Top Quark Physics at the LHC

Outline of Lectures

1. Discovery of Top Quark
2. Top Quark in the Standard Model
3. Production Mechanisms
4. Precision Measurement of Top Quarks
5. Other Top Quark Properties
6. Things That We Don't Know (But Should)

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Some Introductory Comments

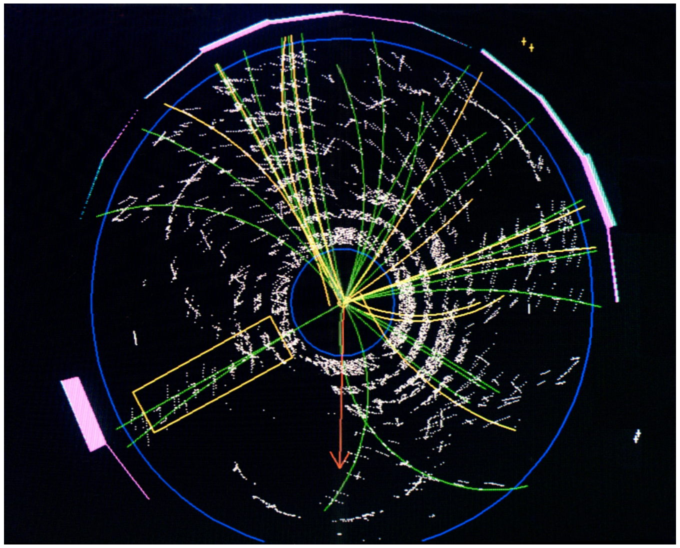
- **Standard approach to these sorts of lectures**
  - **Begin with theoretical background**
  - **Focus on the phenomenological issues**
    - What does theory tell us?
    - What have we learned from measurements?
    - What next?
- **Approach here will be a little more experimental**
  - **Start with discovery with top, then talk about formal stuff**
  - **Work to develop an appreciation of what top quark production & decay looks like**
  - **Talk about all the stuff that you need to know**
    - But work to hide "under the carpet" the details
  - **Objective is to give audience a flavour of what we will learn at the LHC by studying the top quark system**

The Top Quark Revealed

- **Experiments at Fermilab Tevatron**
  - **studying p-pbar collisions at 1.8 TeV**
  - **Looked at ~2x10^{12} collisions**
  - **Searching for events with**
    - Evidence of a W boson
      - **Decaying leptonically into either eve or mnm**
    - 3 or more jets
      - **At least one showing evidence of a b quark decay ("b tag")**
- **Observed an excess of events above SM & instrumental backgrounds**

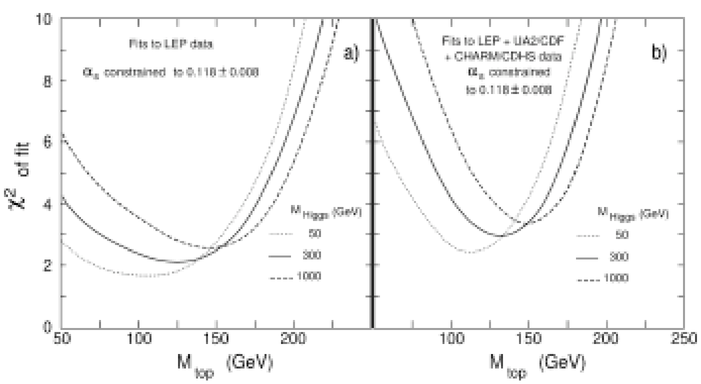
CDF, PRL 74, 2626 (1995)
D0, PRL 74, 2632 (1995)

- **Evidence for a previously unobserved process**
  - **Excess of events equivalent to a >5 standard deviation fluctuation of background**
- **Concluded that the top quark had been observed**



Why Were We So Sure?

- **Case based on experimental & theoretical evidence starting in 1970's**
  - **Observation of CP violation and charm begins the case**
  - **Properties of b quark strengthened it**
    - Couldn't be an SU(2) singlet within SM framework
- **Precision EWK measurements clinched it for most people**



- **Searches pushed the technological envelope**
  - **Rarest process observed in high energy hadron collisions**
    - Best measurements to date

$$\sigma_{tt} = 7.0 \pm 0.3(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lumi})\ \text{pb} \quad (\text{CDF})$$

$$\sigma_{tt} = 8.18^{+0.98}_{-0.87}\ \text{pb} \quad (\text{DZero})$$

CDF, Conference Note 9448 (2009)
D0, Fermilab-PUB-09-092-E (2009)

  - **Had to develop b-tagging tools**
  - **Reconstruct 6-parton final states**

LEP EWK Group, Phys. Lett. B276, 247 (1992)

Interest in Top Quark at LHC

- **Heaviest fermion in theory**
  - **Couples most strongly to Higgs field**
    - Or whatever is responsible for EWK symmetry-breaking
  - **Direct access to part of CKM matrix, V_{tb}**
    - Single top production as well as Γ_t measurement
  - **In many models, new particles couple preferentially to t-tbar**
- **Properties are predicted in SM**
  - **Some are quite sensitive to "new" or "beyond-SM" physics**
- **Important calibration tool for LHC experiments**
  - **Leverage Tevatron experience to more rapidly understand detectors and environment**
- **Both general purpose experiments have increasingly prioritized top studies**
  - **CMS published host of notes**
  - **ATLAS recently published its "CSC" book**
- **Basis for these talks are**
  - **Studies at Tevatron**
  - **Studies at 14 TeV pp collisions**
  - **More recent studies at 10 TeV**

ATLAS Collaboration, "Expected Performance of the ATLAS Experiment", CERN-OPEN-2008-20 (Dec 2008).
CMS Collaboration, TOP-08-XX, TOP-09-YY.
A. Quadt, Eur. Phys. J C48, 835 (2006)
T. Liss and !. Quadt, Phys. Lett. B667, 1 (2008)

What I Will and Will Not Cover

- Going to talk about
  - Top quark cross section
    - Use dileptons
  - Top quark mass measurement
    - Use lepton+jets
  - Top quark charge measurement
    - Event reconstruction
  - Top quark spin correlations
    - Illustrates some of the finer points of top quark physics
  - High mass top quark pairs
    - What happens at higher mass
- Not going to talk about measurements of
  - Single top production
  - Top quark rare decays
  - Width of top quark
  - P_T distribution of top quarks
  - Production mechanisms
  - Anomalous decays
    - $t \to H^+ b$, for example
  - Etc.
- Not because they aren't interesting (they are)
  - But we don't have a week….

Anatomy of a pp Collision

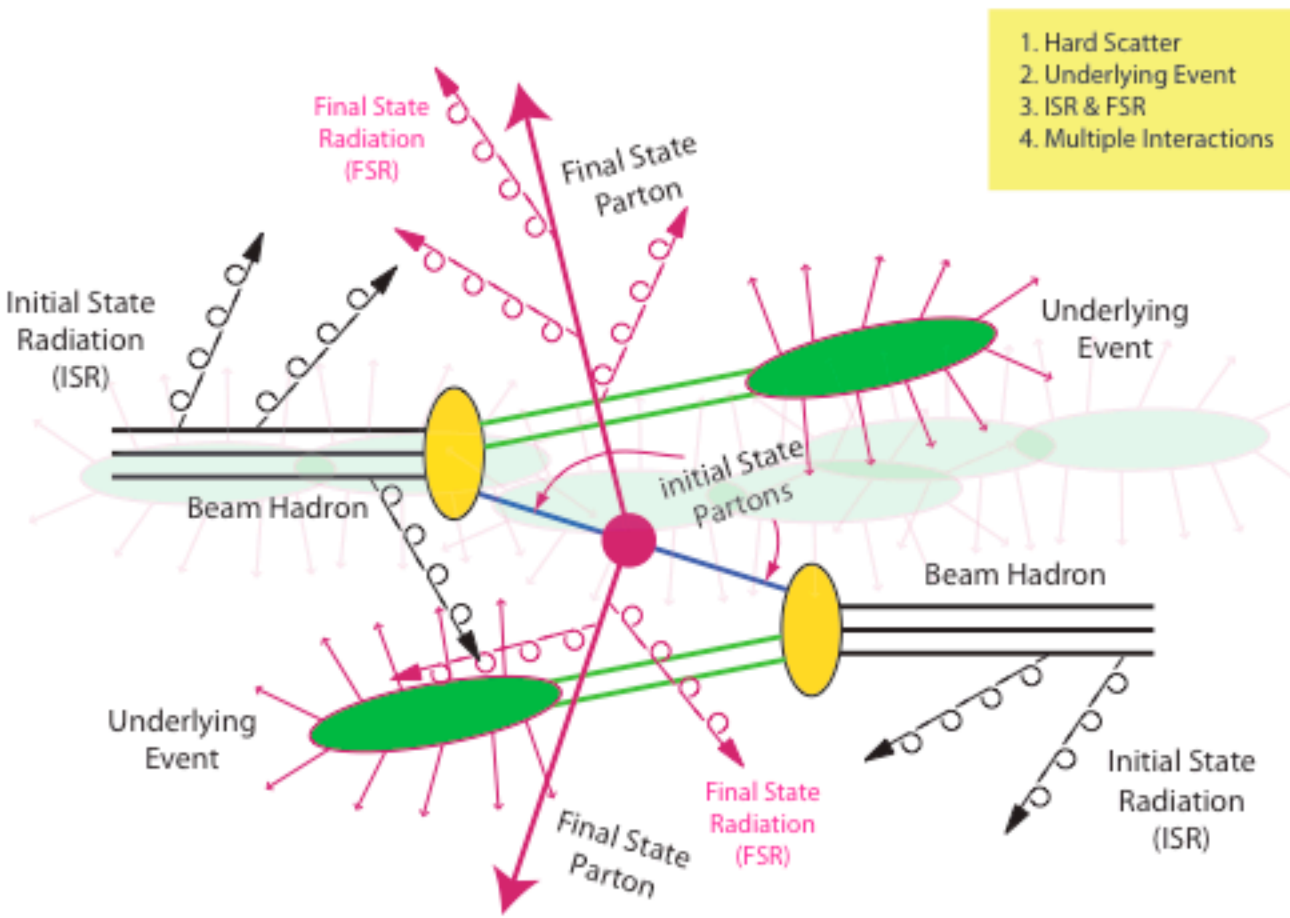
- **Pick apart the collision**
  - **Incoming proton bunches**
    - + beam halo and other garbage
  - **Assume time of interaction << timescale of any other process**
    - Treat hadron as a "bag" of free partons
  - **Two partons interact**
    - Hard scattering process
  - **Rest of hadrons "fragment" into an underlying event (UE)**
    - Caused by initial acceleration?
  - **Maybe (usually?) have one or more independent collisions (pileup)**
    - Increases low-energy particle multiplicities
    - Has effects on instrumentation

- **Acceleration process produces**
  - **Initial State Radiation (ISR)**
  - **Final State Radiation (FSR)**

- **UE characterized by**
  - **~60 particles**
  - **Average PT ~ 0.5 GeV/c**
  - **Distributed uniformly in η**

