Top quark physics at CDF

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On behalf of the CDF collaboration

PURDUE
UNIVERSITY

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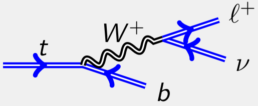
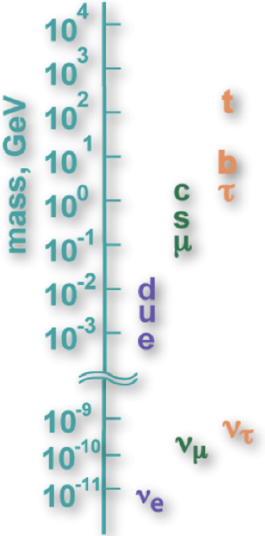
The top quark

What?

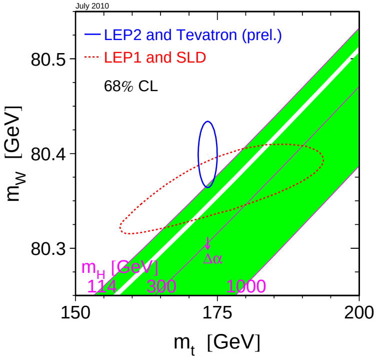
- Discovered in 1995 at Fermilab;
- Mass much larger than any other fermion;
- $L_{\text{Yukawa}} = -\lambda \bar{\psi}_L \Phi \psi_R, \ \lambda = 0.996 \pm 0.006$
  - What is its role in EWSB?
- Only quark that decays before hadronizing:



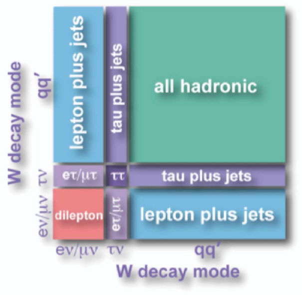


Why is the top quark so important?

- Its mass constrains the Higgs boson mass range;
- But this constraint strongly depends on other top properties
  - e.g. the cross-section;
- The top sector is expected to be sensitive to many new physics processes;



Pair production decay signatures at CDF



- Lepton+Jets
  - Large BR(30%), good S/B ratio
- Dileptonic
  - Highest S/B, but lowest BR(5%)
- All hadronic
  - Highest BR(44%)
  - But very large QCD background
- $\not{E}_T +$ jets
  - Lepton+jets and dileptonic decays where e/μ is not identified;
  - Large acceptance to τ;
  - Large QCD background

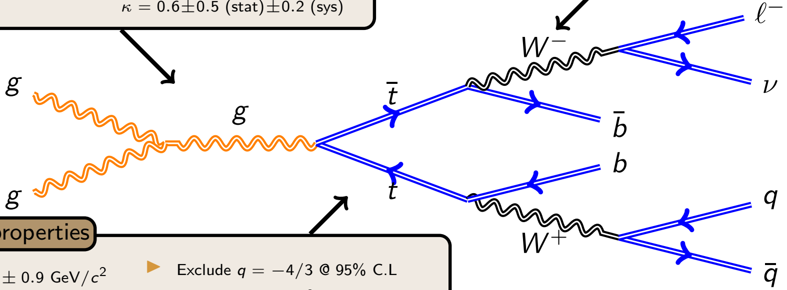
Top quark physics

Production properties

- $M_{Z'} > 900\ \text{GeV}/c^2$ @ 95% C.L.
- $M_{W'} > 800\ \text{GeV}/c^2$ @ 95% C.L.
- $M_{b'} > 372\ \text{GeV}/c^2$ @ 95% C.L.
- $F_{gg} = 0.07^{+0.15}_{-0.07}$ (stat+sys)
- $A_{fb} = 15 - 40\%$ (parton level)
- Spin correlations: $\kappa = 0.6 \pm 0.5$ (stat) ± 0.2 (sys)

Decay properties

- $V_{tb} = 0.91 \pm 0.11$ (exp) ± 0.07 (theory)
- No evidence for charged Higgs
- $f_0 = 0.67 \pm 0.10 \& f_+ = 0.02 \pm 0.05$
- $\mathcal{B}(t \to Zq) < 3.3\%$ @ 95% C.L.
- $\mathcal{B}(t \to gu) < 0.2\%$ @ 95% C.L.



