Top Physics at CDF

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XVIII Rencontres de Physique de La Vallee d'Aoste
La Thuile
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Motivations for Studying Top

- Only known fermion with a mass at the natural electroweak scale
  - Window into the problem of EWSB?
- New physics may appear in production (e.g. topcolor) or in decay (e.g. charged Higgs).

Run I Top Studies

- Observed in 1995 in first ~70 pb^{-1} of Run I data.
- Final Run I top analyses based on ~110 pb^{-1}.
  - Production cross sections in many channels
  - Mass: 174.3 $\pm$ 5.1 GeV (CDF/DØ combined)
  - Event kinematics
  - W helicity, limits on single top production..

- overall consistency with the Standard Model.
- but only ~100 top candidates

  $\rightarrow$ analyses statistics-limited.

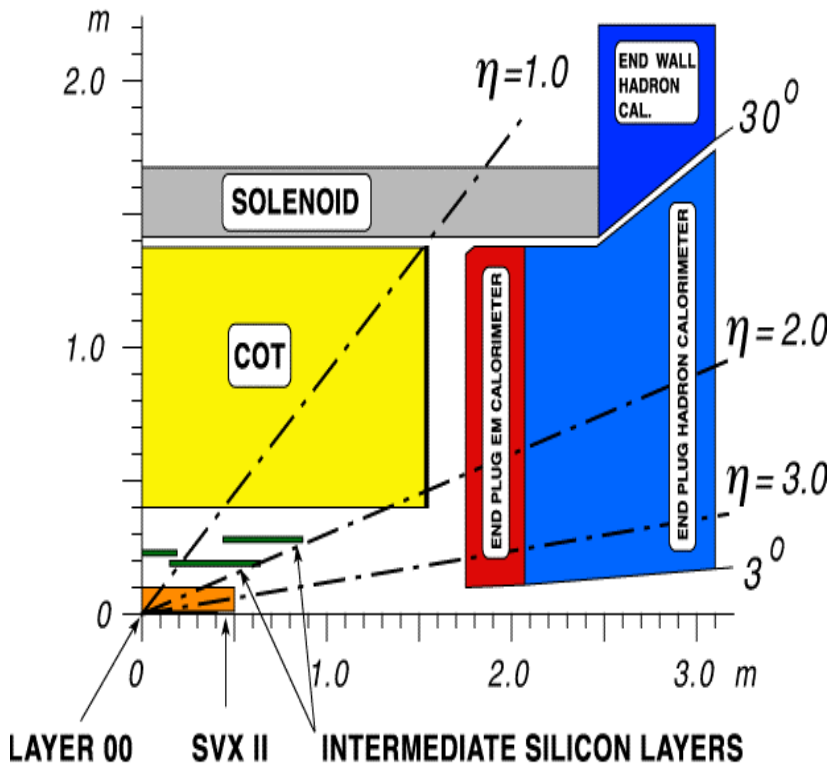
Improvements for Run II

- Accelerator:

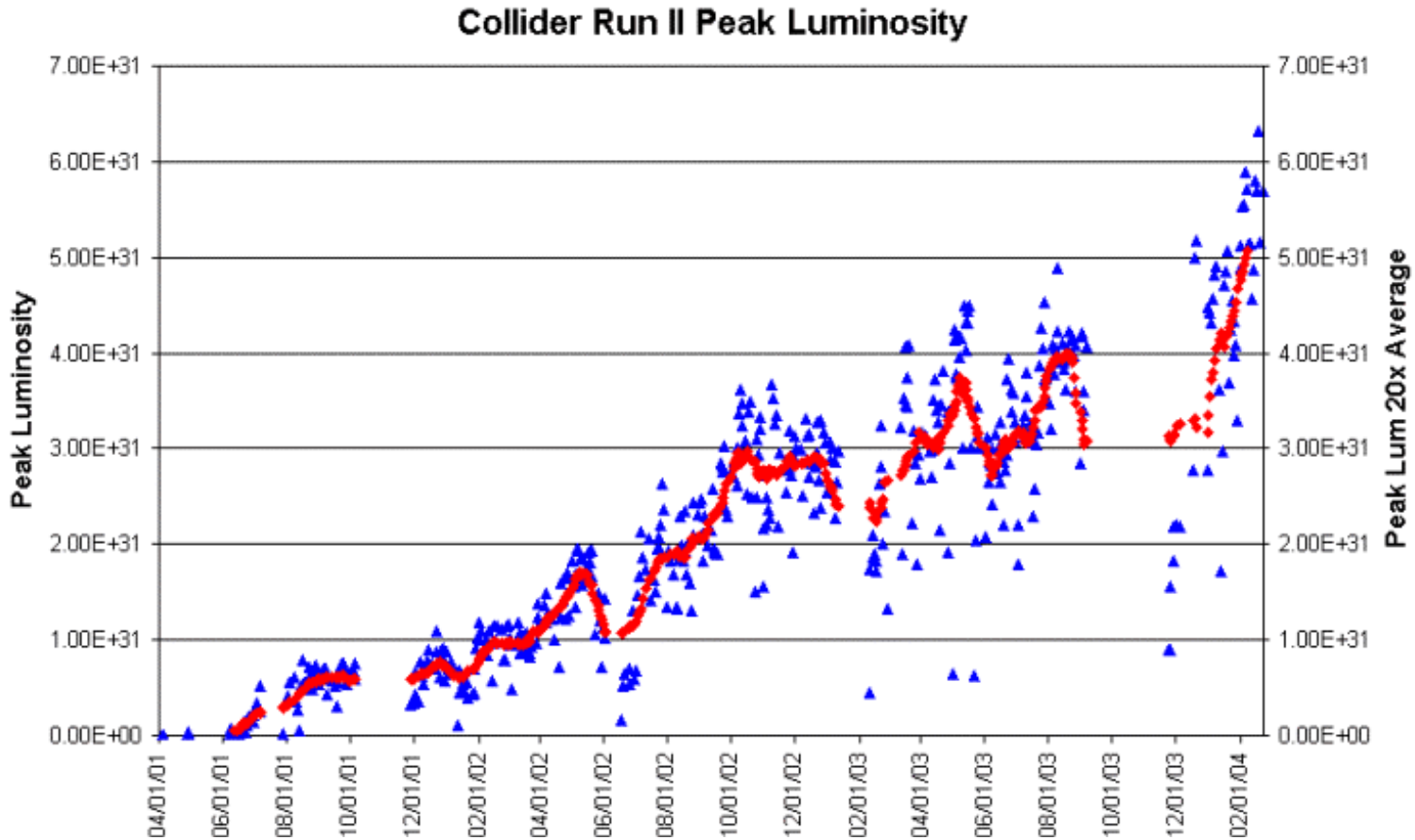
  sqrt(s) = 1.96 TeV (was 1.8 TeV in RunI)

  ->30-40% increase in top cross section

- CDF Detector:
  - -New DAQ
  - -New Silicon system
    - ->improved b-tagging
  - -Extended muon systems
  - -Calorimeter endplug for forward coverage
  - -New central drift chamber



Tevatron Peak Luminosity

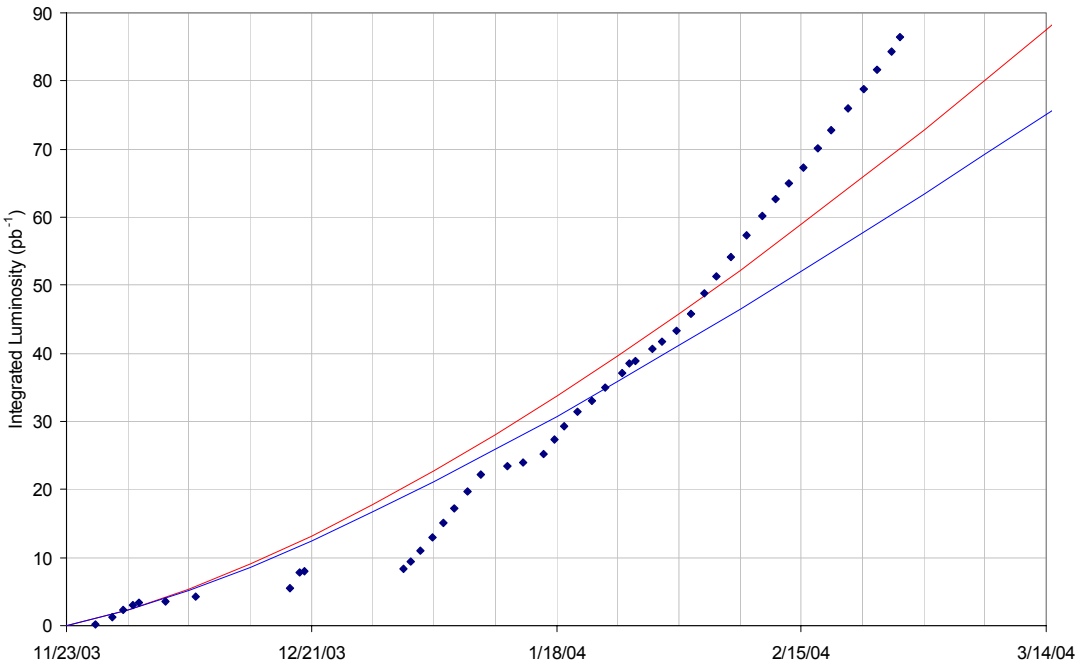


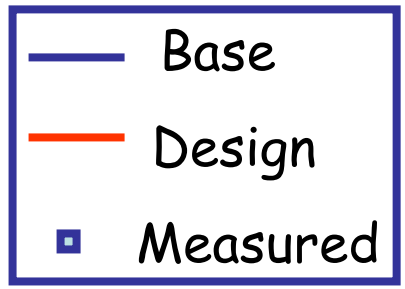
Record Luminosity: 6.3×10^{31} (3x better than Run I)