- **Multiple interactions depend on**
  - **Instantaneous luminosity and crossing rate**
    - Increases low-energy particle multiplicities
  - **Long read-out times result in "pileup" effects from one crossing to the next**

Picturing a Hard Scatter



First Look at Hard Scattering

- We assume two partons interact
  - Each has momentum fraction x_1, x_2 of hadron
    - Given by parton distribution function (PDFs)
    - Either valence (u,d) or gluons & sea quarks
  - Cross section given by

$$\sigma = \sum_{\substack{initial\ partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \sigma^i_{part}(\tau s)$$

σ^i_{part} is partonic cross section for process i

$\tau = x_1 x_2$

C. Diaconu, hep-ex/0901.0046v1

- "Factorize" the problem:
  - Subprocess cross section
    - Summed over colours & spins
  - Colour average factors (C_{ij})
    - C_{ij} = 1/9 for quarks
    - C_{ij} = 1/64 for gluons
  - Parton distribution functions (PDF)

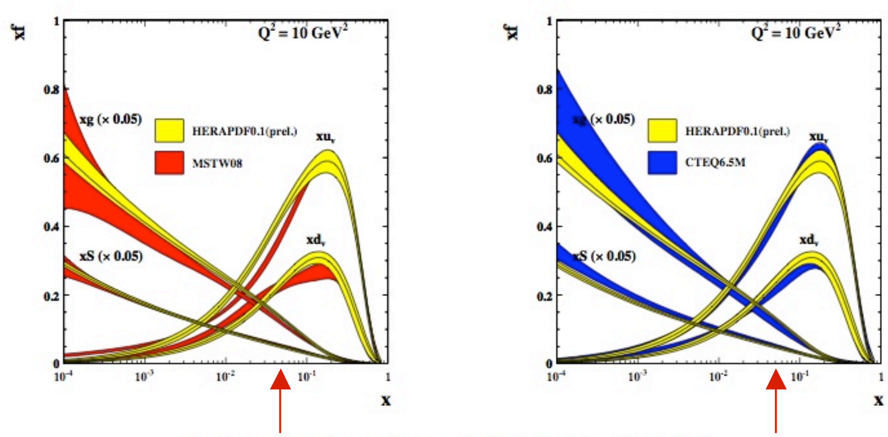


Figure 4: HERAPDF0.1 fit compared with MSTW and CTEQ fits.

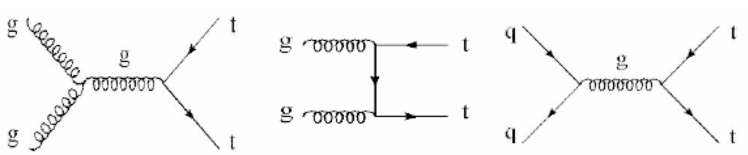
$$2M_{top} \approx \sqrt{s x_1 x_2}$$

Top Quark Production

- **Start with primary partonic process**

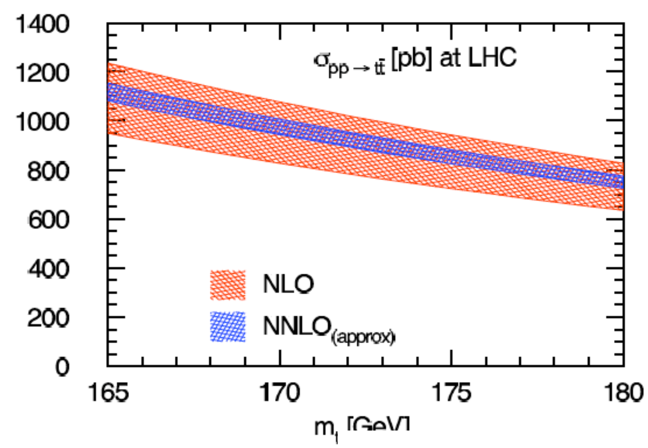
$$\sigma_{gg}(\hat{s}) = \frac{\pi\alpha_s^2}{3\hat{s}}\left[\left(1+\rho+\frac{\rho^2}{16}\right)\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta\left(\frac{7}{4}+\frac{31}{16}\rho\right)\right]$$

    - > $\rho = 4m_t^2/\hat{s}$, β velocity
  - **gg is dominant source at LHC**
  - **q-qbar annihilation modest addition**

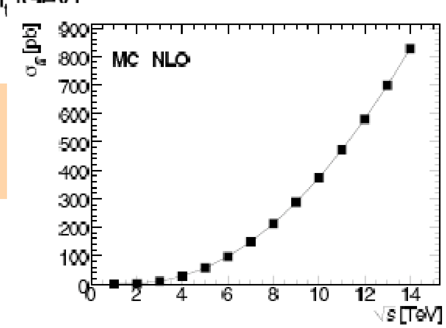


- **Lowest order process dominates**
  - **Much work done on higher-order effects**

- **Total cross section sensitive to**
  - **Top quark mass m_t**
  - **Resummation effects**
  - **Centre of mass energy**

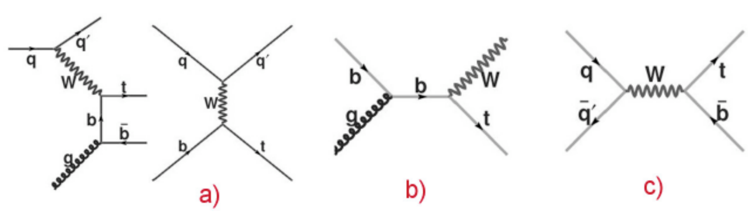


S. Moch and P. Uwer, *Nucl. Phys. Proc. Suppl.*, 182:75 (arXiv : 0807.2794), 2008.

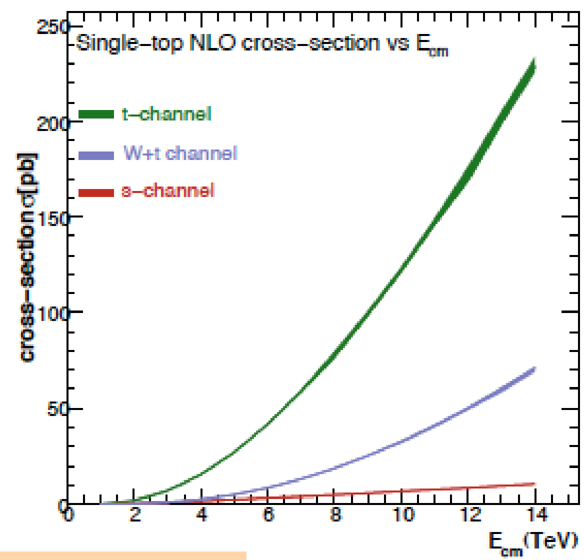


Single Top Quark Production

- Single top quark production also occurs
  - Challenge here is that backgrounds are significant
  - At Tevatron, took x100 more data to observe
- Situation is expected to be just as challenging given rates
  - Three mechanisms
    - t-channel (dominant - 230 pb)
    - Wt channel (66 pb)
    - s-channel (11 pb)



- An important process to study
  - One of the few ways that one can measure V_{tb}
  - Final state is similar to that arising from Higgs production
    - W+b-bbar accessible because of leptonic decay of W



See, e.g., Z. Sullivan, arXiv: hep-ph 0408049 (2004).

LHC a Top Quark Factory?

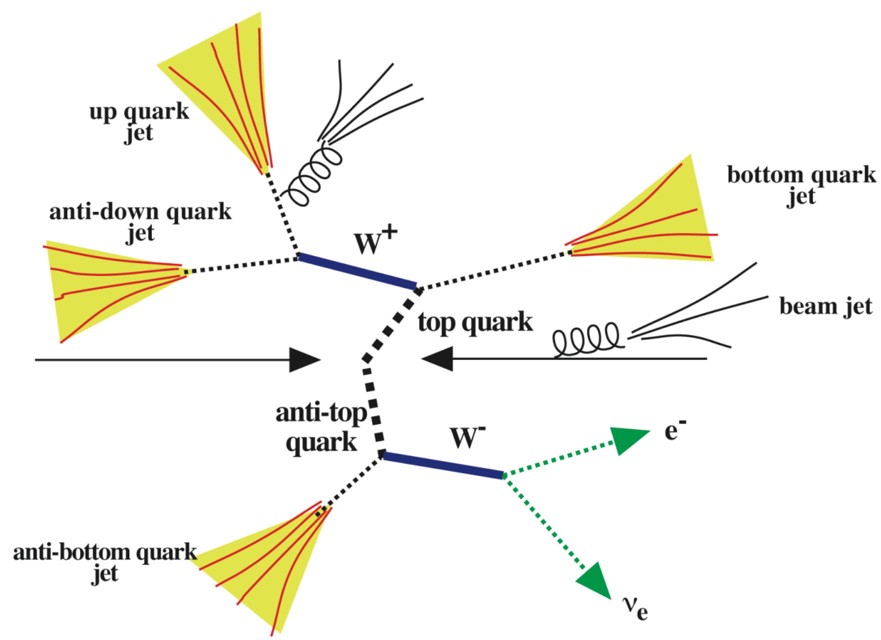
- **Calculate the rates:**
  - **See where some of the numbers come from later**

$$\sigma_{t\bar{t}} \cong 830\ pb\left(\sqrt{s} = 14\ TeV\right)$$
$$\Rightarrow r_{t\bar{t}} \cong \sigma_{t\bar{t}} \times L \times \varepsilon_{acc\times eff}$$
$$= \left(8.3\times10^{-34}\right)\left(1.0\times10^{32}\right)\left(4\times10^{-2}\right)$$
$$= 3.3\times10^{-3}\ \mathrm{s}^{-1} = 1.2/hour$$

  - **With 200 pb^{-1}, can expect**
    - 166,000 produced events
    - 6,600 lepton+jet events

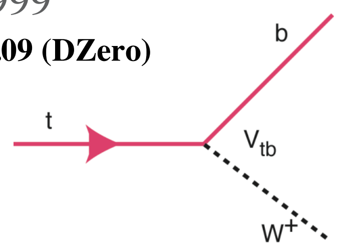
- **Very good calibration source**
    - Lepton ID efficiencies
    - Missing Et
    - Jet Energy Scales
    - B tagging efficiencies

- **Biggest challenge is correctly constructing final state**
  - **Tagging b's reduces this problem**
    - But also reduces the rate of candidate events



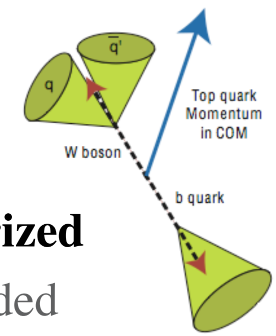
Top Quark Decays

- **Top decays are unique**
  - **Quark doesn't have time to hadronize**
    - Weak decay of bare quark
  - **Weak decay dominated by V_{tb}**
    - CKM unitarity implies BR($t \rightarrow Wb$)>0.999
      - **BR = 0.97±0.09 (DZero)**



