Integrate over unmeasured quantities → Form ensemble probability and calibrate using simulated events

Advantages: More statistical power, probability curve rather than single mass per event, events weighted naturally

Disadvantages: Complex numerical integration (much CPU)→machinery does not account for all detector effects

Generic Matrix Element Method

Probability to observe a set of kinematic variables x for a given top mass

$d^n\sigma$ is the differential cross section
Contains (LO) matrix element squared

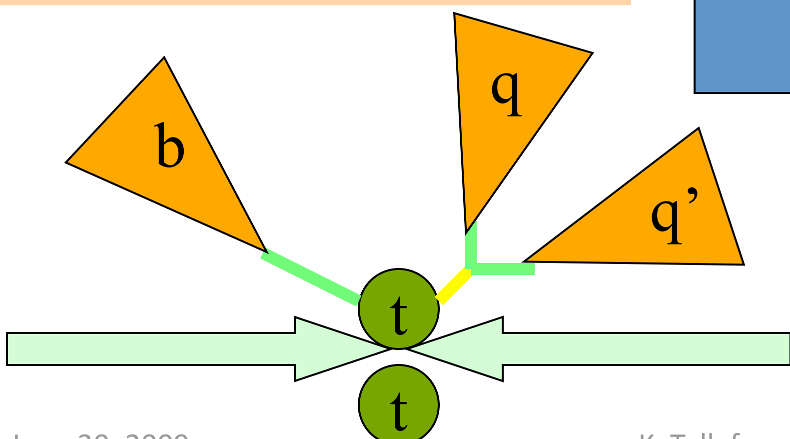
W(x,y) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$$P_{\mathrm{sgn}}(x;m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y;m_t)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x,y)$$

Normalization depends on m_t
includes acceptance effects

f(q) is the probability distribution that a parton will have momentum ***q***

Integrate over unknown q_1, q_2, y

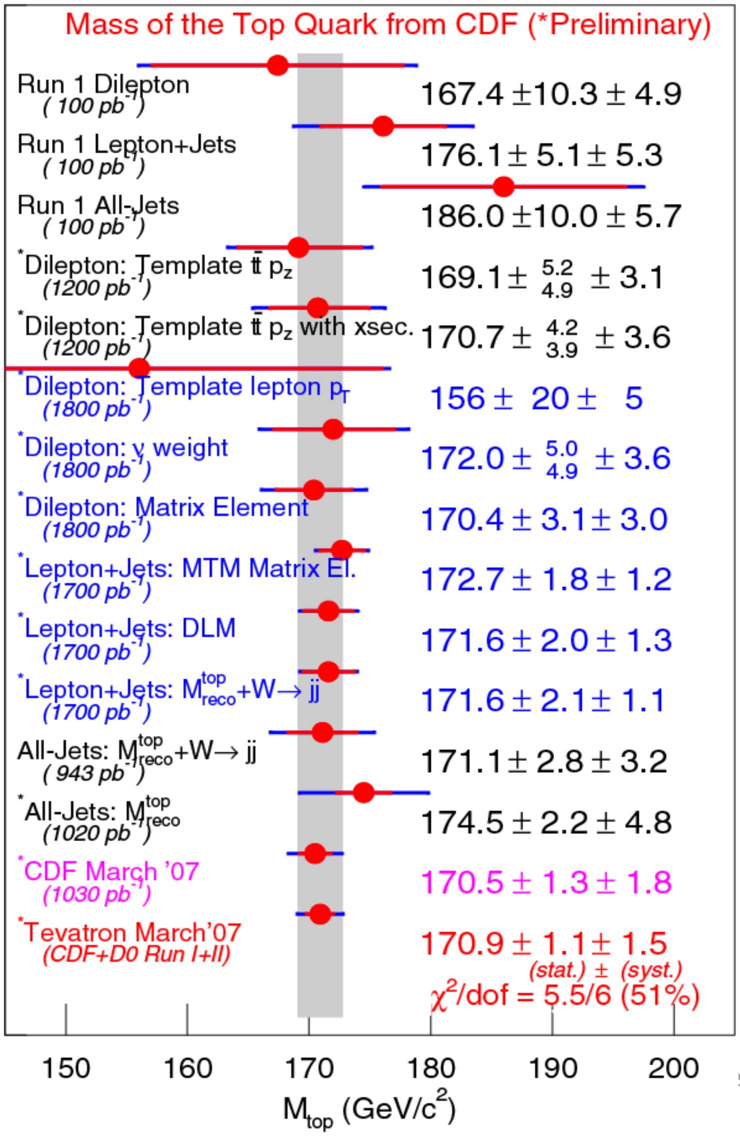


- Maximal extraction of information, but phase space integration is very CPU intensive
- Additional background probability term with varying levels of sophistication

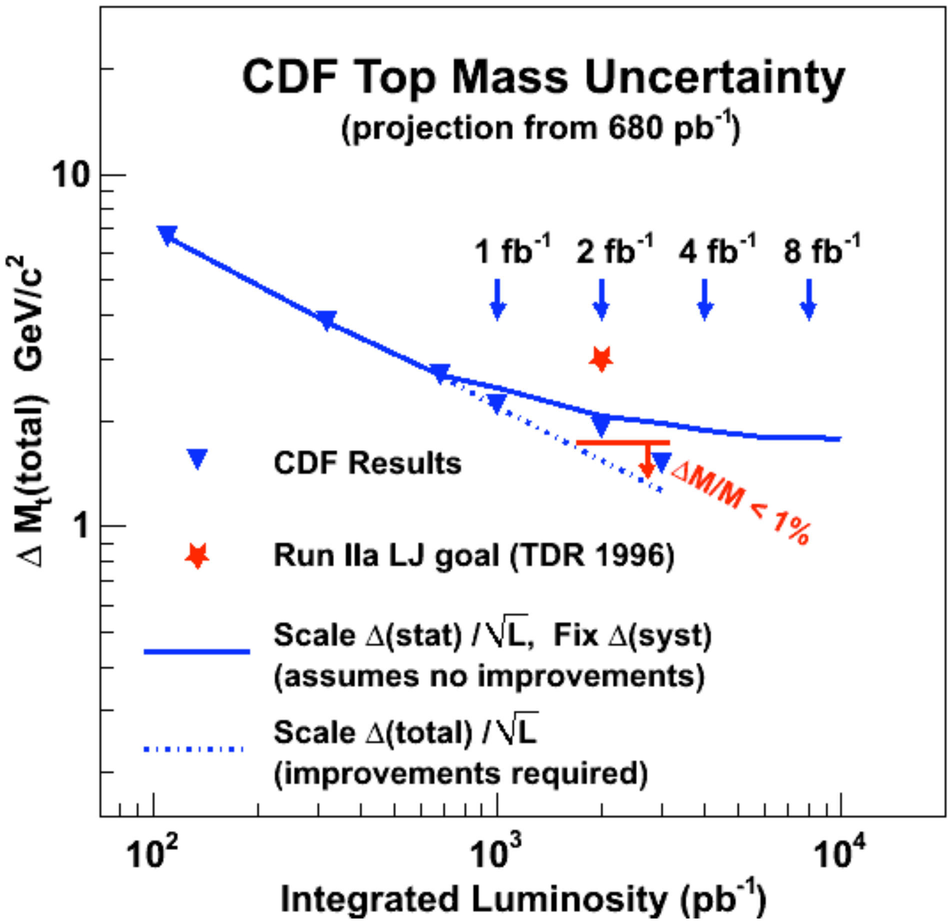
R. Demina (Rochester, D0)

Philosophy in Run II

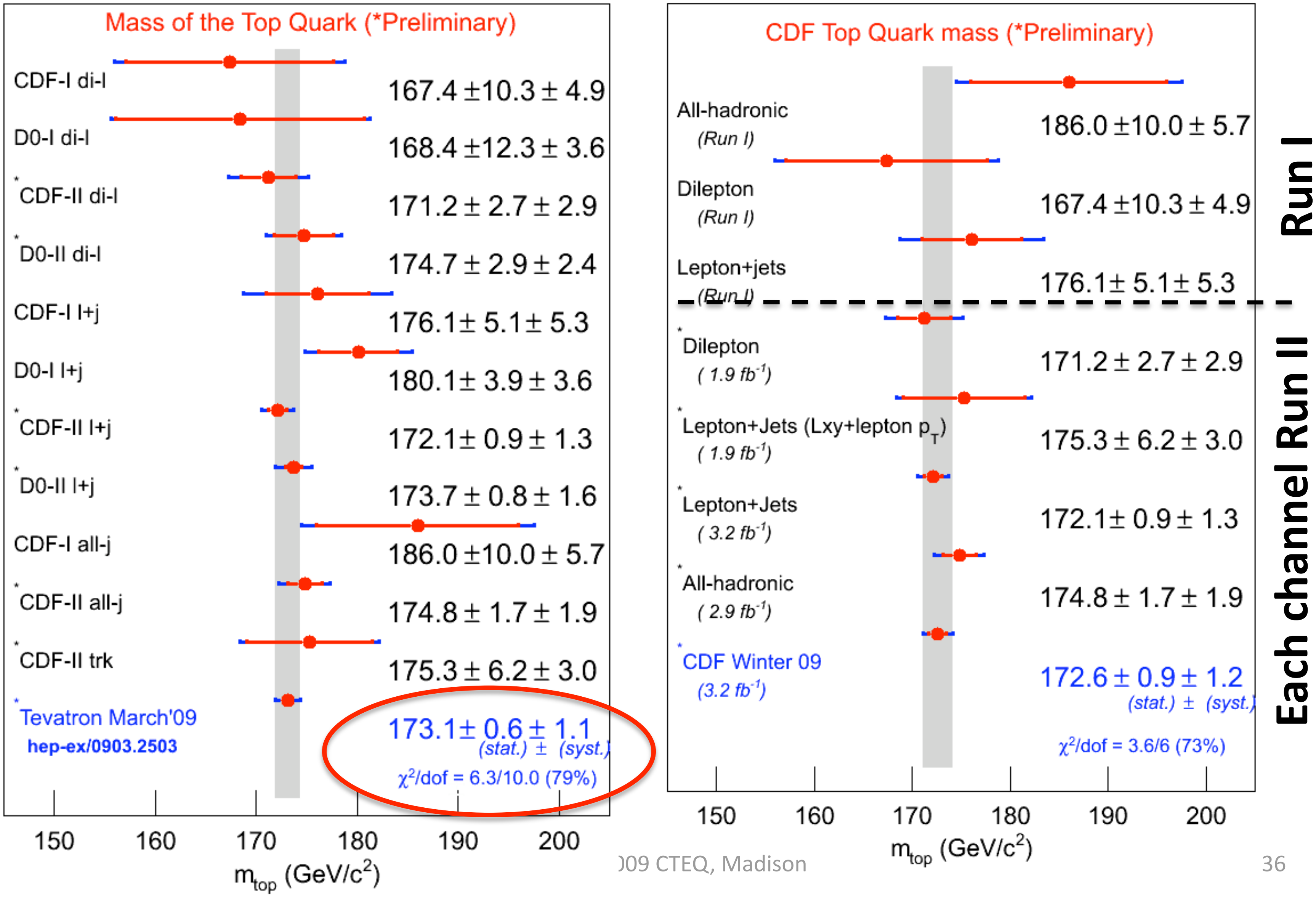
March 2007



March 2009



Tevatron Top Mass (March 2009)



Systematics, Systematics, Systematics

Current list:

1. JES (for non-in situ)
2. **Residual JES**
3. **b-JES**
4. ISR&FSR
5. PDF uncertainties
6. Generator & modeling
7. Multiple interactions (a.k.a Pile-up)
8. Background fraction & Shape
9. Lepton Energy scale

Working on:

1. **MC generators**: checking against NLO MCs
2. **Color reconnection** – more later

Systematic	LJ	DIL	Combination
Residual JES	0.7	3.3	0.6
Generator	0.7	1.2	0.7
PDFs	0.3	0.8	0.3
b-JES	0.2	0.2	0.2
bkgd shape	0.2	0.3	0.2
gg fraction	0.2	0.2	0.2
Radiation	0.2	0.2	0.1
MC statistics	0.1	0.5	0.1
lepton energy scale	0.1	0.3	0.1
pileup	0.2	0.2	0.3
Combined	1.1	3.7	1.1

Systematics for Template Analysis using 2.7 fb^{-1}

Residual JES

- Use jets from hadronic W resonance in messy ttbar environment to measure the average response of jets
- In-situ measured JES does not fully measure shifts in JES scale along different parameter space curves (e.g. jet P_t and η)

- Even for in-situ measurement still evaluate JES uncertainty using standard procedure by shifting JES +/- 1σ
    - Must re-compute acceptances and shapes for both ttbar and backgrounds

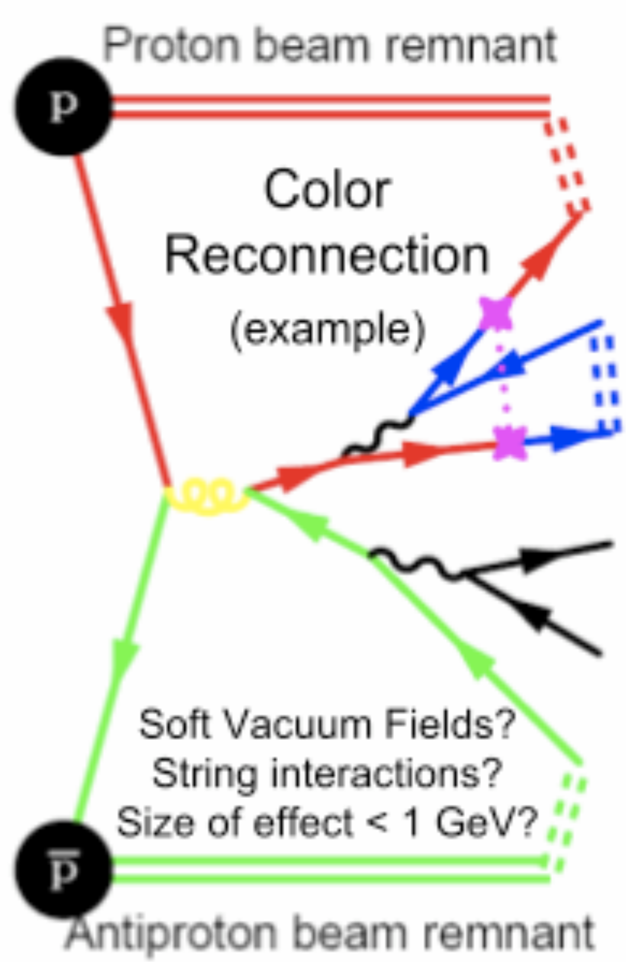
JES for b quarks

- Derive JES from W daughter jets, but b jets carry most M_{top} information

- Study 3 components due to difference between b and q jets:
  - **Semi-leptonic branching ratios**
    - Move b anc c BRs together by +/- 1σ
  - **B fragmentation uncertainties**
    - Reweight to LEP/SLD Bowler parameters
  - **Calorimeter response uncertainties**
    - Shift b-jet energies by +/-1% then re-run PEs

Color Reconnection Studies

- Pythia 6.4 includes:
  - P_T ordered showering which allows for parton showers to interact with the underlying event
  - new color reconnection models
- Study by Wicke and Skands on toy top mass measurement see ~1 GeV differences
  - **see Wicke and Skands, arXiv 0807.3248 and hep-ph/0703081**

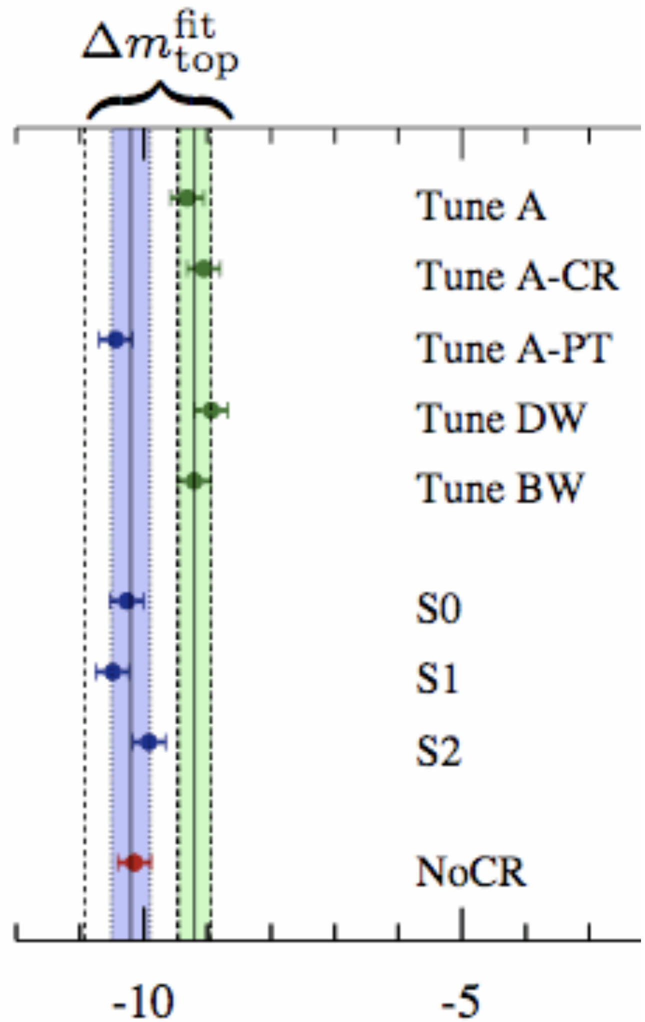


Color Reconnection Studies

Virtuality ordered PS (old)

P_T ordered PS (new)

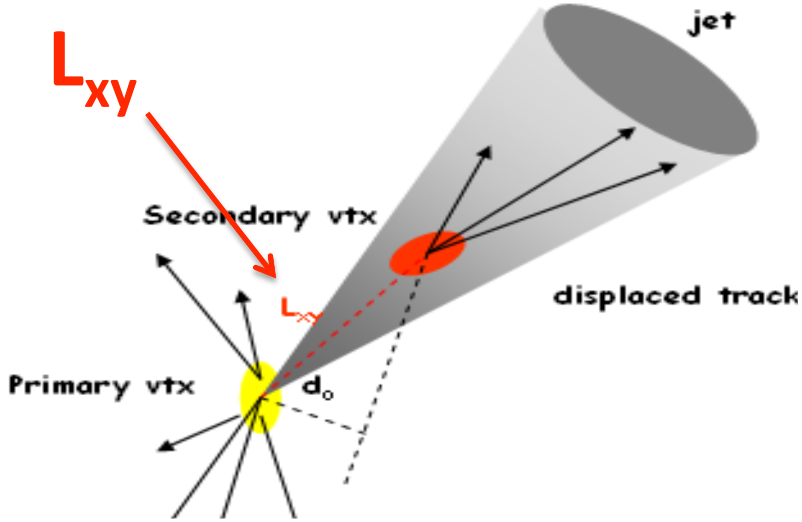
- Results:
  - Total spread +/- 1 GeV
- CDF and D0 are studying new Pythia tunes within our analysis methods
  - From preliminary studies added uncertainty of 0.4 GeV to systematics for the winter 2009 results