Intrinsic properties

- $M_t = 173.2 \pm 0.9\ \text{GeV}/c^2$
- $M_t - M_{\bar{t}} = -3.3 \pm 1.7\ \text{GeV}/c^2$
- $\Gamma_t < 7.5\ \text{GeV}/c^2$ @ 95% C.L.
- Exclude $q = -4/3$ @ 95% C.L
- $M'_t > 335\ \text{GeV}/c^2$ @ 95% C.L
- No evidence for scalar top or top + dark matter

Top quark physics: production properties

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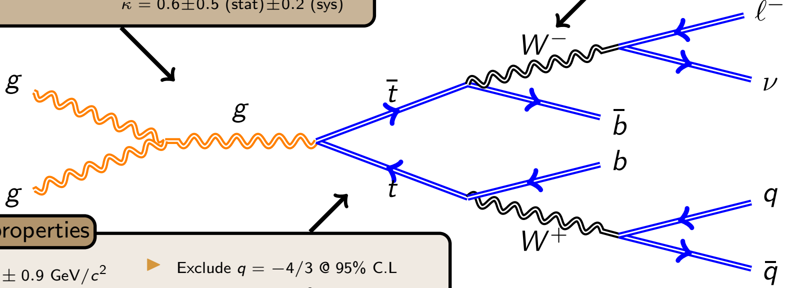

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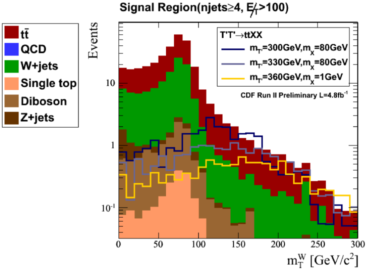
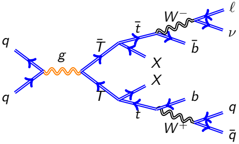
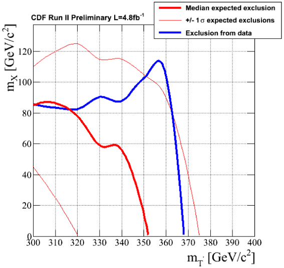
Dark matter with top quarks in lepton + jets [4.8fb^{-1}]

- Dark matter could couple to SM particles, and thus be produced at hadron colliders;
- Search for $p\bar{p} \to t\bar{t} + X\bar{X} \to b\ell\nu\bar{b}q\bar{q} + X\bar{X}$;



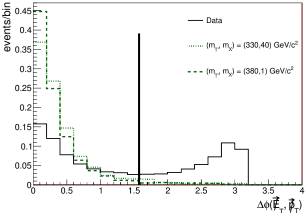


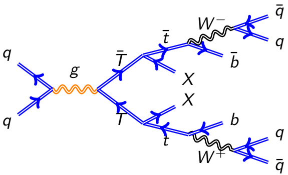


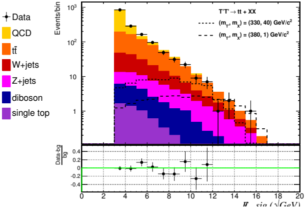
Excluding $m_{T'} < 360\ \text{GeV}/c^2$ for $m_X < 100\ \text{GeV}/c^2$ at 95% C.L.

[New EPS2011] Dark matter with top quarks [5.7fb^{-1}]

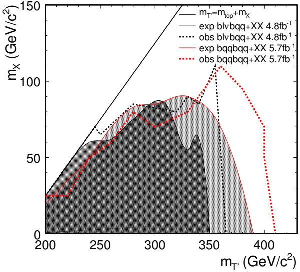
- Search for $p\bar{p} \to t\bar{t} + X\bar{X} \to bq\bar{q}\bar{b}q\bar{q} + X\bar{X}$ with $5 \leq N_{jets} \leq 10$;







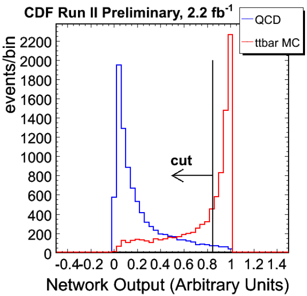
- Missing momentum flow ($\not{p}_T$, tracker) is complementary to ($\not{E}_T$, calorimeter);
  - They are correlated for events with a missing particle, e.g. neutrino;
  - They are either correlated or anti-correlated in case of a mis-measured jet (main bkg.);
- Data-driven QCD model from $\Delta\phi(\not{E}_T, \not{p}_T) > \pi/2$ region;