- **Top quark width**
  - **Determined by SM couplings and mass**
  - **Prediction is Γ_t = 1.3 GeV/c^2**
    - Measure Γ_t < 12.7 GeV/c^2 at 95% C.L.
    - Observed width dominated by resolution

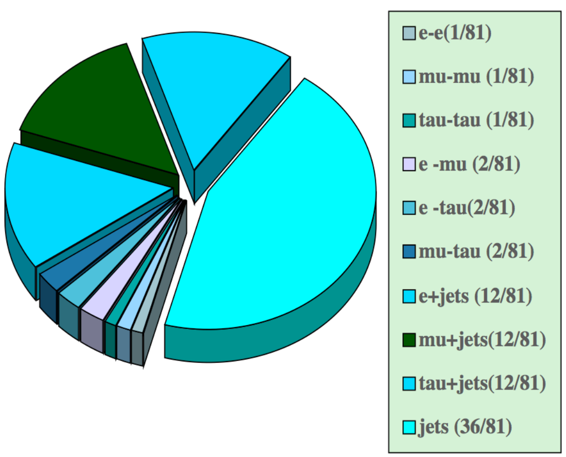
- **Two-body decay kinematics**
  - **W decay results in 3-body final state**
  - **SM predicts W is longitudinally polarized**
    - Smaller left-handed component
    - No right-handed decay



- **This effects decay kinematics**
  - **Can measure polarization using, e.g., spectra of final state particles**

Top Quark Decay Modes

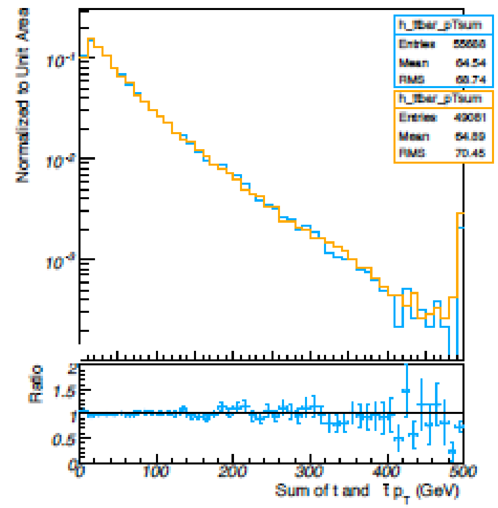
- Assuming SM, decay modes defined by
  - 100% decay to Wb
  - W decay to
    - eν, μν, τν (10.8±0.1)% each
    - c-sbar, u-dbar (33.8±0.2)% each
- Since top quarks most readily studied via pair-production
  - All-hadronic (multijet) final states
  - Lepton + jets final states
  - Dileptons



- Experimental challenges include
  - Reconstruction of 6-parton final state
    - Identify partons as final state "objects"
      - Perhaps most complex final state studied
    - Associate objects to correct partons
      - Best algorithms in l+jets mode is ~60% correct
  - Very "busy" final state
    - Additional jets produced
      - Initial & final state radiation
  - Multiple neutrinos
    - Particularly problematic in dilepton modes

Top Quark Kinematics

- Top quark is produced "centrally"
  - Mode of P_T distribution ~ 90 GeV/c
  - Most tops are within |η|<3
  - Produced back-to-back
  - ttbar system has modest P_T
- Defines kinematics of final state daughters



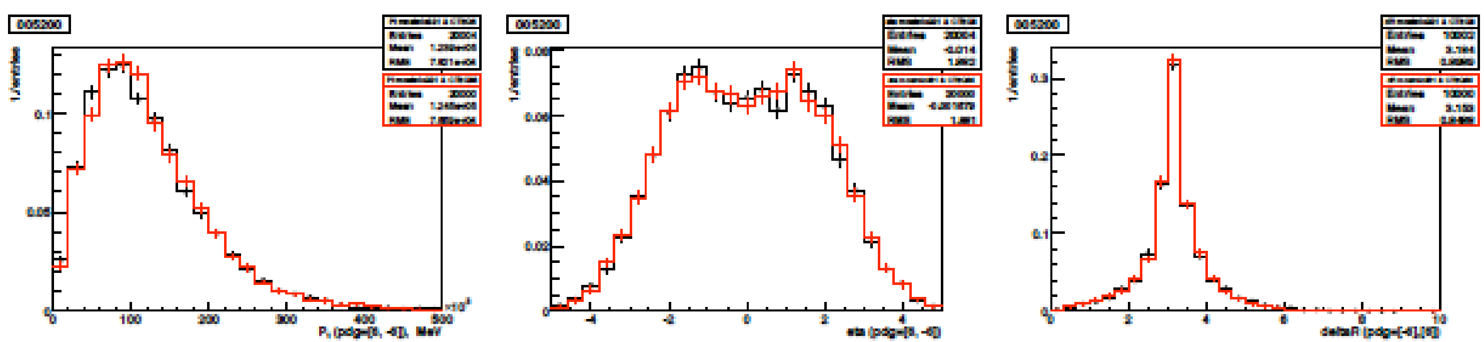
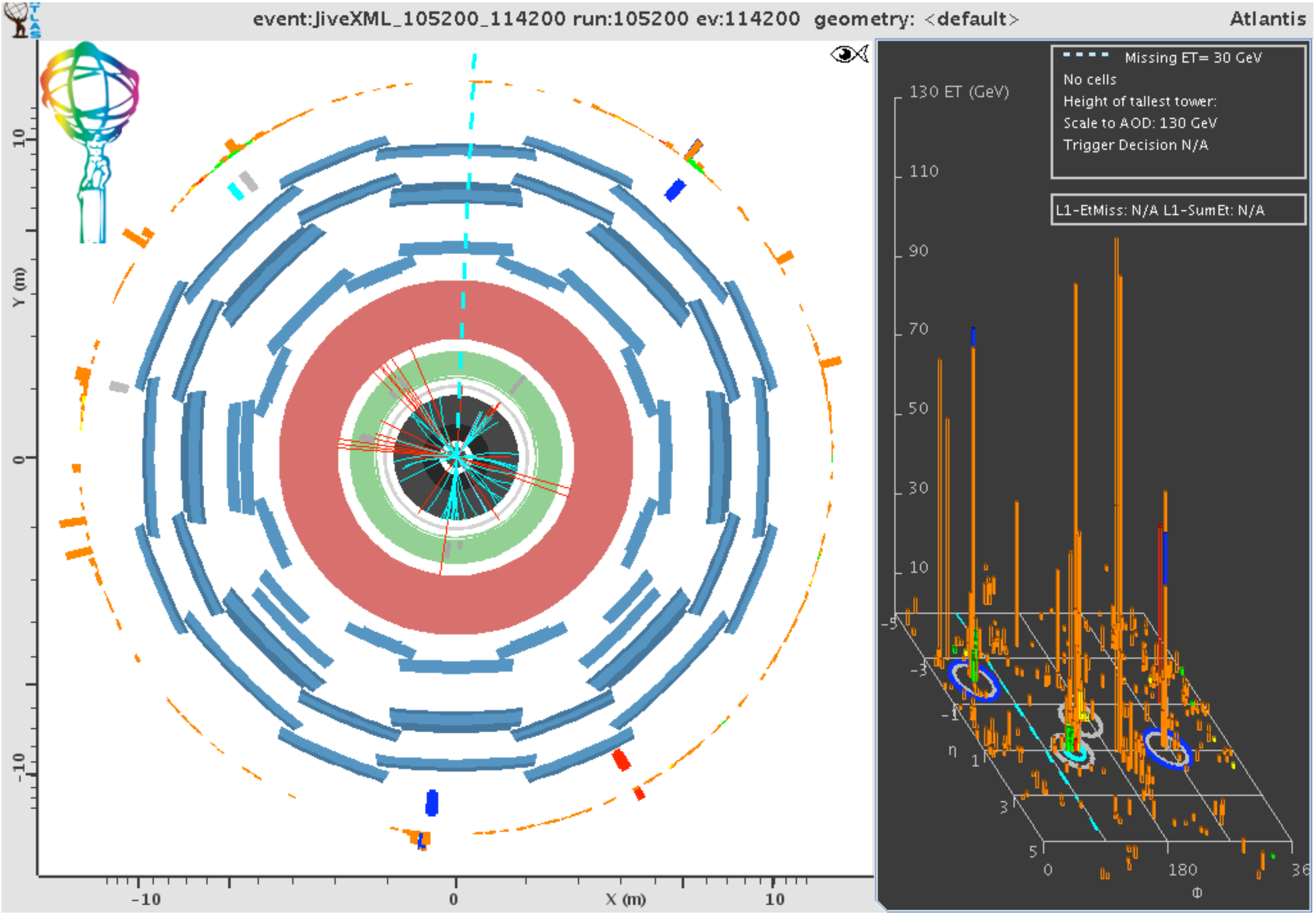


Figure 16: *top and anti-top quarks p_T, η and δR (spherical angle between t and $\bar{t}$ quarks) distributions in the $t\bar{t}$ events. The histogram with black circle markers correspond to CTEQ6 sample. The histogram with the red squares correspond to the CTEQ6.6 sample. Histograms are filled with MC@NLO event weights, ± 1.*



event:JiveXML_105200_114200 run:105200 ev:114200 geometry: <default>
Atlantis
Y (m)
X (m)
Missing ET= 30 GeV
No cells
Height of tallest tower:
Scale to AOD: 130 GeV
Trigger Decision N/A
L1-EtMiss: N/A L1-SumEt: N/A
130 ET (GeV)
η
Φ

Acceptance x Efficiency

- **Have to decide channel to focus on**
  - **Semi-leptonic channel is favourite "whipping boy"**
  - **Require**
    - One W to decay leptonically (e/μ required in final state)
      - **Charged lepton with <P_T>~ 50 GeV/c**
      - **Neutrino with energy <P_T>~ 50 GeV/c**
      - **This also accepts some W->τν**
    - One W to decay hadronically
      - **2 jets with average <P_T>~ 50 GeV/c**
    - Two b jets
      - **Maybe require jets, maybe tagged?**
      - **On average, a little harder…**
  - **Estimate BR = (2/9)x(2/3)x2=8/27=30%**
    - But need to run full MC! Why?