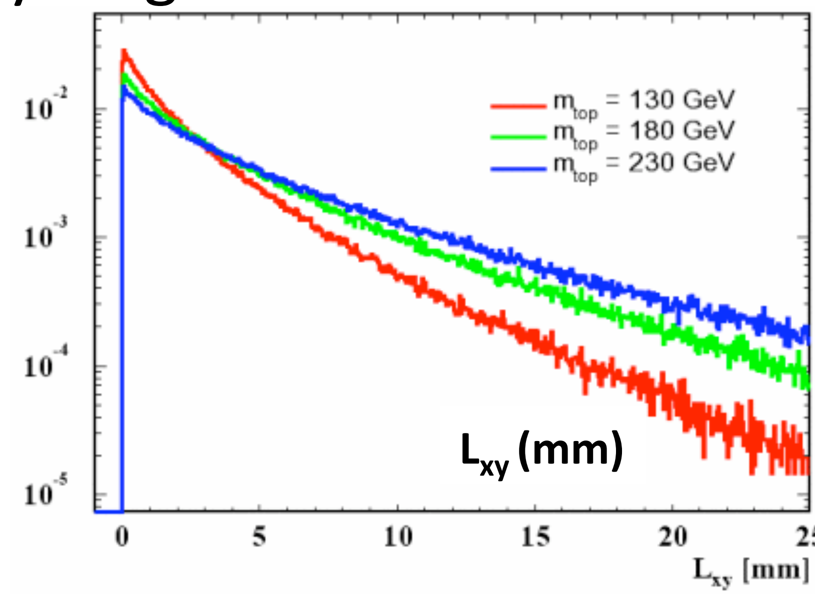


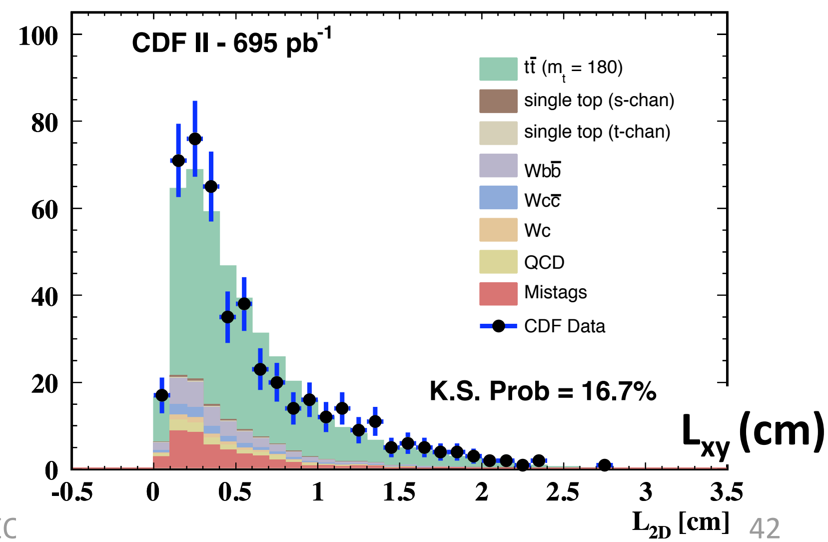
L+jets Template Method using L_{xy}

L_{xy} = average transverse decay length of B-hadron

$L_{xy} \propto$ b-jet boost $\propto M_{top}$



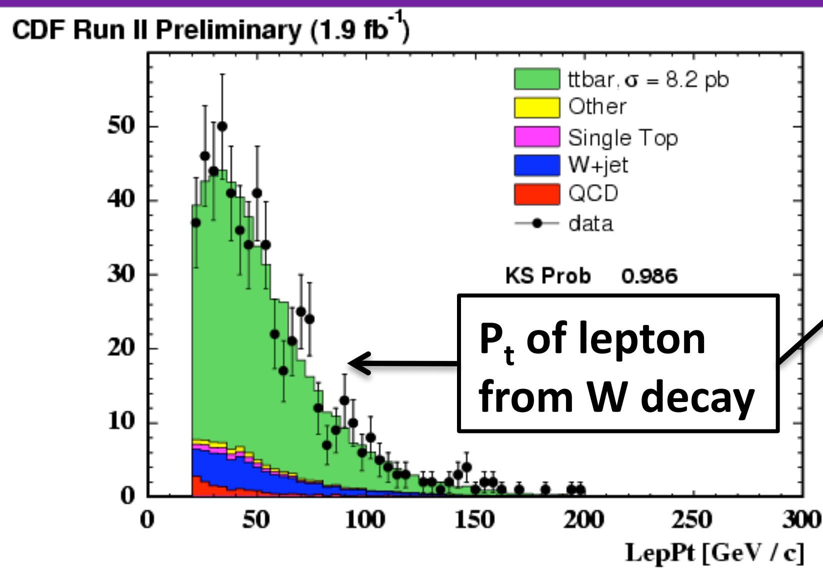


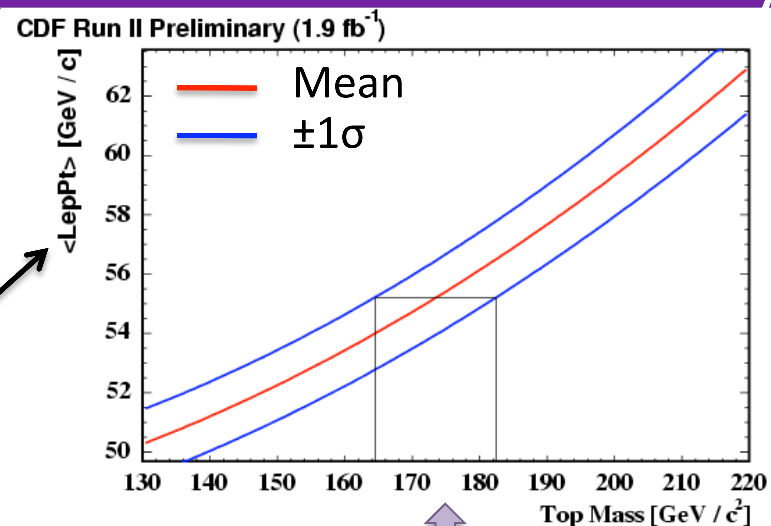


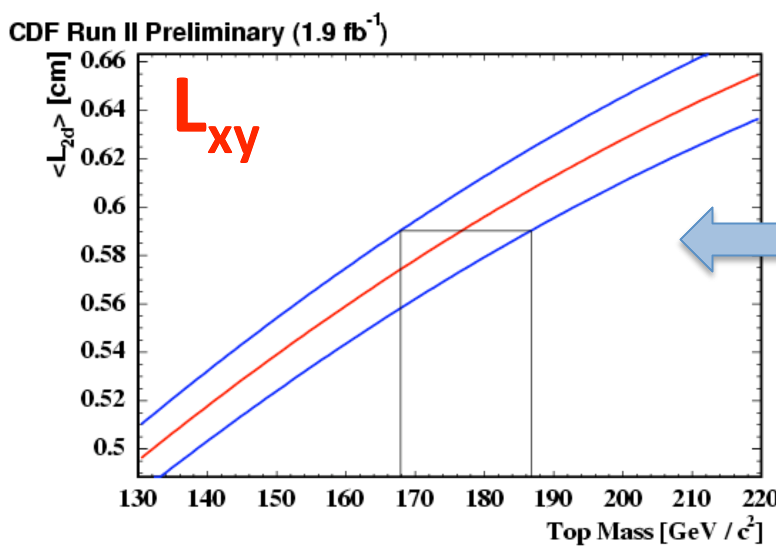
Mtop = 180.7 +15.5/-13.4 (stat) +/- 8.6 (syst) GeV/c^2

PRD 75:071102 (2007)

L+jets - Combining Lepton P_t + L_{xy}







Mtop = 176.7 +10/-8.9(stat) +/-3.4(syst) GeV/c^2 using L_{xy} alone

Mtop = 173.5 +8.9/-9.1(stat) +/-4.2(syst) GeV/c^2 using Lepton P_t alone

Combined Result using 1.9 fb^{-1}:
Mtop = 175.3 +/- 6.2 (stat.) +/- 3.0 (syst) GeV/c^2

Interesting Lesson…

L_{xy} and Lepton P_t don't depend on JES, right?

Source of Systematic Error	Uncertainty (GeV/c^2)
Monte Carlo Generator	0.7
Initial State Gluon Radiation	1.0
Final State Gluon Radiation	0.9
Parton Distribution Functions	0.5
Event Selection (Jet Energy Scale)	0.3
Background Shape	6.8
Background Normalization	2.3
Multiple Interactions	0.2
Data/MC $\langle L_{2D} \rangle$ Ratio	4.2
Total	8.6

Systematics for L_{xy} result using 695 pb^{-1}

Event selection was affected for jets near 20 GeV threshold cut

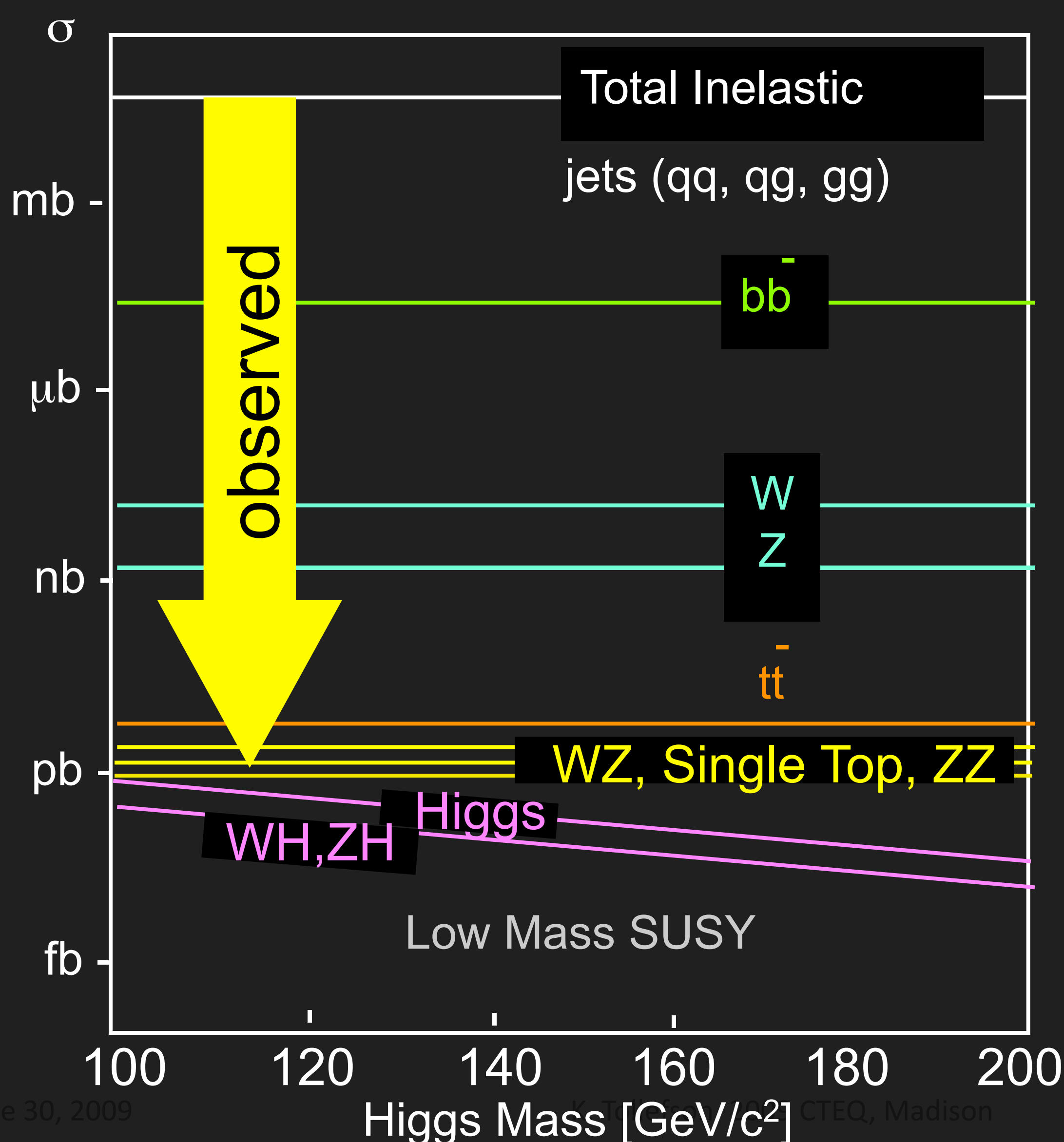
Systematic	L2d	LepPt	Combination
QCD Radiation	0.9	2.3	1.5
PDFs	0.3	0.6	0.5
Generator	0.7	1.2	0.6
L2d Scale Factor	2.9	0	1.4
LepPt scale	0	2.3	1.1
Bkg Shape	1.0	2.3	1.6
Out of Cone JES	1.0	0.3	0.6
Total	3.4	4.2	3.0

Systematics for L_{xy} and $LepP_t$ results using1.9 fb^{-1}

Systematic	L2d	LepPt	Combination
Level 1, Eta Dependent	0	0	0
Level 4, Multiple Interactions	0.1	0	0
Level 5, Absolute	0.2	0.1	0.1
Level 6, Underlying Event	0	0	0
Level 7, Out of Cone	1.0	0.2	0.6
Level 8, Splash out	0.1	0.1	0.1
Simultaneous	1.0	0.3	0.6

Single Top

On the Road to Higgs



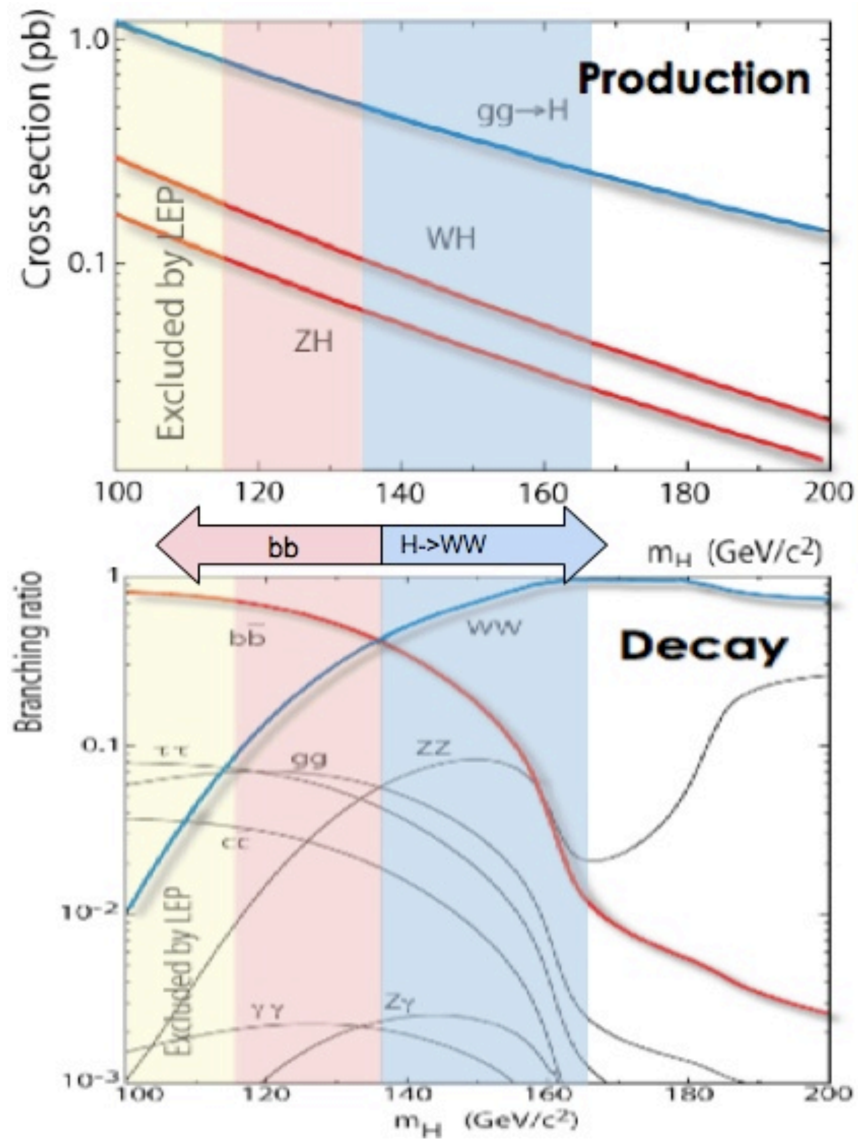
M_W ~ 0.05%

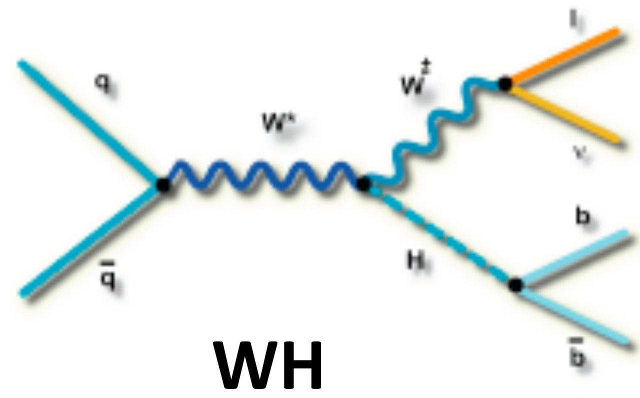
M_{top} ~ 0.7%

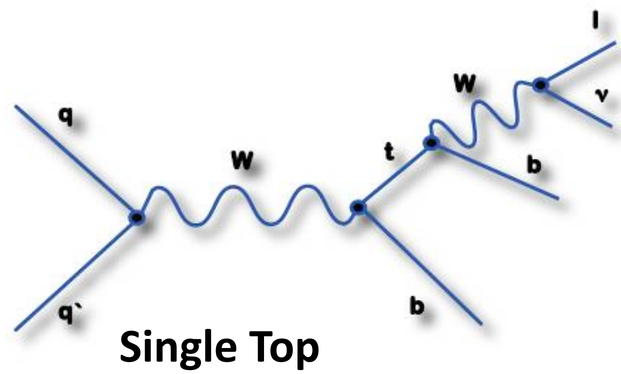
Observed WZ, ZZ and Single Top

Excluded $160 < M_{Higgs} < 170$ GeV at 95% CL

SM Higgs and Single Top



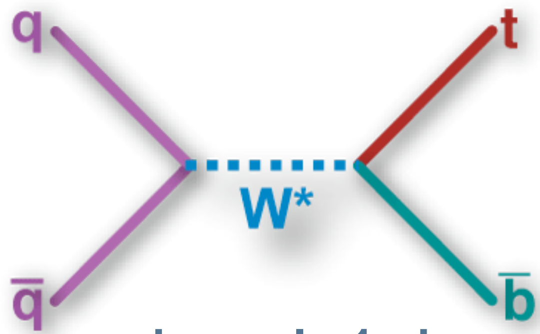




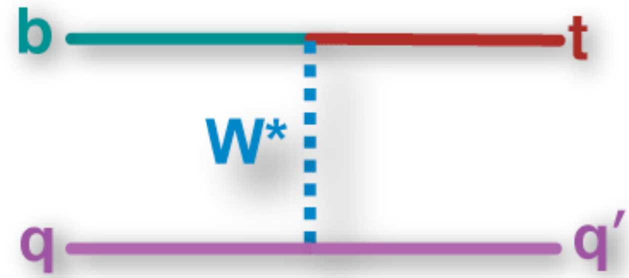
Single top is large background to low mass Higgs searches.