First store w/antiprotons from recycler

Current to tape: $350 pb^{-1}$, for this talk: up to $200 pb^{-1}$

Tevatron Luminosity





Integrated Luminosity (fb^{-1})				
	Design Projection		Base Projection	
	per year	Accum-ulated	per year	Accum-ulated
FY03	0.22	0.30	0.20	0.28
FY04	0.38	0.68	0.31	0.59
FY05	0.67	1.36	0.39	0.98
FY06	0.89	2.24	0.50	1.48
FY07	1.53	3.78	0.63	2.11
FY08	2.37	6.15	1.14	3.25
FY09	2.42	8.57	1.16	4.41

Predicted for 2004: 380 pb^{-1} delivered (design)

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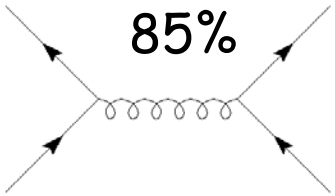
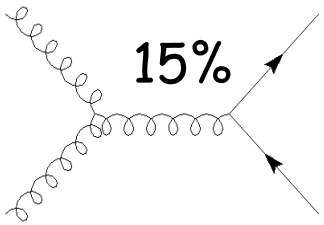
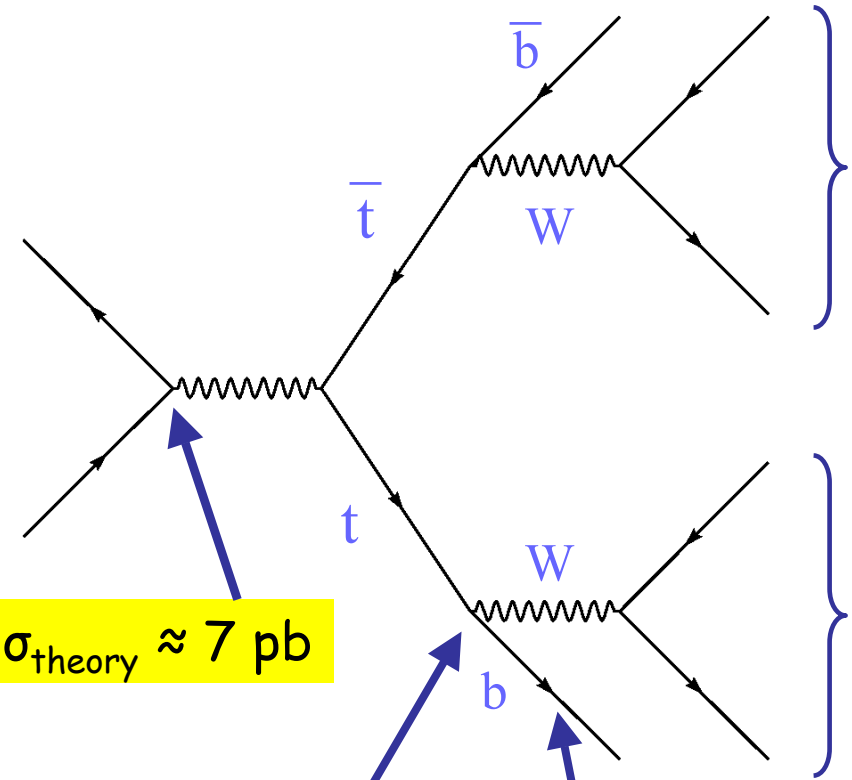
Pair-production and Decay Basics

Pair Production:





NB: qq, gg fractions reversed at LHC



$\sigma_{theory} \approx 7$ pb

BR($t \rightarrow Wb$) ≈ 100%

Event topology determined by the decay modes of the W's

b-jet: identify via secondary vertex or soft lepton tag

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t-tbar Final States

- **Dilepton**
  - BR = 11%
  - 2 high-P_T leptons + 2 b-jets + missing-E_T
- **Lepton + jets**
  - BR = 44%
  - single lepton + 4 jets(2 b-jets) + missing-E_T

Highest signal:noise

High pt decay products

Central/spherical topology

- **All-hadronic**
  - BR = 45%
  - six jets, no missing-E_T

More challenging backgrounds (QCD multijet)

- **Tools:**
  - Lepton ID (tracking, detector coverage)
  - Calorimetry (calibration)
  - B identification (tagging)
  - Simulation

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Programme:

- Top cross-section
  - dilepton channel **New results**
  - Lepton+jets channel **New results**
- Single top physics **New results**
- Top Mass
- W helicity in top decay

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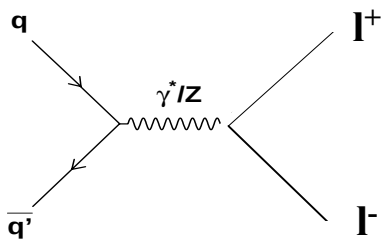
Measuring the ttbar Cross Section

- starting point for all top physics
- Requires detailed understanding of backgrounds and selection efficiencies.
- Test of QCD
  - Latest calculations: NNLO + NNNLL
  - Departures from prediction could indicate nonstandard production mechanisms, i.e. production through decays of SUSY states.

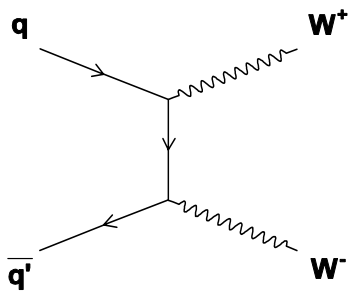
Dilepton Cross Section: lepton+track

- Signature: 1 lepton+1 isolated track, missing E_t, $\geq$ 2 central jets
- Acceptance: ~2x better than Run I
- ~20% from τ
- Background:

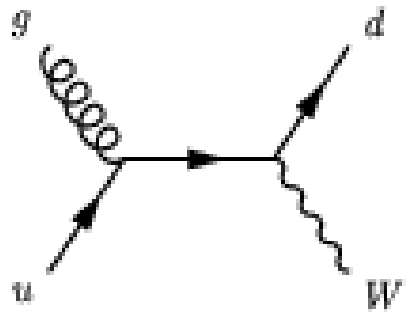
Drell-Yan



WW, ZZ, WZ



W+jets ("fakes")

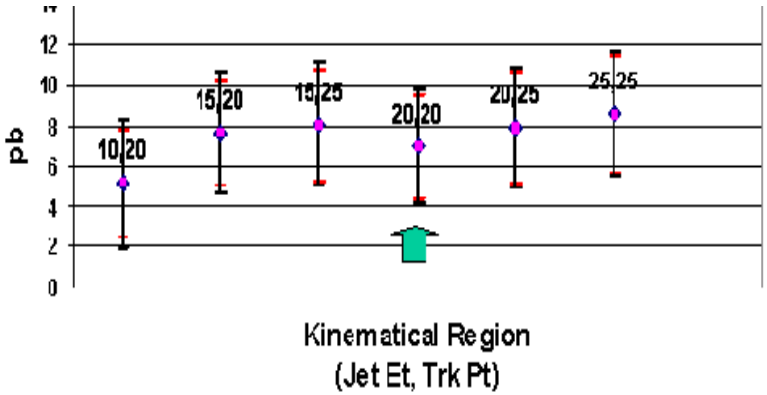


Relative weight depends on number of jets

Dilepton Cross Section: lepton+track

	njet = 0		njet = 1		njet >= 2	
	#	error	#	error	#	error
top-dilep	0.29	0.04	3.38	0.13	11.53	0.24
Di boson	24.12	0.56	6.89	0.31	1.32	0.14
DY	26.78	5.66	16.59	3.42	4.25	1.00
Total Pbg	50.90	5.69	23.48	3.44	5.57	1.01
Fakes	13.78	1.57	4.16	0.49	1.48	0.19
Total bg	64.68	5.90	27.64	3.47	7.06	1.02
Total pred.	64.97	5.90	31.02	3.47	18.59	1.05
observed	73		26		19	