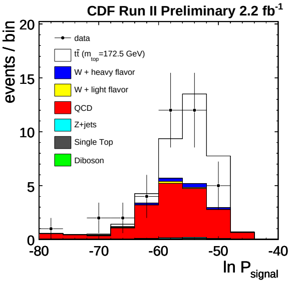


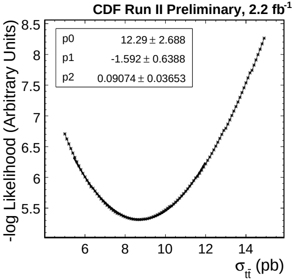
Excluding $m_{T'} < 400$ GeV/c^2 for $m_X \leq 70$ GeV/c^2 @ 95 % C.L.

- Cross-section and top mass measurement in τ+jets;
- Probing top properties in a channel possibly sensitive to new physics;
- First measurement of the top mass in the τ+jets channel;
- Using neural network to remove dominant QCD background;

$$\sigma(t\bar{t}) = 8.8 \pm 3.3 \text{ (stat)} \pm 2.7 \text{ (syst) pb}$$
$$M_t = 172.7 \pm 9.3 \text{ (stat)} \pm 3.7 \text{ (syst) GeV}/c^2$$





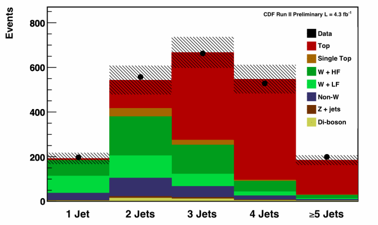


Top cross-section in lepton+b-jets [4.3fb^{-1}]

Counting experiment after background understanding:

- W+HF cross section underestimated in the MC: W+HF content measured in data in the 1 or 2 jet event sample
- b-tagging mistag rate measured in data, parametrization applied to W+jets;
- CDF measures ratio of $t\bar{t}/Z \to \ell\ell$ with the same trigger and use the theoretical Z cross section to remove the uncertainty due to luminosity measurement

PRL 105 012001 (2010)



$$\sigma(t\bar{t}) = 7.32 \pm 0.36 \text{ (stat)} \pm 0.59 \text{ (syst)} \pm 0.14 \text{ (Z theory) pb}$$

Top cross-section in lepton+jets [4.6fb^{-1}]

One step further: signal/background discrimination:

- $t\bar{t}$ more energetic, central and isotropic than W+jets
- NN input variables: H_T, aplanarity, sphericity, etc.
- Template fit of $t\bar{t}$ and W+jets to the discriminant output
- CDF measures ratio of $t\bar{t}/Z \to \ell\ell$ with the same trigger and use the theoretical Z cross section to remove the uncertainty due to luminosity measurement

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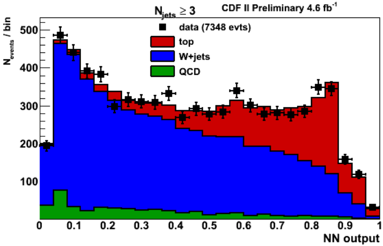
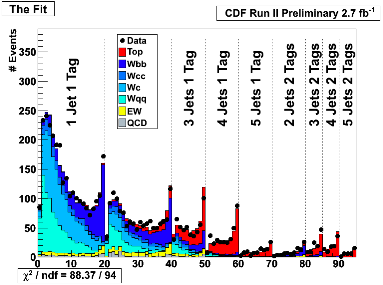


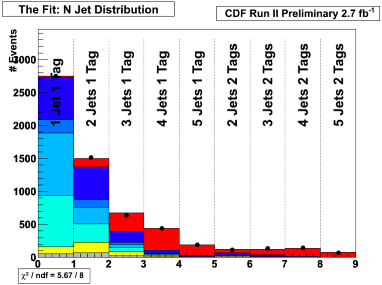
$$\sigma(t\bar{t}) = 7.82 \pm 0.38\ (\text{stat}) \pm 0.37\ (\text{syst}) \pm 0.15\ (\text{Z theory})\ \text{pb}$$