Single Top Production

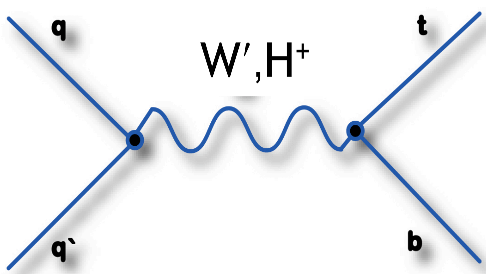
At the Tevatron

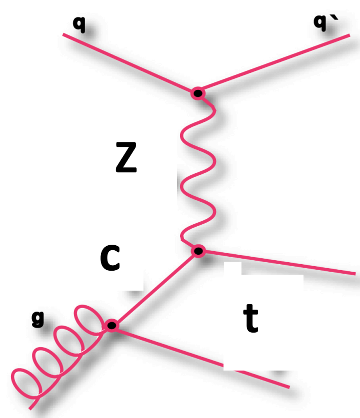


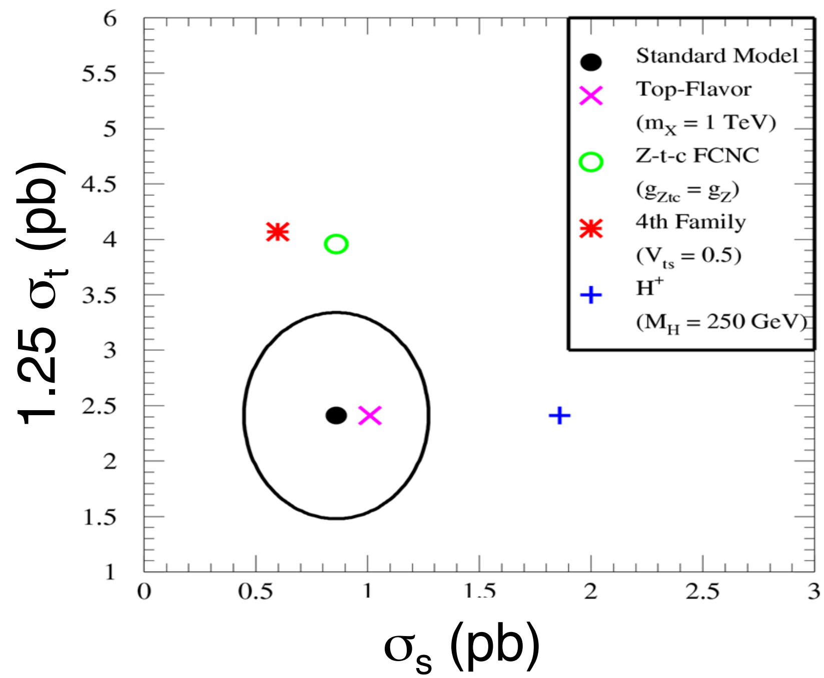
s-channel ~1 pb



t-channel ~2 pb





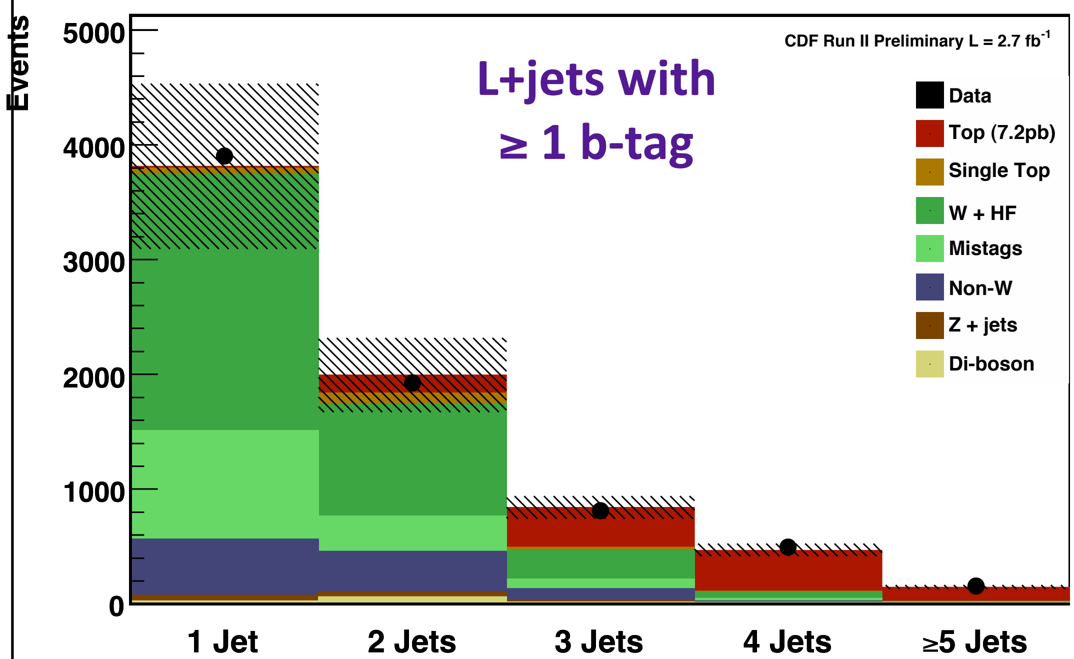


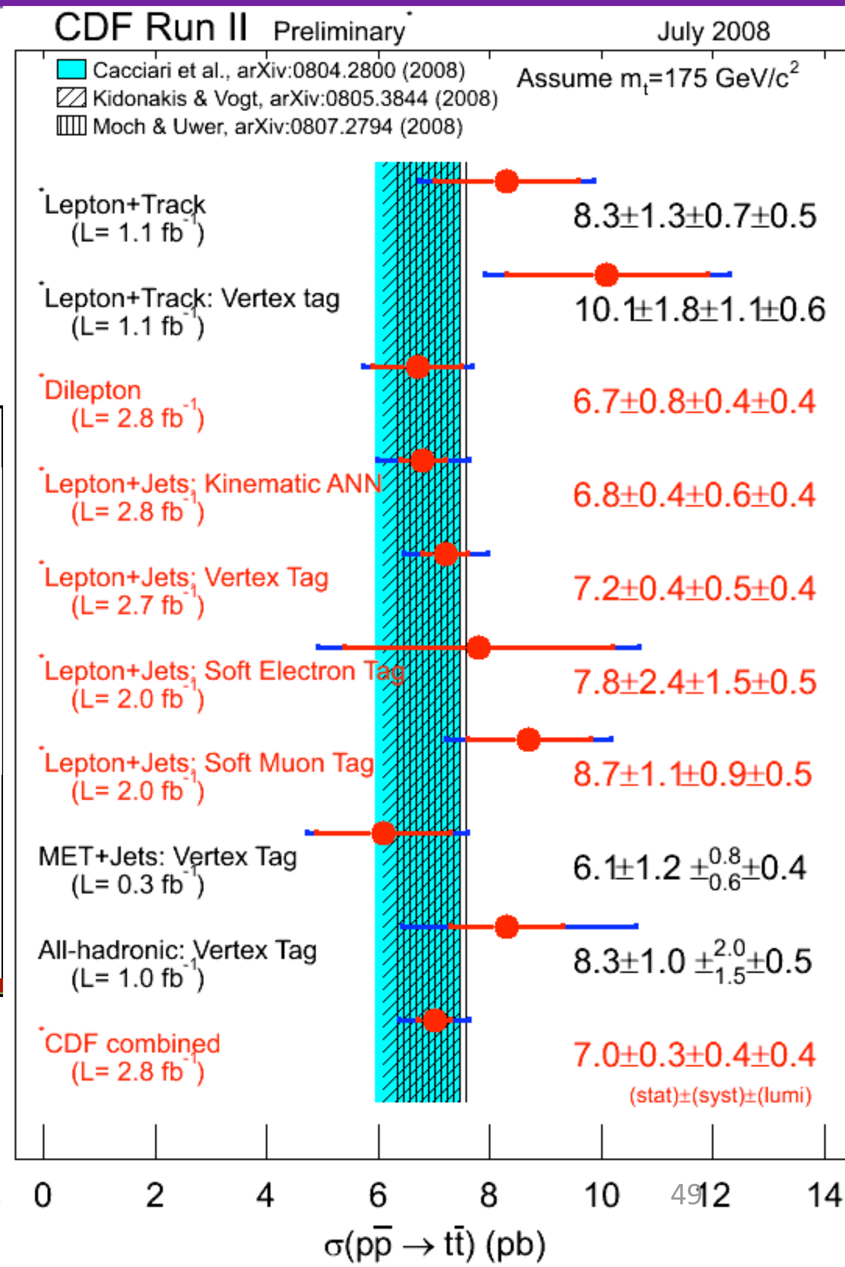
Tait, Yuan PRD63, 014018 (2001)

In SM $\sigma \propto |V_{tb}|^2$

Top Pair Production Cross Section

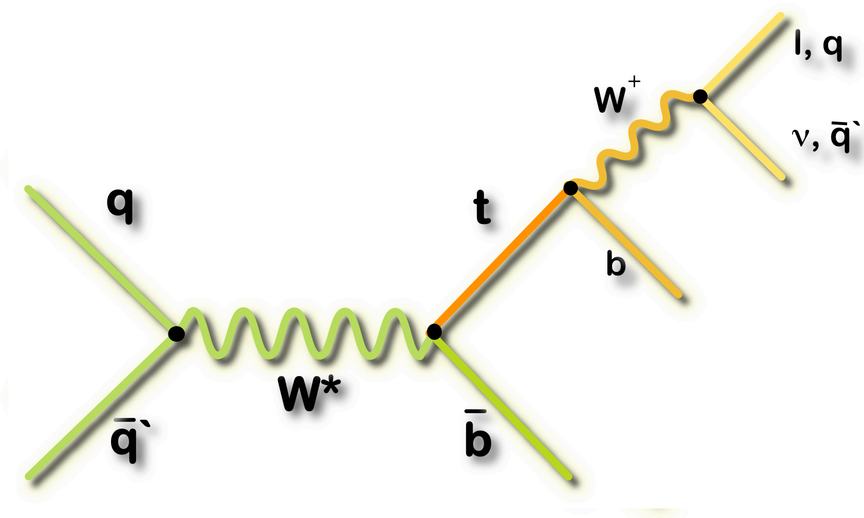
$$\sigma_{t\bar{t}} = \frac{\mathcal{N}_{obs} - B}{\mathcal{A} \cdot \int \mathcal{L}\, dt}$$

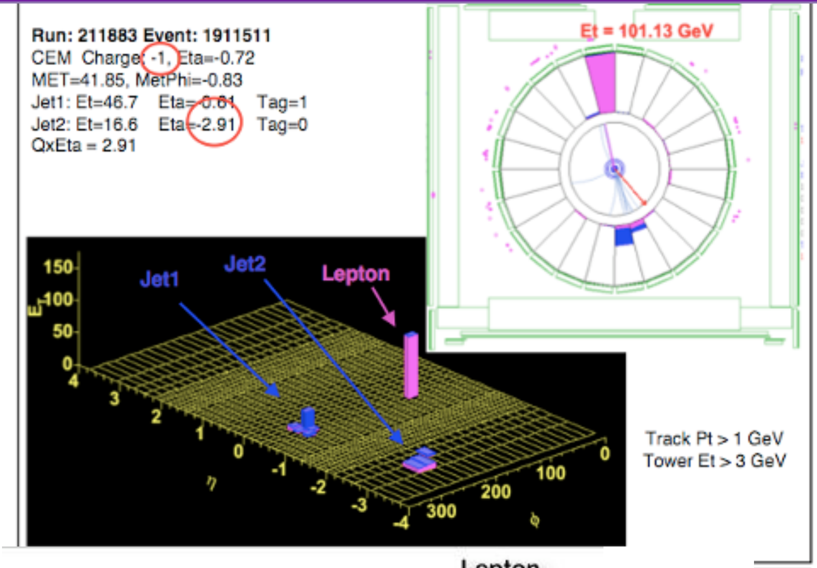




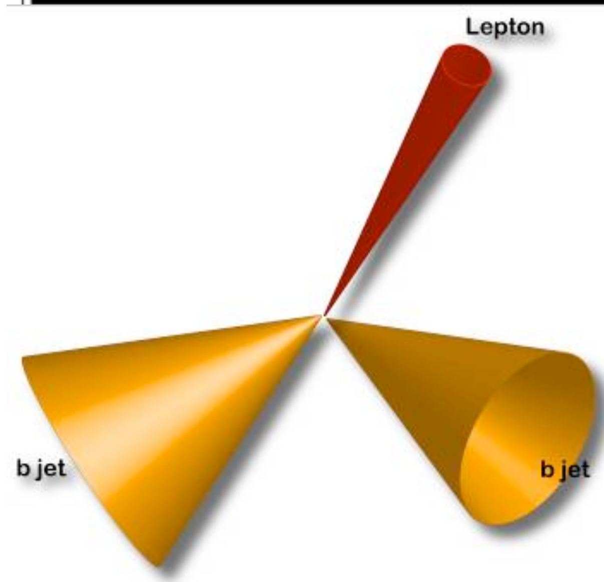
Single Top Event Signatures

Top Pair Production with decay into Lepton + 4 Jets final state are very striking signatures!

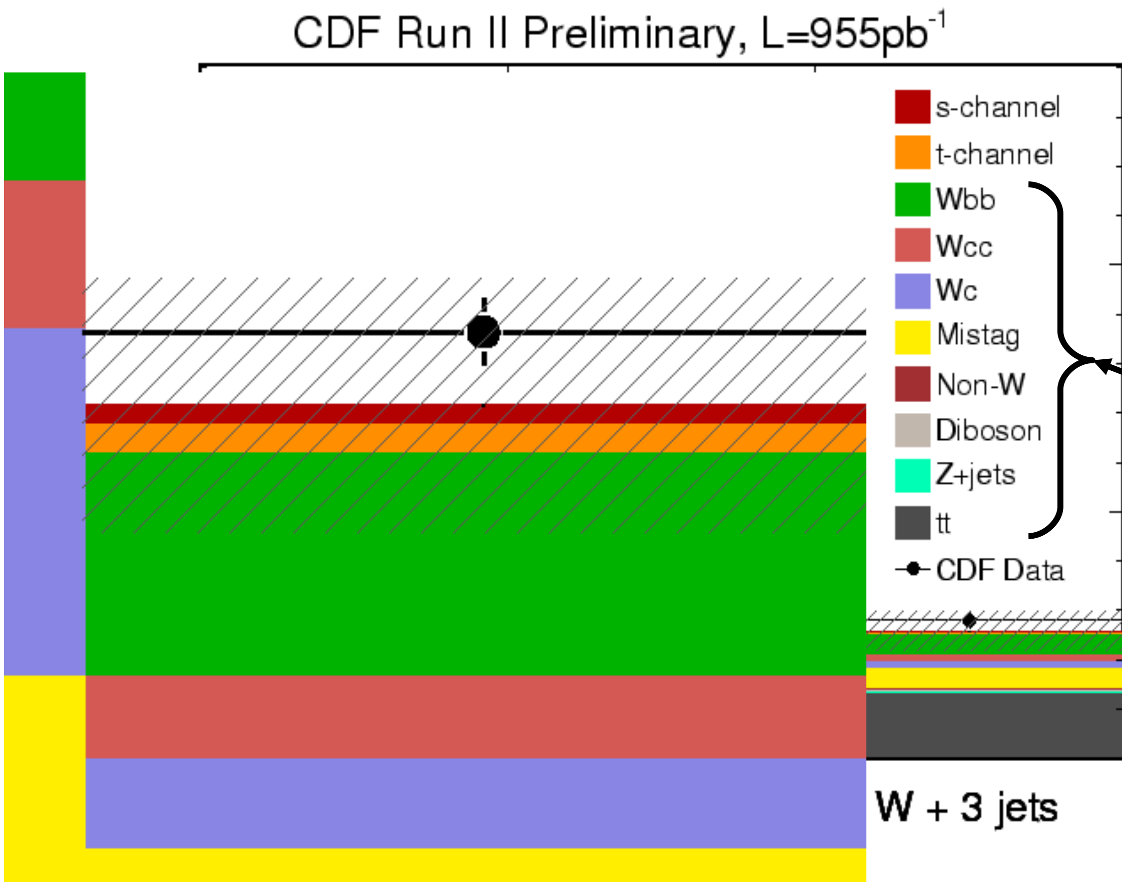




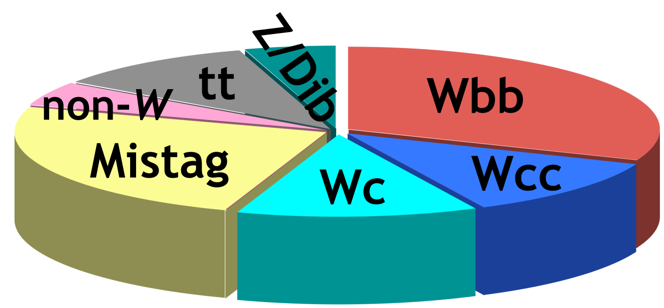
Single top Production with decay Into Lepton + 2 Jets final state is less distinct!



Single Top Backgrounds



Backgrounds!
- Best channels S/B~1/20
- Signal smaller than background uncertainty!



Background Estimates

s-channel	58.1 ± 8.4
t-channel	87.6 ± 13.0
Single top	145.7 ± 21.4
tt	204.1 ± 29.6
Dibosons	88.3 ± 9.1
Z + jets	36.5 ± 5.6
W + bb	656.9 ± 198.0
W + cc	292.2 ± 90.1
W + cj	250.4 ± 77.2
W + light flavor	501.3 ± 69.6
Non-*W*	89.6 ± 35.8
Total background	2119.3 ± 350.9
Total prediction	2265.0 ± 375.4
Observed	**2229**

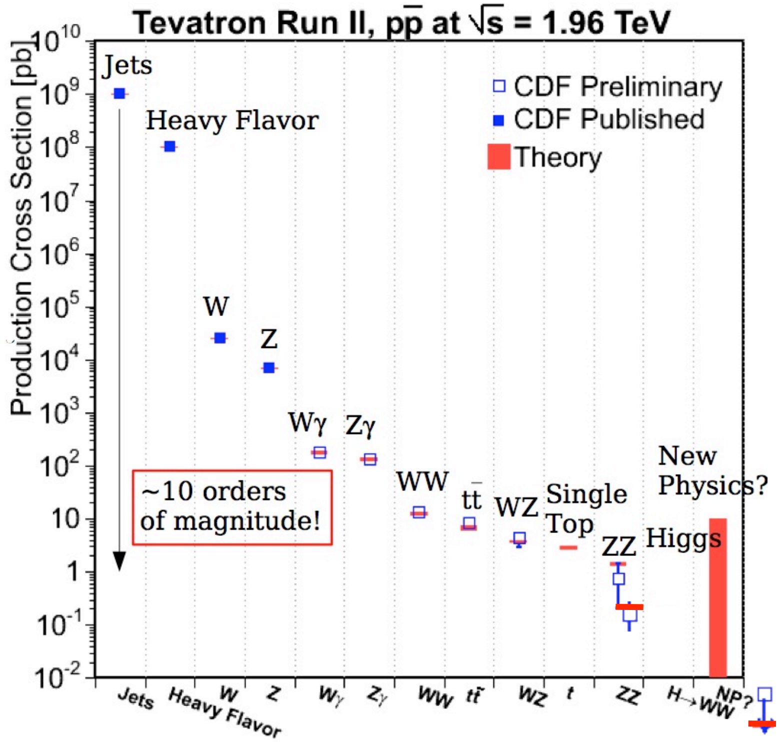
~30% (W + bb, W + cc, W + cj uncertainties)

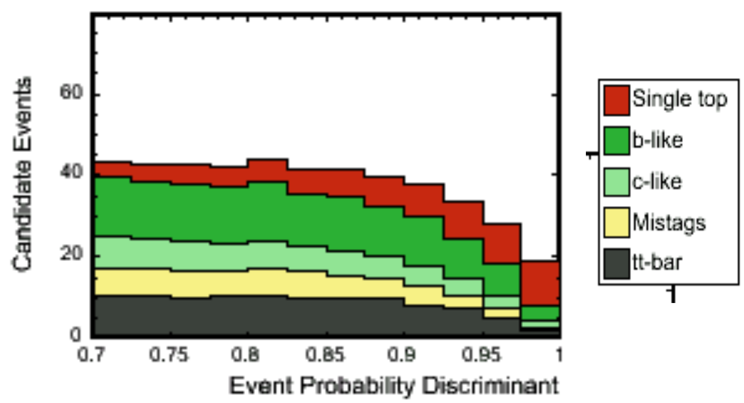
MET + high p_T lepton + 2 jets (with 1 or 2 b-tags) in 3.2 fb^{-1}

Remember Zack's talk: Need help from theorists to understand W+HF production better

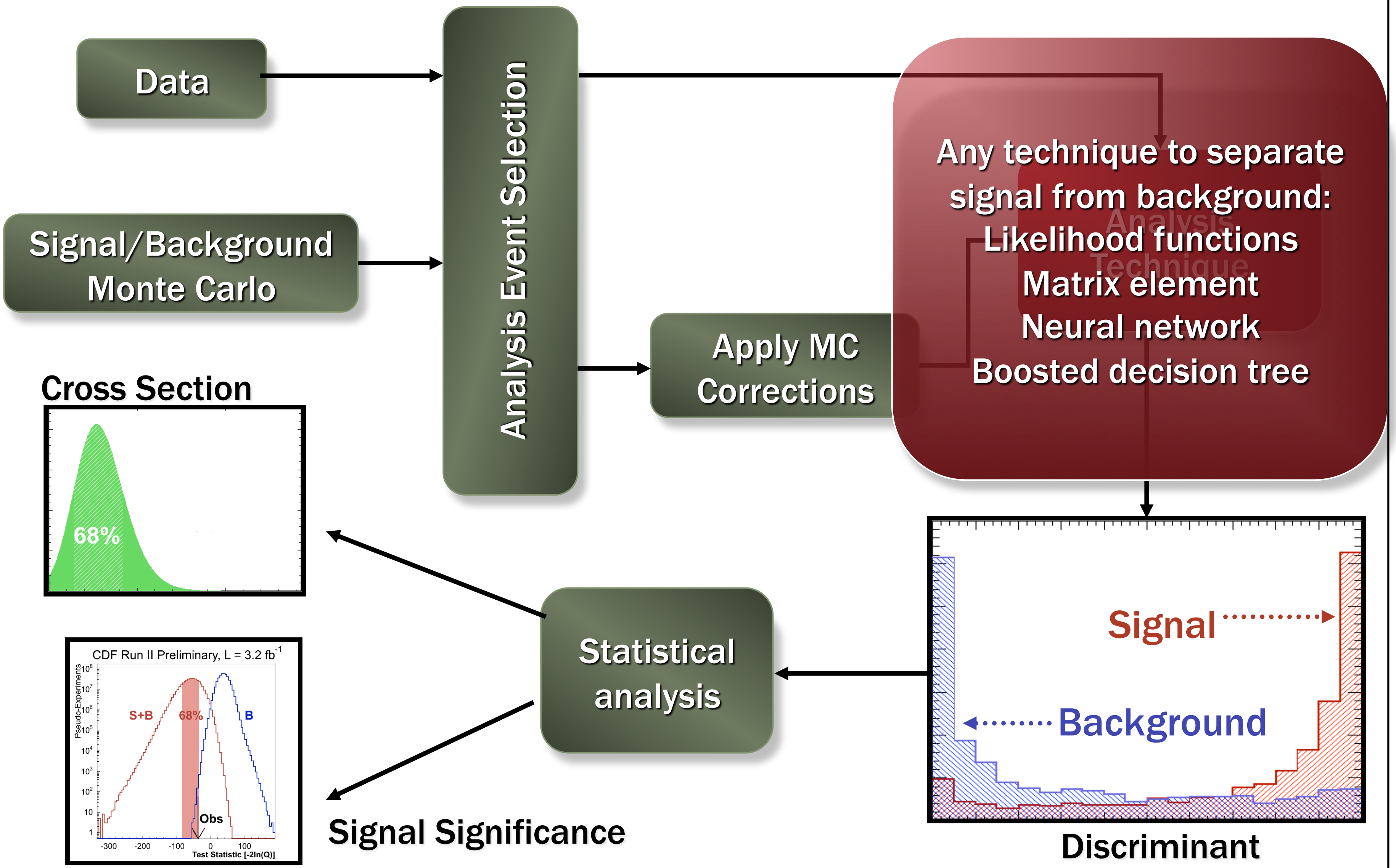
Analysis Strategy

- Single Top production is rare (~3 pb)
  - Signal:Background (S:B) ~ 1:10^9
- First step:
  - Trigger and ID clean leptons/MET improves S:B by a factor ~10^6
  - High p_T lepton triggers (e,μ)
  - MET + jets triggers (recover non-fiducial leptons + hadronic τ decays)
- Second step:
  - Topological event selection
  - Efficient *b*-tagging
  - Careful background estimates
- Third step:
  - Advanced analysis techniques
  - S:B > 1:1 in most significant bins