Measured cross section for different jet E_t and track p_t thresholds



New result

$$\sigma_{tt} = 6.9^{+2.7}_{-2.4}(stat) \pm 1.2(syst) \pm 0.4(lumi)\, pb$$

New results

Dilepton cross section: ee, eμ, μμ

Different background composition, higher S:N, lower acceptance

⇨ Events with 1 "tight" and 1 "loose" e or μ

$$\sigma_{t\bar{t}} = 8.7^{+3.9}_{-2.6}(stat) \pm 1.4(syst) \pm 0.5(lumi)\ pb$$

lepton composition: 1 ee, 3 μμ, 9 eμ

⇨ 2 "tight" leptons (e, μ)

$$\sigma_{tt} = 8.1^{+4.4}_{-3.4}(stat) \pm 1.6(syst) \pm 0.5(lumi)\ pb$$

lepton composition: 1 ee, 2 μμ, 4 eμ

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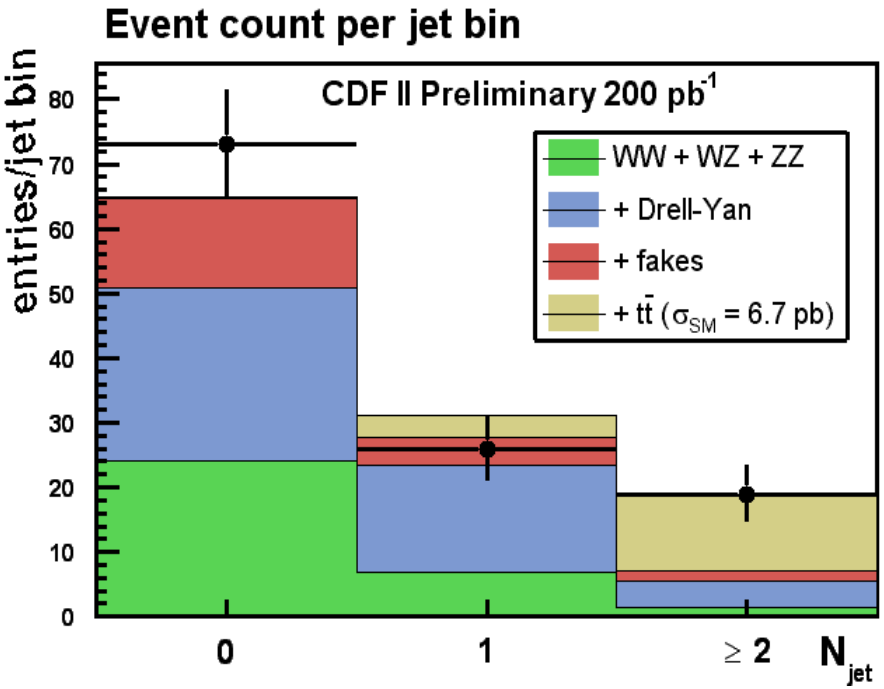
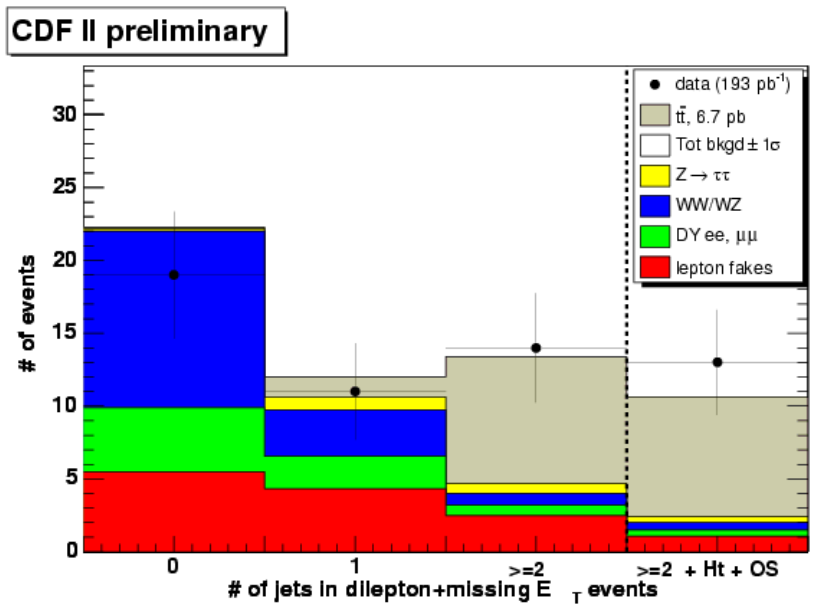
Jet Multiplicity in Dilepton Events

Lepton + track:



ee, eμ, μμ:



ttbar signal bin

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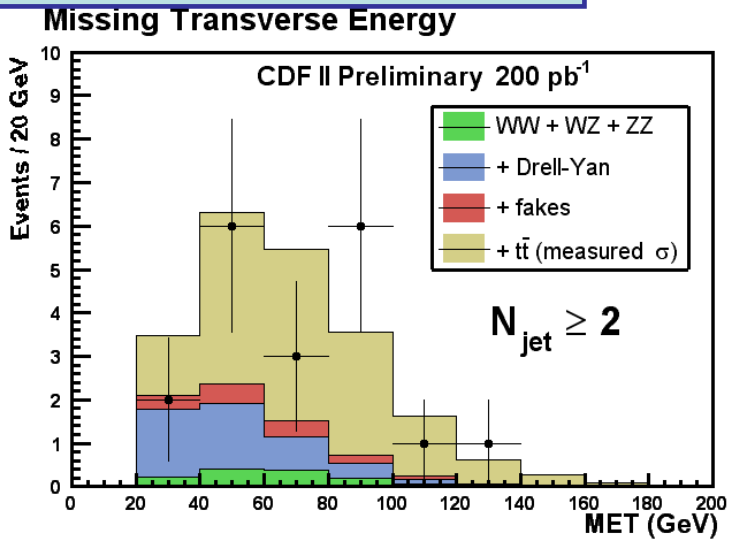
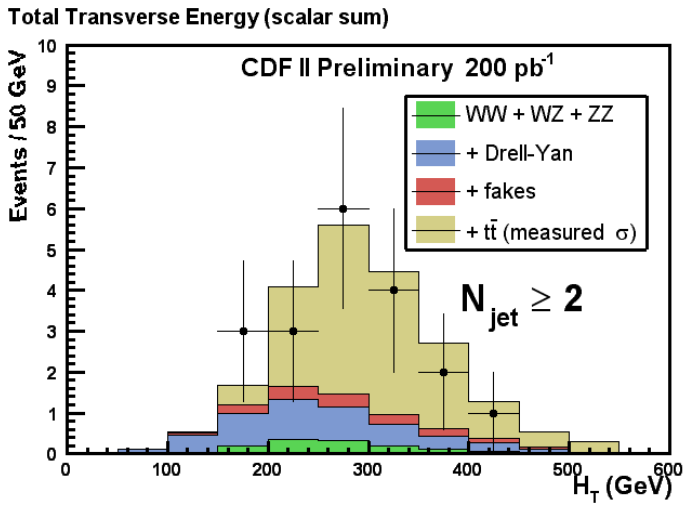
Dilepton Kinematics

RunI: had seen hints of discrepancy in kinematic distribution:

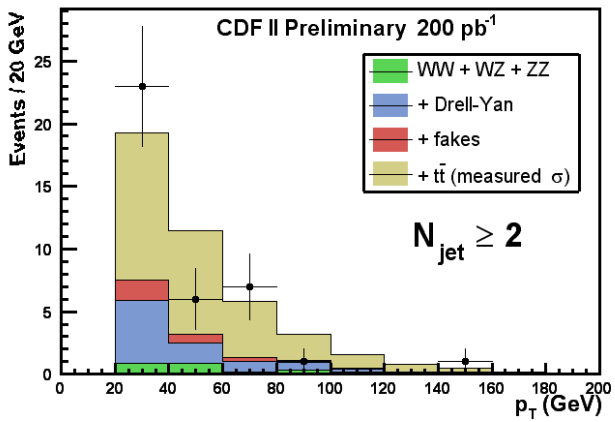
Missing E_T



H_t:Scalar summed E_T of jets, leptons, and missing E_T



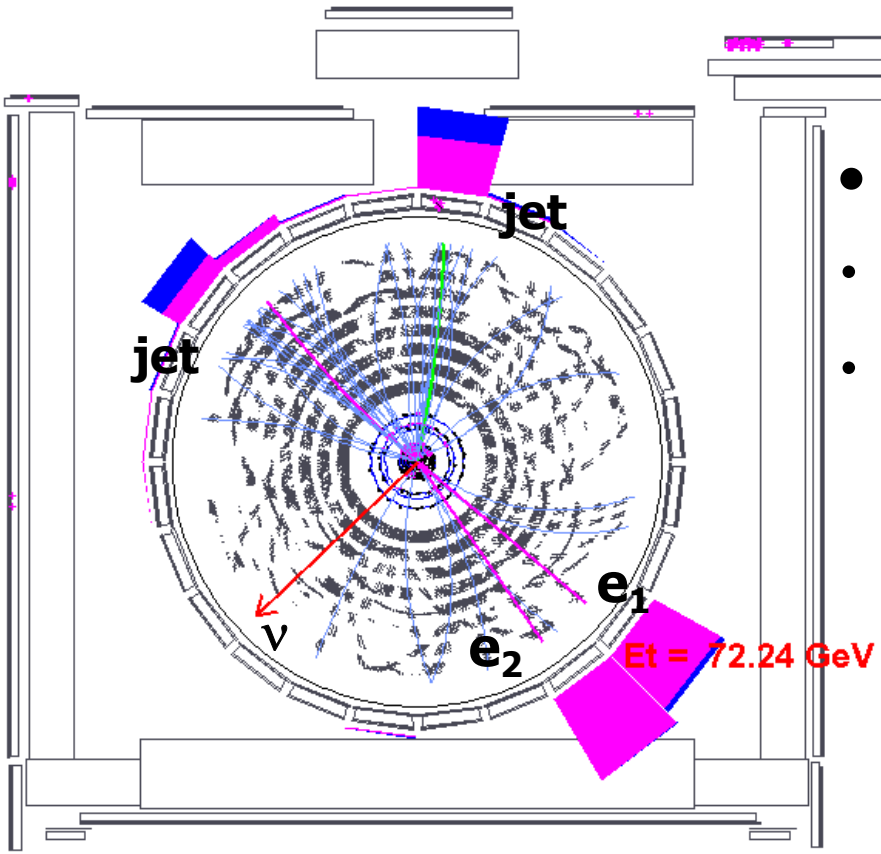
Leptons transverse momentum



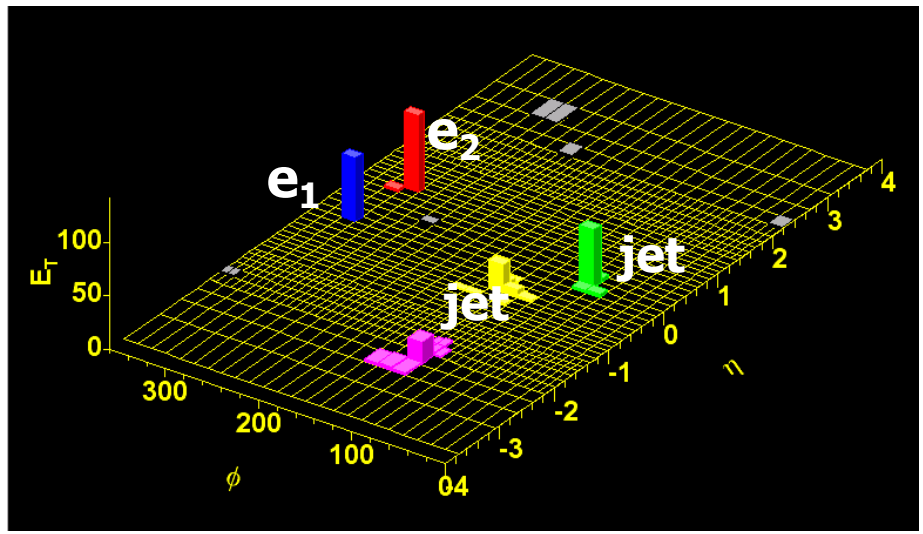
With higher statistics in Run II

see good agreement with SM

Dilepton event display



- 2 electrons (E_{T1}=73 GeV, P_{T2}=63 GeV)
- Missing E_T = 59 GeV
- 2 central jets + 1 forward jet



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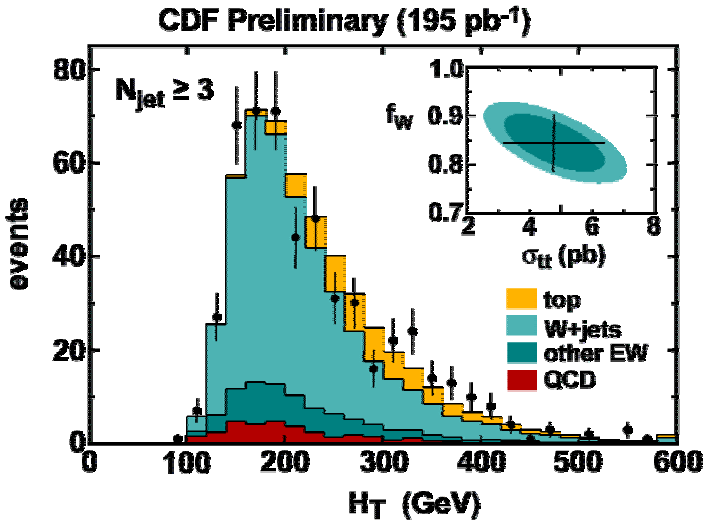
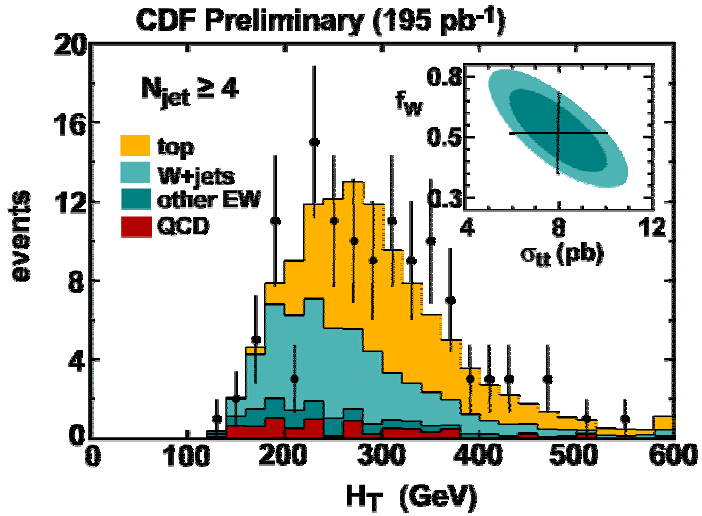
New results

Cross Section – lepton+jets using kinematic fits

Isolate signal from large W+jets background using **kinematic shapes: H_t (scalar sum of energy in the event)**





W+>=3 jets: observe 519 events

Top fraction from fit: 0.13+-0.04

$$\sigma_{tt} = 4.7 \pm 1.6(stat) \pm 1.8(syst)\, pb$$

Largest systematic: jet energy scale

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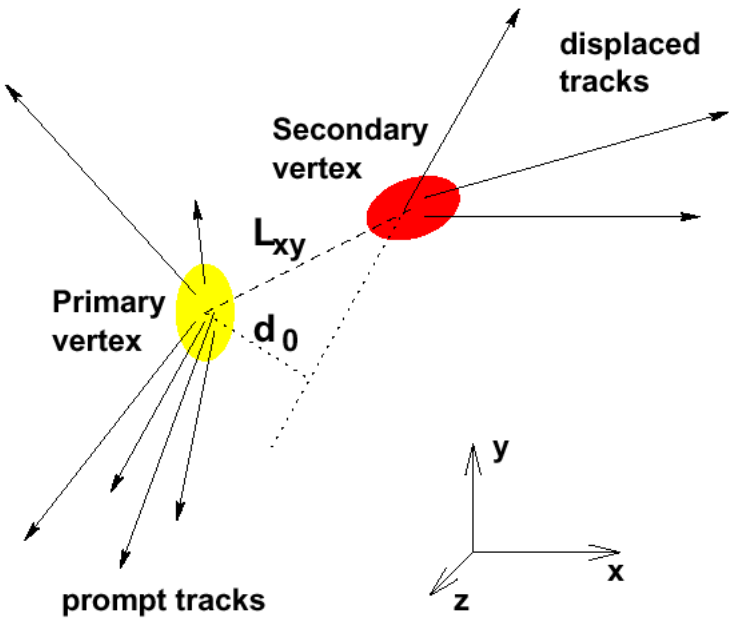
Tagging high-p_t jets: Silicon vertex tag (SVX-tag)



- Signature of a B decay is a displaced vertex:
  - Long lifetime of B hadrons ($c\tau$ ~ 450 μm)+ boost
  - B hadrons travel L_{xy}~3mm before decay with large charged track multiplicity

Top event efficiency: 55%

False tag rate (QCD jets): 0.5%

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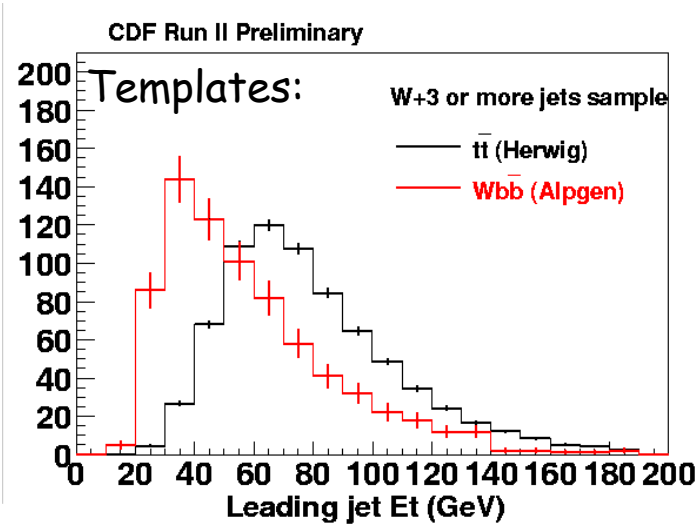
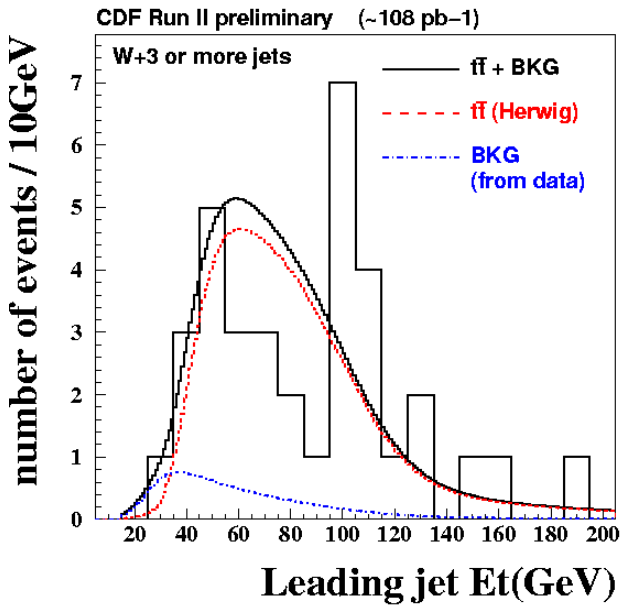
Cross Section – lepton+jets using kinematic fits + SVX-tag