Top cross-section in lepton+jets: simultaneous S & B fit [2.7fb^{-1}]

Looser event selection, better constraint on backgrounds

- Use events with 1lepton, $\geq$1jet, $\geq$1b-tag to measure signal cross section and background contributions;
- Templates: NN based flavor separator, N_{jets}, $N_{b-\text{tags}}$;
- Simultaneous in situ fit for $\sigma(t\bar{t})$, W+HF fractions and systematic sources;
- Potentially very sensitive as more data is added;

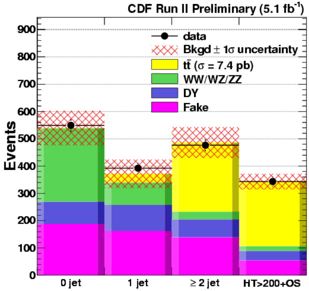


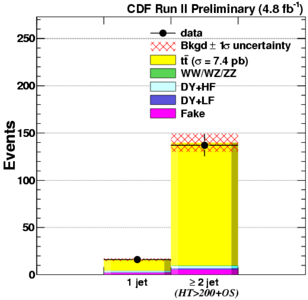


$$\sigma(t\bar{t}) = 7.64 \pm 0.57\ (\text{stat+syst}) \pm 0.45\ (\text{lumi})\ \text{pb}$$

Signal/background discrimination

- H_T and $\not{E}_T$ significance cuts, or b-tagging

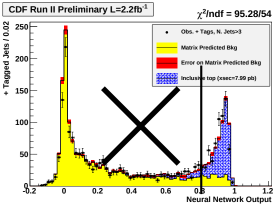


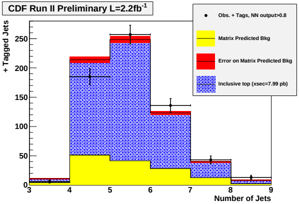


$$\sigma(t\bar{t}) = 7.40 \pm 0.58 \text{ (stat)} \pm 0.63 \text{ (syst)} \pm 0.45 \text{ (lumi) pb [pre-tag]}$$
$$\sigma(t\bar{t}) = 7.25 \pm 0.66 \text{ (stat)} \pm 0.47 \text{ (syst)} \pm 0.44 \text{ (lumi) pb [tagged]}$$

$\not{E}_T$+jets: alternative way to τ channels, and recover unidentified e/μ

- Independent from lepton+jets channel
- At least 3 strict identified jets, at least one b-tagged jet;
- NN trained against background, $NN > 0.8$ background estimation;
- b-tag rate/misrate from data in a 3 jet sample (small signal contamination);
- Counting experiment: counts the number of b-tagged jet;

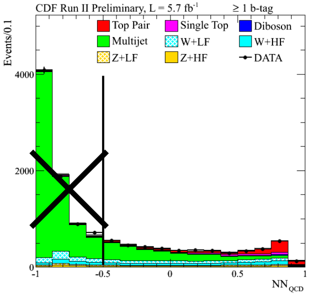


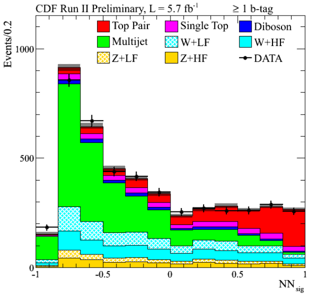


$$\sigma(t\bar{t}) = 7.99 \pm 0.54 \text{ (stat)} \pm 0.76 \text{ (syst)} \pm 0.46 \text{ (lumi) pb}$$

Top in $\not{E}_T$+2 b-jets [5.7fb^{-1}]