- **Have to decide on trigger:**
  - **Inclusive e or μ**
    - P_T > 20-25 GeV/c
    - |η| < 2.5
  - **Acceptance ~ 85 %**
  - **Efficiency ~ 90-95%**

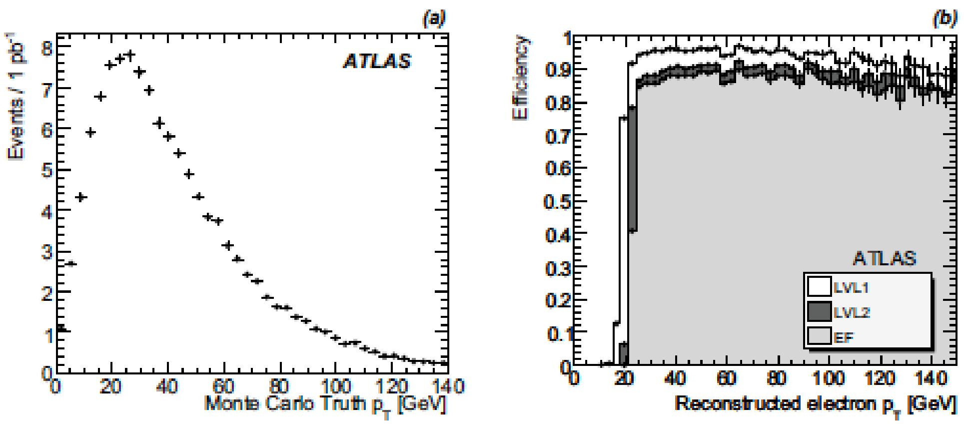
L1/L2/L3 Inclusive Lepton trigger

- **Offline selection requirements**
  - **Lepton ID**
  - **E_T^{miss} > 20 GeV**
  - **3-4 jets**
    - E_T>20-60 GeV
    - |η| < 2.5
  - **B tagging?**
    - Single b-tag efficiency around 50-60%

Think "Trigger!"

- Triggering on top quarks straightforward
  - Rely on inclusive lepton & dilepton triggers
    - E_T thresholds around 20 GeV
  - Multijets are harder
    - Use complex jet criteria, e.g.
      - ≥4 jets P_T>60 GeV/c
      - ≥2 jets P_T>100 GeV/c
      - ≥1 jets P_T>170 GeV/c
    - S/B still poor
  - E_T^{miss} + jets provides redundant trigger

- Example:
  - Inclusive lepton triggers
    - Efficiency of ~90% for selected lepton+jet events



Trigger	Signal Efficiency [%]	Relative Background Rate	S/B
4j60_2j100_j170	6	0.13	$2.8 \cdot 10^{-3}$
5j45_2j60_j100	16	0.34	$3.0 \cdot 10^{-3}$
6j35_5j45_4j50_3j60	10	0.18	$3.7 \cdot 10^{-3}$

Detector Acceptance & Efficiency

- **Detectors designed with specific physics processes in mind**
  - **Break these down into**
    - Total transverse energy
    - Charged leptons (e, μ, τ)
    - Jets (quarks & gluons)
    - Missing transverse energy
  - **Huh? But aren't we supposed to be discovering stuff?**
    - Hope is that by focusing in detection and triggering of "basic elements", one will have a broad enough menu that new phenomena will be recorded
  - **Doesn't seem like a bad idea**
    - But creates practical challenges
    - Very large "trigger" menus

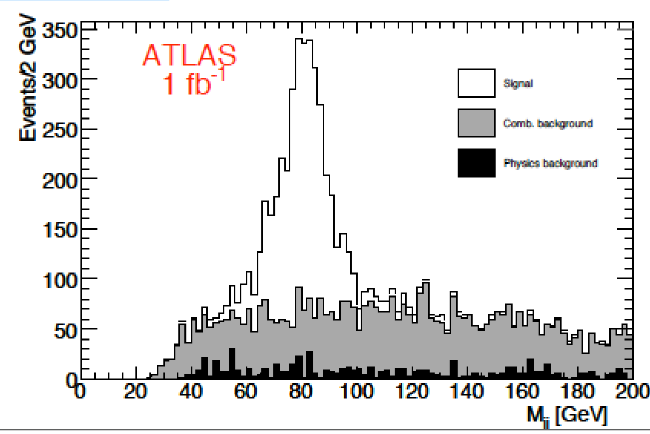
- **Helpful to separate detector effects:**
  - **Acceptance: Fraction of events of a given process "contained" within the detector**
  - **Efficiency: Fraction of contained events/objects ultimately passing some set of criteria ("cuts")**
  - **Resolution: Accuracy of measurements of specific event-related quantities**
- **Warning: Not a strict convention on how these terms used!!**
  - **Always make sure you define what you mean**

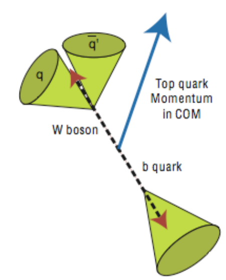
Tools for Top Reconstruction

- **Lepton Identification**
  - **Electron & muon ID critical**
    - Reject QCD backgrounds
    - Allow precise kinematic measurements
- **Jet reconstruction**
  - **Messy objects**
    - spatially large and hard to measure
  - **Algorithms are important**
    - Emphasize “small” jets
    - Cone sizes ~ 0.4-0.5 in R
  - **B tagging critical**
    - Efficiencies ~ 0.6
    - Rejections ~ 200
- **Missing Transverse Energy**
  - **Needs good calorimetry**
  - **Have largely lost P_z information**

- **Efficiency is a key issue**
  - **Detecting top quarks important over large backgrounds**
    - Intrinsic S/N = 10^{-10}
  - **Important for rare processes**
- **Two additional challenges are**
  - **Calibration (especially of jets)**
    - Talk about this later
  - **Full event reconstruction**
    - Lots of jets produced

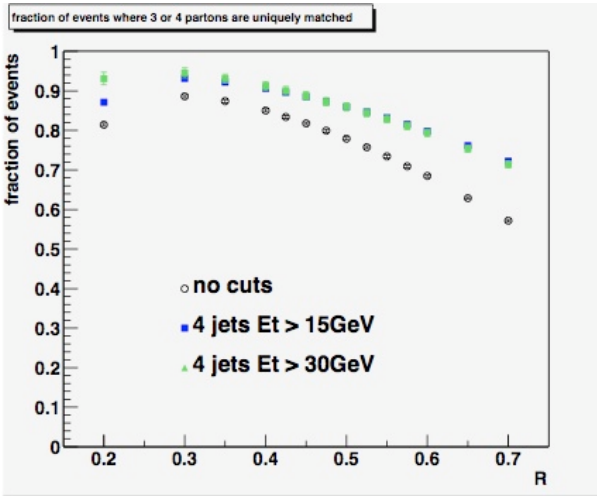
W reconstruction
In Lepton+Jets
Events

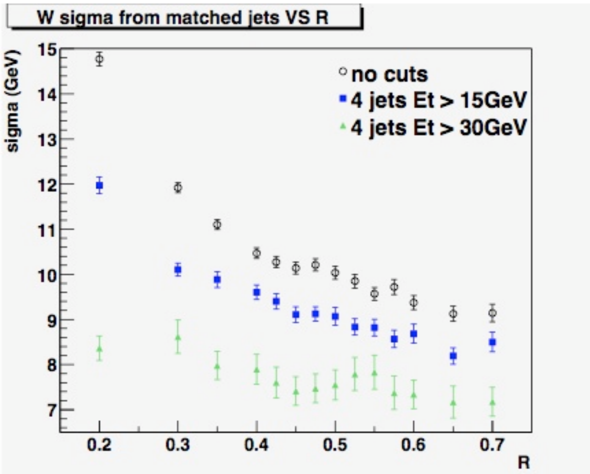




How Are These Chosen?

- **Study acceptance**
  - **Learn that top quark production ~ “central”**
  - **Primary backgrounds (W+bb+jets) more distributed in η**
  - **Lepton ID and jet reconstruction limiting factors**
- **Maximize efficiency**
  - **Requires S/N studies**
  - **Look at different algorithms for event reconstruction**
  - **Need to be systematic**
    - But recognize that one has to make compromises





Radius of jet cone

Top Quark Cross Section

- **Standard technique to measure cross section is**

$$\sigma = \frac{N_{obs} - N_{bkgd}}{\varepsilon A \int L\,dt}$$

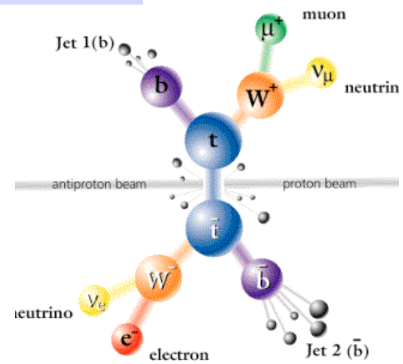
$$N_{obs}, N_{bkgd} = \text{number observed, background events}$$

$$\varepsilon A = \text{efficiency times acceptance}$$

$$\int L\,dt = \text{integrated luminosity}$$

- **Problem breaks down into**
  - **Define selection to**
    - Get good efficiency
    - Reject backgrounds
    - Understand uncertainties
  - **Estimate the uncertainties**

- **Look at cross section in dilepton mode**
  - **Intrinsically cleaner**
    - Lower QCD and W+bb backgrounds
  - **Also intrinsically smaller**
    - Efficiencies are <1%
  - **Have some challenges**
    - τ decays
      - **Decaying leptonically**
    - Leptons from b & c decay



2 Electrons	Total	2 W	1W 1b	1W 1c	1W 1Tau	1W 1Other
# Events	1,494	1,246	38	1	176	7
rate	100.0	83.4	2.5	0.1	11.8	0.5

2 Muons	Total	2 W	1W 1b	1W 1c	1W 1Tau	1W 1Other
# Events	2,831	2,203	313	6	258	3
rate	100.0	77.8	11.1	0.2	9.1	0.1

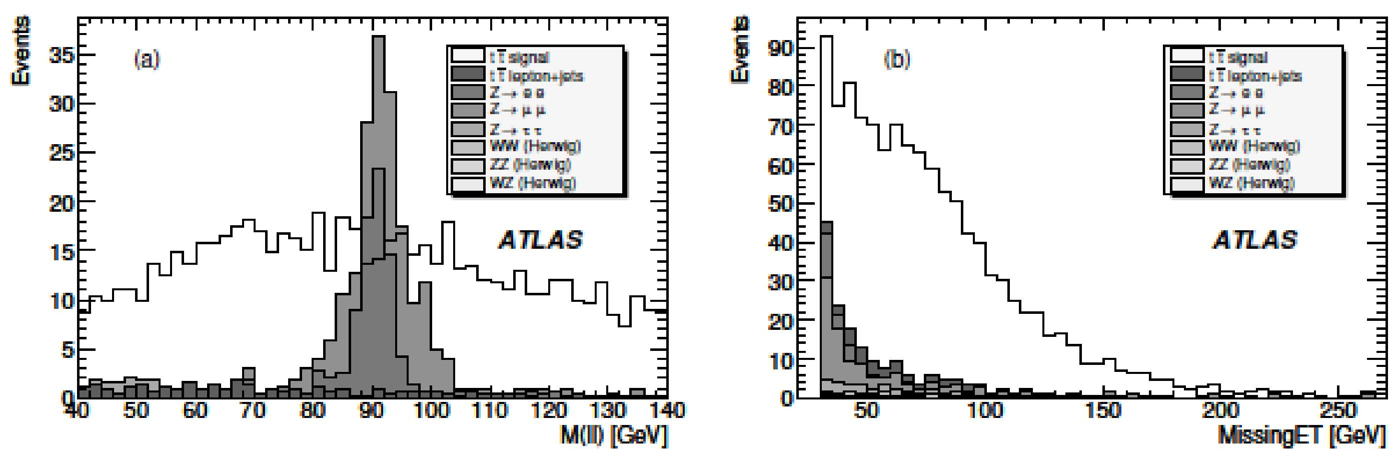
1 E 1Mu	Total	2 W	1W 1b	1W 1c	1W 1Tau	1W 1Other
# Events	4,167	3,293	320	5	453	18
rate	100.0	79.0	7.7	0.1	10.9	0.4