In addition to shape information: require at least one b-tag





W+>=3 jets: observe 35 events

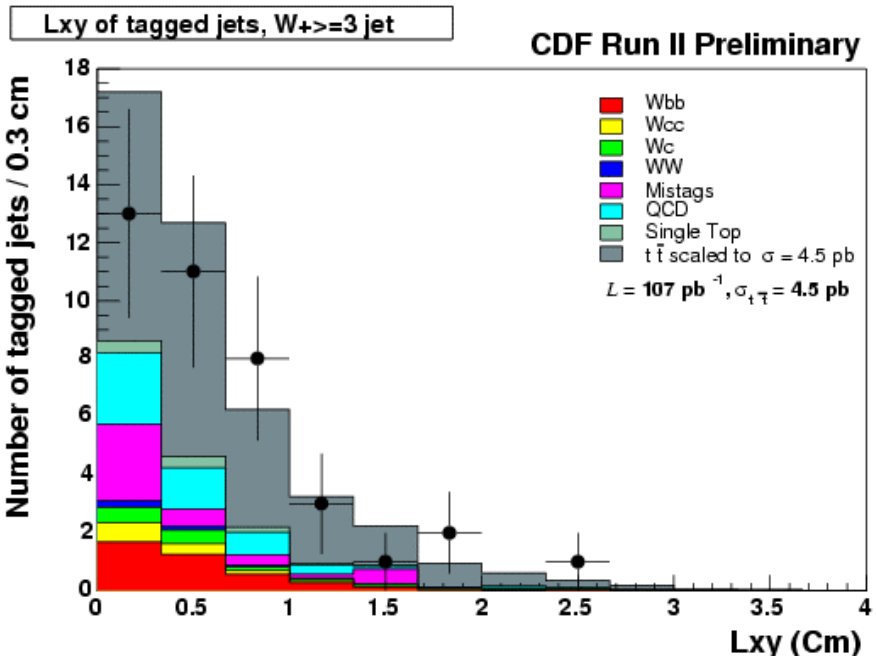
Top fraction from fit: $0.88^{+1.0}_{-1.6}$

Using 108 pb^{-1}

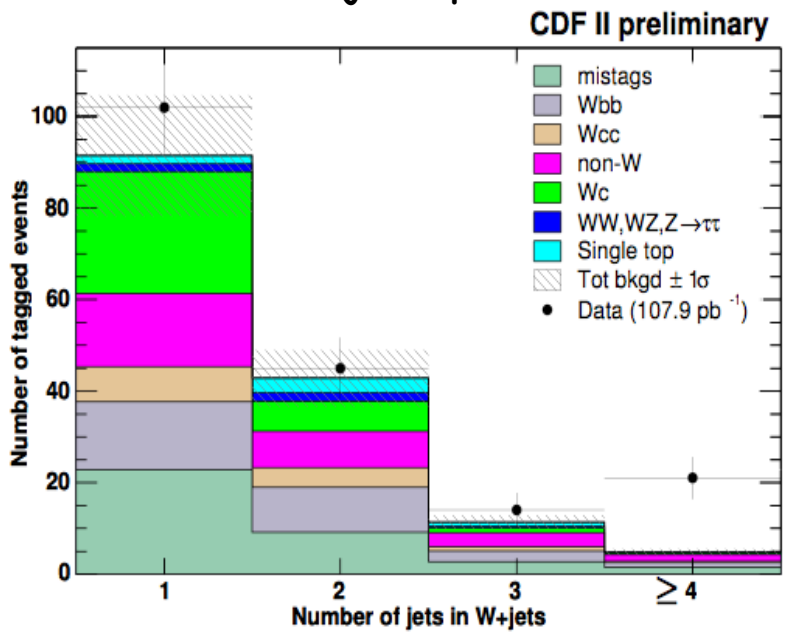
$$\sigma_{tt} = 6.9^{+1.6}_{-1.9}(stat + fit) \pm 0.9(syst)\,pb$$

Cross Section – lepton+jets using SVX-tag

2d displacement of tagged jets:



Number of jets per event:



W+>=3 jets: 35 positive tags

Expected background (mistags, QCD,..): 15.1+-2

Using 107 pb^{-1}

$$\sigma_{tt} = 4.5^{+1.4}_{-1.3}(stat) \pm 0.8(syst)\,pb$$

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New results

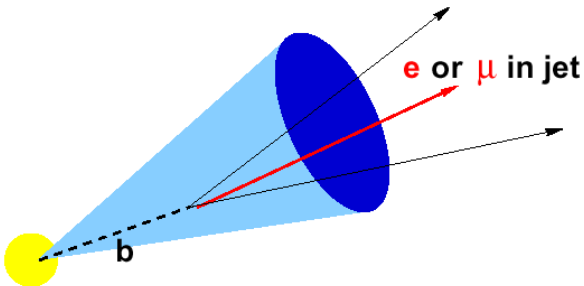
Cross Section – lepton+jets using "Soft Lepton Tag"

tag semi-leptonic decays of B

⇒ leptons have a softer p_T spectrum than W/Z leptons

⇒ They are less isolated

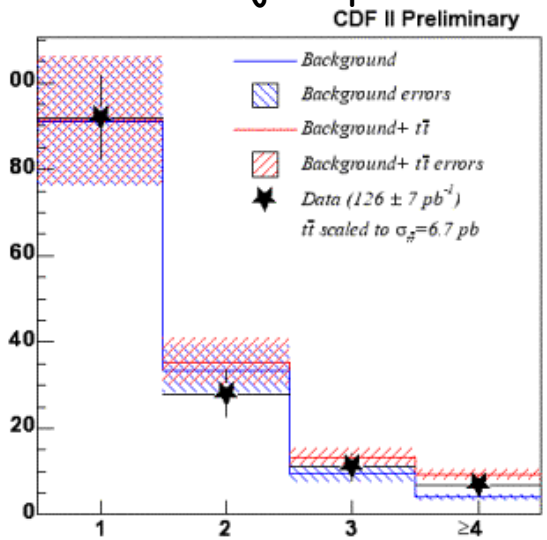
⇒ Identify low-p_t muon



Top Event (>2 jets)
Tag Efficiency:15%
False Tag Rate
(QCD jets): 3.6%

- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

Number of jets per event:



Using 125 pb^{-1}

$$\sigma_{tt} = 4.1^{+4.0}_{-2.8}(stat) \pm 1.9(syst)\,pb$$

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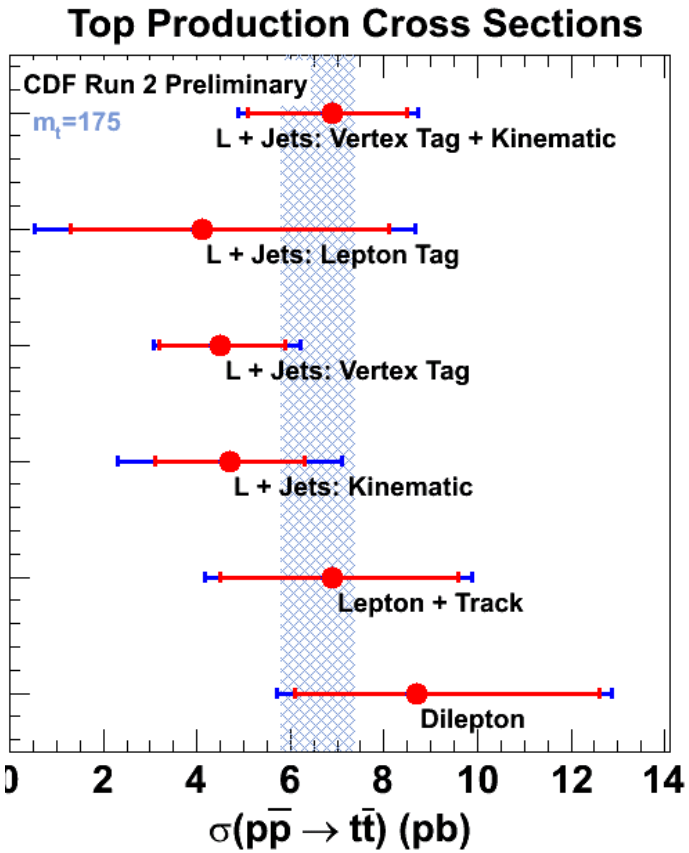
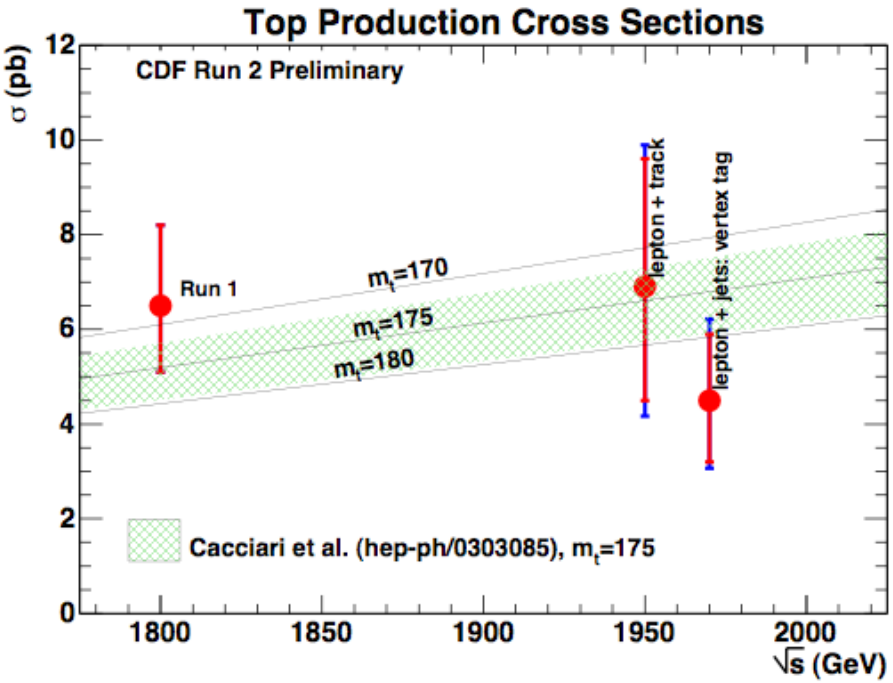
Summary of Cross Section Results