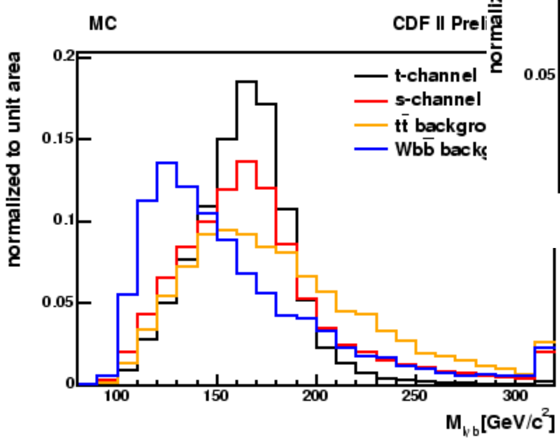


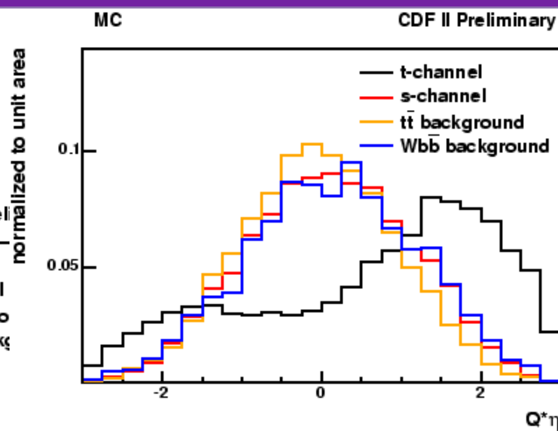
General Analysis Method

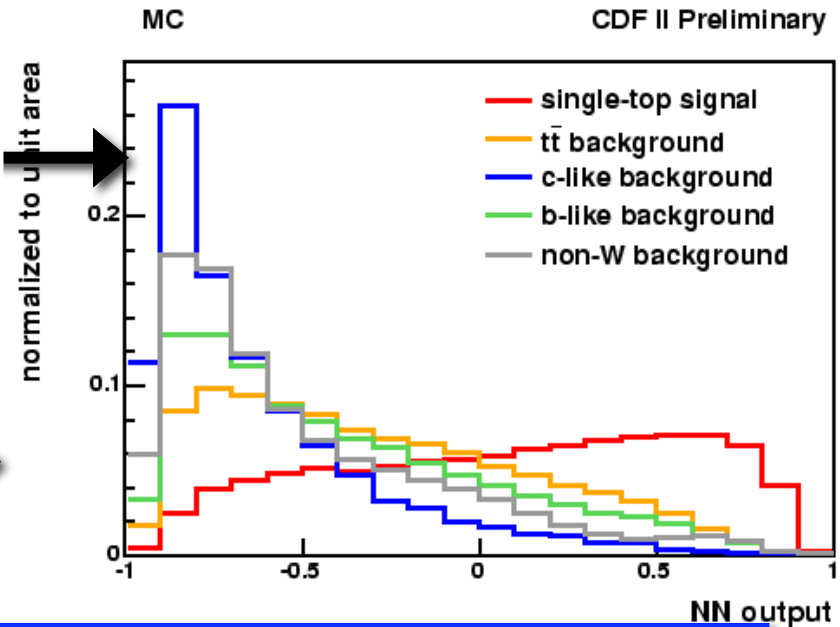


Advanced Techniques

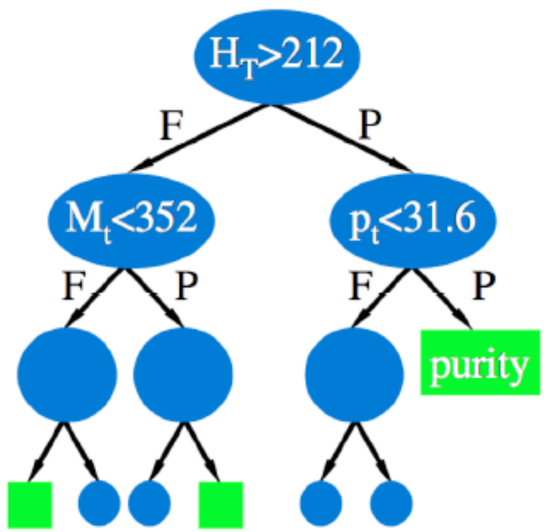
Neural Networks







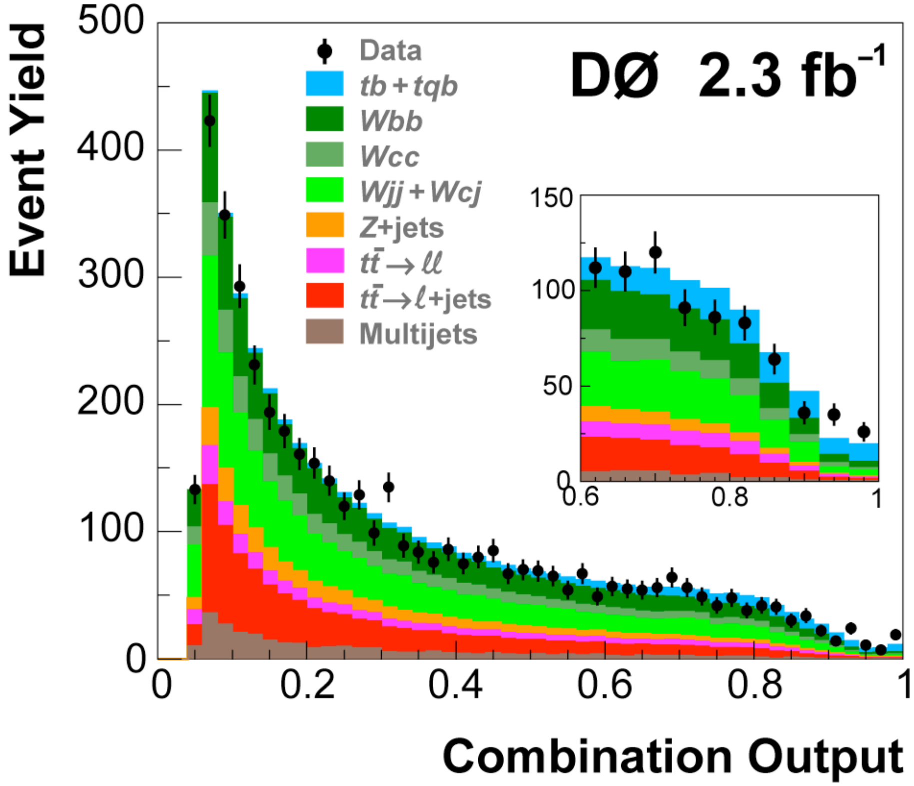
Boosted Decision Trees

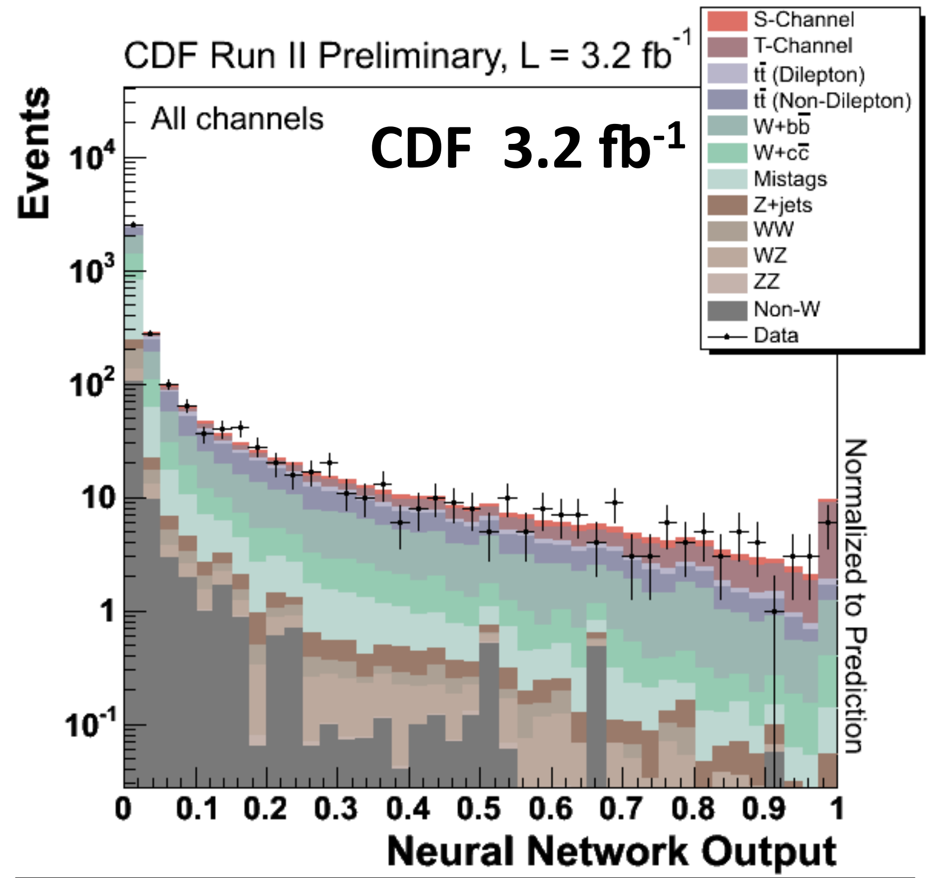


multivariate techniques can coax signal out from large backgrounds

boosted decision trees, matrix element reconstruction, bayesian neural networks, likelihood discriminants

Single Top ~~Discovery~~ Observation





Expected sensitivity: 4.5σ

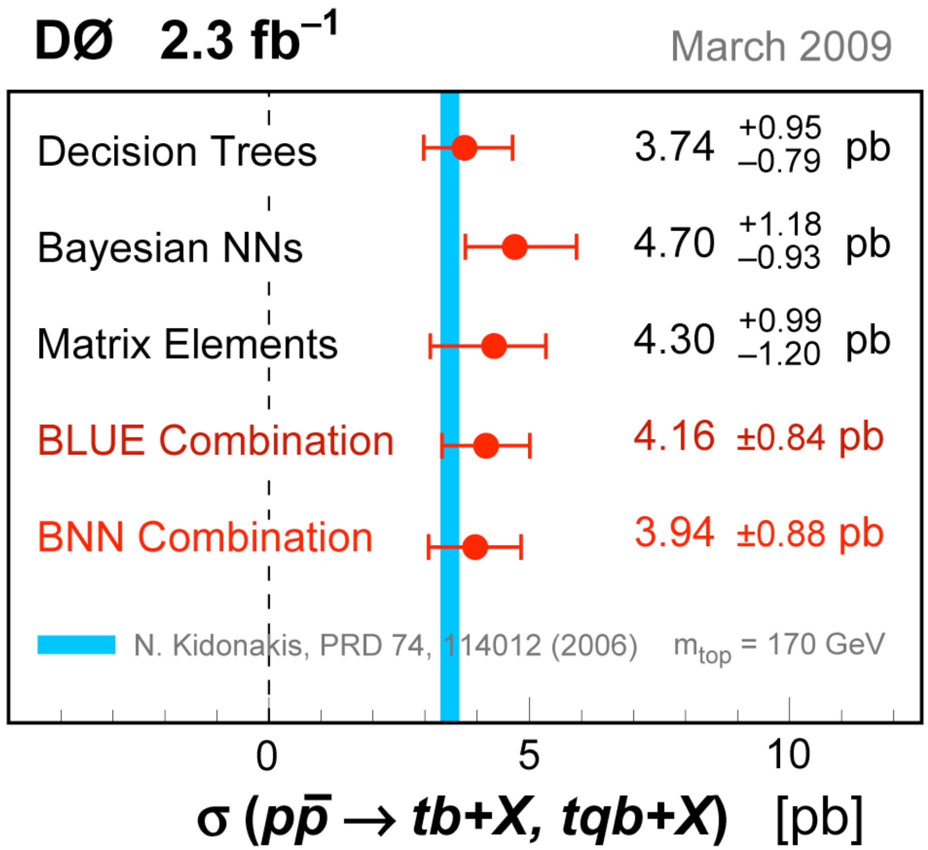
Observed p-value: 2.5×10^{-7} : 5.0σ

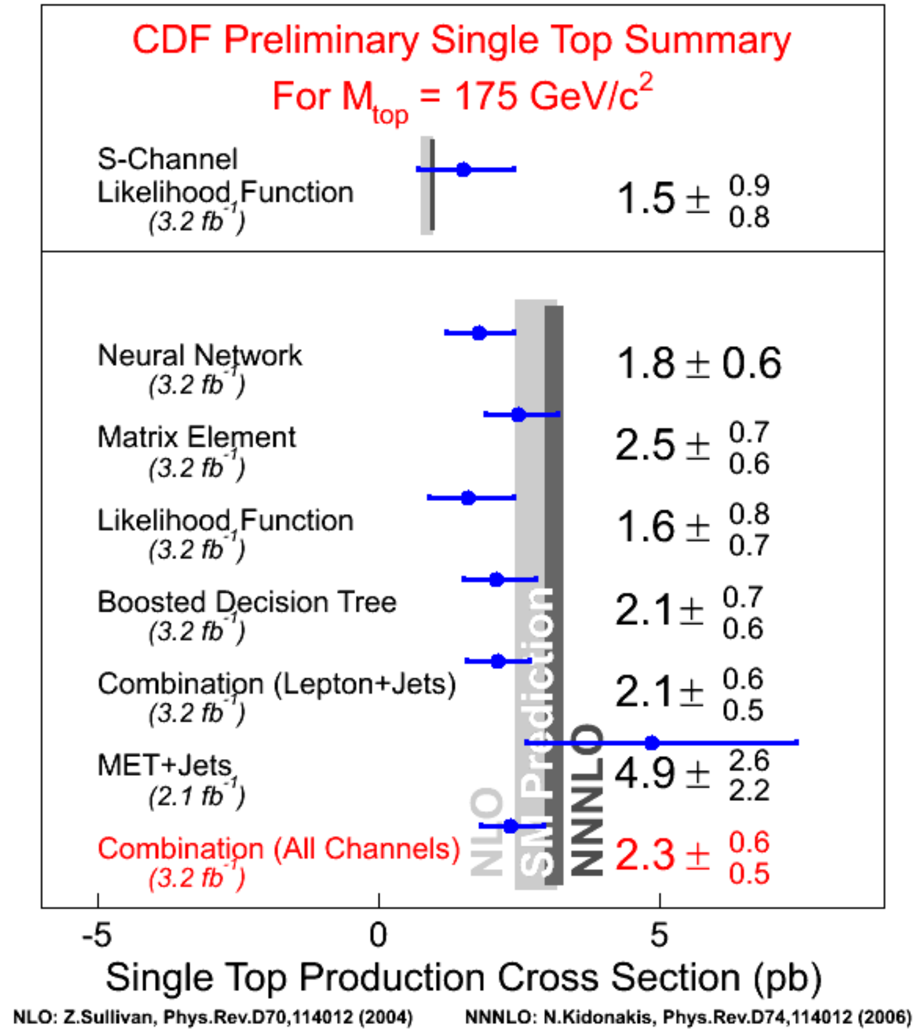
Expected sensitivity: >5.9σ

Observed p-value: 3.1×10^{-7} : 5.0σ

Single Top has been observed!

Single Top Cross Section





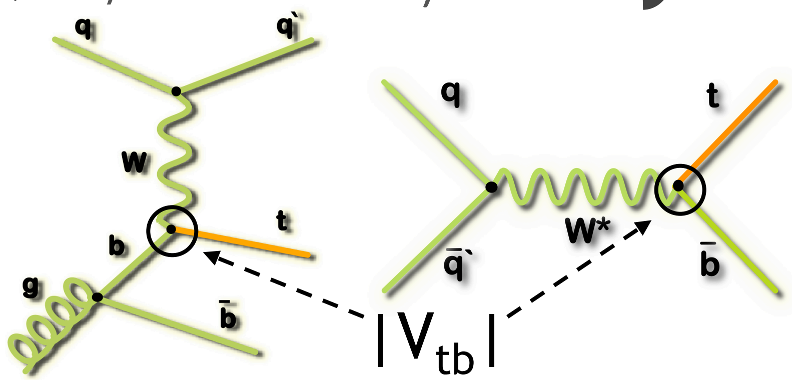
also recently NLO t-channel 2→3
Campbell et. al. hep-ph 0903.0005

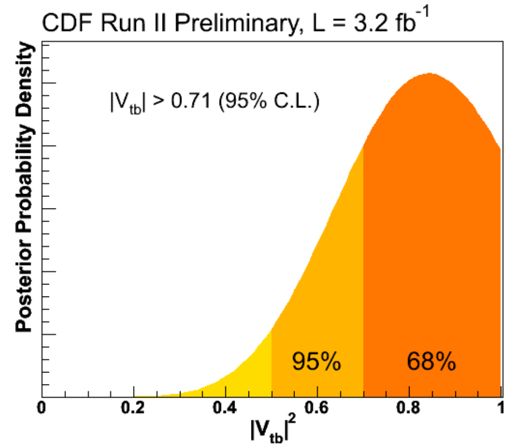
CDF and D0 are currently working on a Tevatron combination

Direct $|V_{tb}|$ Measurement

- Use cross section result to measure $|V_{tb}|$
- Assume Standard Model (V-A) coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$ (from BR($t \rightarrow Wb$) measurements)

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$





D0 combined fit:

$|V_{tb}|$>0.78 at 95% C.L.

Release upper constraint:

$|V_{tb}|$= 1.07 ± 0.12 (stat+syst)

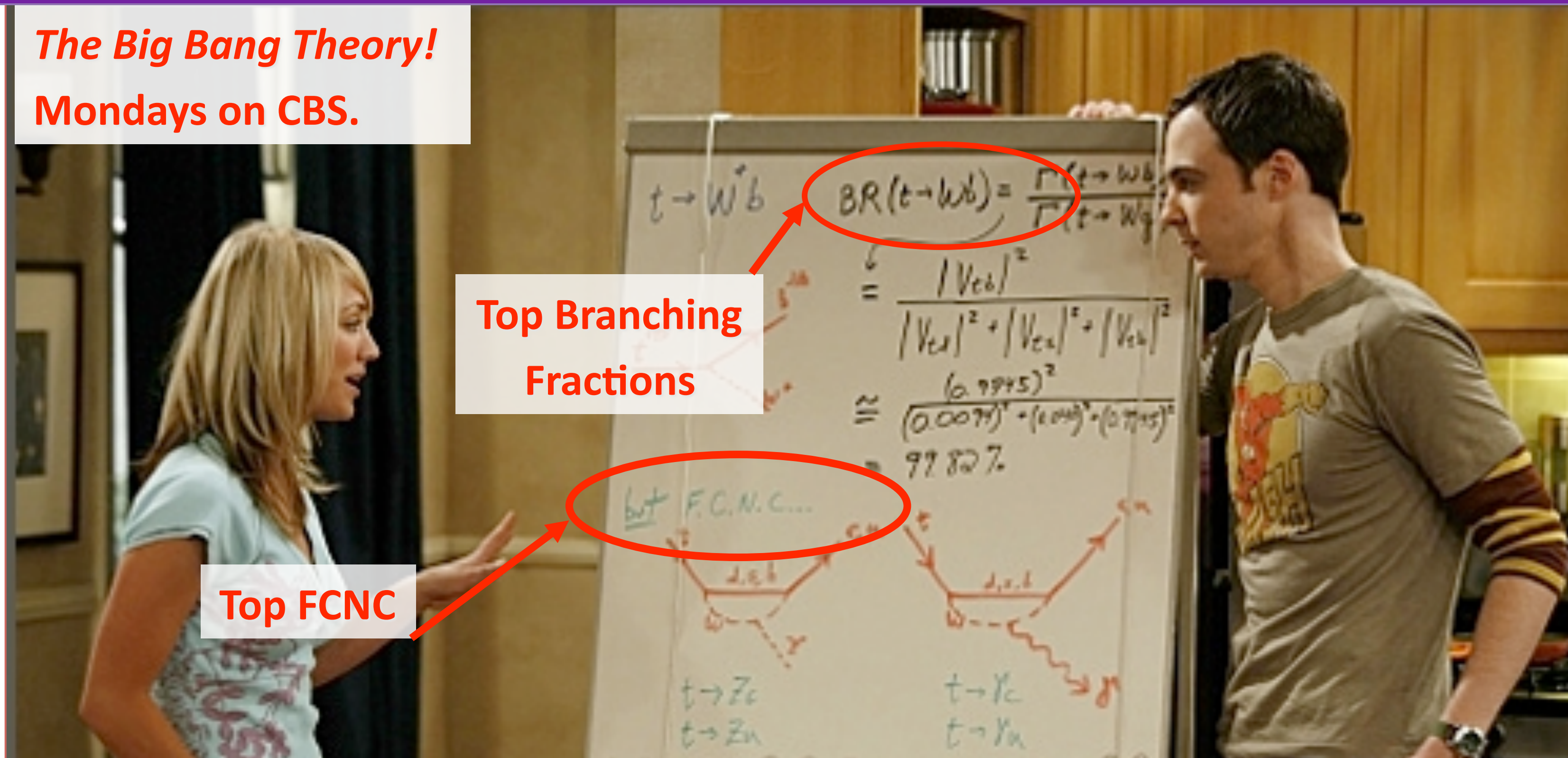
CDF combined fit:

$|V_{tb}|$>0.71 at 95% C.L.