Dilepton Cross Section

- **Intrinsic backgrounds are large**
  - **Z/W boson production**
    - Eliminate by identifying Z mass peak
- **Motivates selection:**
  - **Two clean lepton candidates**
    - $P_T > 20$ GeV/c
  - **$E_T^{miss} > 30$ GeV**
  - **≥2 jets $P_T > 60$ GeV/c**
  - **Reject Z's**

Sample	σ(pb)	Filter(%)	σ_{eff}(pb)	$e\mu$	ee	$\mu\mu$
$t\bar{t}$ (di-lepton)	833	7(2l)	55	699	312	381
$t\bar{t}$ (semi-leptonic)		48(1l)	397	31	20	8
$Z \to e^+e^-$	2015	86	1733	5	37418	0
$Z \to \mu^+\mu^-$	2015	89	1793	153	0	51139
$Z \to \tau^+\tau^-$	2015	5	101	249	101	159
$W \to e\nu$	20510	63	12920	42	69	0
$W \to \mu\nu$	20510	69	14150	152	0	40
WW	117	35	41	76	32	44
WZ	48	29	14	6	41	52
ZZ	15	19	3	1	25	31
single top	324	31	99	5	3	2

Number of events
For 100 pb^{-1}



Cross Section Results

- **Have significant yield for selection**
  - **Backgrounds under control as well**
    - Dimuons are in worst shape
  - **Expect about 987 signal events with 228 background in 100 pb^{-1}**
- **Systematic uncertainties**
  - **First pass would suggest ~5%**
    - Dominated by jet energy scale
  - **Luminosity uncertainty also ~5%**
  - **Statistical uncertainty**
    - 4% for 100 pb^{-1}
- **Overall, looks straightforward**
  - **But note where Tevatron has had greatest challenge**

dataset	$e\mu$	ee	$\mu\mu$	all channels
$t\bar{t}$ (di-lepton)	555	202	253	987
ε [%]	6.22	2.26	2.83	11.05
$t\bar{t}$ (semi-leptonic)	24	11	4	39
$Z \to e^+e^-$	0.0	9	0.0	20
$Z \to \mu^+\mu^-$	5	0	51	79
$Z \to \tau^+\tau^-$	17	4	6	25
WW	6	2	2	10
ZZ	0	0.2	0.4	0.9
WZ	1	0.6	1	3
$W \to e\nu_e$	7	7	0.0	14
$W \to \mu\nu_\mu$	25	0.0	7	33
single top Wt	0.7	0.5	0.0	1
single top s-chann.	0.0	0.0	0.0	0.1
single top t-chann.	2	0.8	1	4
Total bkg.	86	36	73	228
S/B	6.3	5.6	3.4	4.3

$\Delta\sigma/\sigma$ (%)	eμ	ee	$\mu\mu$	All
CTEQ6.1 Variation	2.4	2.9	2.0	2.4
MRST2001E Variation	0.9	1.1	0.7	0.9
JES -5%	(2.0)	-	(3.1)	(2.1)
JES + 5%	2.4	4.1	4.7	4.6
FSR	2.0	2.0	4.0	2.0
ISR	1.1	1.1	1.2	1.1
Total				5.0

Tevatron Data with B-Tagging

- Most accurate top quark cross section
  - Lepton+jets
  - SECVTX b-tagging
- Strategy
  - Use MC to determine overall acceptance
  - Measure trigger efficiency with W->lν
  - Measure lepton ID efficiency with Z->ll
  - Measure b-tagging efficiency in data
  - Estimate systematic uncertainties

<table>
<tr><th>Systematic</th><th>Inclusive (Tight)</th><th>Double (Loose)</th></tr>
<tr><td>Lepton ID</td><td colspan="2">1.8</td></tr>
<tr><td>ISR</td><td>0.5</td><td>0.2</td></tr>
<tr><td>FSR</td><td>0.6</td><td>0.6</td></tr>
<tr><td>PDFs</td><td colspan="2">0.9</td></tr>
<tr><td>Pythia vs. Herwig</td><td>2.2</td><td>1.1</td></tr>
<tr><td>Luminosity</td><td colspan="2">6.2</td></tr>
<tr><td>JES</td><td>6.1</td><td>4.1</td></tr>
<tr><td>b-Tagging</td><td>5.8</td><td>12.1</td></tr>
<tr><td>c-Tagging</td><td>1.1</td><td>2.1</td></tr>
<tr><td>l-Tagging</td><td>0.3</td><td>0.7</td></tr>
<tr><td>Non-W</td><td>1.7</td><td>1.3</td></tr>
<tr><td>W+HF Fractions</td><td>3.3</td><td>2.0</td></tr>
<tr><td>Mistag Matrix</td><td>1.0</td><td>0.3</td></tr>
<tr><td>Total</td><td>11.5</td><td>14.8</td></tr>
</table>

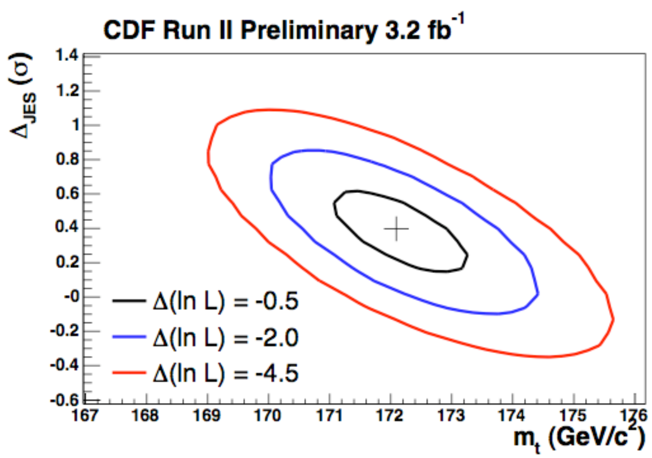
TABLE XI. Summary table of the $t\bar{t}$ acceptance, for a top quark mass of 175 GeV/c^2.

	CEM	CMUP	CMX	Total
Sample (total)	344 264	344 264	344 264	344 264
# Events w/o b-tag	15 893	9791	3617	29 301
Acc. w/o b-tag (%)	$4.09 \pm 0.03 \pm 0.36$	$2.13 \pm 0.02 \pm 0.19$	$0.959 \pm 0.016 \pm 0.085$	$7.18 \pm 0.04 \pm 0.61$
# Tagged Events	8490	5202	1965	15 657
Tag Efficiency (%)	$53.4 \pm 0.4 \pm 3.2$	$53.1 \pm 0.5 \pm 3.2$	$54.3 \pm 0.8 \pm 3.3$	$53.4 \pm 0.3 \pm 3.2$
Acc. with b-tag (%)	$2.19 \pm 0.02 \pm 0.23$	$1.14 \pm 0.01 \pm 0.12$	$0.512 \pm 0.009 \pm 0.054$	$3.84 \pm 0.03 \pm 0.40$
Integ. Lumi. (pb^{-1})	162 ± 10	162 ± 10	150 ± 9	

D. Acosta et al., PRD 71, 052003 (2005)

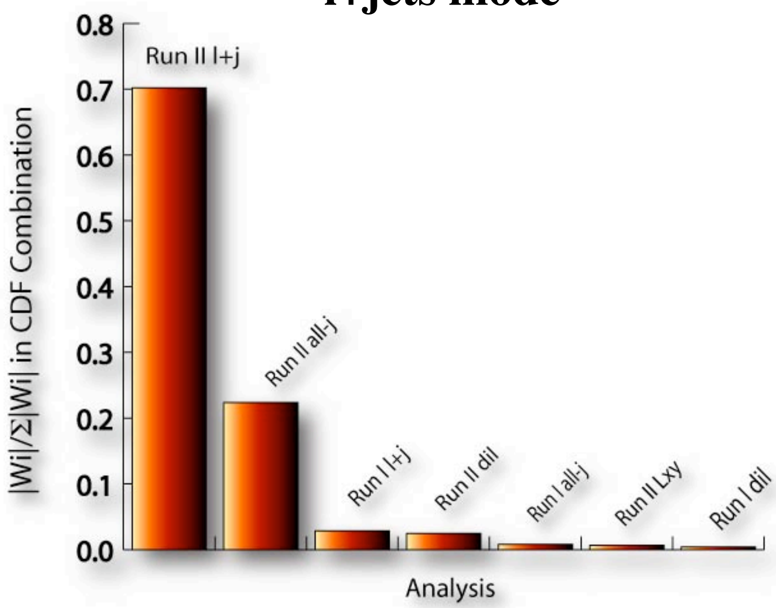
Top Quark Mass

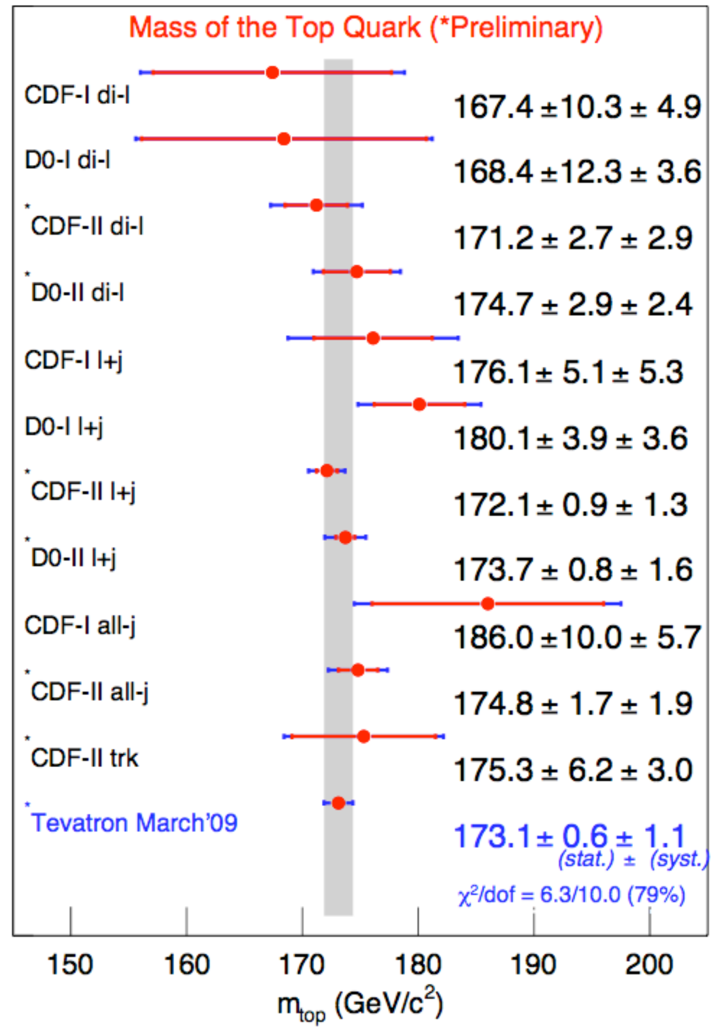
- **A precision measurement of top quark mass m_t scientifically important**
  - **Tests consistency of Standard Model**
  - **Bare quark – first opportunity to study one directly**
  - **Heaviest fermion, so couples strongly to Higgs boson**
- **Not just "another" quark mass**
  - **Heaviest fermion in theory**
    - Couples to Higgs boson in SM
    - m_Z, m_W, m_t and m_H are all related
  - **At a level of ~0.5 GeV/c², start to test other aspects of theory**
    - Stability of pole mass with respect to MS-bar mass
    - Non-perturbative QCD effects become important
- **Presents important experimental challenges**
  - **Requires us to understand**
    - Jet energy scales very well
    - Effects of underlying event
- **Tevatron experiments have "raised the bar"**
  - **Precision ~0.7%, or 1.1 GeV/c²**
  - **Found solutions to many problems**
  - **Achieving comparable precision at LHC will be a challenge!**