√s-Dependence:



⇒Main data driven systematics (jet energy scale, ISR, ε_{btag}) scale with $1/\sqrt{N}$

RunII($2fb^{-1}$) $\delta\sigma_{tt}/\sigma_{tt}$ <10%

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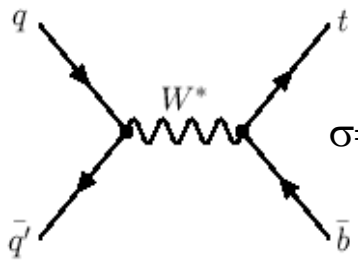
Single Top Physics

- Probe top EW coupling
  direct determination of V_{tb}
- Sensitivity to new physics:
  t-channel:anomalous couplings, FCNC
  s-channel: new charged gauge bosons

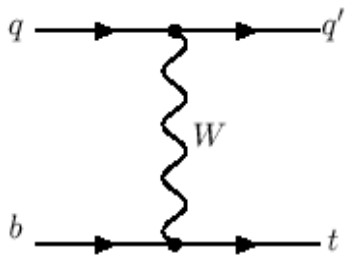
- Strategy:
  Isolate W+ exactly 2 jets and tag one jet
  Likelihood Fit to Q*η (t-channel)
  Likelihood Fit to H_t (combined)

s-channel



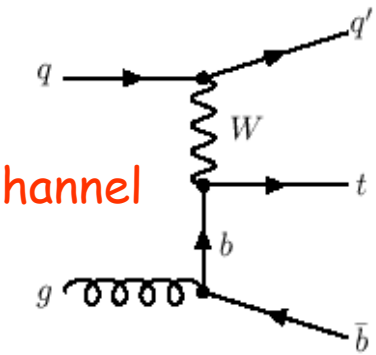
(a)

$\sigma = 0.88 \pm 0.11$ pb



(b)

t-channel



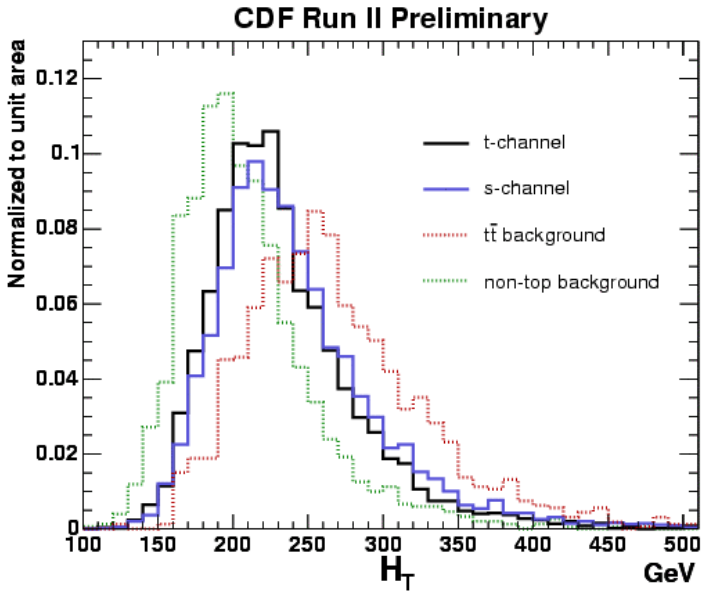
$\sigma = 1.98 \pm 0.24$ pb

B.W.Harris et al

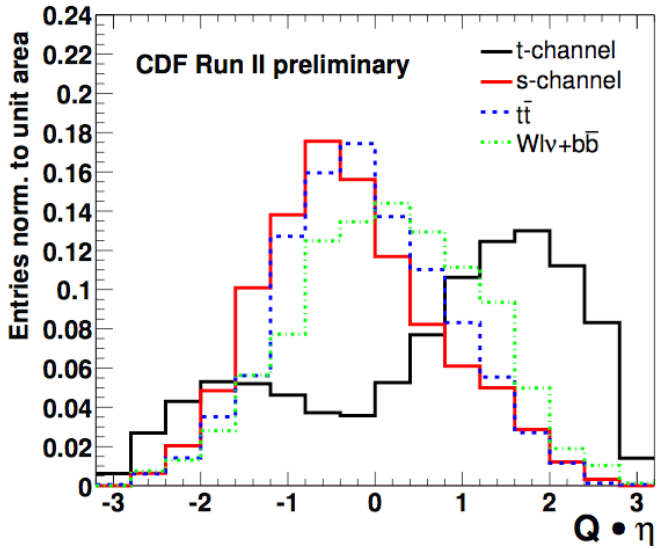
Q: charge of lepton, η pseudorap of forward jet

Single Top Physics

Templates from MC (combined):



t-channel:

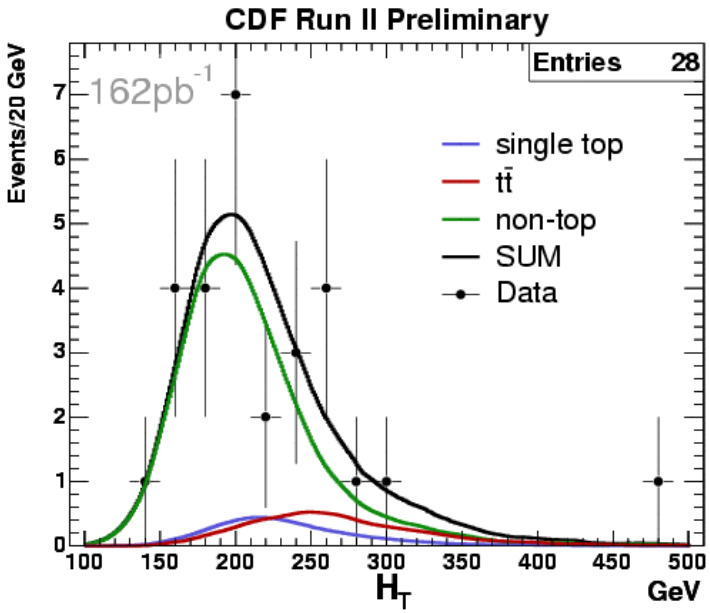


Process	N events	
	Combined Search	t-channel search
t-channel	2.39 +- 0.56	2.34 +- 0.54
s-channel	1.19 +- 0.25	1.16 +- 0.24
t tbar	3.47 +- 1.04	3.39 +- 1.02
non-top	20.7 +- 4.1	17.4 +- 3.3
Sum	**27.8 +- 4.3**	**24.3 +- 3.5**

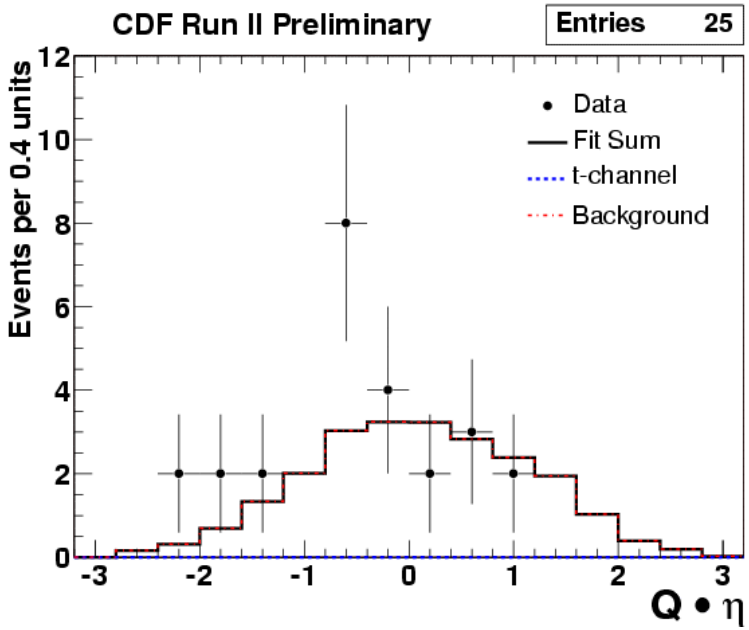
New results

Search for Single Top

Fit to the data (combined search):



t-channel search:



Using 162 pb^{-1} of data:

σ_t(t-channel)<8.5pb @95% C.L.

σ_t(combined)<13.7pb @95% C.L.