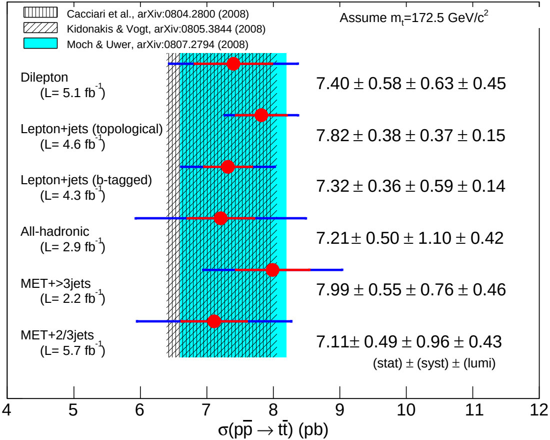
- Many new particles can appear here
  - Higgs ($ZH \to \nu\nu b\bar{b}$); SUSY: $\tilde{b}\bar{\tilde{b}} \to b\tilde{\chi}^0\bar{b}\tilde{\chi}^0$;
  - Technicolor: $\rho_T^{\pm} \to Z\pi_T^{\pm} \to \nu\nu b\bar{q}$; Third generation leptoquarks;
- $\sigma(t\bar{t})$ measurement here is a test of the backgrounds for Higgs and NP;
- Independent from other measurements: can be combined easily;
- Using same strategy as in search for $ZH \to \nu\nu b\bar{b}$:
  - Suppress overwhelming QCD background using multivariate technique (NN)
  - Isolate the signal from remaining backgrounds, likelihood scan of NN output





$$\sigma(t\bar{t}) = 7.11 \pm 0.49 \text{ (stat)} \pm 0.96 \text{ (syst)} \pm 0.43 \text{ (lumi) pb}$$

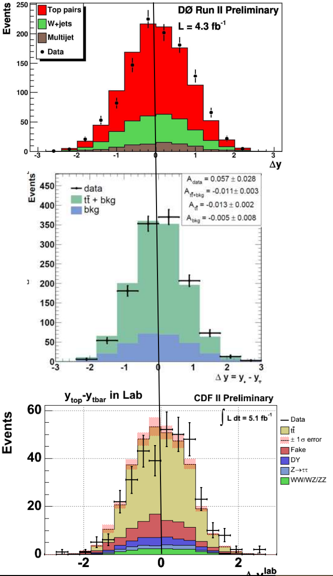
Summary of cross-section measurement at CDF



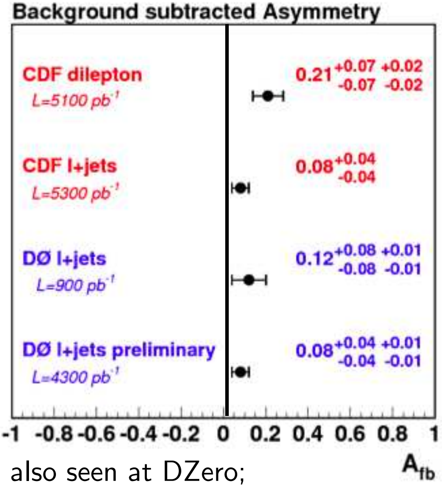
This is still the state of the art!

Results are consistent, and the best channel (lepton+jets) is precise to 6.5%: strong constraint on new physics models.

Top quark charge asymmetry: A_{fb} (at the Tevatron)



Any new physics scenario must to contend with precisely measured $t\bar{t}$ properties.



Effect also seen at DZero;

More in talks on Saturday;

Top quark physics: decay properties

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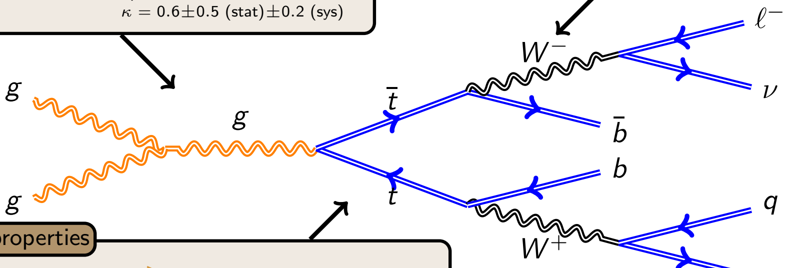