Latest Tevatron Results

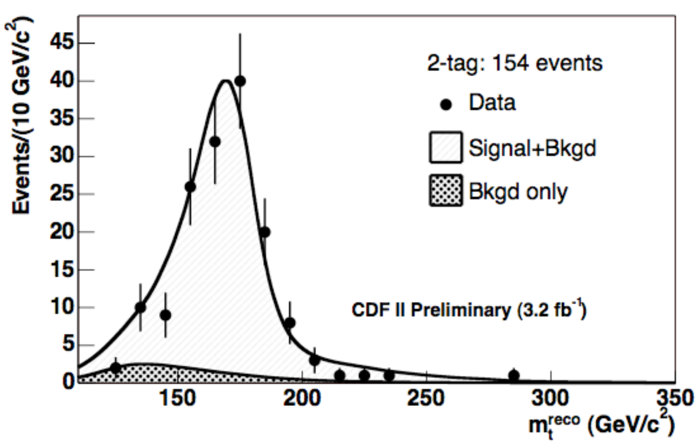
- Measured mass in essentially all modes
  - With half of available Tevatron data, systematics limited
  - Most precise measurement is in l+jets mode





Mass Measurement Techniques

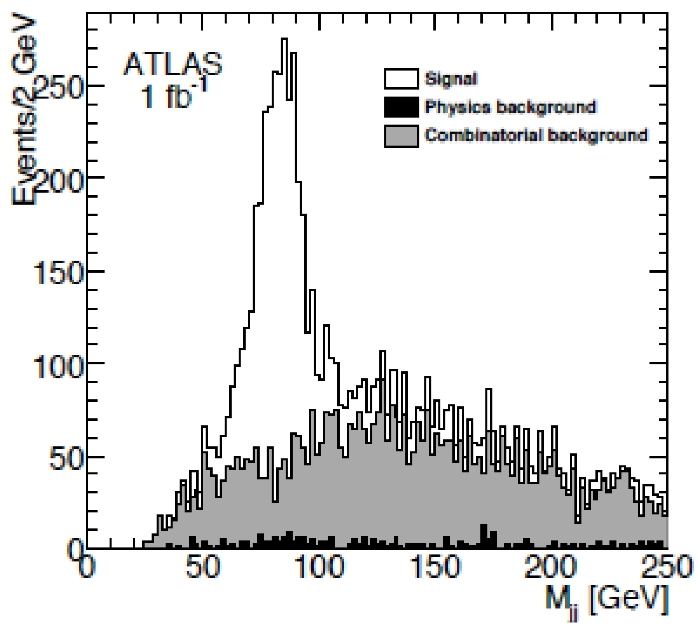
- **All techniques based on simple kinematics**
  - **Heavier the object, the more energetic the daughters**
- **Variations in how one correlates observed final state with m_t**
  - **Directly measure using 4-momentum reconstruction**
    - Correct for resolution effects
  - **Employ matrix element approach**
    - Use “transfer functions” for detector resolution
  - **Look at subset of information**
    - Example, lepton P_T
- **Many complications**
  - **Cannot reconstruct final state of 6 partons correctly**
  - **Jet energy calibrations**
  - **Background sources**
- **Example of how well one can do:**
  - **Mass reconstruction in double-tagged lepton+jet events**



Example LHC Analysis

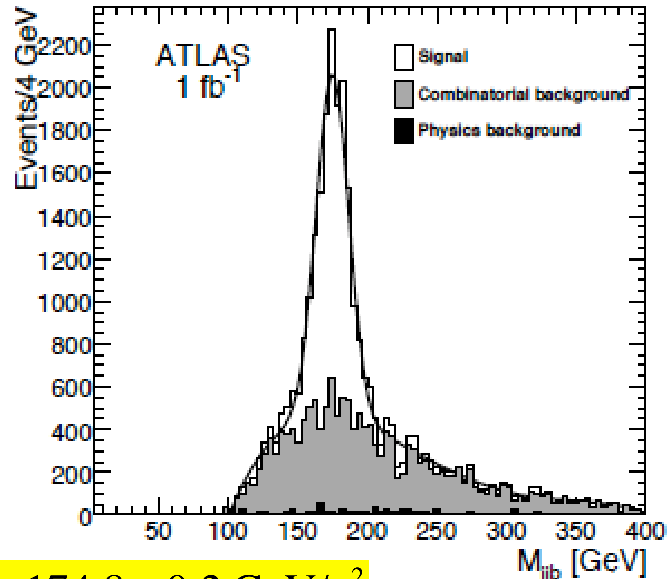
- Select l+jets mode
  - Require e(μ) with P_T>25(20) GeV/c
  - Require Missing E_T>20 GeV
  - 4 or more jets
    - P_T>40 GeV/c and |η|<2.4
  - Require two b-tagged jet
  - Use inclusive lepton trigger
    - About 90% efficient on e/μ + jets
- Selection has 1.8% efficient
  - Expect 16 pb of selected events
  - Jet and b-tag cuts selected to reject backgrounds
- Reconstruct final state
  - Choose 4 highest P_T jets
  - Use a χ^2 to choose best parton assignments
  - Use dijet mass to constrain jet energy scale
    - Perform a fit to extract m_t

Process	Number of events	1 isolated lepton $p_T > 20$ GeV and $\not{E}_T > 20$GeV	>= 4 jets $p_T > 40$ GeV	2 b-jets $p_T > 40$ GeV
Signal	313200	132380	43370	15780
W boson backgrounds	9.5×10^5	154100	9450	200
all-jets (top pairs)	466480	1020	560	160
di-lepton (top pairs)	52500	16470	2050	720
single top, t channel	81500	24400	1230	330
single top, W t channel	9590	8430	770	170
single top, s channel	720	640	11	5



LHC m_t Precision

- **Statistical accuracy**
  - **At 0.2 GeV/c², not limiting factor**
  - **Resolution ~11-12 GeV/c²**
- **Systematic uncertainties dominate**
  - **Mass depends linearly on jet energy scale (JES) uncertainties**
    - Light quark jet JES constrained by W mass to <1%
    - B-jet JES comes from MC modelling
      - **Tevatron estimates ~0.5%**
  - **Model uncertainties are likely larger in practice**
    - This will be area of intense work

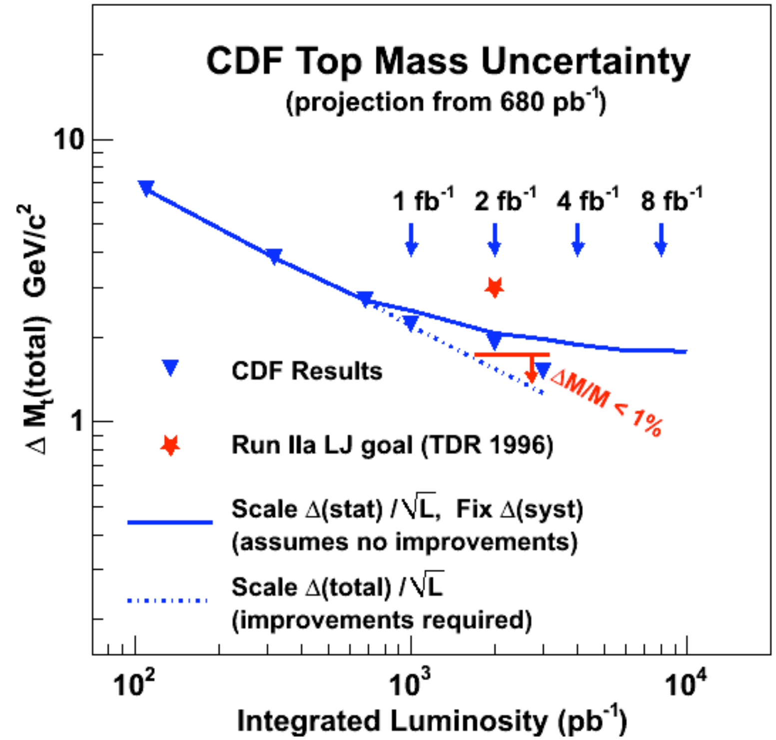


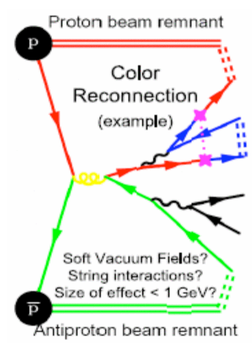
$m_t = 174.8 \pm 0.2$ GeV/c^2

Systematic uncertainty	χ^2 minimization method	geometric method
Light jet energy scale	0.2 GeV/%	0.2 GeV/%
b jet energy scale	0.7 GeV/%	0.7 GeV/%
ISR/FSR	$\simeq$ 0.3 GeV	$\simeq$ 0.4 GeV
b quark fragmentation	$\leq$ 0.1 GeV	$\leq$ 0.1 GeV
Background	negligible	negligible
Method	0.1 to 0.2 GeV	0.1 to 0.2 GeV

Many Other Mass Measurements

- Use all channels
  - Dileptons
  - Multijets
- More importantly, use different techniques with different systematics
  - Decay length of b
  - Lepton P_T distribution
  - Multivariate techniques
    - Neural networks
    - Maximum likelihood
- Very quickly systematics-limited
  - More statistics helps, but only if systematics are tackled
    - For example, colour reconnection effects

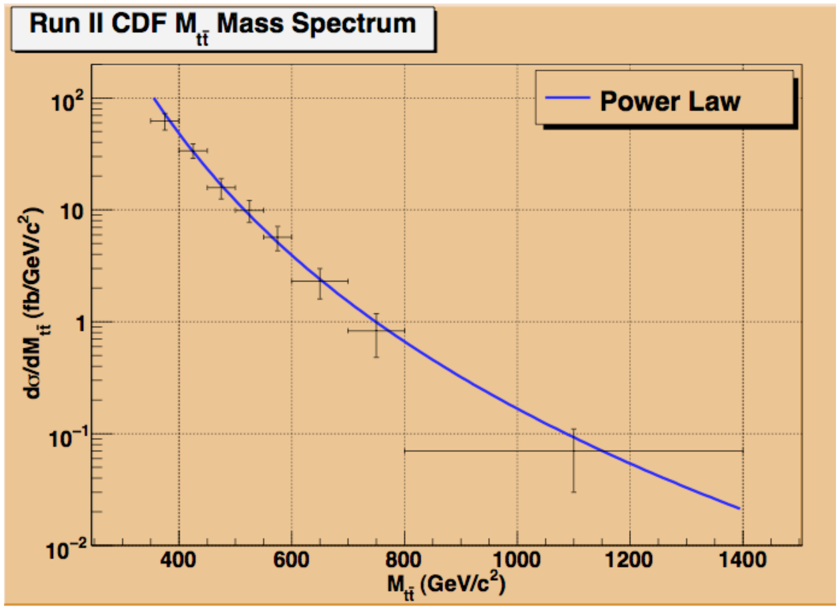




D. Wicke and P. Skands, arXiv:0807.3248V1

Top Quark Properties

- **Many important properties, e.g.,**
  - **Top quark charge**
  - **Spin polarizations**
  - **Flavour-changing neutral currents (FCNC) in top decays**
  - **t-tbar resonances**
- **In many cases, there are early Tevatron results**
  - **Suffer from low statistics**
  - **"Top factory" mode allows one to extend all of these in significant ways**
  - **Area where there will be much new territory to cover**



$$\frac{d\sigma}{dM_{t\bar{t}}} \propto \left(M_{t\bar{t}}\right)^{(-6.1\pm 0.9)}$$

What We Know Already?