Uncertainty	2fb^{-1}
$\delta\sigma$(tbX)	26%
$\delta\Gamma(t\rightarrow Wb)$	28%
$\delta\|V_{tb}\|$	14%

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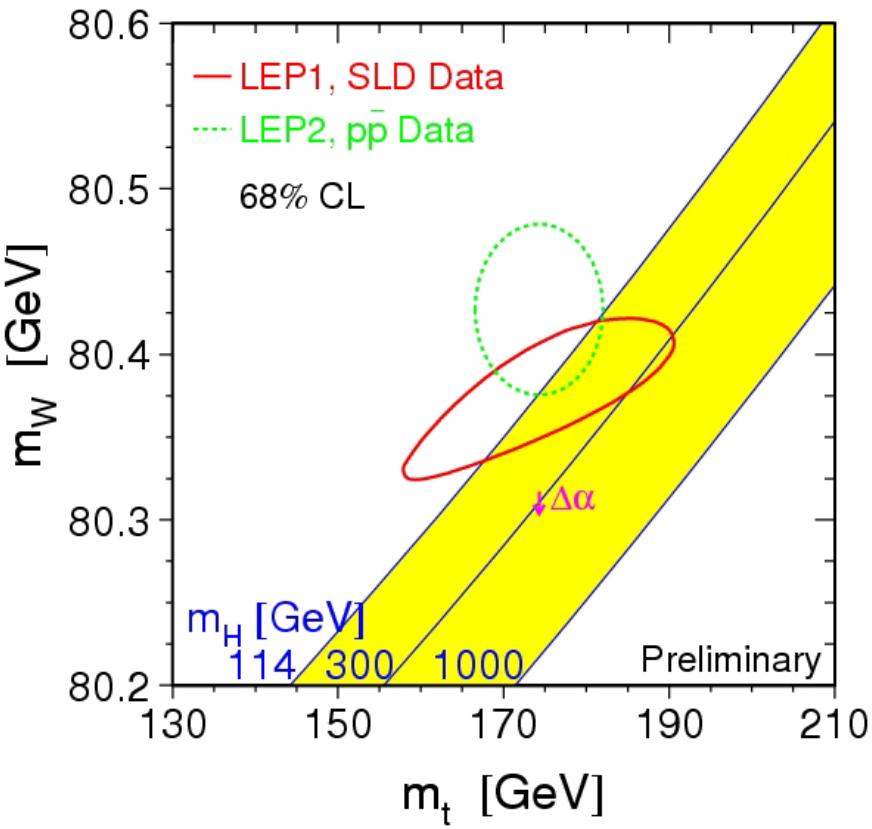
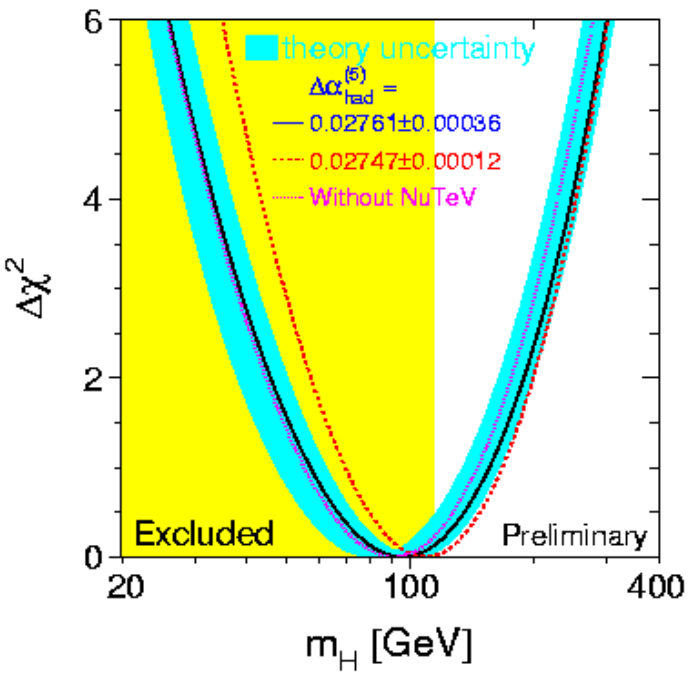
Top Mass Measurement

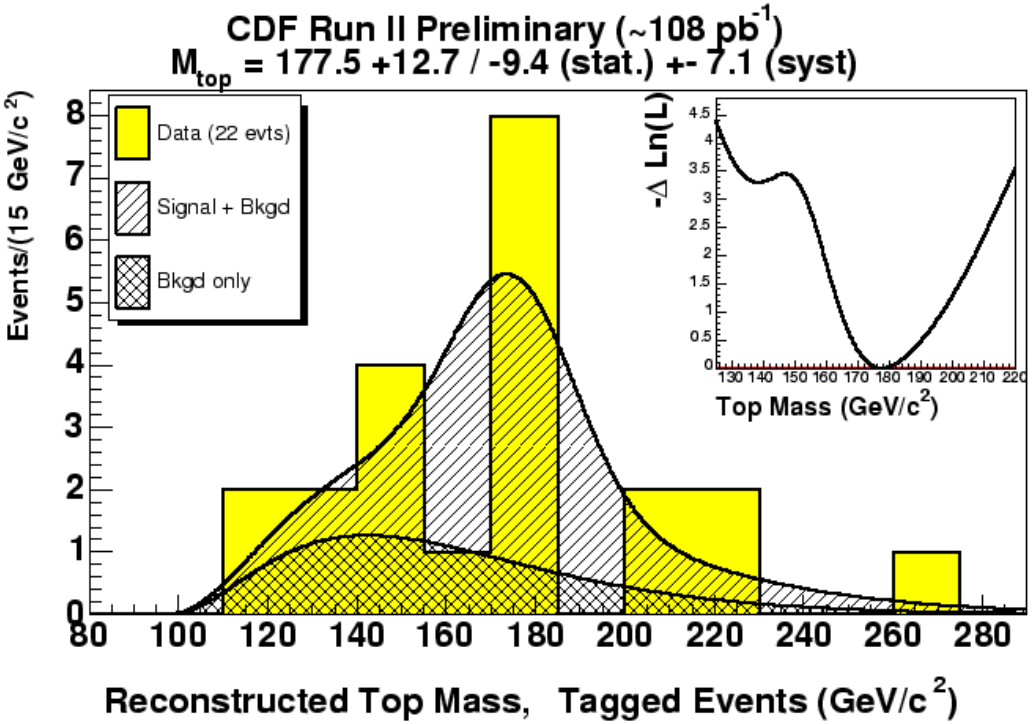
M_{top} is a precision electroweak parameter that helps constrain the mass of the Higgs.





Top Mass: Lepton + 4 jets with SVX-tag

22 vertex-tagged events from lepton+4 jet sample



- -6 parton/jet matching assignments possible
- -test for consistency with top using kinematic constraints
- -pick lowest χ^2
- -fit resulting mass distribution to background + signal templates at different values of M_{top}

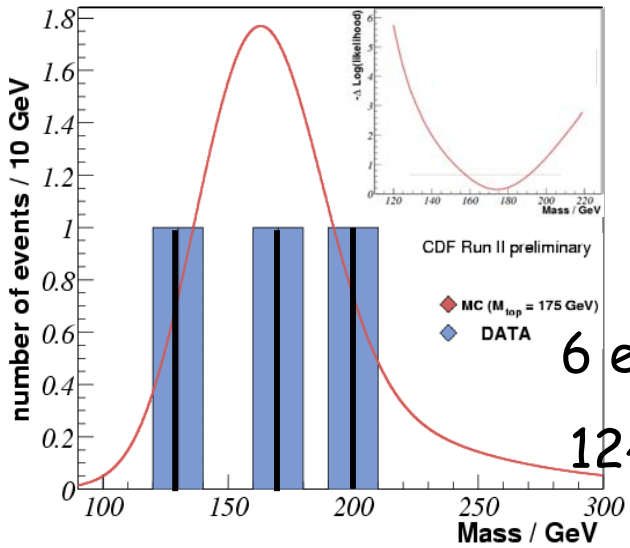
Likelihood fit result: $m_{top} = 177.5\ ^{+12.7}_{-9.4}(\text{stat.}) \pm 7.1(\text{syst.})$ GeV/c^2

Dominant syst: jet energy scale, expecting significant impr. soon

Top Mass: Dilepton Channel

- Underconstrained system
- Use $P_{ttbar,z}$ to weight the mass fit distribution
- Likelihood fit to top mass templates

$$175.0^{+17.4}_{-16.9}(\text{stat}) \pm 7.9(\text{syst})\ \text{GeV}/c^2$$



6 events

124 pb^{-1}

Improved tools are underway:

- "Dynamic Likelihood" method (matrix element convoluted likelihood) K.Kondo 1988 J.Phys.Soc.57 4126
- results expected soon

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W Helicity Measurement

- Top decays before it can hadronize, because width Γ_t = 1.4 GeV > Λ_{QCD}.
  - Decay products preserve information about the underlying Lagrangian.
  - Unique opportunity to study the weak interactions of a bare quark, with a mass at the natural electroweak scale!
- SM Prediction:
  - W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex.
  - W helicity reflected in kinematics: W lepton pt,…