$|V_{tb}|$= 0.91 ± 0.11 (stat+syst) ± 0.07 (theory)

Z. Sullivan, Phys.Rev. D70 (2004) 114012

Top Physics on Prime Time



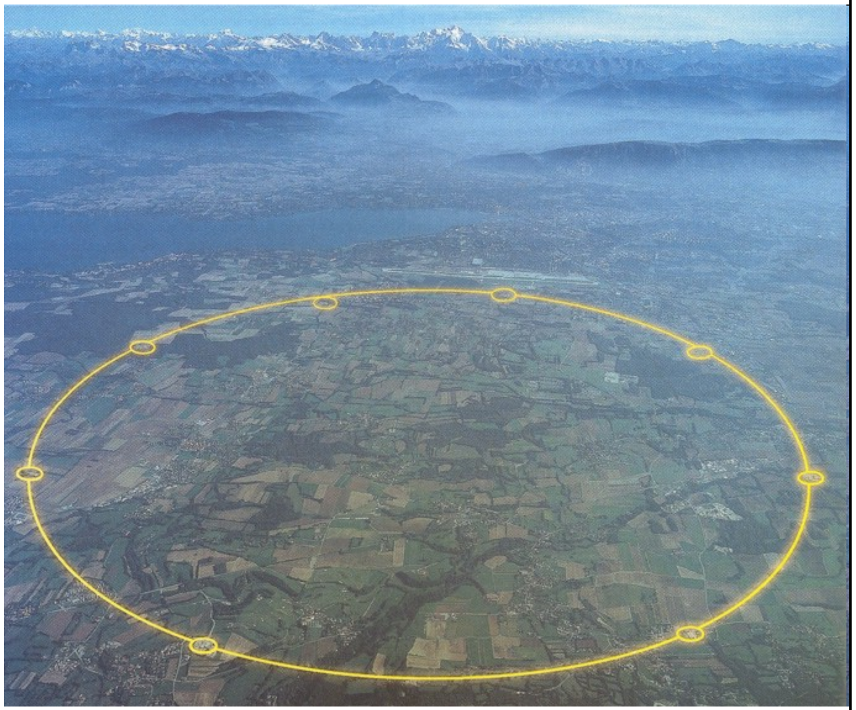
Many more Top results from Tevatron on public webpages:

CDF: http://www-cdf.fnal.gov/physics/new/top/top.html

D0: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Top Physics at the LHC

- LHC is a Top Factory
  - Top pair cross section grows by x100
    (remember Steve Mrenna's quiz?)
  - Access to more rare top decays for precision tests of SM
  - Standard candle
    - Calibration of b-tagging, jet energy scale, etc.
    - Single top test bench for finding Higgs



My View of the World

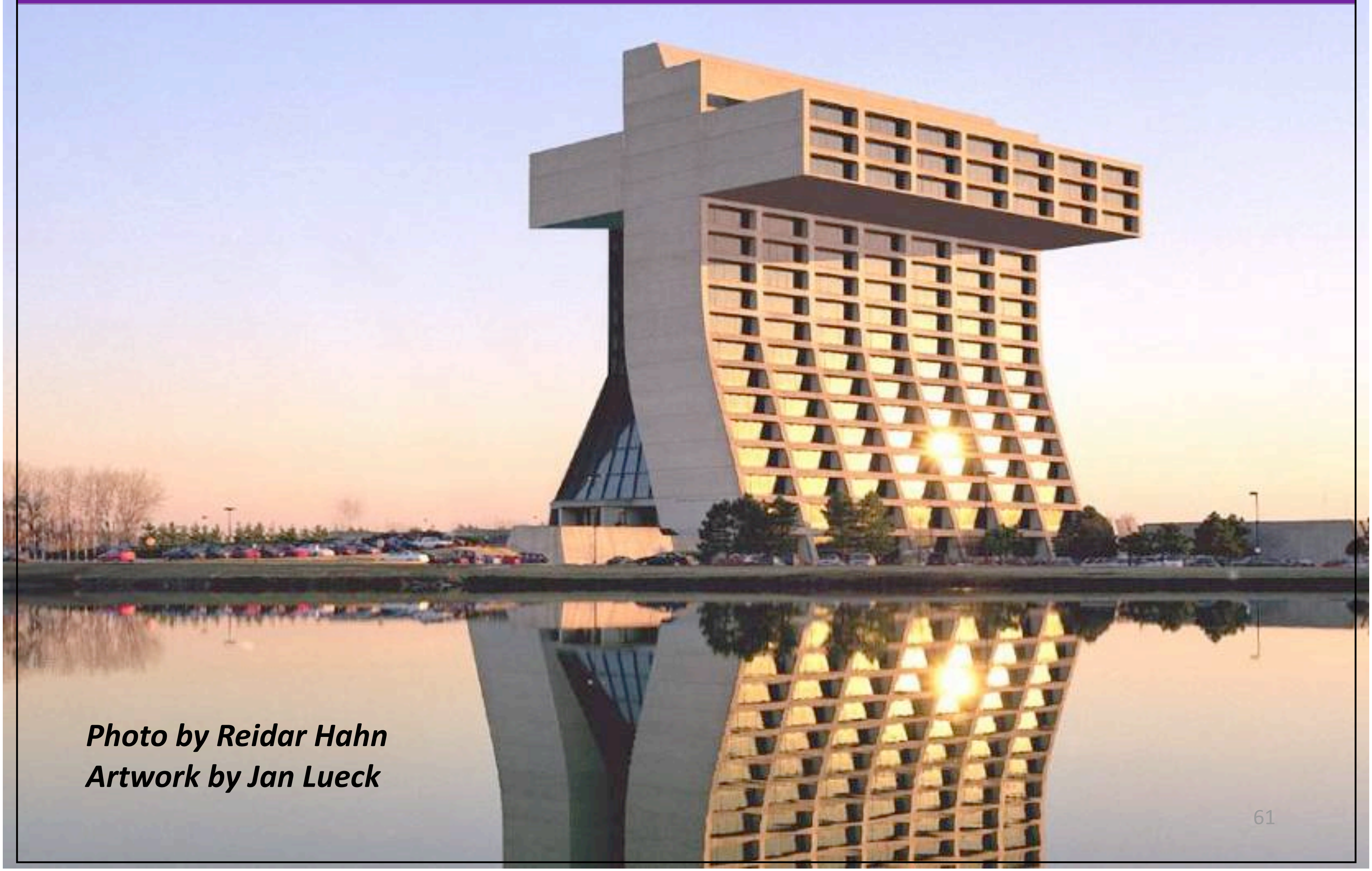
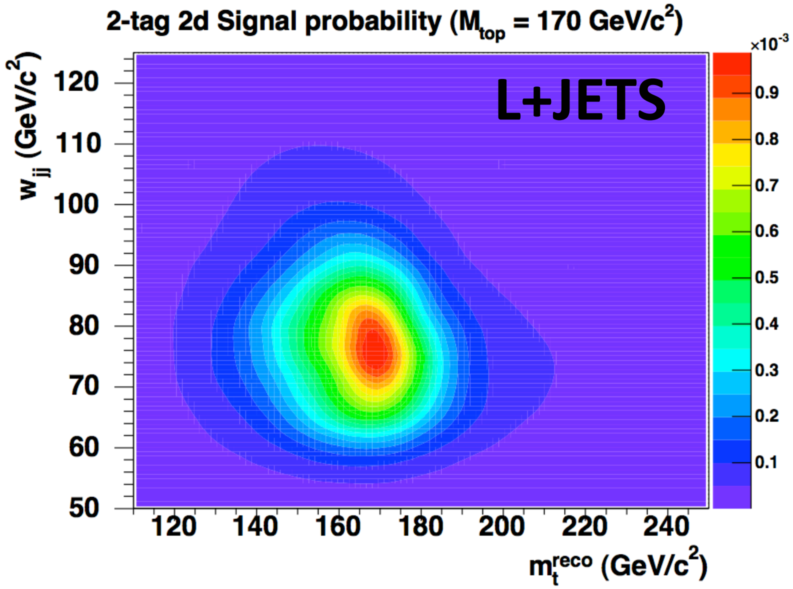


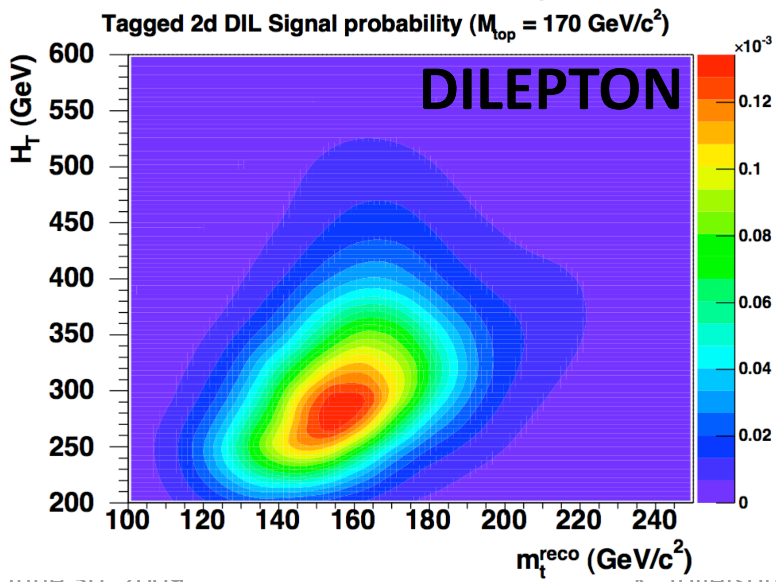
Photo by Reidar Hahn
Artwork by Jan Lueck

Backup Slides

Top Mass

New Twist on Template Method

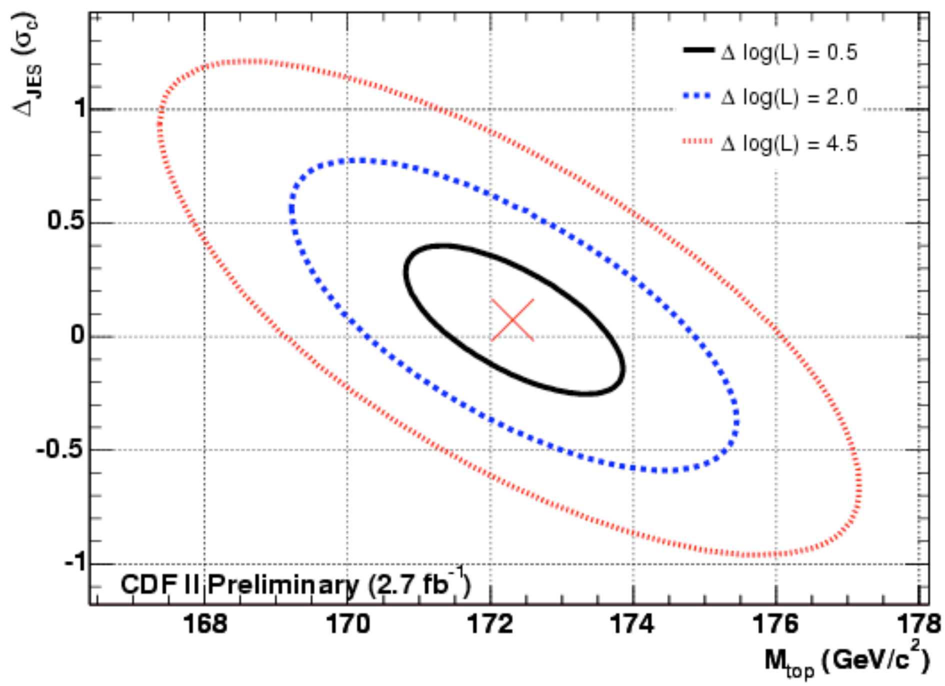




- Simultaneous fit in 2 channels :
  - L+jets and Dilepton
- In-situ JES calibration applied in both channels
- No assumptions:
  - Correlations in systematics
  - On likelihood shapes

PRD submitted for 1.9 fb^{-1} result: hep-ex. 0809.4808

Template Results with 2.7 fb^{-1}



Systematic	LJ	DIL	Combination
Residual JES	0.7	3.3	0.6
Generator	0.7	1.2	0.7
PDFs	0.3	0.8	0.3
b-JES	0.2	0.2	0.2
bkgd shape	0.2	0.3	0.2
gg fraction	0.2	0.2	0.2
Radiation	0.2	0.2	0.1
MC statistics	0.1	0.5	0.1
lepton energy scale	0.1	0.3	0.1
pileup	0.2	0.2	0.3
Combined	1.1	3.7	1.1

Measurements in traditional manner (i.e. DIL no in-situ JES)

Mtop = 172.3 +/- 1.5 (stat.+JES) +/- 1.1 (syst) GeV/c^2
= 172.3 +/- 1.9 GeV/c^2

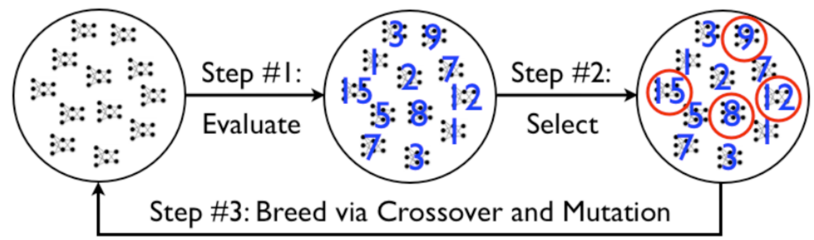
Comparable to L+jets Matrix Element analysis with 2.7 fb^{-1}:
Mtop = 172.2 +/- 1.3 (stat.+JES) +/- 1.0 (syst) GeV/c^2
= 172.2 +/- 1.7 GeV/c^2

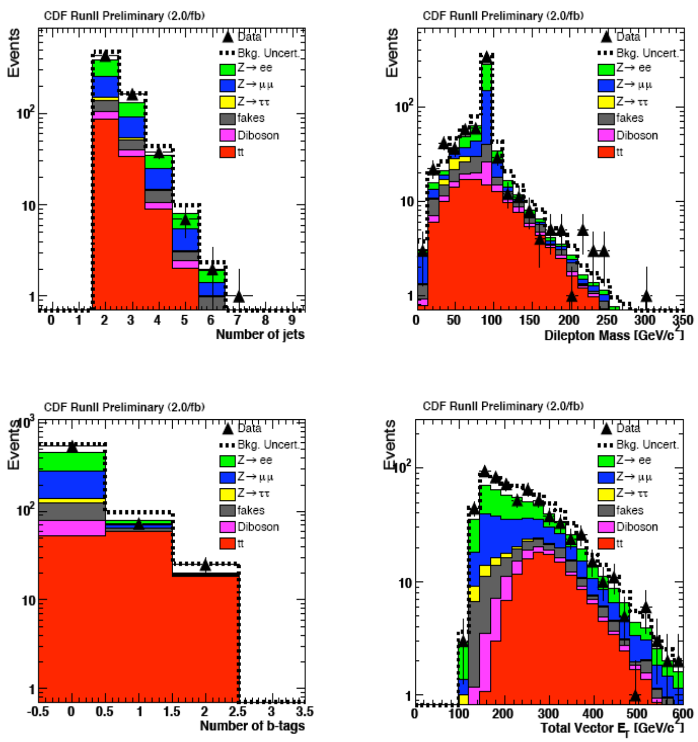
Optimizing Dilepton Selection

Event selection optimized to yield smallest expected statistical uncertainty by means of neuro-evolution:

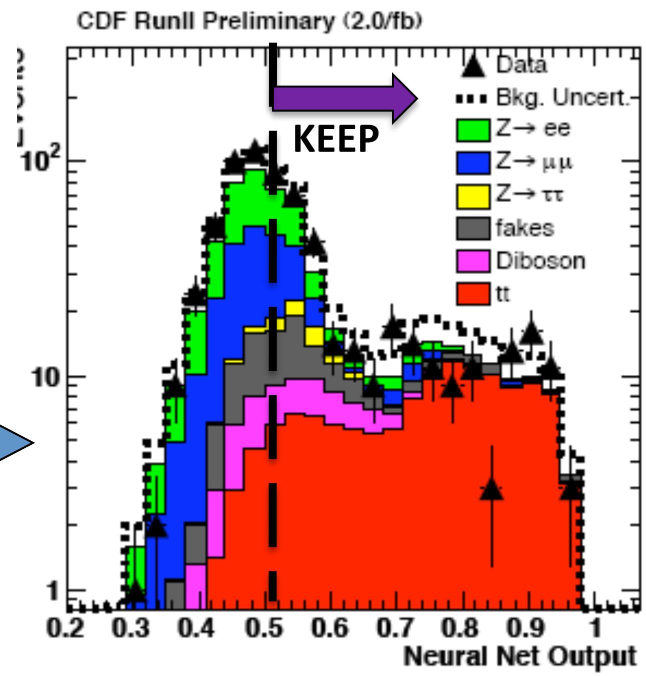
- Start with random collection of neural nets
- Determine analysis sensitivity of each network (fitness function)
- Discard low sensitive nets and combine topology and node weights through mutation

Neuro-evolution optimization





Converged NNet



Ref: S. Whiteson and D. Whiteson, *Proceedings of the Nineteenth Annual Innovative Appllications of Artificial Intelligence Conference*, p1819-1825, July 2007

K. Stanley and R. Mijkulainen, *Evolutionary Computation* 10(2):99-127, 2002

Dilepton Results using 2.0 fb^{-1}

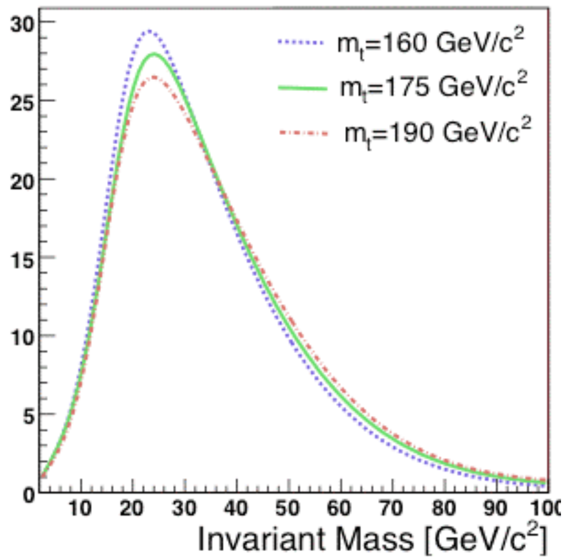
- After event select use matrix element technique
- New event selection expected statistical uncertainty improvement of 20%

Source	Size (GeV/c^2)
Jet Energy Scale	2.5
Lepton Energy Scale	0.1
Generator	0.7
Method	0.4
Sample composition uncertainty	0.3
Background statistics	0.5
Background modeling	0.2
FSR modeling	0.3
ISR modeling	0.3
PDFs	0.6
Total	2.9

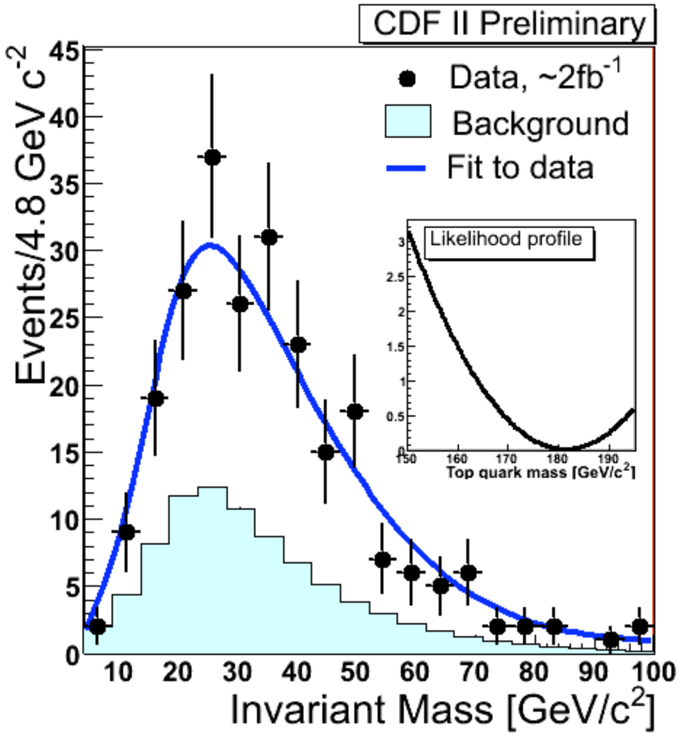
Mtop = 171.2 +/- 2.7 (stat.) +/- 2.9 (syst) GeV/c^2
= 171.2 +/- 4.0 GeV/c^2