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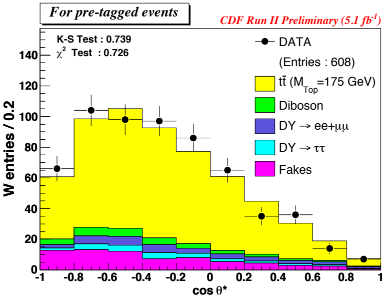
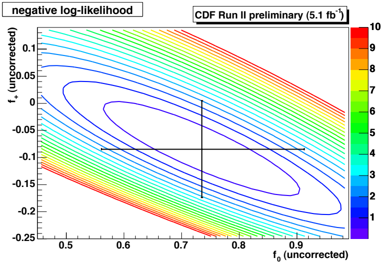
- First model-independent, simultaneous measurement of *W* boson helicity exclusively in dilepton channel;
- Combination of measurements from untagged and tagged samples;





$$f_0 = 0.74^{+0.18}_{-0.17}(\text{ stat}) \pm 0.06 \text{ (syst)};\ f_+ = -0,09 \pm 0.09(\text{ stat}) \pm 0.04 \text{ (syst)}$$

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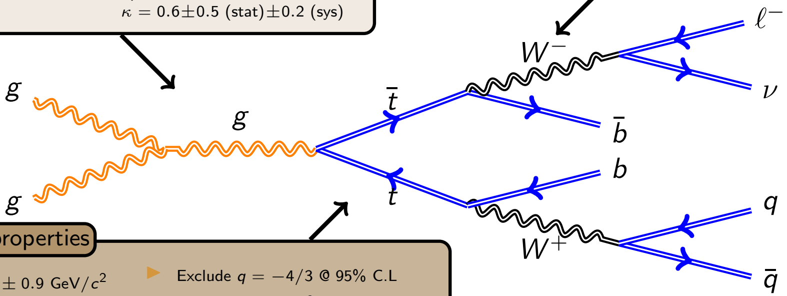

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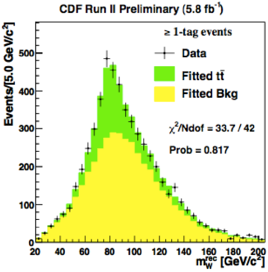
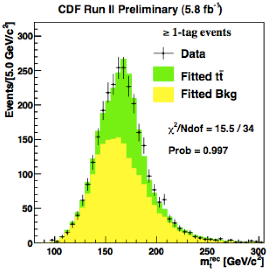
M_t in $t\bar{t} \to b\bar{b}q\bar{q}q\bar{q}$

- Using b-tagging and multivariate techniques to isolate the signal from the overwhelming QCD background;
- Jet energy scale (JES) is the largest systematic uncertainty;
  - Using $W \to q\bar{q}$ decays to constrain it in situ;
- Fully reconstruct the kinematics so to reconstruct the top quark mass;

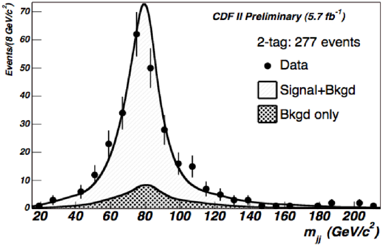
$$M_t = 172.5 \pm 1.7 \text{ (stat+JES)} \pm 1.2 \text{ (syst) GeV}/c^2$$



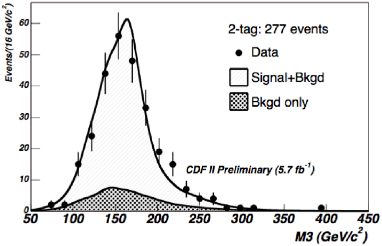


M_t in $t\bar{t} \rightarrow b\bar{b}q\bar{q}\not{E}_T$

- Limited lepton ID mostly due to limited detector coverage;
- But $t\bar{t}$ has striking kinematics:
  - Still possible to reconstruct one W and one top in this final state;
- Background modeled from low-end of NN separating $t\bar{t}$from data;



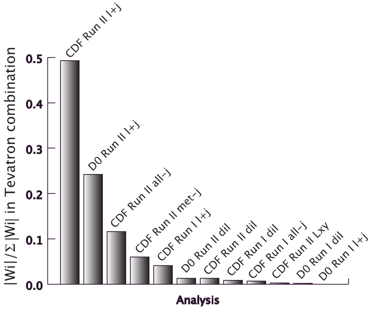
Dijet pair closest to W mass to measure jet energy scale.