95% CL upper limit on BR: $90 < H^+ < 150$ GeV

BR($t \rightarrow Zq$) < 3.7% at 95% CL

$F_0 = 0.62 \pm 0.11$ & $F_+ = -0.04 \pm 0.05$

$M_t = 172.6 \pm 0.9_{stat} \pm 1.2_{sys}$ GeV/c^2

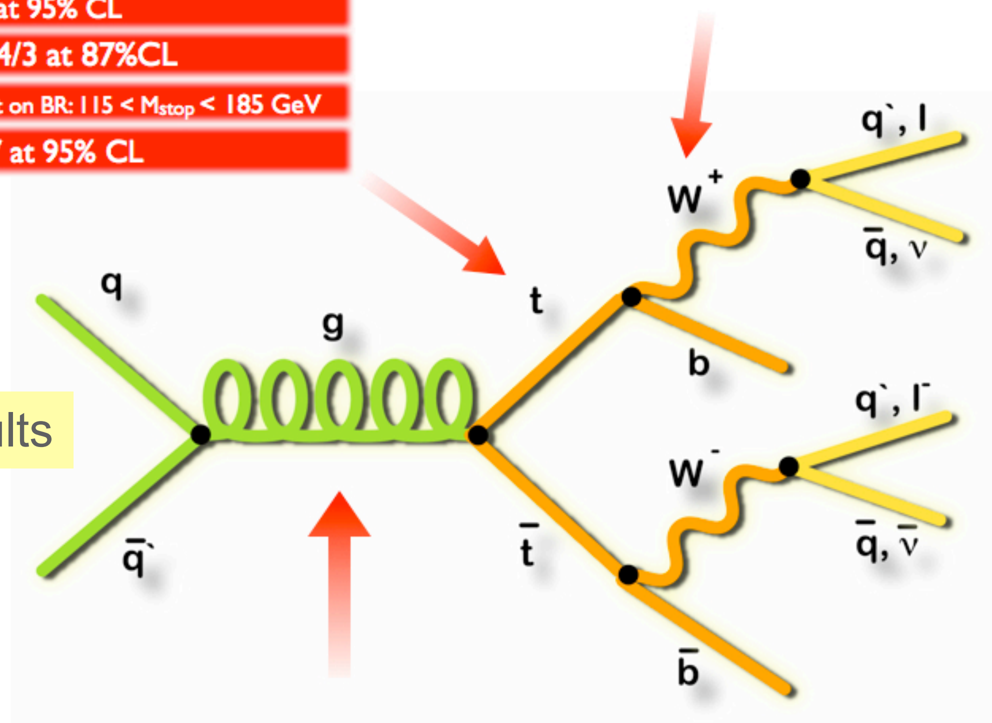
$\Gamma_t < 13.1$ GeV at 95% CL

Exclude $q = -4/3$ at 87%CL

95% CL upper limit on BR: $115 < M_{stop} < 185$ GeV

$M_{t'} < 311$ GeV at 95% CL

Compendium of CDF Results



$\sigma_{l+jets} = 6.9 \pm 0.4_{stat} \pm 0.4_{sys} \pm 0.1_{z\text{-theory}}$ pb

$\sigma_{ll} = 6.7 \pm 0.8_{stat} \pm 0.4_{sys} \pm 0.4_{lumi}$ pb

$\sigma_{all\text{-}jets} = 8.3 \pm 1.0_{stat} \pm 2.0_{sys} \pm 0.5_{lumi}$ pb

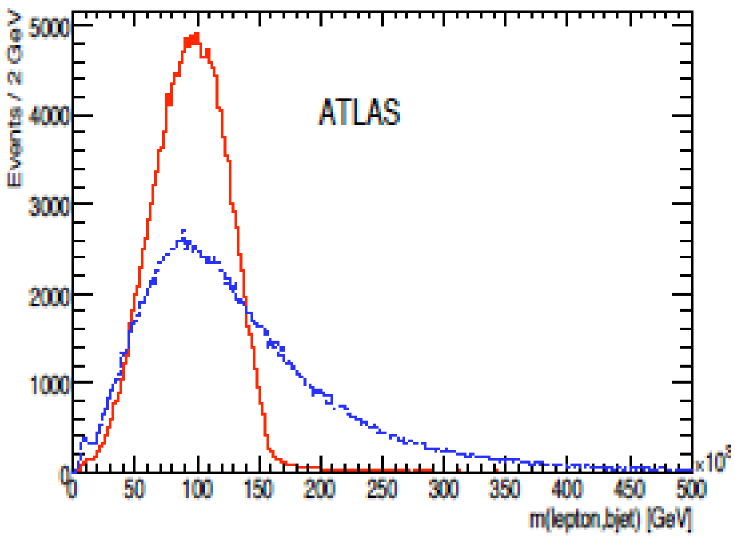
$F_{gg} = 0.07\ ^{+0.15}_{-0.07}$ (stat+sys)

$A_{fb}^{lab} = 0.19 \pm 0.07_{stat} \pm 0.02_{sys}$

$M_{Z'} < 800$ GeV at 95% CL

Top Quark Charge

- To directly measure the top quark charge
  - Need to show correlation
    - W+b versus W-b
  - One technique is to fully reconstruct t-tbar events
- Employ "standard" selection
  - Isolated e(μ)
    - P_T>20(25) GeV/c and |η|<2.5
  - ≥4 jets
    - P_T>30 GeV/c and |η|<2.5
    - At least two b-tagged jets
  - E_T^{miss} > 20 GeV
- Yield is about 2.5% of total production
  - So about 21,000 events in 1 fb^{-1}



- Associate W and b using kinematics
  - Invariant l+b mass < 155 GeV/c^2
    - Maximizes $\varepsilon(2P-1)^2$
      - ε being efficiency
      - P being "purity"
- Use method to determine b jet charge
  - Track counting algorithm
  - Semi-leptonic b decay

Charge Results

- **One intuitive algorithm**
  - **Sum charges of all tracks in a jet**

$$Q_{bjet} = \frac{\sum_i q_i |j_i \bullet p_i|^\kappa}{\sum_i |j_i \bullet p_i|^\kappa}$$

j_i = b jet axis

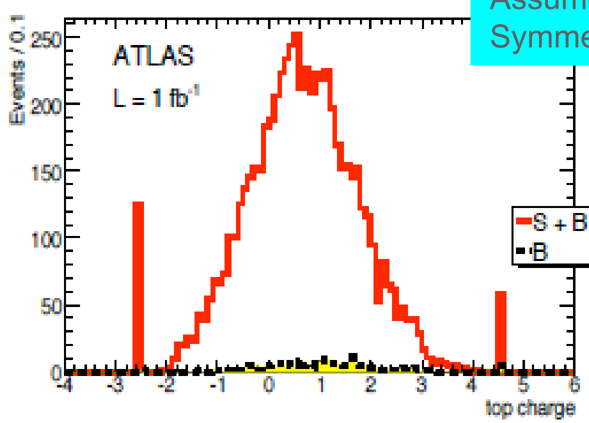
q_i, p_i = track charge, vector

$\kappa = 0.5$

  - **Have to use MC to calibrate**
    - Results in $Q_b/Q_{meas} = 3.54 \pm 0.16$
    - Source of largest systematic uncertainty

- **Results in top charge distribution**

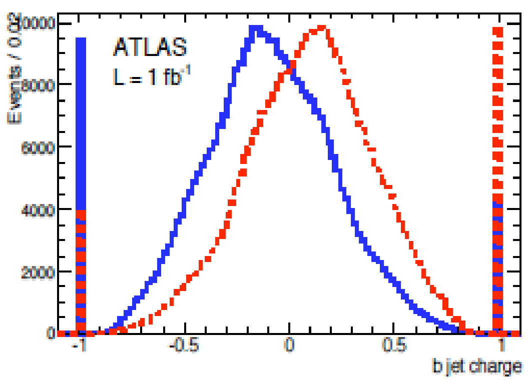
Background Assumed Symmetric!