Submitted PRL: hep-ex/0807.4652

L+jets - Template Method using SLTu



Invariant mass of lepton from W and muon from semileptonic b decay

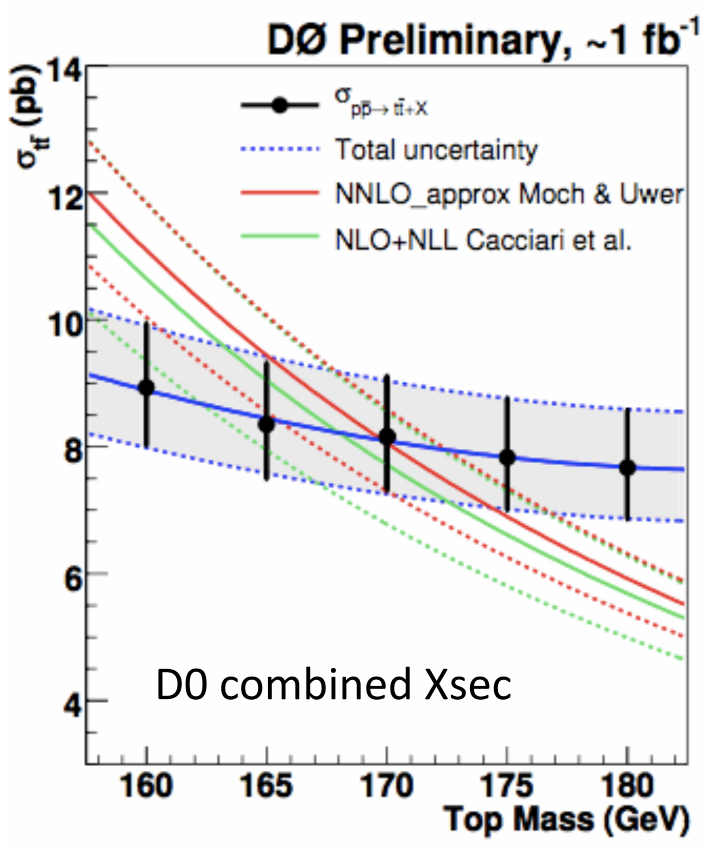


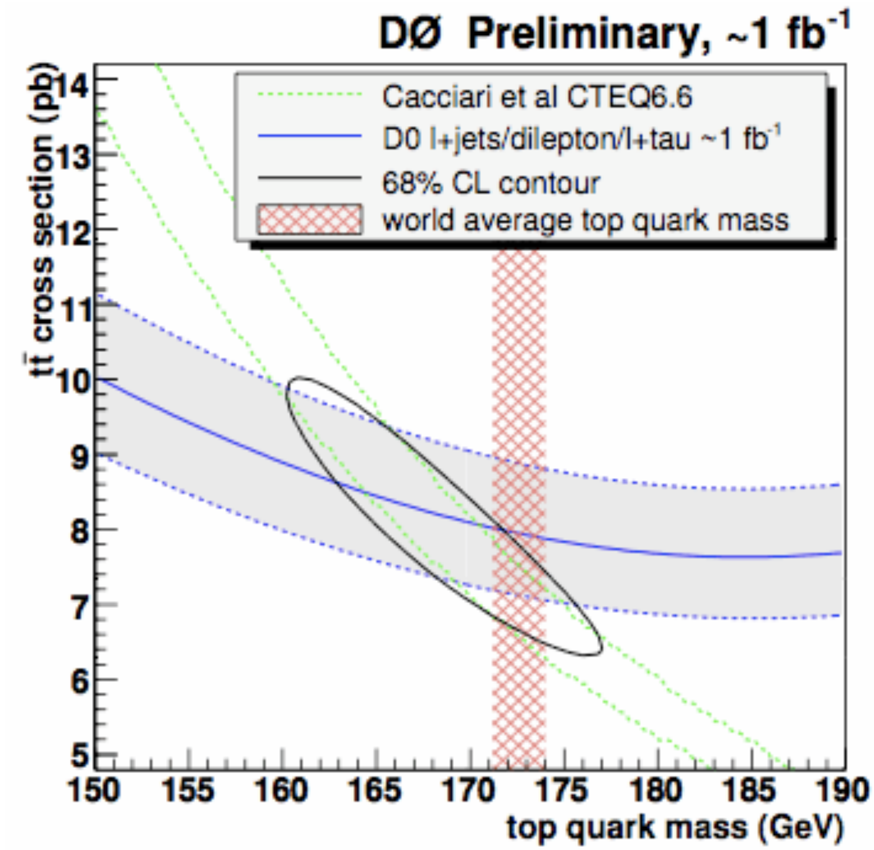
CDF II Preliminary (2 fb^{-1})

Source	Δm_t [GeV/c^2]
Linearity	±0.3
Background modeling	±1.8
Lepton energy/momentum scale	±0.9
SLT momentum	±0.9
MC modeling	±2.1
JES	±0.3
PDFs	±1.0
ISR/FSR	±1.3
Pileup	±0.5
Total	±3.5

Mtop = 181.3 +/- 12.4(stat.) +/- 3.5 (syst) GeV/c^2

Top Mass from the Cross Section



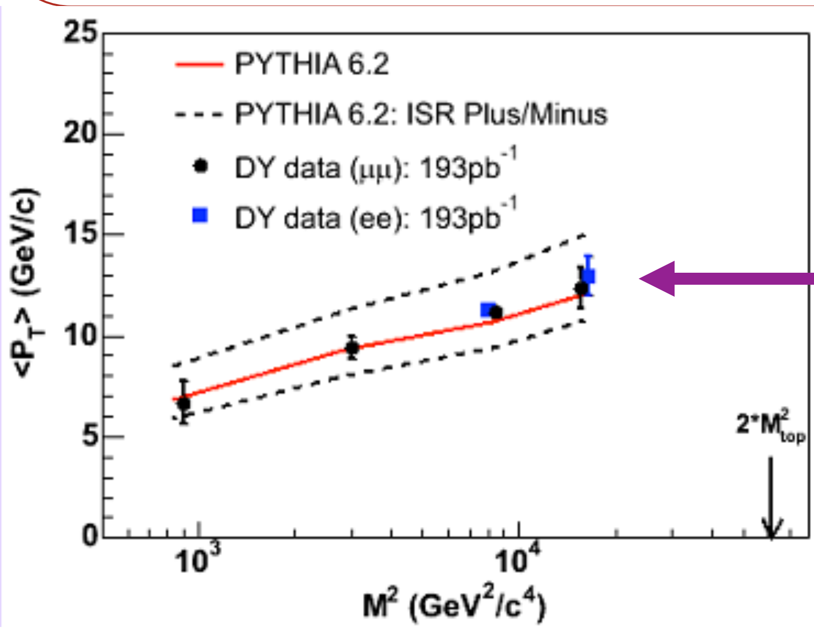


Using NLO+NLL

Mtop = 167.8 +/- 5.7 GeV/c^2

ISR/FSR

- Use dedicated Pythia samples with increased/decreased amount of ISR/FSR
- Variations in pythia parameters are determined by studying dimuon events only sensitive to ISR
- FSR parameters are varied within similar bounds, assuming the physics is similar
- Extrapolation from DY data to ttbar events is large
- Pythia parameters control mainly the soft part of FSR, might overlook hard (NLO type) radiation

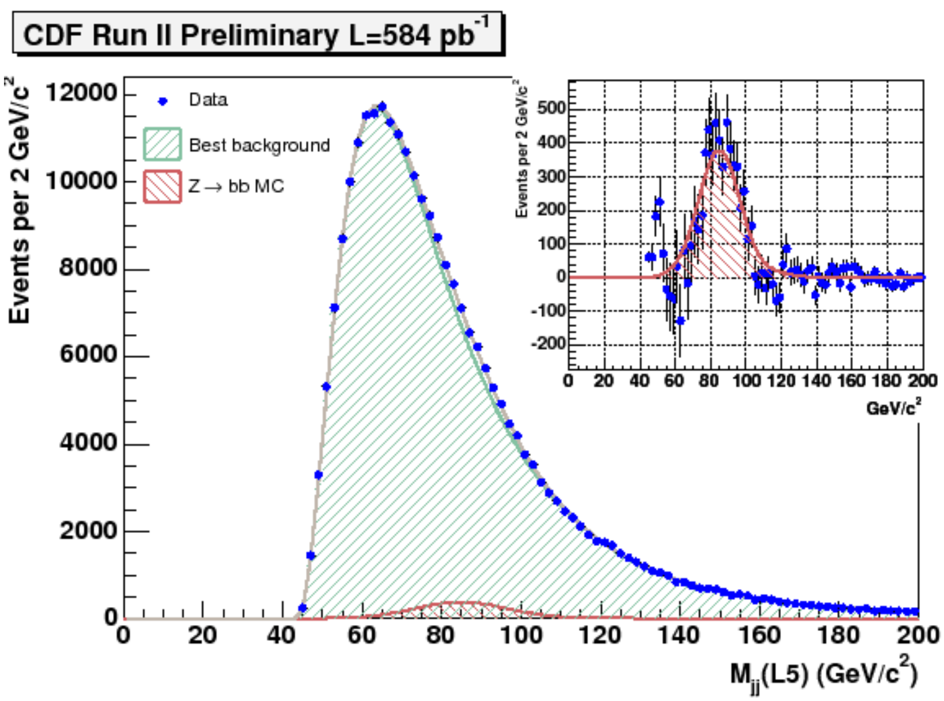


Will try to pin down this uncertainty band by using new data and adding higher mass points

Currently changed to samples where ISR and FSR are simultaneously increased or decreased

b-JES using Z(bb)

- Di b-jets with Et>22 GeV, ΔΦ>3.0,$E_t^{(3rd)}$<15 GeV using SVT impact parameter trigger at L2
- To measure data/MC b-JES



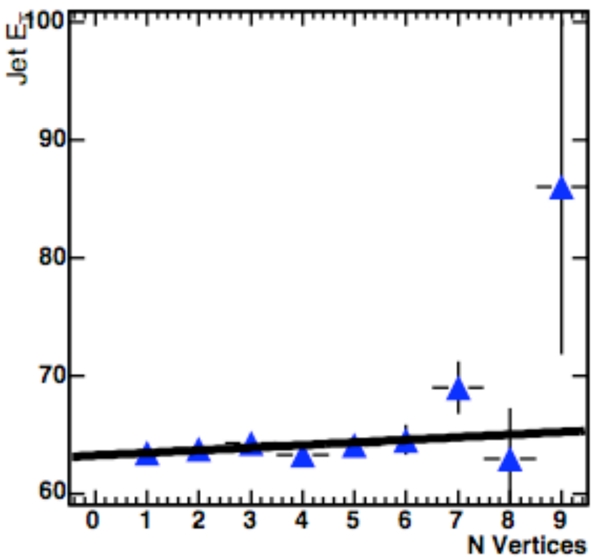
- Has not applied to b-JES in top mass
  - different cone size
  - different pt spectrum

$$\text{b-JES} = 0.974 \pm 0.011(stat) +^{+0.017}_{-0.014}\ (syst)$$

Multiple Interactions (Pile-up)

- Our MC simulates only one parton-parton interaction per event
- We add additional min bias events according to our lumi profile and determine JES correction
- In ttbar events our MC still underestimates the amount of multiple parton-parton interactions in each collision
- How does this propagate into an Mtop uncertainty ?

B-Jet Et increases with ~200 MeV
For each additional vertex



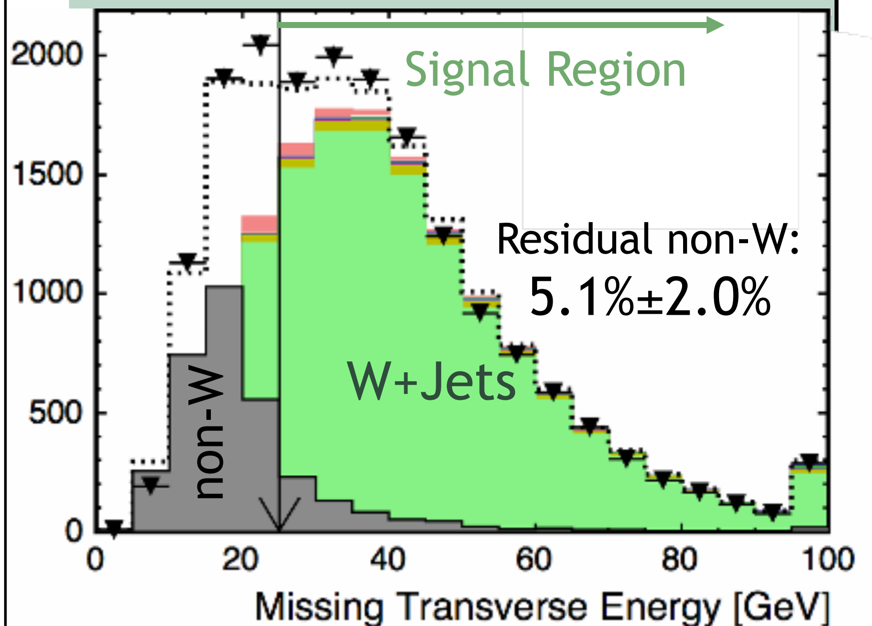
- We find mean of ~2 vertices per event in our current 2 fb^{-1} dataset
- We know that B-Jets affect M_{top} most
- We know how a 1% bjet ET increase affects M_{top}
- Total effect is O(200 MeV) on M_{top}

Single Top

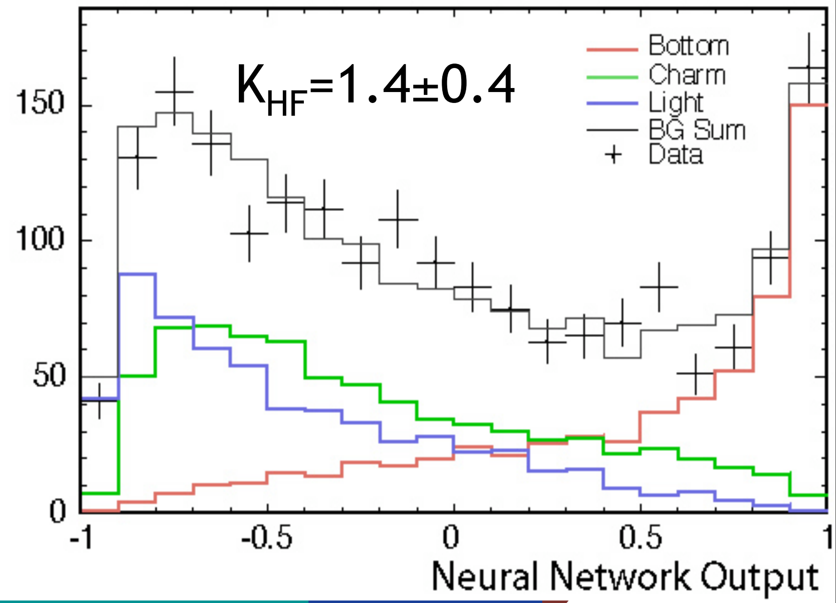
Single Top Backgrounds

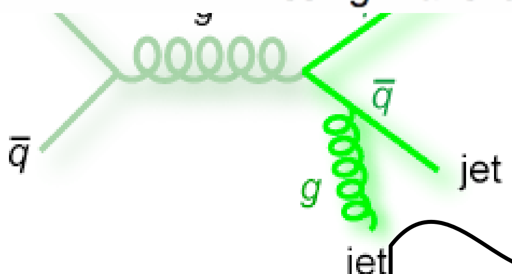
Top/EWK (WW/WZ/Z→ττ, ttbar)

- MC normalized to theoretical cross-section



C driven





data driven

Mistags (W+2jets)

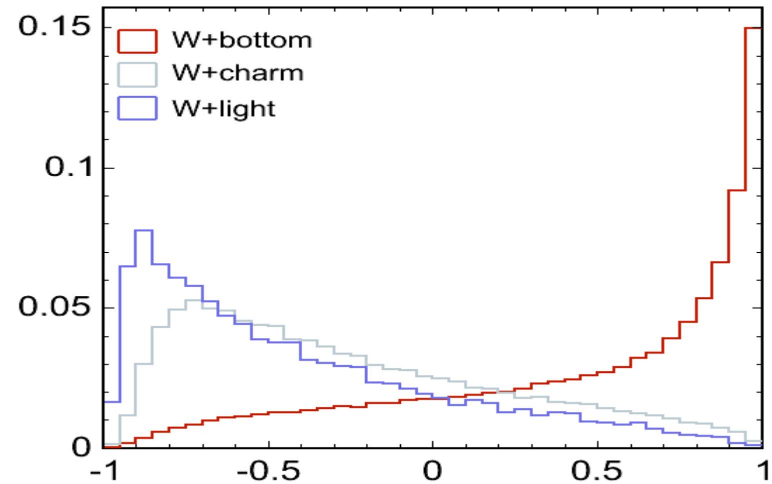
- Falsely tagged light quark or gluon jet
- Mistag probability parameterization obtained from inclusive jet data
- Apply mistag probability to generic W +jets sample

B-tagging and Flavor Separation

- Even with a fully reconstructed secondary vertex required, ~50% of the background in the W + 2 jets sample do NOT contain bottom quarks

SecVtx tagging rates:
- Bottom ~50%
- Charm ~9%
- Mistag ~ 0.5-1%

- Train Neural Network with secondary vertex tracking information (25 input variables) for bottom/charm/light flavor separation
  - L_{xy}, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information, etc...



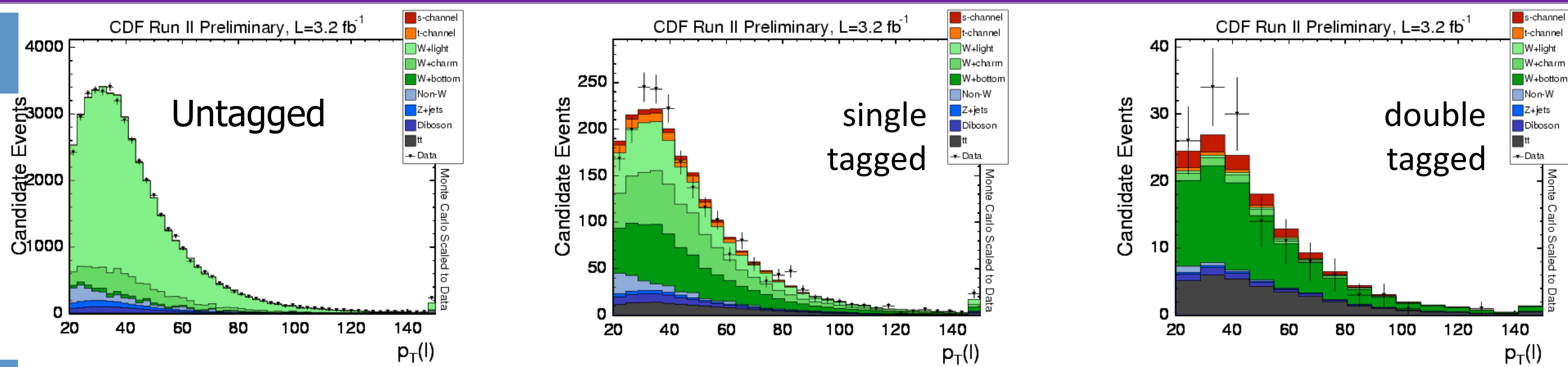
mistags / charm .... bottom

- Replaces Yes-No tag decision by a continuous variable *(0<b<1)* - used in all lepton + jets analyses

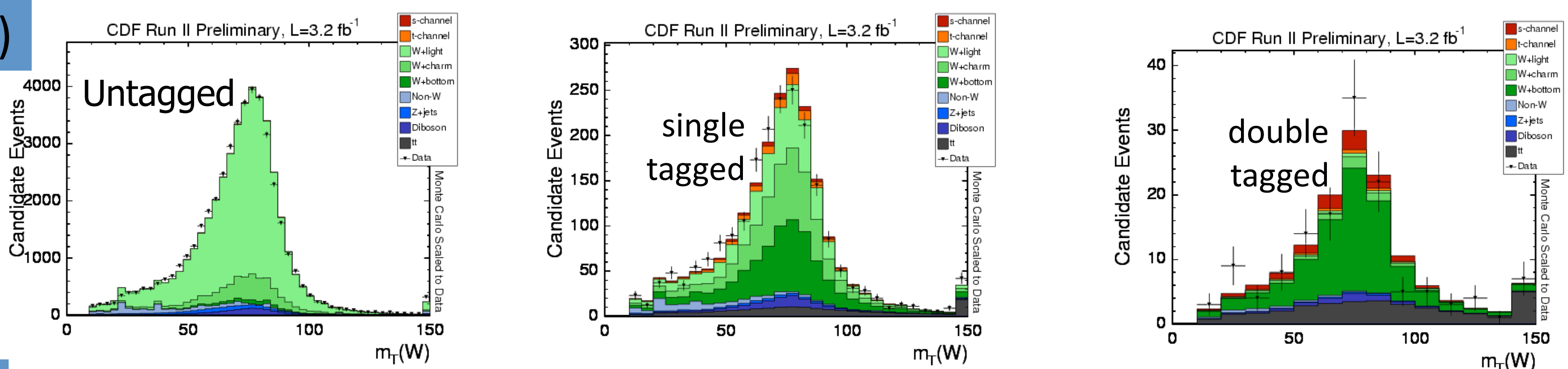
- Improves sensitivity by ~10-15%!