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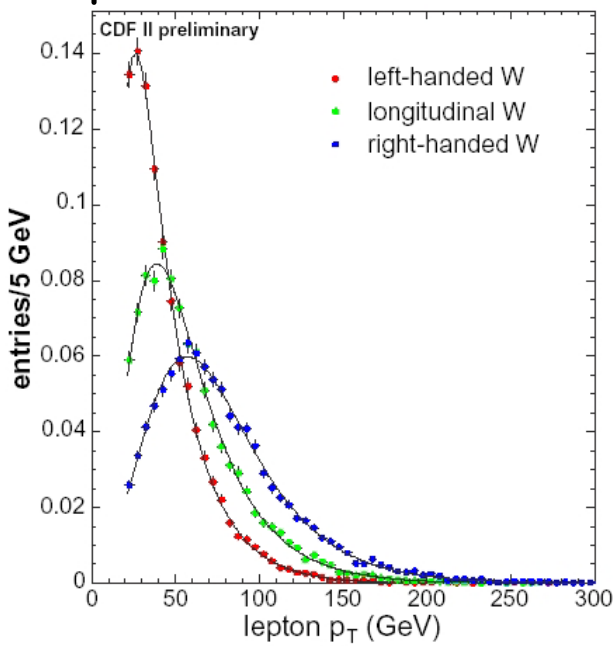
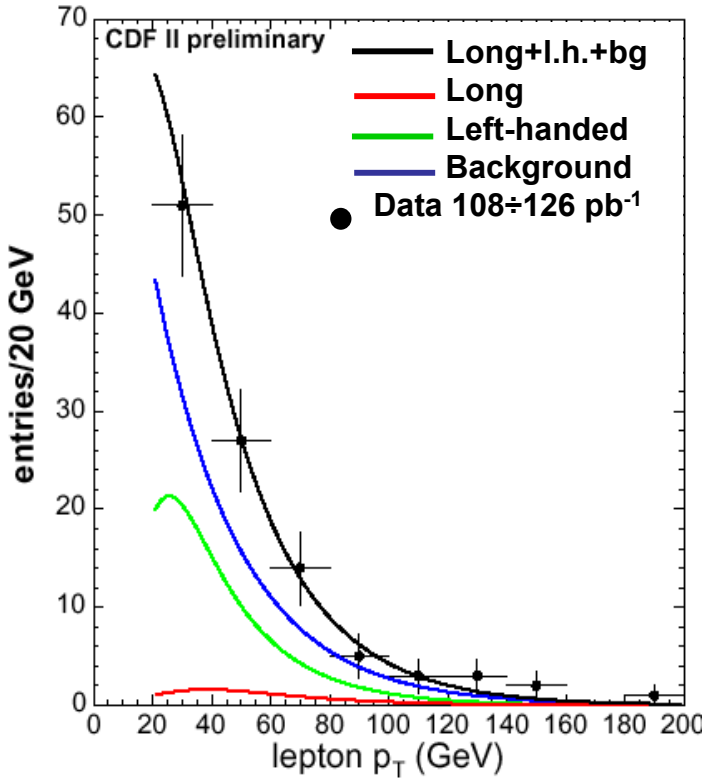
Helicity affects lepton P_T in lab frame

Templates from MC:





SM V-A predicts W helicity:

F_0 = 70% longitudinal
F_- = 30% left-handed

[V+A: 70% long., 30% r.-h.]

CDFI Result (106pb^{-1}):
$F_0 = 0.91 \pm 0.37 \pm 0.13$
$F_+ < 0.28$ @ 95% C.L.

CDFII result soon

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Conclusion and Outlook

Now using 2x the RunI data set

- Improving measurements of cross section, mass
- W helicity, single top… are making progress.
- We expect ~50x more data compared to Run I!
- What's ahead: top $\rightarrow H^+$

  Study of τ channels

  measure V_{tb}

  ttbar resonant production

  rare decays

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Backup Slides

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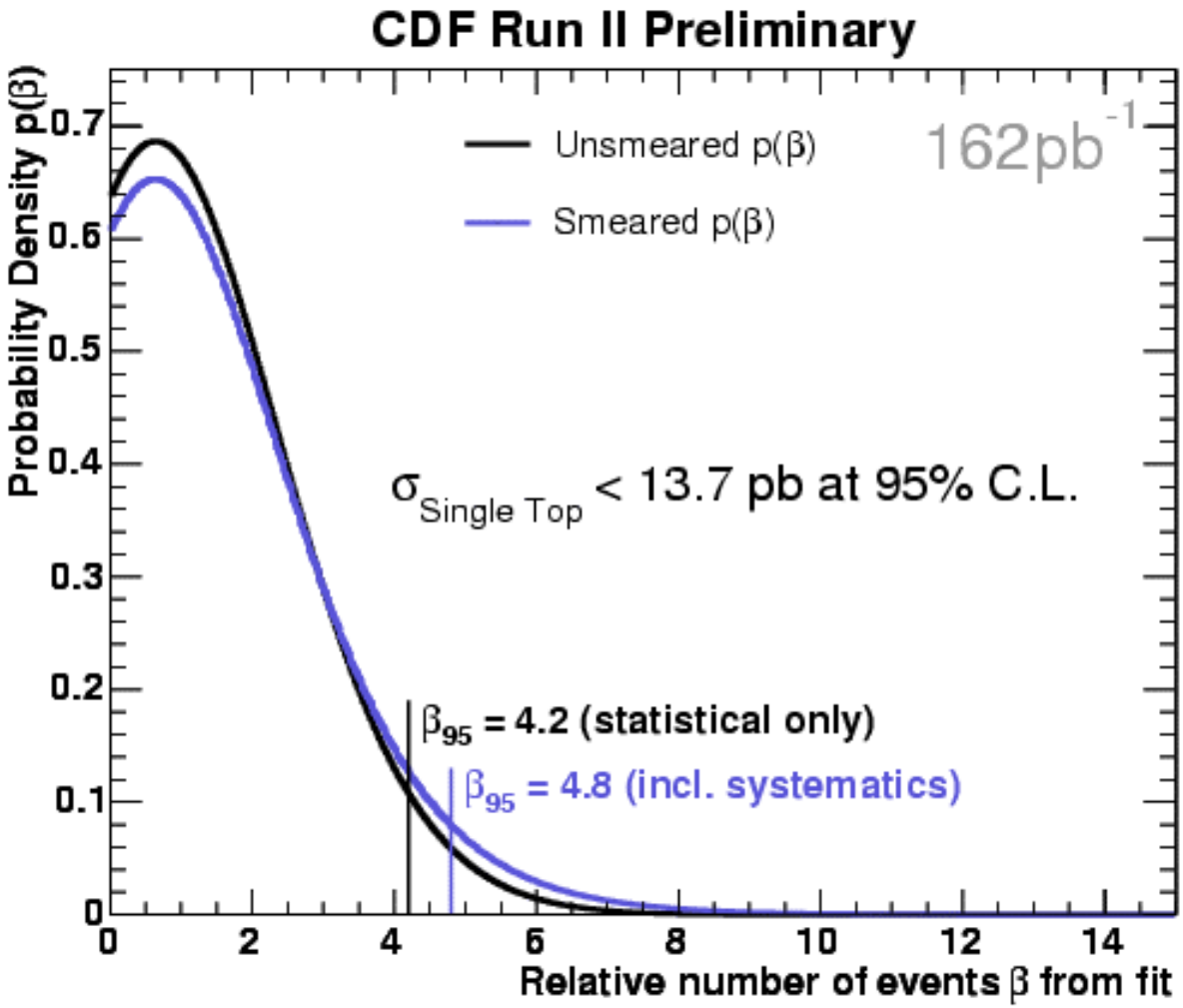

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Matrix Element Method

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

$d^n\sigma$ is the differential cross section

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

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

$$P(x;\alpha) = c_1 P_{ttbar}(x;\alpha) + c_2 P_{background}(x)$$

- Leading-Order ttbar->lepton+jets matrix element, PDFs
- 12 jet permutations, all values of P(ν)
- Phase space of 6-object final state
- Detector resolutions

- Only *W*+jets, 80%
- VECBOS subroutines for *W*+jets
- Same detector resolutions as for signal
- All permutations, all values of P(ν)
- Integration done over the jet energies

- Convolute probability to include all conditions for accepting or rejecting an event

$$P_{measured}(x;\alpha) = Acc(x)P(x;\alpha)$$

- Form a Likelihood as a function of: Top Mass, F_0 (longitudinal fraction of W bosons)

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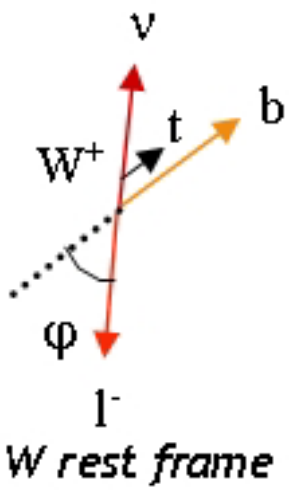
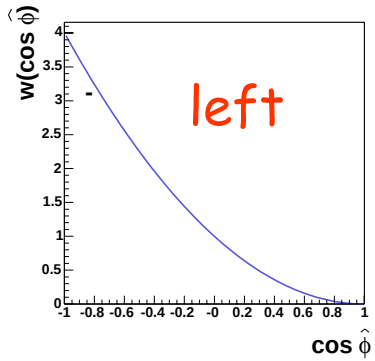
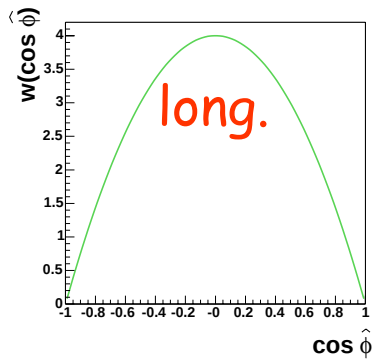
W Helicity Measurement, contd.

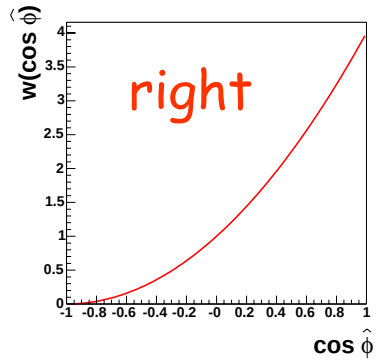
The angular dependence of the semileptonic decay in the W rest frame is given by

$$w(\cos\varphi_{l^-\bar{b}}) = F_- \cdot \frac{3}{8}(1-\cos\varphi_{l^-b})^2 + F_0 \cdot \frac{3}{8}(1-\cos^2\varphi_{l^-b}) + F_+ \cdot \frac{3}{8}(1+\cos\varphi_{l^-b})^2$$









$$F_- = \frac{2\omega}{1+2\omega} \approx 0.3 \qquad F_0 = \frac{1}{1+2\omega} \approx 0.7 \qquad F_+ = 0$$

where $\omega = M_W^2/M_{top}^2$

parameter to measure

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