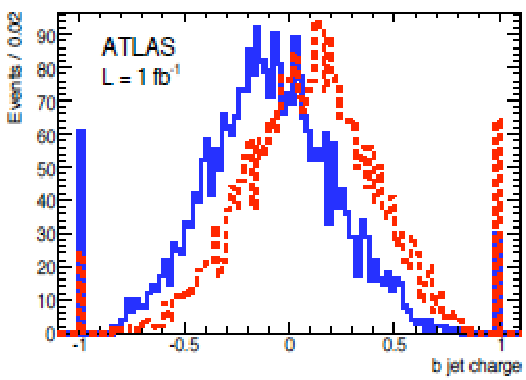


- **With 1 fb^{-1}**

$Q_t = 0.67 \pm 0.06\,(\text{stat}) \pm 0.08\,(\text{syst})$

  - **20 σ measurement**
  - **Relies on good modelling of b jets!**



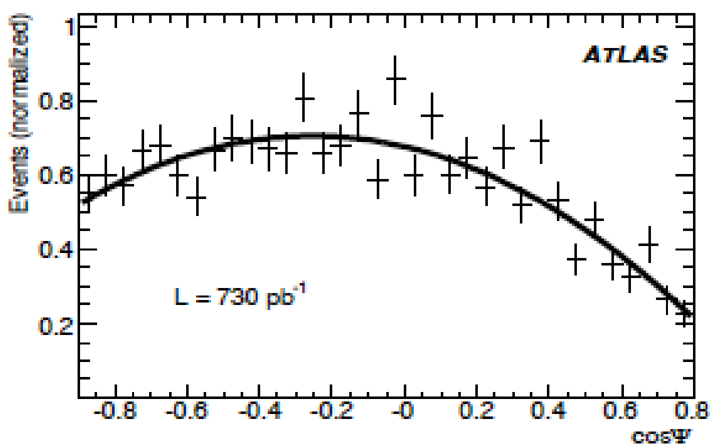


Top Quark Spin Effects

- Two sources of "spin" effects
  - Top quark decay vertex
  - Top quark spin correlations
- Top quark decay results in polarized W boson
  - Three possible polarization states
    - "Longitudinal" (F_0) is preferred

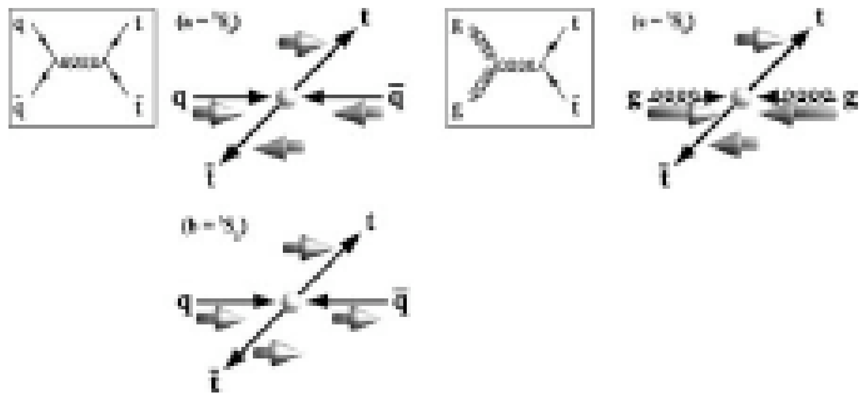
$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\Psi}{2}\right)^2 + F_R\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

    - SM: F_0=0.695, F_L=0.304
    - Look at lepton decay angle Ψ in top quark rest frame
  - Sensitive to physics of top quark decay vertex
- Need to be careful about selection
  - Standard selection creates some bias in Ψ
  - Have to correct with MC
  - In 1 fb^{-1}, expect to measure F_0
    - Statistical uncertainty ~0.04
    - Systematic uncertainty ~0.02



Top Quark Spin Correlations

- Top quark spin correlations at production
  - Reveal nature of the production mechanism
    - SM predicts s-channel gg fusion will dominate
    - At threshold, forces top quarks to be anti-aligned
      - At least in “beam-line” basis
- Strategy is to use top quark decay products as spin analyzers
  - Measure the correlations and compare with expectations
  - Use angle of decay lepton (θ_i) with respect to parent top
    - In t-tbar rest frame

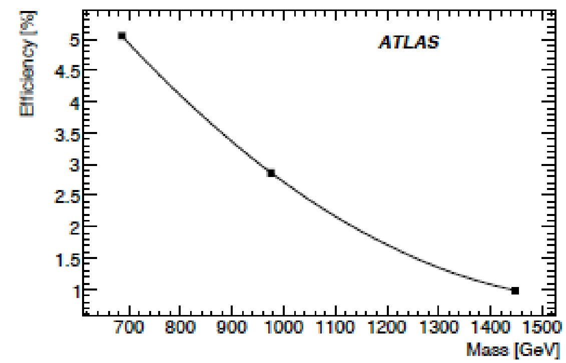


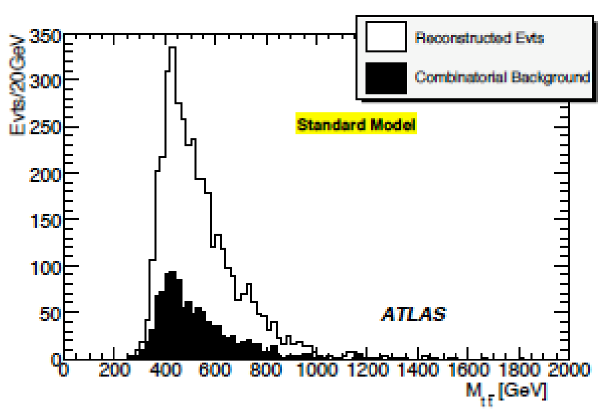
$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A|\alpha_1\alpha_2|\cos\theta_1\cos\theta_2)$$

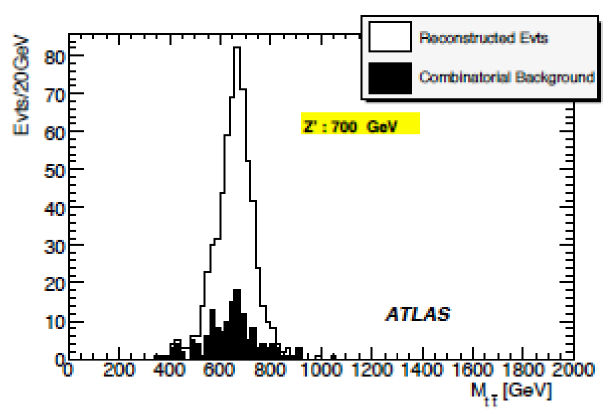
- Have to measure analyzing power with MC
  - Can measure A with 1 fb^{-1}
    - Statistical uncertainty of ~0.2
    - Systematics are less well-understood (0.2-0.3?)
  - Remains a challenge

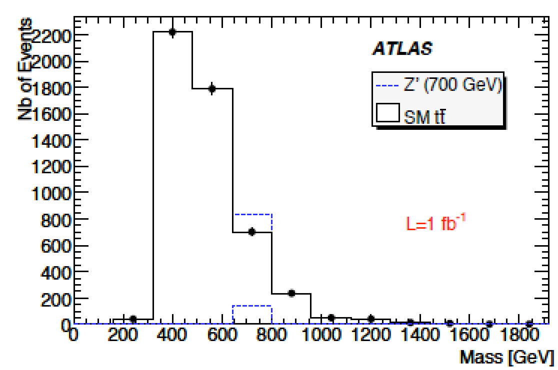
Top Pair Resonances

- Top quark pairs unique probe to search for high mass objects
  - Many BSM interactions couple preferentially to t-tbar
  - Expect to see effects at high M_{tt}
- Default approach: use standard event selection
  - Look for excess of events
- Works till $M_{tt} \sim 0.75\text{-}1\ \mathrm{TeV/c^2}$
  - Suffer from jet "merging"
    - Efficiency for Z'→t-tbar drops precipitously





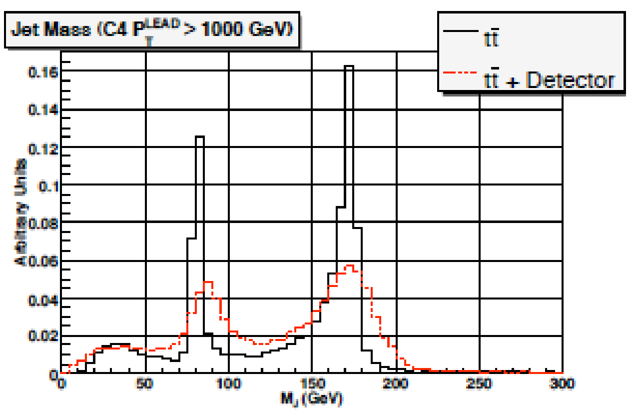




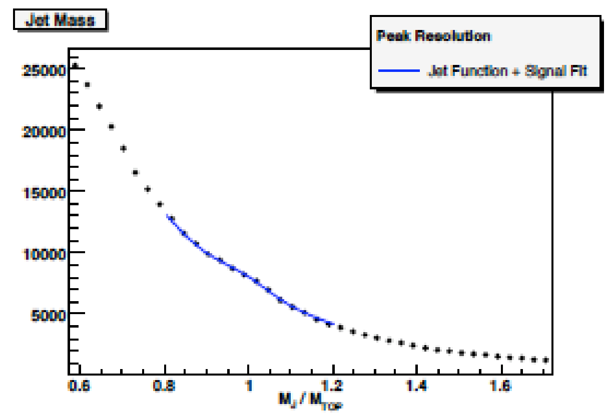
High Mass Top Pairs

- **Much recent work to understand high mass top system**
  - **"top jets" become interesting**
  - **But significant challenges**
    - Lose lepton ID
      - **QCD backgrounds explode**
    - Mass reconstruction strategy changes
- **Example is shown below**
  - **Using R=0.4 cone jet algorithm**

L.G.Almeida et al., Phys.Rev. D79, 074012,(2009)

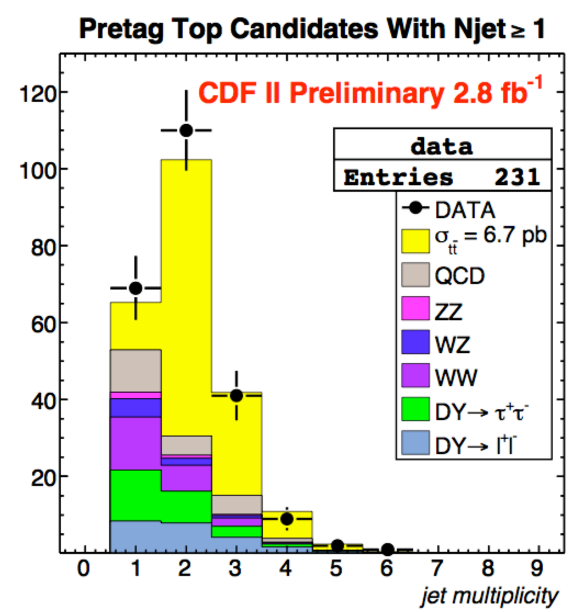


- **Challenge is understanding QCD background**
  - **Signal (P_T>1 TeV/c) ~ 100 fb**
  - **Background from QCD ~ 10 pb**
- **Looking at jet shape variables**
  - **Very early days in strategy development**
  - **Clearly a high-statistics measurement (>20 fb^{-1}?)**



What We Don’t Know (But Should)

- **Sense of “certainty” around top quarks perhaps misplaced**
  - **Don’t understand experimental conditions well**
    - Effects of pileup will be a challenge
    - ISR/FSR models aren’t very predictive
  - **Underlying physics is uncertain**
    - What really causes mass?
    - What are the top quark’s couplings?
    - How does the t-tbar system get produced?
- **Not going to get answers to these until we have real data**
  - **One example: extra jet production**
    - Look at dilepton events at Tevatron
    - See lots of extra jets!



CDF Public Note 9647 (2008)

Summary

- **Hope this has given you a flavour of top quark physics at the LHC**
  - **High statistics provides a unique environment for top studies**
    - Trade off between analyzing power and systematic effects
  - **Environment is still challenging**
    - Backgrounds are large
    - High luminosity environment
- **Can do much with restrictive selections**
  - **However, somewhat "brute force"**
  - **Analyses will require greater sophistication than studies to date**
- **Data is now essential**
  - **Allow us to prepare for next decade of top quark physics**