Examples of Input Variables

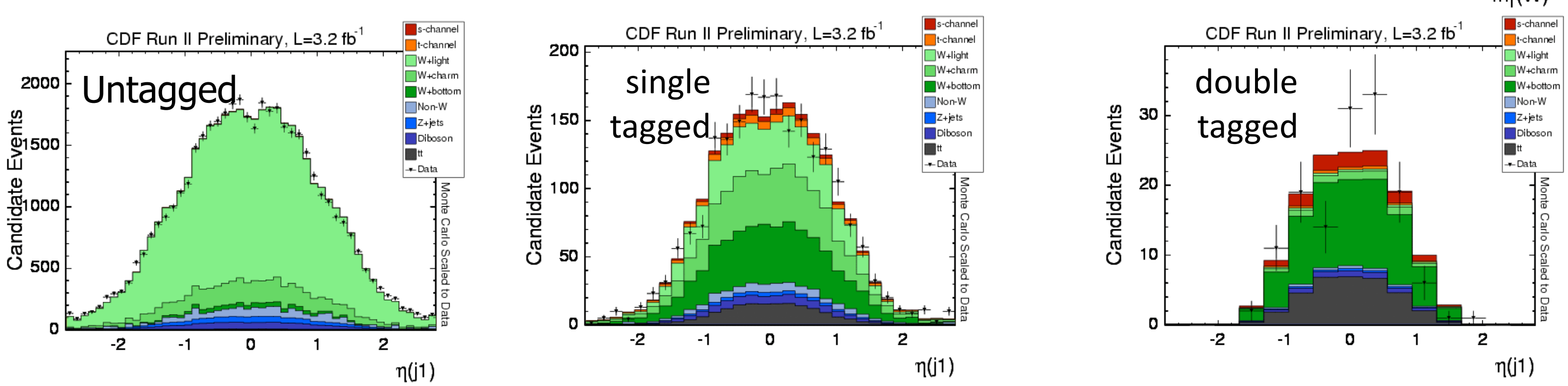
P_T^{lepton}



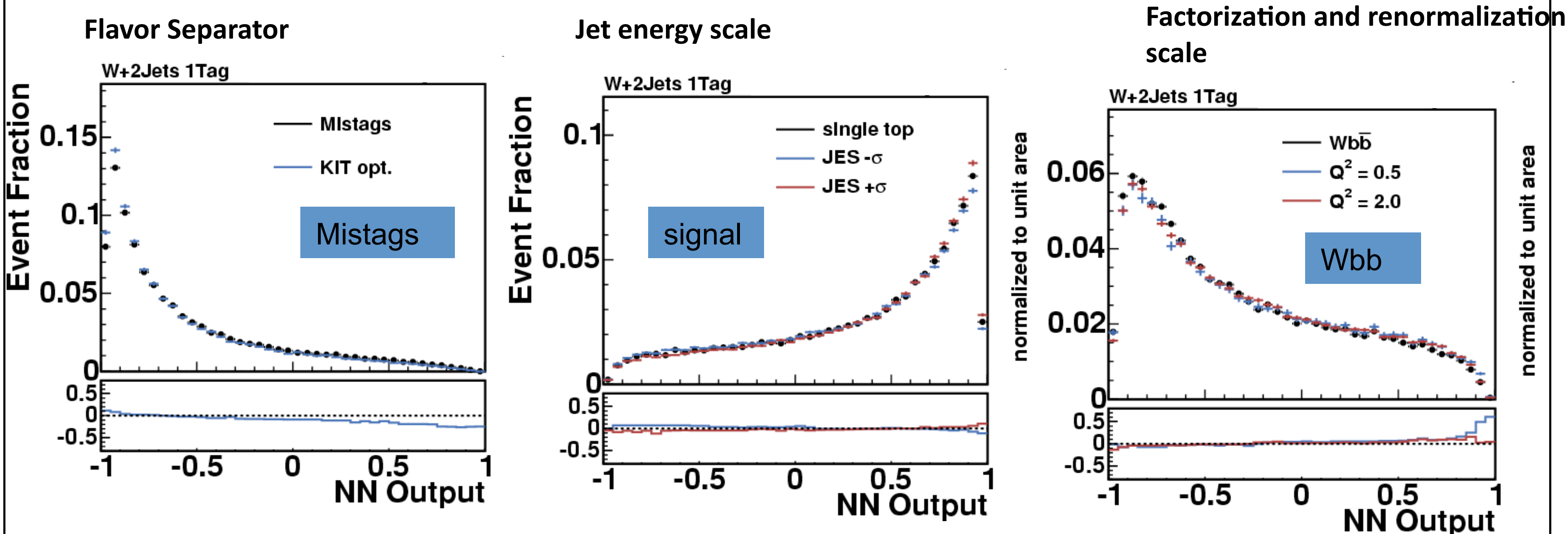
$M_T(W)$



$J_1(\eta)$



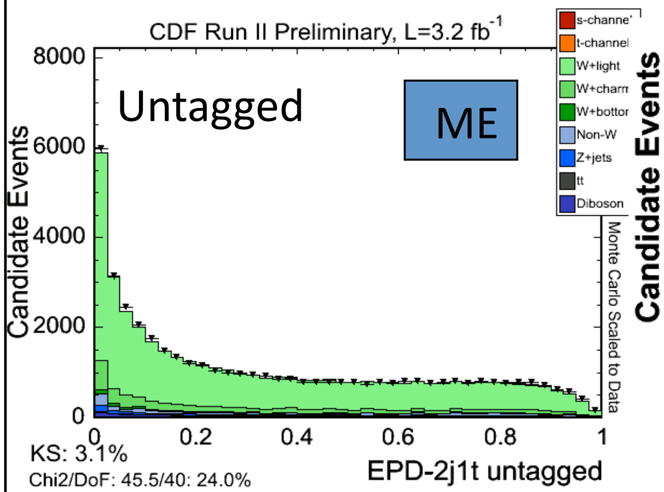
Template Shape Uncertainties

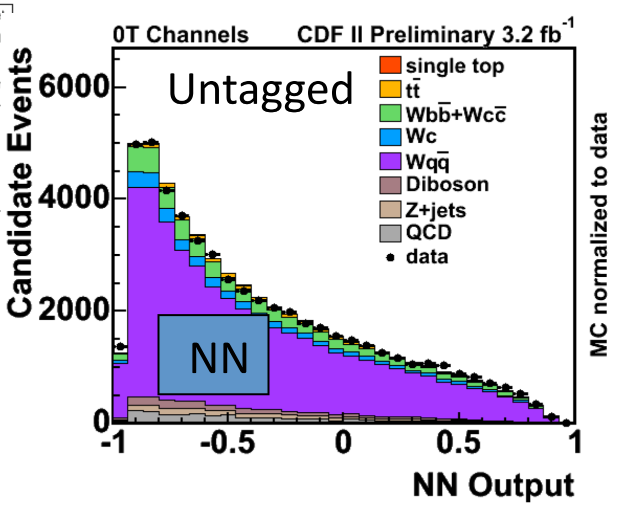


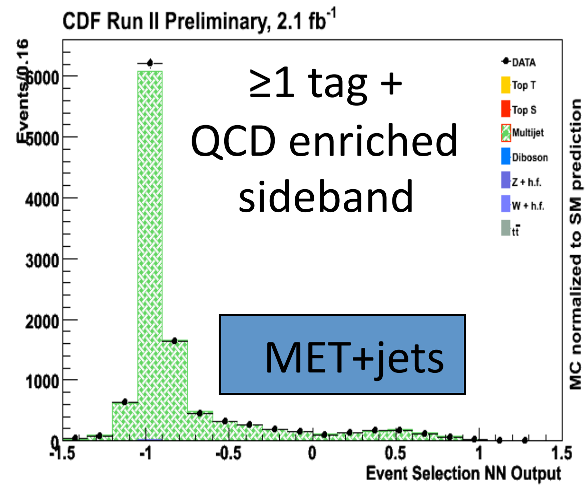
- A total of 370 shape uncertainties evaluated!
- Each template, each source of shape error, each channel (#tags, #jets, extended muon coverage)
- Shape uncertainties affect sensitivity - most are quite small but some appreciable

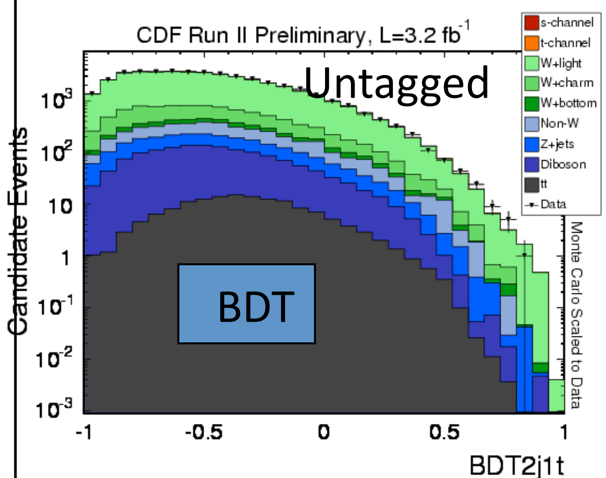
Sideband Cross Checks (many…)

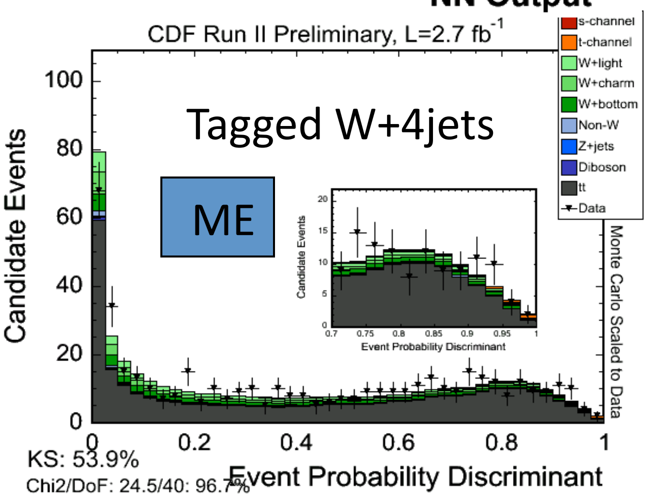
Extensive side band cross checks performed to check modeling before unblinding the signal region.

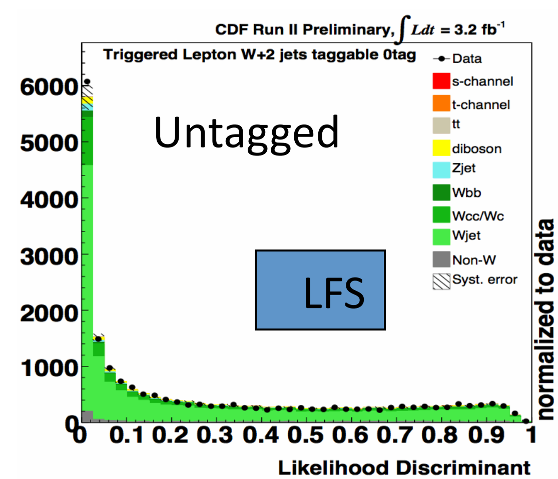






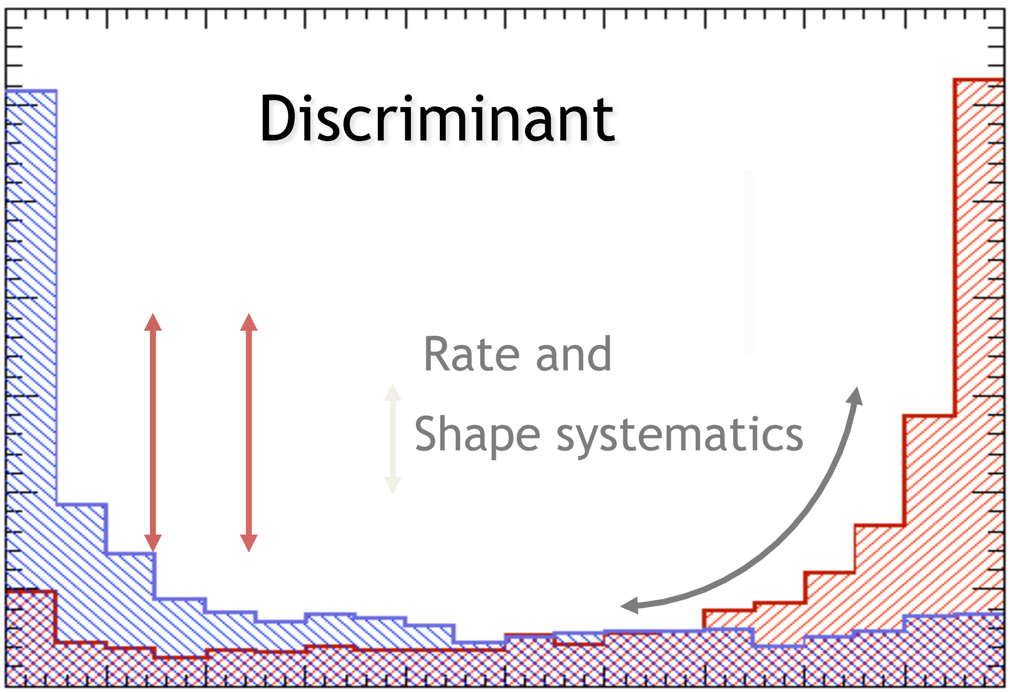






Likelihood Fit

Use binned maximum likelihood fit of templates to the data:



Systematic uncertainties can affect rate and template shape and are taken into account:

- Rate systematics give fit templates freedom to move vertically only
- Shape systematics allow templates to 'slide horizontally' (bin by bin)

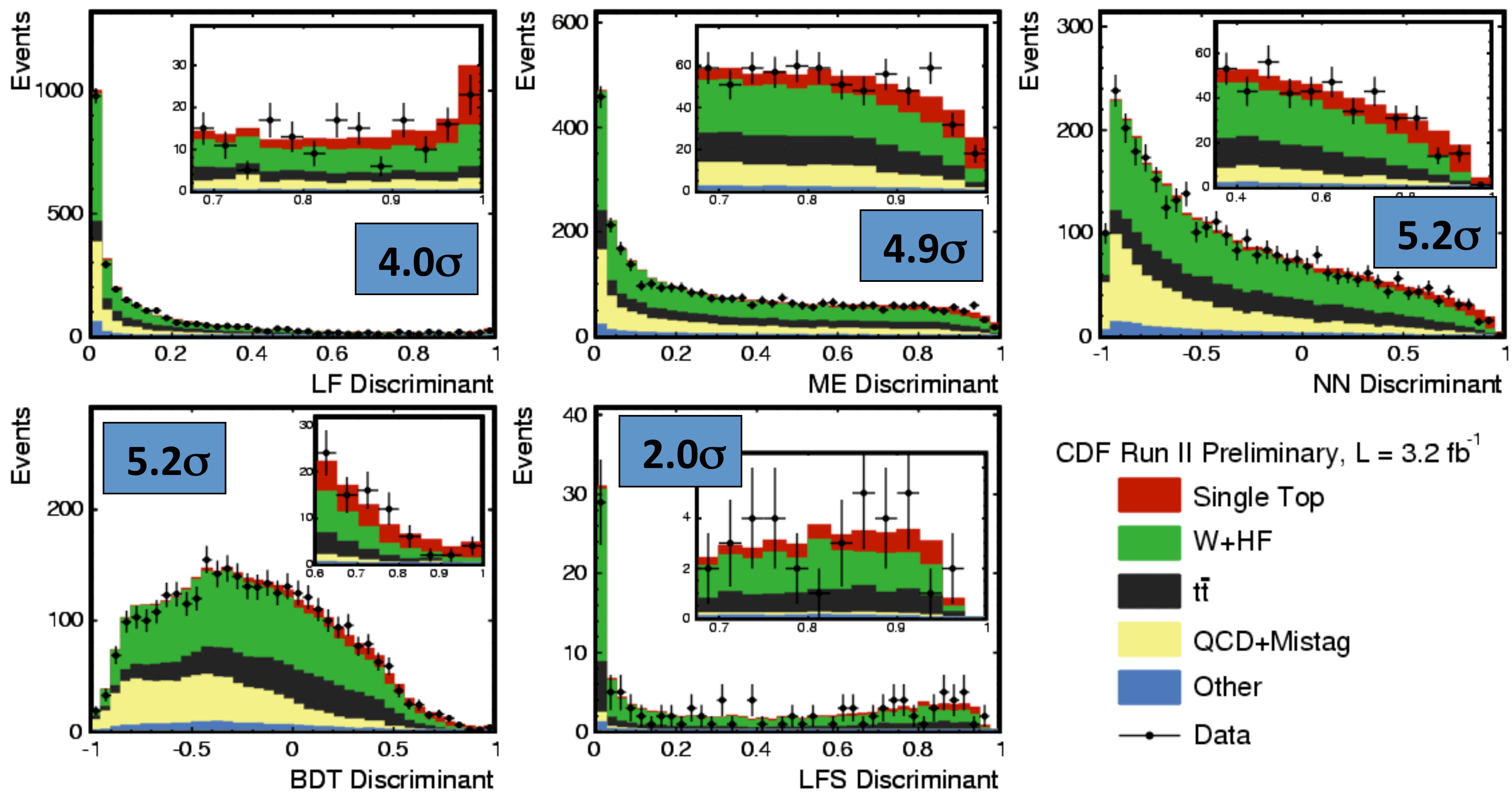
Systematic Uncertainties

Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0...10%	✓
Initial + Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓

Also, MC statistics treated as a source of systematic uncertainty in each bin independently

Largest uncertainty on background normalization

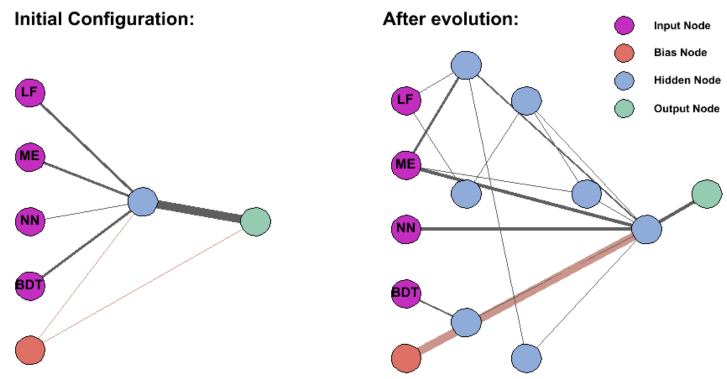
CDF Discriminants and expected Sensitivity with 3.2 fb^{-1}



Discriminants normalized to prediction

Combination Strategy

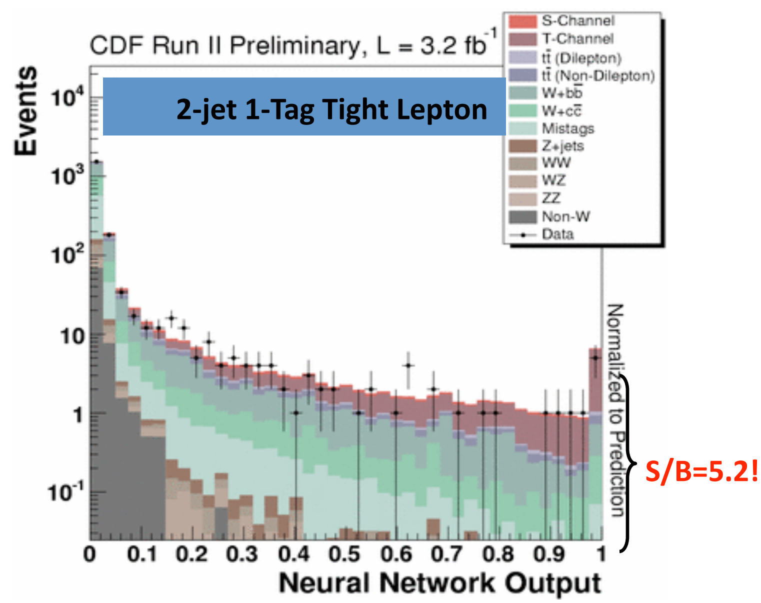
- Combination using "Super Discriminant" (SD)
  - Combine individual analyses into one, more powerful - use discriminant outputs as input to NN
  - Evolutionary neural networks trained to give the **best expected p-value**, not classification error function
  - Candidate networks compete with each other
  - Gained 13% over most sensitive input