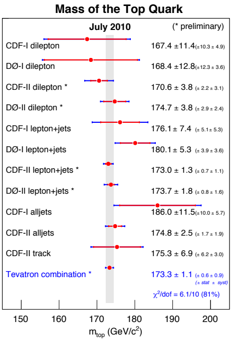


Reconstruct one of the two decaying top to measure the top quark mass.

$$M_t = 172.3 \pm 2.4 \text{ (stat+JES)} \pm 1.0 \text{ (syst) GeV}/c^2$$

Summer 2010 Tevatron top mass combination





Combining over 5,000 top pair events from orthogonal datasets.

$$M_t = 173.3 \pm 1.1 \text{ GeV}/c^2 = 173.3 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)}$$

Summer 2011 combination expected soon!!!

Precision of about 1 GeV/c^2!!!

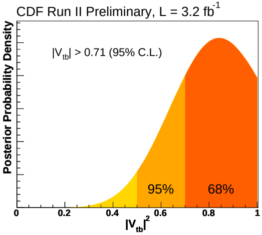
Summary

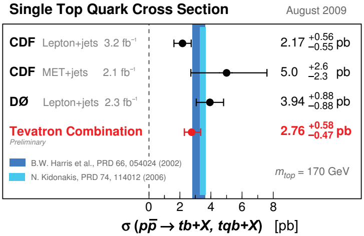
- Sixteen years after its discovery, the CDF/Tevatron dataset helped expand our knowledge of the top quark, thanks to extensive measurements of top quark intrinsic properties, study of its production and decay;
- With the LHC results, Tevatron will still play an important role:
  - Some Tevatron measurements – its mass! – have broad impact to our field, and will be a long standing legacy;
  - Others such as charge asymmetry, spin correlations are complementary to the LHC program
- Study of forward-backward asymmetry of top events shows discrepancy with current NLO QCD prediction.
  - Waiting for NNLO calculation.
  - Also, twice the data available to soon confirm or disprove the existing excess!
  - More about this in Saturday sessions;

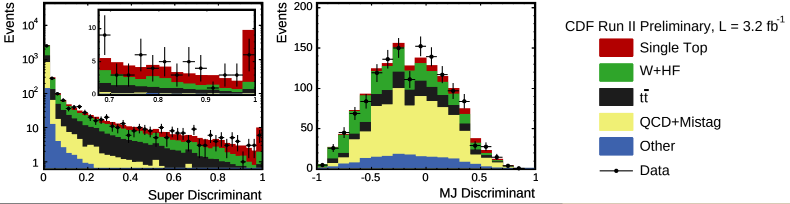
More results and details on our webpage:

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

- Single top was observed in 2009 by both Tevatron experiments;
- CDF used up to 3.2fb^{-1}; Was this updated ?
- We are working on an update with more than twice the dataset;
  - Will likely be ready for Lepton-Photon: stay tuned!







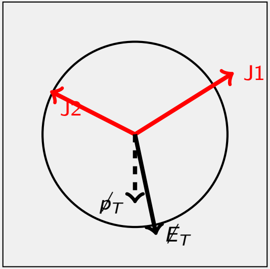
Backup Slides

Intrinsic $\not\!\!E_T$ vs. instrumental $\not\!\!E_T$

How we measure $\not\!\!E_T$

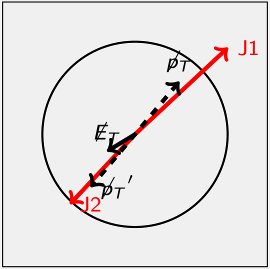
- Typically provided by the transverse energy imbalance ($\not\!\!E_T$) in the **calorimeter**;
- We also use the **transverse momentum flow imbalance** ($\not\!p_T$) from the **spectrometer**;
  - $\not\!p_T$ largely correlated with $\not\!\!E_T$ in presence of neutrinos (or $\tilde{\chi}^0$, etc.);
  - Very different for instrumental $\not\!\!E_T$: $\not\!p_T$ and $\not\!\!E_T$ either correlated or anti-correlated;

Exemple: $ZZ \to \nu\nu b\bar{b}$



[$\not\!\!E_T$ aligned to $\not\!p_T$]

Example: QCD $b\bar{b}$



[$\not\!p_T$ is not aligned to $\not\!\!E_T$]