Neuro-Evolution of Augmenting Topologies (NEAT)

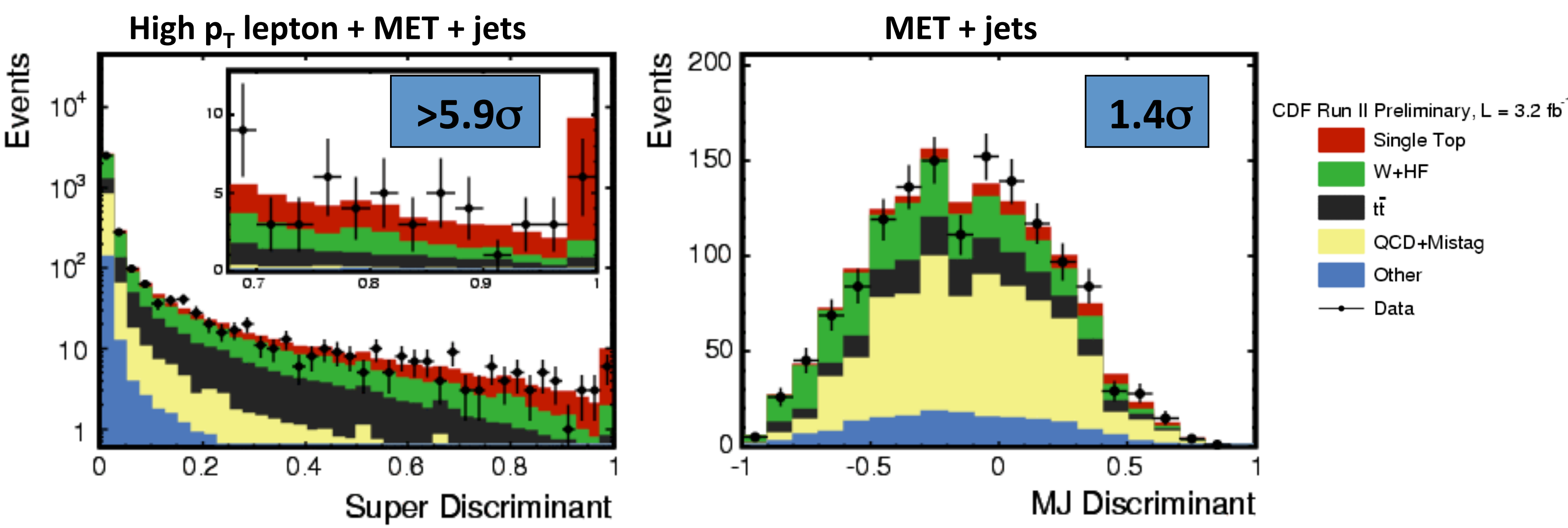
K O. Stanley and R. Miikkulainen, Evolutionary Computation **10** **(2)** 99-127(2002)

- Optimization of
  - Network topology
  - Inter-node weights
  - Output histogram binning



Channels are divided up at least as finely as any ingredient analysis:
(2 jets + 3 jets) x (1 tag + 2 tags) x
(2 Lepton Categories) = 8 Channels

Combination

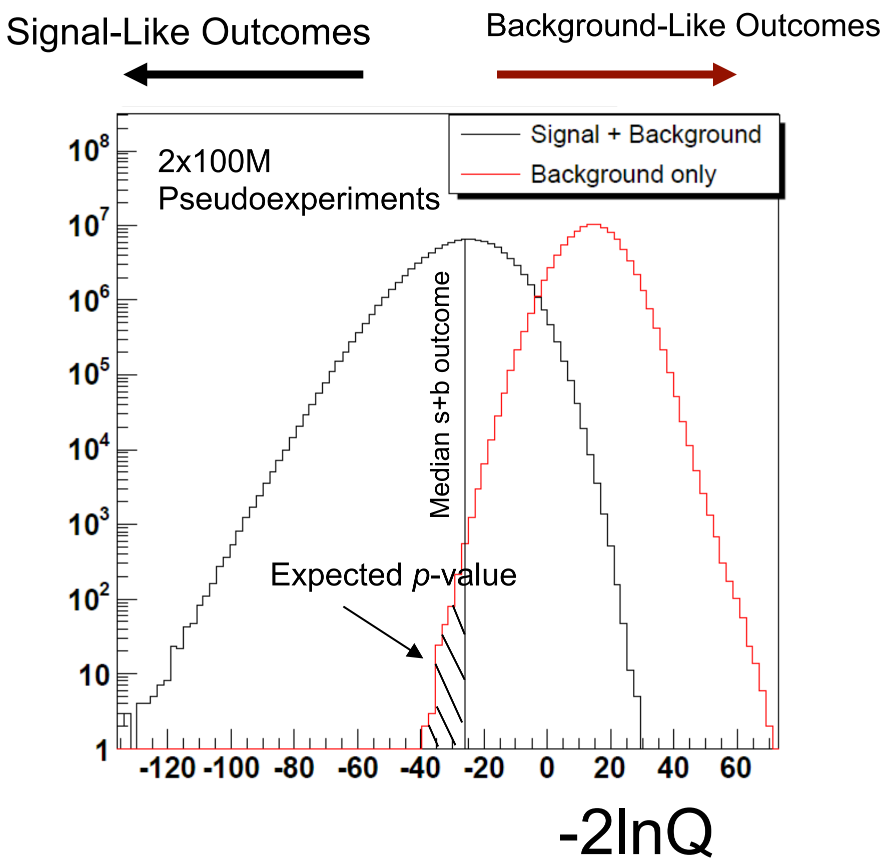


Perform combined cross section fit over the two orthogonal analyses (SD + MJ)

Hypothesis Testing: p-values

p-value = probability of upward fluctuation of background to the data or something even more "signal-like"

Outcomes ranked as signal-like using -2lnQ



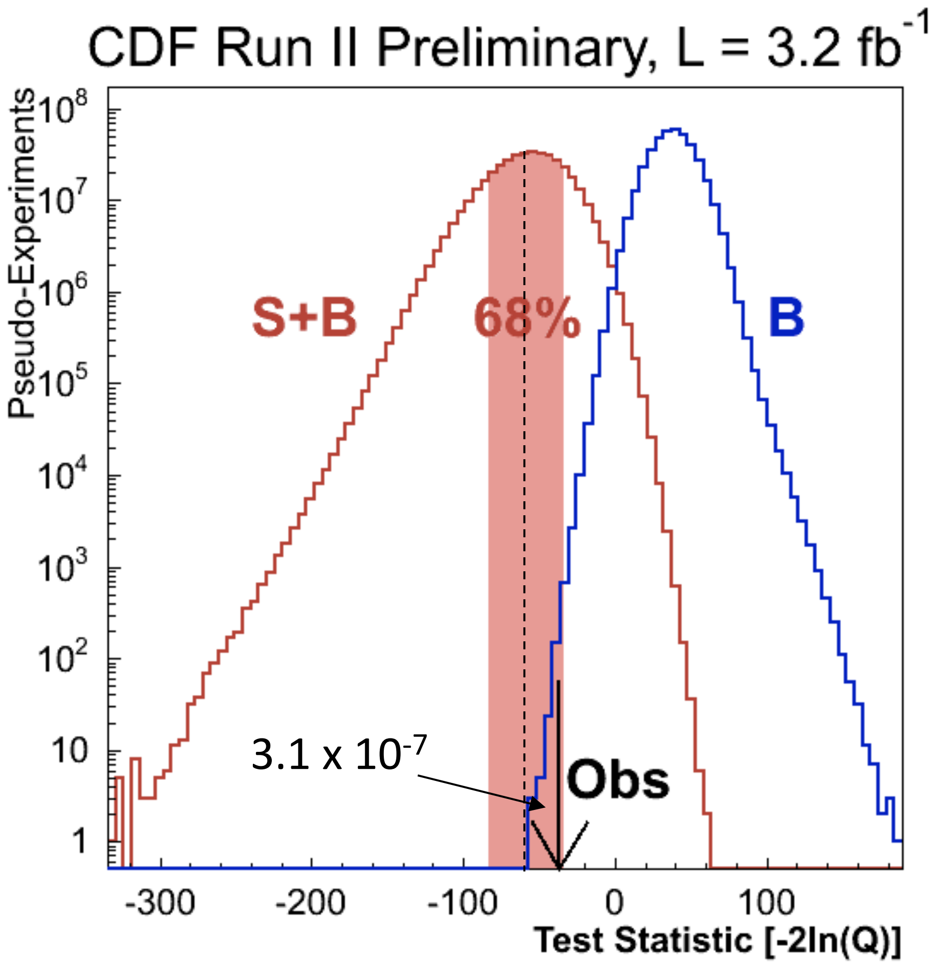
$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

θ=nuisance parameters

Neyman-Pearson Lemma: Q is the uniformly most powerful test

Fit for W+LF and W+HF scale factors. Fluctuate **all** nuisance parameters in Pseudo-experiments

Significance



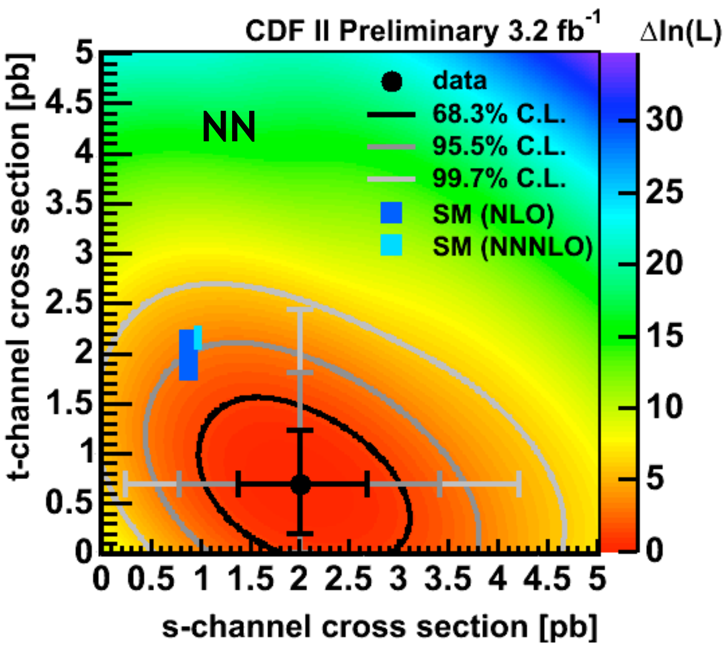
Analysis	Significance Std.Dev. (σ)	Sensitivity Std.Dev. (σ)
NN	3.5	5.2
ME	4.3	4.9
LF	2.4	4.0
LFS	2.0	1.1
BDT	3.5	5.2
SD	4.8	>5.9
MJ	2.1	1.4
Combined	5.0	>5.9

Expected p-value : xxx $\times 10^{-10}$: >5.9σ
Observed p-value: 3.1 $\times 10^{-7}$: 5.0σ

400 Mio pseudo-experiments!
(130,000 CPU hrs)

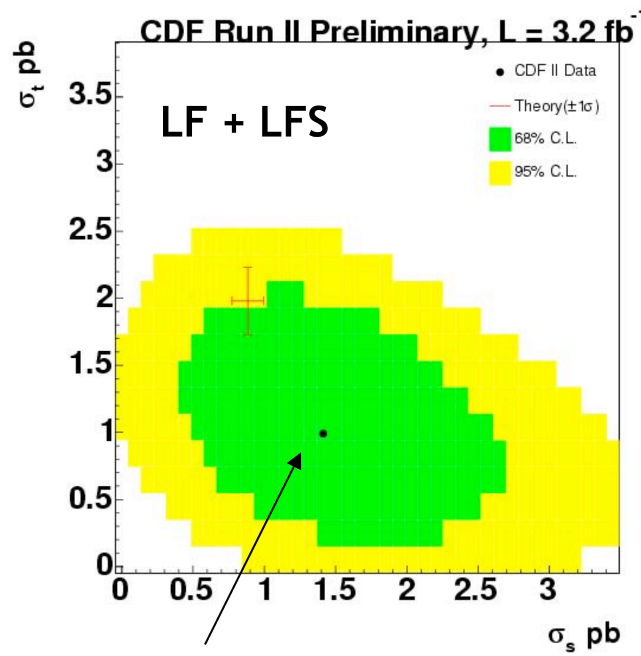
Two Dimensional Interpretation

- Measure σ_s and σ_t separately
- Interesting because s- and t-channels have different sensitivity to BSM models
- Train dedicated s-channel and t-channel discriminants and fit 2D



$\sigma_s = 2.0^{+0.7}_{-0.6}$ pb

$\sigma_t = 0.7^{+0.5}_{-0.5}$ pb

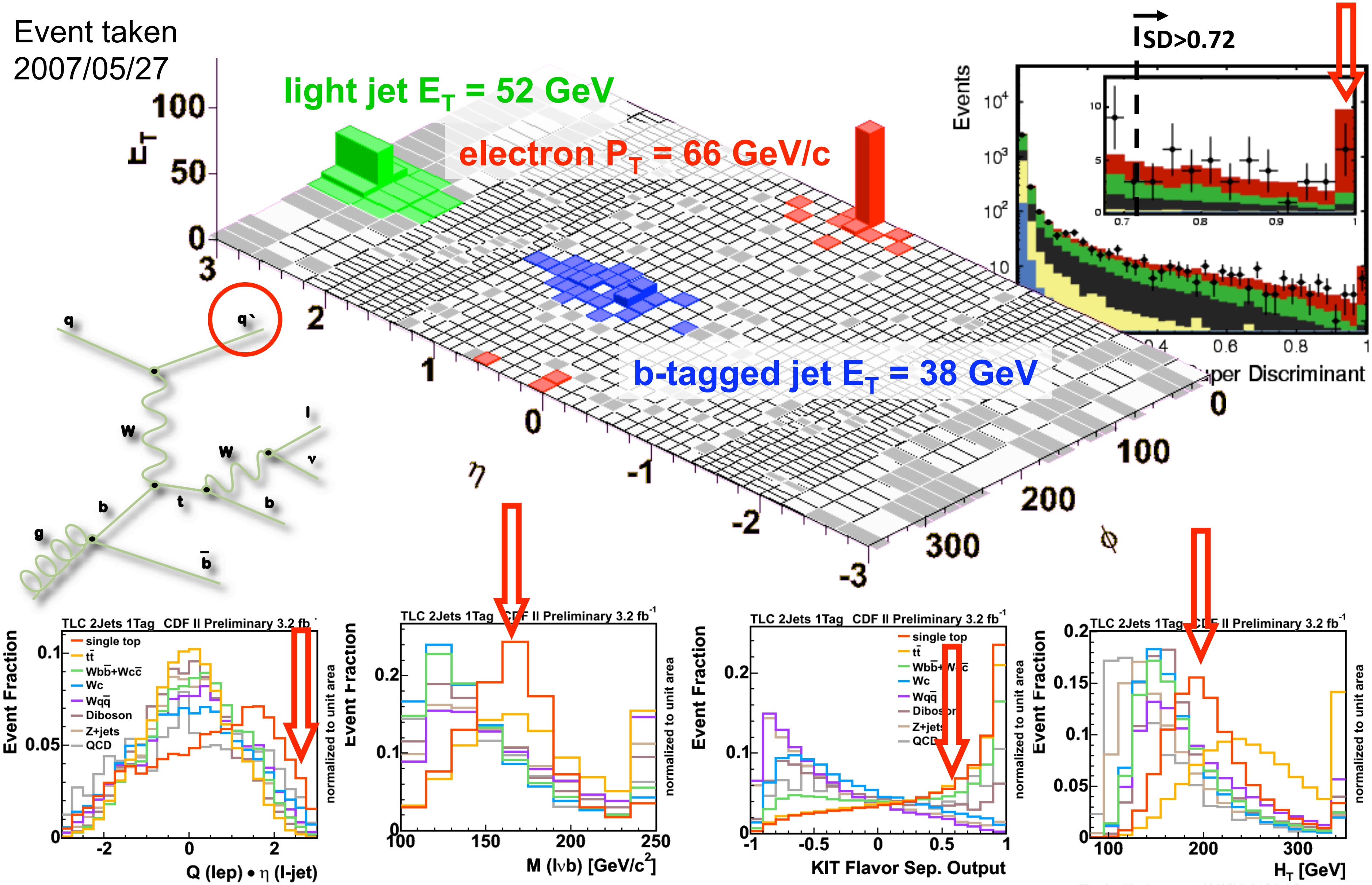


σ_s= 1.4 pb

σ_t= 0.98 pb

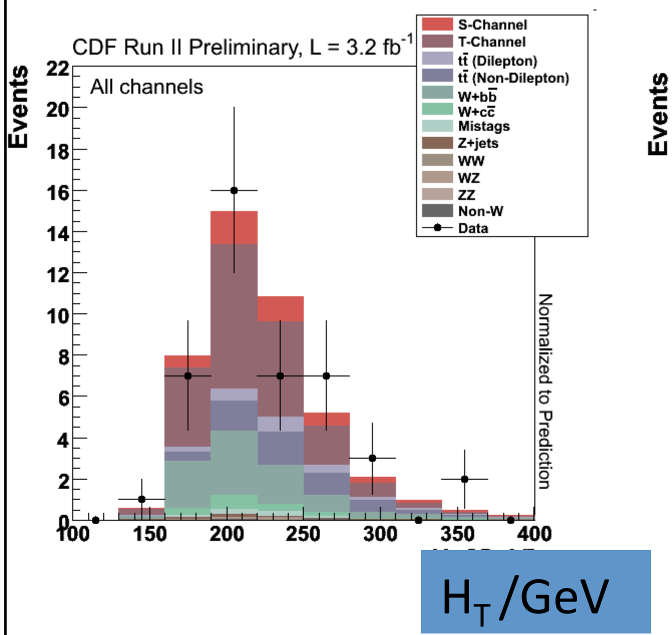
A Golden CDF Event

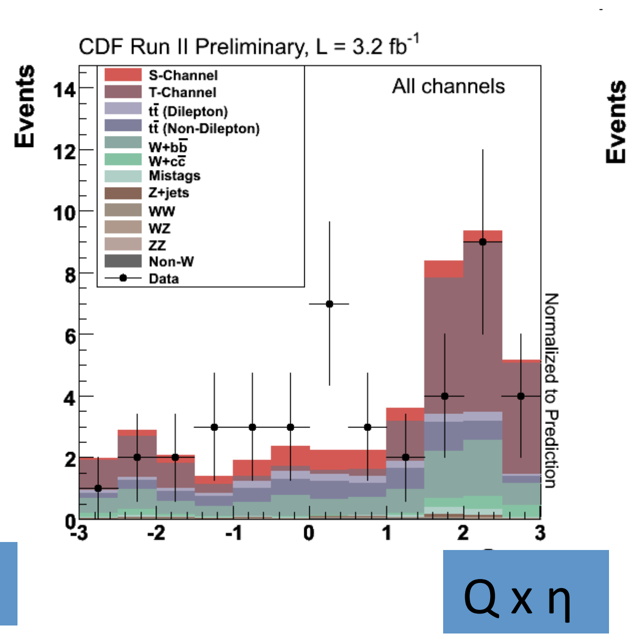
Event taken
2007/05/27

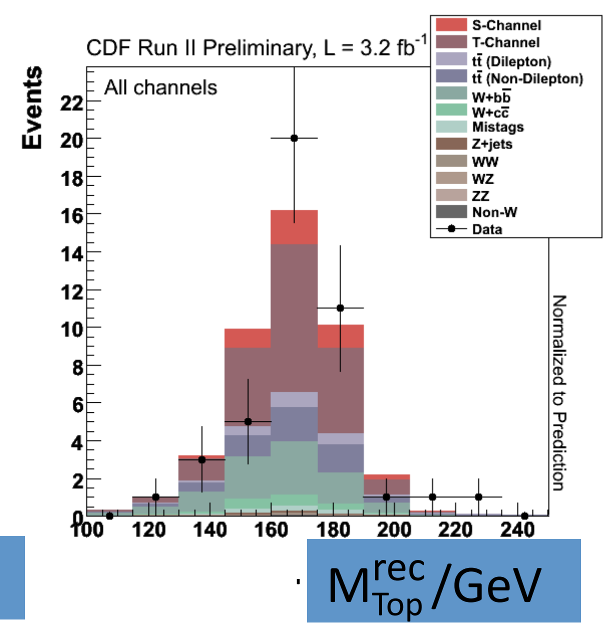


Signal Features

SD>0.72







Purity S/B ~ 1.2